A CASE STUDY IN PLATELET INVENTORY MANAGEMENT†

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Abstract. Transfusion science has recently recognized several blood components which are useful in treating specific patient problems. The change from whole blood transfusions to blood component transfusions has resulted in regional blood centers spending more time and money extracting and managing blood inventories.

Platelets are a type of blood cell which can be transfused to seal a patient's bleeding blood vessels. Blood centers extract platelets from a donated unit of whole blood through a costly process which must be started within a few hours of donation. Each platelet unit has a transfusable lifetime of only five days, after which it must be destroyed. These characteristics make platelets a difficult product to manage efficiently.

Hospitals and regional blood centers struggle to maintain an adequate stock of platelets while minimizing the high cost of platelet outdating. Finding a balance between these conflicting objectives is difficult; the situation is complicated by batch demands (patients generally receive transfusions in doses of six to eight units) and by short platelet life spans. This paper examines one regional blood center in the Chicago area, its current demand-driven platelet inventory management system, and the effectiveness of implementing periodic review inventory policies.

Key words. Health Care – Blood Bank: Inventory

1. Introduction. Human blood inventory management problems are characterized by several complicating factors, including product perishability, supply uncertainty, demand stochasticity, and high shortage costs. These factors have attracted the attention of numerous researchers who, as a result, have extended the boundaries of inventory management theory (see [9]).

Recent advances in medical technology, changes in the blood bank industry, and the emergence of the AIDS epidemic have further complicated the blood inventory management problem. The United States blood supply is shifting (see [3, 10]), leaving blood banks to compete for donors as well as hospital clients. Competition forces blood banks to lower product prices, while increasing governmental regulation raises production costs. Transfusion science has made it possible to separate each donated whole blood unit into components, so that patients receive transfusions appropriate to their needs. Blood inventory management problems are now characterized by higher costs, tighter supplies, and multiple products, each of which has a fixed life span, a distinct (and often time-sensitive) production process, a specific set of storage requirements, and a stochastic demand which varies across hospitals.

In this paper, we examine the issues relating to blood inventory management for one blood component, allogenic platelets. Working with a blood bank in the Chicago area, we are able to evaluate the current state of platelet inventory management by developing appropriate performance measures. Utilizing blood bank data and survey responses, we are able to assess the ordering practices followed by the blood bank's 35 client hospitals. Building on results from inventory theory, we implement a deterministic event simulation to evaluate a number of policy options for improved platelet inventory management. Finally, we consider the status of the blood bank's information systems and capital investment capabilities and suggest an appropriate course of action.

2. Current Management Strategies.

2.1. Allogenic Platelets. Initial discussions with blood bank personnel identified allogenic platelet inventory management as a costly, inefficient area of daily operations. A multi-stage, time-sensitive production process makes platelets expensive to produce. Once extracted, a platelet unit has a transfusable life span of only five days, with a typical transfusion requiring six to eight type-compatible units. The demand for platelets is stochastic and extremely volatile due to this batch arrival process. Platelets are used for patients undergoing open heart surgery and for those with blood clotting problems, indicating a high cost (in terms of increased patient risk) for unmet demand. Blood bank personnel calculated that over 20 percent of platelet units produced are destroyed due to outdating because of excessive hospital inventory levels. This high rate of outdating incurs a tremendous cost to the blood bank and wastes scarce production resources.

Current blood bank accounting policies charge hospitals for platelet units as they are shipped. Units returned before outdating are credited back to the hospital. (In some cases, hospitals even receive credit for returned outdated units.) The blood bank established these policies because of the uncertainty inherent in platelet transfusions. A hospital may place an order for units required by a surgical patient, but complications or changes in treatment may make these units unnecessary.

In effect, what the blood bank has implemented is a pseudo consignment policy, wherein hospit-

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The research reported here was supported by the National Science Foundation through NSF Grants No. DDM-922 4998 and DMI-952 3048. Additional support was provided by a grant from Heartland Blood Centers, Aurora, IL.

als only pay for those units which are transfused. Typically, consignment strategies are beneficial because they provide the supplier with inventory mobility while providing the customer with immediate product access. The blood bank's policy does nothing to provide inventory mobility. The blood bank relinquishes control of platelet units upon shipment and regains it only after receiving hospital returns. Hospitals pay no direct cost for excessive ordering, while the blood bank pays production and shipping costs for all units that outdate. Overall, this policy increases operating costs and shrinks profits for the blood bank, as only a fraction of costs can be passed on to client hospitals in this competitive market. The goal of this study is thus to develop more appropriate policies which discourage excessive hospital ordering and decrease platelet outdates while maintaining customer satisfaction.

2.2. Platelet Data Collection. Policy formulation required first capturing the demand and usage patterns for platelet units at the blood bank's 35 client hospitals. Shipping system records provide a comprehensive picture of hospital ordering practices, specifying the urgency (stock, asap, or stat) of orders placed and the number and blood type of units shipped in response. Unfortunately, the shipping records retained by the blood bank are incomplete and thus, in order to maintain reasonable data integrity, we were forced to extract data from accounting system records. From this system, we were able to determine the number and blood type of platelet units charged (i.e., shipped) to each hospital daily, during the period July 1, 1995 to June 15, 1996. We were also able to determine the number of those shipped units which were later credited (i.e., returned).

To simplify the data analysis, we aggregated charges and credits across blood types and worked primarily with data for generic allogenic platelet units. To capture the pattern of transfusions and inventory levels for client hospitals, we made the following assumptions:

1. All units are shipped to hospitals fresh (with five days of transfusable life remaining)
2. All returns occur three days following the original shipment
3. Units are transfused uniformly over the days between shipment receipt and return.

Under these assumptions we calculated daily estimates of the number of units shipped to each hospital, the number of units transfused to patients, the number of units returned to the blood bank, and the number of units remaining in inventory.

We extracted the percentage of units ordered stat from the shipping system and applied it to the shipments accounted for above, assuming reasonable consistency in ordering practices. Finally, we surveyed hospital blood bank supervisors on hospital policies for setting target inventory levels, ordering blood products, selecting units for transfusion, and returning units to the regional blood bank. This information, combined with the data described above and personnel interviews, gave us a detailed picture of current platelet inventory management practices.

2.3. Inventory Management Performance. To evaluate current inventory practices, we first established useful measures of performance. Through our initial data analyses, we identified an inverse relationship between the percentage of stat units ordered and the percentage of units returned. This relationship captures the tradeoff hospitals face when establishing platelet inventory levels. Low inventory levels will result in a high transfusion rate and few outdates, but will require more units to be delivered stat. High inventory levels will be replenished through stock orders based on expected patient demand which, if inaccurate, will result in high returns. These measures are also of interest to the blood bank, which must balance the costs of outdating against the cost, flexibility, and transportation resources required by stat orders.

In evaluating each hospital's performance according to these measures, the statistics revealed a wide range of inventory practices. The percentage of returns ranged from 4 to 52 percent, and the percentage of stat units ranged from 2 to 33 percent. Some of this variability can be attributed to differences in hospital size and patient populations, but surveys also revealed hospital policies, practices and attitudes that account for these vast differences. For example, one hospital attempts to hold enough inventory to respond to a trauma during the hour that it takes for a stat delivery to arrive, while another hospital sets target inventory levels according to the highest reported daily usage for the previous month. Other hospitals set target levels for a variety of reasons, with one supervisor reporting a policy of, "If the refrigerator looks bare, order blood!"

These practices result in a chaotic management scheme for the regional blood bank. The size, number, and urgency of orders varies across hospitals and from day to day. Additional energy must be expended to manage the flow of returns and outdates back to the blood bank, where credits are issued and units are destroyed. While most hospitals reported using a first-in-first-out (FIFO) inventory depletion strategy, many supervisors reported policies that return units having one or two transfusable days remaining. Since fresh platelets have a life span of only five days, these policies waste 20 percent of the unit's usable life (unless the blood bank is able to reship returns to another hospital.)

Overall, these results describe a system of hospitals joined only by a common supplier. Each follows its own practices, established by its own logic, to assure continuation of its own daily procedures. The inefficiency in such a system is apparent in high transportation costs, personnel requirements, and outdate rates.

3. Improved Management Strategies. To improve inventory management strategies, we needed to do more than simply improve performance along the measures identified above. The blood bank's executive board is composed of a number of officials, over fifty percent of whom are client hospital executives. Any policy changes must be approved by the board, which has historically disapproved of policies charging additional costs to hospitals. The policy we suggest must therefore provide an incentive for more accurate hospital ordering without incurring any additional hospital costs.

An appropriate inventory strategy must also consider the blood bank's limited resources. Not only is the blood bank limited in capital available for large-scale project investment, but also in computer resources for monitoring sophisticated inventory strategies. (For example, the primary means of communication between hospitals and the blood bank is via telephone, so real-time monitoring of systemwide inventory levels is not feasible.) Thus, we focused our search for improved inventory management strategies on easily implemented, low cost, low technology solutions.

3.1. Hospital Risk Pooling. Large day to day variations in transfusion levels surfaced as volatile peaks and valleys in client hospitals' transfusion patterns. These images led us first to consider risk pooling as a method of smoothing out inventory levels. By clustering the hospitals into groups and aggregating transfusion levels within each group, we expected the variance in daily transfusion levels to drop. Implementing an inventory policy which takes advantage of risk pooling effects requires that all hospitals within a group draw from a common inventory pool. Fulfilling this requirement forces a shift in transportation resources. Currently the blood bank makes multiple deliveries to each of its client hospitals, including stat shipments made by taxicab. Under a clustered policy, the blood bank would supply one location for several hospitals, with more consistent delivery sizes and frequencies. Additional transportation would be required between the inventory pool and each of the group's hospitals, including taxicab service to supply hospitals with stat platelets from the inventory pool. Reducing overall inventory transportation costs therefore requires that hospitals be clustered to minimize the number and length of trips between the inventory pools and their assigned hospitals.

P-median problems involve finding the location of P facilities on a network so that the total cost is minimized, where the cost of meeting a demand at a node equals the quantity of demand at the node times the distance between the node and the nearest facility. The problem further requires that all nodes be served by exactly one facility, and it has been proven that at least one optimal solution locates the facilities on network nodes. We can thus solve a P-median problem with a network of hospitals and blood bank facilities, using accounting-based demand data and distances measured between actual locations. The solution obtained will locate inventory pools at some set of P nodes, and will assign hospitals to exactly one pool in a way which minimizes the demand-weighted distance between hospital and inventory pool.

We first compiled a distance matrix of blood bank facilities and client hospitals*, and then assigned hospitals demand values corresponding to the hospital's total demand for the period July 1, 1995 through June 15, 1996. Using SITATION (in [1]), we solved the corresponding P-median problem, identifying ten potential inventory pool locations and hospital group assignments. Comparing the coefficients of variation for mean shipment levels, we found the expected variance reduction which should translate into more accurate platelet demand predictions.

Aggregating charges and credits within each cluster, we captured group transfusion and inventory patterns. Unfortunately, clustering hospitals into groups does nothing to insure that platelet inventories are managed effectively. If a hospital which orders excessively to meet its own demand must now manage a platelet inventory serving several hospitals, explosive platelet ordering is likely to bring increased outdating. To benefit from hospital clustering, the blood bank must determine the appropriate platelet inventory levels for each hospital group and establish policies for implementation.

3.2. Inventory Policy Selection. Inventory theory includes several models for managing perish-

* Distances were obtained using a map of Illinois and the program Trip Quest, Copyright 1996 GeoSystems Corp., Inc. Trip Quest is an automated route finder located in Sept. 1996 at http://www.mapquest.com.

able product inventories (see [6, 5, 7]). These models are primarily based upon dynamic programming formulations involving multidimensional state variables, and thus are computationally impractical for real problem instances. Our desire to find implementable policies thus led us to more classic inventory theoretic results. (s, S, t) policies have long been supported for managing general product inventories with stochastic demands (see [4]). In such a policy, the product inventory level is reviewed every t periods, and if inventory is less than s, an order is placed to bring inventory up to S. The performance of such policies depends on the selection of appropriate values for parameters s, S, and t. Theoretical methods have been developed for determining optimal parameter values, requiring an explicit statement of the demand distribution, inventory cost functions, and other problem specifications (see [4]).

As described, (s, S, t) inventory policies are an attractive option for managing platelet inventories. Although parameter values would vary between hospitals, these policies would be a tested standard for hospitals to follow. A system based on periodic review would end the constant stream of platelet orders, and would allow the blood bank to maintain a tentative schedule for deliveries. Although occasional stockouts would require additional stat orders, the number of these costly trips should be reduced significantly from current levels. Additionally, the implementation of such policies is relatively simple. The blood bank would assign parameter values s, S, and t to all hospitals holding platelet inventory, and the hospitals would monitor inventory and place orders accordingly. No additional equipment is required, no expensive information systems are needed, and only minimal training is necessary to complete implementation.

The blood bank must still determine appropriate parameter values for each inventory facility and must convince hospitals of the effectiveness of such policies. As noted above, theoretical methods for establishing optimal parameter values require extensive input about the demand process and other system characteristics. Capturing the actual demand distribution is a difficult numerical analysis task, and was beyond the scope of the current study. In order to determine appropriate parameter values, we instead developed a deterministic event simulation to test the performance of a wide range of parameter values on the transfusion data described above. While such a program will not establish the theoretical optimum values, it will determine parameter values which perform well in the real system.

3.3. Deterministic Event Simulation. The deterministic event simulation takes as inputs current performance measures, upper bounds for improved policy performance (set arbitrarily below the current measures to ensure policy improvement), and transfusion values for the period July 1, 1995 to June 15, 1996. We examine a variety of parameter combinations, with t ranging from 1 to 5 (deliveries spaced more than 5 days apart insure stockouts, as the platelet life span is only 5 days), S ranging from 1 to t times the maximum daily transfusion rate reported, and s ranging from 1 to S. For each combination, the policy is implemented. All units ordered are assumed to be received fresh and are outdated five days later, if not used. We assume that hospitals follow a FIFO inventory depletion policy. Finally, statistics are calculated and if the policy parameter combination shows significant improvement in the performance measures (as determined by upper bounds), policy statistics are recorded.

The simulation was run for each group of hospitals, using aggregated transfusion numbers and performance statistics. Simulation results listed for each group the (s, S, t) policies which would improve the group's inventory management performance. One hospital group showed no parameter combinations which would improve inventory management. The low demand for platelets experienced by the hospitals in that group made storing platelets for these hospitals unprofitable. Graphing each (s, S) parameter combination as a point on a graph for a fixed t value with axes associated with performance measurements, tradeoff curves were developed for each of the remaining nine groups. These graphs illustrate the benefits gained by implementing various (s, S, t) policies and the tradeoffs between stat orders and platelet outdates.

The simulation was also run for each individual hospital, in order to distinguish improvements made by implementing policy changes from improvements gained by first clustering hospitals and then making policy changes. Simulation results reported policies that showed improvement on both performance measures for twelve client hospitals. Tradeoff curves for each of these hospitals show multiple improved policy parameter combinations and illustrate the balance between stat orders and outdated units.

Selecting a good combination of parameters involved selecting a point on the tradeoff curve which represents the desired levels of performance. Color coding S values on each tradeoff curve clarified the effect of selecting one parameter over another. Increasing the value of S increases the percentage of outdates while decreasing the value of s typically in-

		Units Ordered	Mean Inventory	Inventory Variance	Stat Units	% Stat Units	Returns/ Outdates	% Units Retn./Outdt.
Group 1	- Current	4077	14.7	102.3	1308	32.1	548	13.4
	- (s,S,t)	3749	16.6	79.5	258	6.9	206	5.5
Group 2	- Current	9278	44.0	364.2	1576	17.0	3104	33.5
	- (s,S,t)	6457	31.9	224.4	187	2.9	233	3.6
Group 3	- Current	5380	29.5	169.4	269	5.0	2507	46.6
	- (s,S,t)	3476	22.4	101.2	157	4.5	569	16.4
Group 4	- Current	5322	19.6	130.4	1284	24.1	795	14.9
	- (s,S,t)	4821	21.6	132.7	289	6.0	280	5.8
Group 5	- Current	5184	17.8	160.1	1452	28.0	550	10.6
	- (s,S,t)	4913	24.8	138.9	247	5.0	239	4.9
Group 6	- Current	5802	18.1	156.1	1335	23.0	282	4.9
	- (s,S,t)	5748	23.1	161.2	321	5.6	200	3.5
Group 7	- Current	3651	16.6	117.4	657	18.0	1092	29.9
	- (s,S,t)	2923	14.2	65.2	212	7.3	355	12.1
Group 8	- Current	3046	11.8	78.2	809	26.6	571	18.7
	- (s,S,t)	2627	11.3	41.3	200	7.6	160	6.1
Group 9	- Current	3498	14.8	66.4	883	25.3	847	24.2
	- (s,S,t)	2915	13.5	53.1	170	5.8	246	8.4

Table 1: Group Policy Performance Comparison

creases the percentage of stat orders. Increasing the period length t shifts the entire tradeoff curve outward. From these observations, and the desire to smooth out the blood bank's platelet inventory operations, parameter combinations were selected for each of the nine hospital groups using a period of 2 days. Similarly, policy parameters were selected for the twelve hospitals whose simulations uncovered policy improvement options.

3.4. Improved Performance Measures. Minor alterations to the simulation program recorded additional information on the selected policies' performance, including a report of daily inventory levels, standard and stat shipments, and total units shipped. From this data we were able to quantify the change in performance through a number of measures. Table 1 illustrates the performance improvements found for the various groupings of client hospitals.

3.5. Policy Performance Testing. To test the performance of the (s, S, t) policies against current inventory practices, we examined the performance of each on an independent set of transfusion data. The blood bank supplied a test set of accounting data, including platelet charges and credits, for the period June 16, 1996 to September 1, 1996. Following the same methods as described above, daily transfusion values were calculated from the test data set for this period. The altered version of the simulation program was then run for the nine groups and twelve individual hospitals with selected (s, S, t) policies, reporting values for the performance measures described above. Current performance values were calculated for the test data set as well, and validation of the improvements reported above was completed.

4. Suggested Improvements. The benefits of implementing (s, S, t) policies for either the nine hospital groups or the twelve individual hospitals have now been documented and tested. Clustering hospitals into groups condenses a set of 35 hospital inventories into nine inventory pools and six independent hospital inventories. This reduction in inventories carries with it a reduction in phone calls, a simplification of transportation routes, and an increase in communication between hospitals. Unfortunately, creating hospital clusters and managing inventory pools requires significant work with respect to implementation. Small hospitals must be convinced to relinquish control of their platelet inventories to large hospitals. Lines of communication between hospitals must be established and the benefits of policy changes must be experienced by hospital administrators through lower component prices, faster deliveries, and less inventory juggling. We consider this strategy to be the best for the overall blood bank system, its client hospitals, donors and patients, but several steps need to be taken before full scale implementation could be accomplished.

Executing (s, S, t) policies at a small number of individual hospitals could result in significant performance improvements, without incurring any of the implementation difficulties mentioned above. Simulation for some hospitals consistently suggest vast performance improvements in the areas examined above.

The high platelet volume circulating through the three largest hospitals constitutes 43 percent of platelet units shipped to the twelve hospitals during the test data period. Additionally, 65 percent of the reduction in platelet shipments due to (s, S, t) policy implementation were units saved by these three hospitals. Similarly, these three hospitals made up 753 of the 1221 unit reduction in platelet outdates when (s, S, t) policies were implemented and 218 of the 765 unit reduction in stat units ordered. Limited implementation would not allow the blood bank to take advantage of risk pooling effects, but it would be a step toward standardizing inventory policies and reducing the current system waste and expense.

5. Future Research. Before beginning implementation of any scale, the effects of multiple blood types must be considered. All analysis to date has focused on managing type-aggregated allogenic platelet units. Working with aggregate platelet transfusion figures allowed us to simplify the platelet inventory problem, enabling us to evaluate several policy options. Although it is beyond the scope of the current study to re-evaluate policies for each hospital and hospital group under multiple blood types, one hospital was examined to validate the effectiveness of (s, S, t) policies for type-specific inventory management. As expected, establishing separate (s, S, t) policies for each blood type worsened the hospital's performance on all measures, as compared to performance on the type-aggregated platelet unit policy. The results did continue to show improvement over current practices, however, and we expect that with more extensive data analysis, effective type-specific policies could be established. Additional research on the limited substitutability of platelet units of compatible blood types could also be used to make type-specific policies perform better.

Other areas for future research focus on the supply side of the platelet inventory problem. The (s, S, t) policies suggested assume that units ordered will be received in a timely manner. This assumption does not always hold in the blood bank industry, as shortages in supply occur frequently. Previous research has shown that for a limited supply, it is optimal to allocate inventory to make the probability of stockout equally likely for all clients (see [8]). Such a policy does not consider the special nature of platelet demand. Procedures requiring platelets vary, both in the number of units needed and in urgency to the patient. Following a strategy of equalizing risk of stockout may thus result in unnecessary loss of life. Further research on managing blood component inventories in times of supply shortage is thus necessary.

6. Conclusions. This study analyzes the management of one product at various hospitals served by a Chicago regional blood bank. Policies are suggested which can reduce the number of platelet units outdating while also reducing the number of units ordered on a stat basis. Combining these results with a system design for clustering hospitals into groups which share an inventory pool, we can also attempt to eliminate costly and wasteful returns, and to reduce the transportation costs associated with delivering blood components. Although several assumptions have been made to bypass data limitations, the extent of the improvements shown suggest that there is much room for improvement in current platelet inventory management practices. The (s, S, t) policies discussed are a low-tech strategy (requiring little or no capital investment) for beginning improvements.

Once implemented, these inventory management strategies should easily extend to other blood components and products. Platelets are an appropriate starting point, as their life span is the shortest of the blood components. When additional components are added, the blood bank can schedule inventory review periods to coincide with those previously established for platelets, aligning deliveries for all components to a hospital. Eventually, hospitals with enough volume to support holding inventory will have all components on such a schedule and the number of unscheduled telephone orders will be minimized.

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