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FOREWORD

The problems of operating a blood-supply system are universal in the sense described by Roger E. Levien, IIASA's Director: *"they lie within the boundaries of single nations and can be resolved by their individual actions, but are shared by almost all nations."*

This paper provides an overview of the theory and practice of blood management, based on the author's experience in developing models of blood-supply system operations and using them to assist in installing new blood-management procedures in a major system in the United States. It is of interest both as a contribution to the theory and practice of health-care management and as an excellent example of a successful case of applied systems analysis.

The paper is a concise record of a seminar given at IIASA on August 13, 1979.

As a potential contribution to the IIASA International Series on Applied Systems Analysis, Eric Brodheim and Gregory Prastacos are preparing a book that will be a comprehensive account of their work in this field and its results in application, as well as the work of others.

Dr. Prastacos is Assistant Professor of Decision Sciences at The Wharton School of the University of Pennsylvania; his colleague, Dr. Brodheim, is with the Operations Research Laboratory of the Lindsley F. Kimball Research Institute of the New York Blood Center. In May 1979 the authors won the 1979 International Management Science Achievement Award for their work in this field.

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BLOOD MANAGEMENT SYSTEMS
An Overview of Theory and Practice

by

Gregory P. Prastacos

I. INTRODUCTION

Blood is a living tissue of unique medical value to the human body. It is the vehicle that carries oxygen, nutrients and chemicals to all parts of the body, and carries away all waste products. It appears in 8 major blood types whose frequencies vary from 38% (O+) to 0.5% (AB-) in the human population. It is composed of several components (red cells, white cells, platelets, plasma), all of which can be extracted from whole blood through appropriate procedures. Each one of these components serves a separate function in the human organism, and has a different use in the medical treatment of patients. All of these components are perishable, with their lifetimes varying from 24 hours (platelets) to 21 days (red cells). In this paper we restrict our attention to the management of the supplies of whole blood and red cells, both of which have a lifetime of 21 days, and which, together, account for more than 95% of the transfusions that take place in the U. S. today.

Blood is collected in units of one pint per donor at collection sites such as a Regional Blood Center, a Hospital Blood Bank, or a mobile unit. When collected it undergoes a series of typing and screening tests, and, once processed, if needed (i.e., frozen or separated into components), it is shipped to a Hospital Blood Bank to be stored and be available to satisfy demands for transfusions to patients.

The Hospital Blood Bank operates as an inventory location, storing and issuing the appropriate blood units to satisfy transfusion requests. During the course of a day the Blood Bank receives a random number of transfusion requests for each blood type, each request for a random number of units. Once a request for a patient is received, the appropriate number of units of that type are removed from free inventory and upon successful crossmatching they are placed on reserve inventory for this particular patient. Any of those units that are not transfused are returned back to free inventory. We will define <u>demand</u> to be the number of units requested, and <u>usage</u> to be the number of units transfused. Any units which are not used within their 21-day lifetime are considered <u>outdated</u> and are discarded from inventory.

The problem of managing blood supplies can be examined at two levels: the individual hospital level, or the regional level. At the hospital level, the objective is to determine decision rules to be used by the Hospital Blood Bank's management for the daily operations of the Blood Bank. Such decisions would involve quantities to collect or order from the Regional Blood Center, units to issue from inventory against transfusion requests, portion of fresh units to be frozen so that their lifetimes are extended, and development of computer information systems to provide accurate and timely information and thus assist with the management of the Blood Bank's inventory management. At the regional level, the objective of a Regional Blood Center is to determine achievable targets of performance within a region, and to set up collection and distribution schedules that will achieve these desirable targets.

This paper presents an overview of the recent developments in both the theory and practice of blood inventory management, at both the individual hospital, and the regional levels. We feel that such a review is now needed in order to unify existing knowledge, assess the status of the field, and determine directions for further research. The paper is divided as follows: Section 2 presents a brief historical overview of the Management Science involvement in the field. Section 3 presents an overview of the techniques and models that are applicable to a hospital's inventory management, and Section 4 presents the ones applicable to the management of the regional resources. Our approach is not to present an exhaustive review of all the literature in the field, but rather to address several important issues, and compare and evaluate the achieved results. Hopefully, our reference list is fairly complete. Finally, Section 5 presents some conclusions and areas for further research.

II. BRIEF HISTORICAL OVERVIEW

Managing blood inventories is a very complex task. To realize the difficulty of this inventory problem as compared to most inventory problems, one has to see the following:

1. Blood is a perishable product having a lifetime of 21 days. Therefore, standard inventory theory results do not hold.
2. Its supply and demand are stochastic.
3. Its demand and usage at each hospital are different random variables.
4. There is a large variation in the sizes of hospitals to be served within a region. They range from those transfusing a few hundreds of units yearly, to others transfusing tens of thousands yearly.
5. There is a large variation in the kinds of operations, and the practices among hospitals. As an example, some hospitals transfuse almost always whole blood, whereas others almost always red cells.
6. There is a large variation in the distances involved. Some hospitals are a few hundred feet away from the Center, whereas others are as far as hundreds of miles.
7. There is a large variation in the frequency with which the 8 blood types appear.

Because of this complexity, management science and operations research techniques have been fruitfully used to come up with efficient management rules. The traditional theoretical and practical approach, until recently, has been to decompose a region into its individual hospitals, and determine efficient rules for each hospital. This approach established a decentralized mode of operations, where each hospital would call the Center in the morning in order to place an order for enough units so as to bring its inventories to "safe" values, without having to outdate a large number of units. The Center would try to meet most of these orders, keeping in mind the limited supply, and therefore keeping sufficient inventories back at the Center for future orders, and for emergencies. This uncertainty for both the Center (as far as the hospitals' orders) and for the hospitals (as far as which portion of their order would be met) imposed a competition between hospitals for their supply of blood, and resulted in poor utilization of the regional resources. In the 1971 national survey it was reported that 25% of the national volume of blood collected was outdated [17, 18]. In addition, instances of shortage were reported to be frequent, resulting in postponements of elective surgeries, and personnel and other resources were inefficiently used.

To address this problem, a National Blood Policy [48] was adopted in 1974 which called for "the introduction of systems management to blood service," and for the realization of the following four goals:

1. Adequate supply of blood,
2. Delivery of the highest quality blood service,
3. Patient accessibility to blood service regardless of economic status, and
4. Efficient collection, processing, storage and utilization of the national supply of blood and blood products.

This last goal means minimizing cost by reducing outdating, and establishing regional associations for the management and sharing of the regional blood supplies. This has been the thrust of most of the recent research.

III. HOSPITAL BLOOD BANK MANAGEMENT

(i) Statistical Analysis of Demand and Usage

In trying to determine efficient management rules for an inventory location, one has to analyze the statistical patterns of demand and usage at that location, and derive probability models that can confidently describe these patterns. To address this issue, massive data have to be collected and statistical techniques (e.g., fitting, hypothesis testing) have to be used to derive a model.

A significant amount of work has been done on determining these patterns for Hospital Blood Banks. Among them, Elston and Pickrel [24], Rabinowitz and Valinsky [65] and Yen [69] derived demand models for individual hospitals, and Brodheim, Hirsch and Prastacos [8, 62] have analyzed data from groups of several hospitals, and compared established universal models of demand and usage.

The results indicate that the daily demand pattern is the compound distribution of the number of daily requisitions (N), and the size of each requisition (n), where N is a Poisson random variable, and n is a modified lognormal random variable. The usage U out of a request of size n can be approximated by an exponential-type truncated probability distribution. The reader is referred to [62] for a comprehensive presentation of these results.

(ii) Ordering Policies

Probably the most important management policy in any inventory location is the location's ordering policy. This policy determines the frequency and the size of the orders to be placed by the location (Hospital Blood Bank) to the supplier (Regional Center). The problem is very important in blood management, since the Blood Bank Administrator has to have enough quantities available in stock so as to meet most of the demand, without being forced to outdate an excessive number of units.

A number of theoretical and empirical studies have addressed this problem. The theoretical problem is as follows: Given unit penalty costs s and w to be paid by the Hospital Blood Bank for any units short or outdated, and known probability distributions for the demand and usage of blood at the hospital, determine the optimal ordering policy so as to minimize the total expected average cost.

To our knowledge, all analytical research on this problem has addressed this issue for general perishable products, and has thus made the simplifying assumption that demand and usage are identical. Nahmias [41, 44], Nahmias and Pierskalla [45, 46] and Fries [27] determined the optimal ordering policy for a product with a general lifetime of m periods. They showed that the optimal policy is very complex, and to compute it one has to solve an (m-1)-dimensional dynamic program. In the case of blood, m is very high (m=21), and so a practical solution is extremely difficult to obtain. As a result of this, Cohen [12], Chazan and Gal [11], and Nahmias [43] have examined the simpler policies where the daily order is such as to bring the total inventory up to a certain level. Similarly, Brodheim, Derman and Prastacos [7] and Cosmetatos and Prastacos [15] have examined policies where a constant order is received daily by the hospital. Sensitivity tests performed by Nahmias [42] on the performance of the single critical number order policy, as compared to the optimal policy, indicated that this policy is very close to the optimal one, and therefore constitutes a good substitute.

Simulation, as well as other empirical methods, have also been extensively used in the evaluation of alternative policies and the derivation of optimal inventory levels. This approach offers the advantage of using accurate input data of a Hospital Blood Bank's history, and also of differentiating between demand and usage. This second feature gives a definite advantage to this approach, over the analytical models outlined above, in determining appropriate inventory levels for Hospital Blood Banks. Among the works using this approach we mention those by Elston and Pickrel [25], Brodheim, Hirsch and Prastacos [8], Cohen and Pierskalla [13, 14], and Rabinowitz and Valinsky [65].

(iii) Issuing Policies

Almost as important as the ordering policy is the issuing crossmatching policy used to satisfy requests for crossmatch. To see this one has to remember that blood is a perishable product, and that not all units issued are eventually transfused; instead, a significant portion (in most cases more than 50%) returns to inventory and is available for future requisitions.

Again, most analytical models have been developed for general perishable products, and have thus assumed that demand and usage are identical. For this case it has been shown [56] that issuing the oldest units first (FIFO) minimizes the average quantities short and outdated at the inventory location. Recently, Prastacos and Brodheim [62] took into account the difference between demand and usage, and developed an analytical model for issuing units in a decreasing age sequence from inventory (i.e., FIFO), but assigning them to the patients that maximize the likelihood of using them. They showed that this "modified FIFO-maximum likelihood to be used" policy (FIFO-MLU) minimizes outdating and shortages, and they ran simulation experiments to evaluate the improvement over pure FIFO.

Other sophisticated issuing policies are in use at many Hospital Blood Banks. The most common one is "double crossmatching," in which two patients of the same type share at least one unit in reserve. This policy has been examined, among others, by Rabinowitz [64]. Another policy that is often practiced and has been examined by Pegels et al. [53], is a mixture of FIFO and random issuing policy. No analytical models have been developed for these policies, but simulation has been extensively used to provide measures of their performance.

(iv) Other Management Policies

To improve the efficiency of the Hospital Blood Bank's operation, without reducing the quality of health care delivered to patients, two technological/management alternatives have been examined: (a) utilizing frozen red cells, and (b) changing the legal shelf life of whole blood and red cells.

Freezing red cells is a way of alleviating shortages caused by seasonal inventory imbalances, or unusually high demand for rare blood types. In addition, the technique of freezing-thawing has also been shown to provide red cells superior in oxygen transport capability to those of fresh blood [66]. However, the freezing process is very expensive, and, if implemented on a significant portion of the fresh units, it will increase the operating costs considerably.

Another way of extending the lifetime of blood is through the use os special blood bags containing citrate-phosphate-dextrose (CPD). In this case, the lifetime is extended to 28 days. This procedure is being used in Canada [53], and is also being partially implemented in the United States.

Pegels et al. [50, 53], Bodily [4], Cumming et al. [16], Elston [23], and Kahn et al. [37], among others, have conducted extensive simulation runs to examine the effect of the above policies on the hospital's blood inventory behavior. Their studies showed that the main effect of the freezing policy is an increase in the stabilization of the Hospital Blood Bank's operation, while the number of units outdated daily remains approximately constant. When the lifetime is extended to 28 days, then, if collections remain constant so does the quantity outdating, but, if collections vary so as to keep inventories the same as under the 21-day lifetime, then outdating could be significantly reduced.

(v) Computer-Based Information Systems

In order to handle the large size of data, and provide timely and accurate reports, as well as support for management decisions, a variety of computer-based information systems have been reported in the literature. Among them we mention the ones by Hirsch et al. [30], Masouredis et al. [40], Hogman and Ramgren [31], Pegels et al. [52], and Prastacos et al. [63].

IV. REGIONAL MANAGEMENT

A regional blood distribution system can be characterized by three sets of specifications: (i) the network configuration of the system, (ii) the allocation policies, and (iii) the pricing mechanism in effect.

The most common network configuration is the tree network in which a Regional Center (highest echelon) supplies (or stores blood at) the Local Centers (middle echelons), each of which, in turn, supplies a number of hospitals (lower echelons). A special form of a tree network is the star network, where there are no Local Centers and the Regional Center supplies directly the hospitals. One can see that the star network is also the smallest substructure of any network structure.

The ordering or allocation policies that are usually in effect in a regional blood management system are characterized by one, or a combination, of the following modes of operation: (i) decentralized decision making, where the ordering originates from the lower echelons of the network and is based on each echelon's decision function, and (ii) centralized decision making, where the higher echelon decides on the quantities to be allocated to the lower echelons so as to minimize a total expected cost in the region.

In combination with the above, the Regional Center together with the hospitals has to establish a pricing mechanism through which each hospital will reimburse the Center for some, or all, of the blood supply shipped to that hospital. Three typical pricing mechanisms are: (i) the hospital receives units to keep until used or outdated, and pays for all units received (retention system); (ii) the hospital receives units "on loan" from the Center and pays for them only if the units are used; otherwise the units are returned to the Center after a fixed period of time (rotation system); and (iii) a combination of the above.

(i) Decentralized Decision Making

In a decentralized management system each Hospital Blood Bank tries to determine appropriate order quantities so as to meet most of its daily demand without having to outdate an excessive number of units. To reach a working compromise between anticipated shortages and outdates, unit costs are assigned to every unit short or outdated, and the techniques outlined in section III (ii) are used.

In this case, the Center's objective is to determine its inventory levels (or, collection levels) so as to be able to meet most of the orders placed by the hospitals without outdating excessively, as well as the ages of units to issue against these orders. This problem was examined by Yen [69], who proved that, under certain conditions, an optimal ordering policy exists, and that the optimal age-allocation policy to fill the locations' demands is the one where each location receives an allocation of all ages proportional to its ordering amount with respect to the total ordering amount from all locations.

An inherent difficulty in the development of a decentralized management system is its dependence on the assigned unit penalty costs s and w, since, in the case of blood, these costs are very difficult to estimate, and are mostly subjective. Some of the costs that have been reported in the literature are s=55, w=25, or s=30, w=15, etc. It is understood that different costs lead to different policies for the hospitals and the Center. We show that this problem does not exist in a Centralized Management System.

An additional problem of a Decentralized Blood Management System is that it will, almost always, result in high outdating. To see this, one has to consider the following: all hospitals will decide on inventory levels that will be sufficient to satisfy its daily demand with a probability of at least 80-90%.[1] Such inventories generally correspond to 2-3 days of supply in stock for the common blood types, and to 7-10 days of supply for the rarer blood types, and will, therefore, eventually result in excessive outdating.

It is, hopefully, clear now that, to reduce outdating, some form of Centralized Blood Management System has to be implemented through which hospitals will share (instead of competing for) the regional blood resources.

(ii) Centralized Decision Making

A number of successfully implemented centralized regional blood management systems have been reported in the literature [9, 28, 68].

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1 From a survey performed on 38 hospitals in Long Island, it was determined that, almost unanimously, acceptable stocking levels correspond to 95% probability of meeting the demand [9].

Most of them are based on empirically derived management rules, and have been developed as improvements over previous decentralized systems.

In a centralized system the Regional Blood Center allocates the available regional resources so as to minimize the total outdating, shortage and delivery cost in the region. Prastacos [57, 58] examined this problem and derived properties of optimal and approximately optimal allocation policies for rotation and retention systems of general perishable products. The following gratifying results were shown to hold:

(i) the optimal allocation policy is independent of the unit penalty costs. It minimizes both expected shortages and expected outdates, simultaneously (conservation equation).

(ii) the optimal allocation policy is the one which allocates the regional supply so as to equalize the probabilities of outdating among hospitals, as well as the probabilities of shortage.

(iii) this optimal policy can be computed in closed form for most probability distributions.

Using these results as the basis, Prastacos and Brodheim [61] developed an interactive computer-based planning system to be used by the Regional Blood Center in order to determine:

(i) the minimum possible shortage and outdating targets that can be achieved in the region,

(ii) the level of collections needed to achieve these desirable targets, and

(iii) the distribution schedule to hospitals, to achieve these targets.

The system is based on a mathematical programming model which uses the above results as constraints and uses a "grid" algorithm to obtain the optimal solutions.

This management system, together with advances in the automated handling and processing of blood reported by Brodheim et al. [6, 2] has been implemented in Long Island, New York [9, 10]. The system replaced a typical decentralized system that was in effect before; it has established a routine operation in the management of the blood resources, and has drastically reduced shortages and outdates in the region. The system has received wide recognition [9], and was recently awarded the 1979 International Management Science Achievement Award for excellence in the practice of Management Science.

V. CONCLUSIONS AND EXTENSIONS

In summary, the following conclusions can be drawn from the previous review:

(i) Management Science and Operations Research has been a useful tool in developing systems for the efficient management of blood supplies. It has addressed problems that relate to the inventory management of a Hospital Blood Bank, as well as to the management of the regional supplies.

(ii) The issues relating to the management of a Hospital Blood Bank include the statistical analysis of the demand and usage patterns for blood, ordering policies, issuing policies, and other management policies. The most effective and widely used technique has been simulation. In addition, many analytical models have been developed which, even though they make a number of simplifying assumptions, provide an insight into the solution, as well as useful bounds and approximations.

(iii) Recently, the direction of both research and practice is shifting towards regional management systems. The reason is that a regional management system which promotes the sharing of the regional resources, and in which the hospital allocations are decided according to regional objectives, seems to be more efficient than the traditional decentralized system, which, by nature, establishes the competition between Hospital Blood Banks.

Some of the areas where further research is needed are listed below. They all relate to regional management:

(i) Optimal design of regional networks. This refers to the questions of defining a "blood region," designating Local and Regional Centers, and partitioning the set of HBBs into clusters, each cluster to be served by a Local or Regional Center. The methodologies and techniques that will be developed to address these questions and the answers that will be provided will set the national guidelines for a widely implemented regionalization.

(ii) Analysis of alternative regional management schemes. This refers to a comprehensive comparative evaluation of alternative management and pricing structures. The results of this analysis will assist the RBC in the selection and implementation of the most appropriate one among those structures. Finally,

(iii) Operational issues in product delivery. This refers to questions involving the design of delivery routes, as well as the incorporation of the other blood products in the delivery schedules.

It is our hope that these studies will contribute not only to the development of appropriate methodological techniques, but also to the understanding of issues involved in the implementation of alternative regional structures, and of the incentives and framework they provide for efficient blood inventory management, and thus contribute to the realization of the goals of the National Blood Policy.

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