Essentially, blood banks are facilities which procure, store, process, and dispense blood. To operate effectively in the face of both random supply and random demand, sizable buffer stocks of blood are maintained. The resulting inventory control problem is an extremely complex one for several reasons: (1) both supply and demand are random; (2) approximately 50 percent of all bloods demanded, "crossmatched," and held for a particular patient are eventually found not to be required for that patient; (3) blood is perishable, the present legal lifetime being 21 days in most areas; and (4) each blood bank typically interacts with a number of other banks. This paper presents a framework for the analysis of the whole blood inventory problem at the individual hospital as well as at the regional level, presents a realistic model of blood inventories for both the individual and regional cases, and analyzes the effects of several alternative inventory policies.
BLOOD BANK INVENTORY CONTROL

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I. INTRODUCTION

One of the important medical resources of any community is its system of blood banking facilities. It is through such systems that blood is collected from human donors at one time and place, processed, stored, and ultimately provided for transfusion to hospital patients at some other time and place. In most areas, blood banks are organized into loose regional systems, each composed of anywhere from 20 to 200 hospital blood banks located in some geographically or politically defined area (e.g., a city, a portion of a state). While the hospitals in such a system generally acquire a portion of their blood supply from one or more common central blood banks and one or more donor services, the hospitals typically interact with each other only infrequently in times of emergency. In most cases these systems have developed without the aid of central coordination and presently face a variety of problems which result from ineffective and inefficient modes of operation.

Three of the most common and pressing problems are the following [6]:

- A chronically short supply at the same time that as much as 15 percent to 25 percent of the available supply is lost through outdated (the shelf-life of whole blood is limited by law to 21 days in most areas). This condition results both from a

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maldistribution of blood among blood banks and from a system-wide deficient supply.

- Susceptibility to sudden stockouts resulting from unpredicted large demands at one or more hospitals.
- High operating costs—in particular, large expediting costs and outdated losses.

These problems reflect the importance of the inventory function in blood banks and call for improvements in the control of blood inventories. However, four characteristics of blood banking inventory systems make this a very complex task:

1. Both supply and demand are probabilistic.
2. Approximately 50 percent of all units of blood requested by physicians, "crossmatched" for compatibility with the blood of prospective patients, and reserved are eventually found not to be required for the patient in question and are returned to the "unassigned" inventory.
3. Blood is perishable, the present legal lifetime being 21 days in most areas.
4. Each blood bank typically interacts with a number of other banks.

Because of these complexities, past work in the field of inventory theory has limited applicability. Most attempts to deal with the blood inventory problem have consisted on the one hand of rules of thumb found in practice to provide adequate service [5, 14], and, on the other hand, of analyses and simulations of highly simplified models of a single hospital blood bank [2, 11, 13]. A good review of these studies is given
in Elston [1]. The only previous attempt to consider the interaction of hospital blood banks [15] concentrated on the collection policies of the central blood bank and suffered from an oversimplification of the hospital models.

In the remainder of this paper we shall briefly investigate the potential costs and benefits of improved control of inventories of whole blood both at the individual blood bank and at the regional level.

Before proceeding to the analysis, we must have a set of specific criteria or measures of performance by which to evaluate alternative inventory policies. The three most important measures are the following:

1. **Shortage**: the amount of blood that is requested by physicians and not immediately available.

2. **Outdating**: the amount of blood entering a bank and not transfused before the expiration of the shelf-life (21 days).

3. **The cost of information and transportation systems needed to support inventory policies.**

An additional criterion—the age of blood transfused—was included in the study as an index of quality but will not be discussed here, since it was found to be relatively insensitive to the policies under consideration.
II. INVENTORY CONTROL IN AN INDIVIDUAL HOSPITAL BLOOD BANK

The first phase of a blood inventory control program must focus on the individual hospital. A general model structure for a hospital blood bank, developed on the basis of a survey of the operations of a number of hospitals in several localities, is presented diagrammatically in Figure 1. As shown, the inventory of blood is divided into two portions: the assigned inventory, which consists of blood which has been crossmatched with samples of prospective patients' blood to ensure compatibility and reserved for those patients; and the unassigned inventory, which is available to meet new requests for blood.

The flow of blood through the system is as follows. The unassigned inventory is depleted by physician demands for blood to be crossmatched, by the outdating of blood, and by the shipment of blood to other hospital blood banks. It is replenished with blood ordered from one or more central blood banks, with blood drawn from selected donors (or "ordered" from one or more donor services), with blood drawn from random, or unsolicited, donors, with blood released (unused) from the assigned inventory, and with blood received from other hospital blood banks. The reader should note that shortage, as defined above, applies to the unassigned inventory only. The assigned inventory is supplied with blood demanded by physicians; it is depleted by blood usage (transfusions), by the release of blood demanded but not used, and by outdating. The development of this model is described in detail elsewhere [7].

Several characteristics of whole blood inventories—particularly the need to describe a blood inventory as a 21-dimensional variable (one
Figure 1. The Hospital Blood Bank Whole Blood Inventory Model
dimension for each possible age)—defeat analytical approaches to the study of practical whole blood inventory problems. Accordingly, the model described above has been utilized to examine a variety of inventory policies with the aid of computer simulation. The necessary data were collected at a large hospital blood bank in Boston (the Peter Bent Brigham Hospital blood bank). It was found that the eight major blood types could be treated independently, and here we shall report the results for a type (B+) which was used at the rate of about 800 units per year. While these results apply in detail only to this particular blood bank, the characteristics of the results are of general validity.

The most basic inventory policy in a hospital blood bank is the establishment of a daily inventory ordering level (a different level for each blood type), which we designate by "S." With such a policy, the unassigned inventory is counted each morning, and, if it is less than S, the difference is ordered from available sources; if the unassigned inventory is equal to or greater than S, no blood is ordered. Here we shall assume that the bank is always able to begin with at least S units; the impact of randomness in supply is discussed in [7].

Of the various criteria suggested earlier, the two which are significantly affected by this policy are shortage and outdated.

To demonstrate the simultaneous effects of the inventory ordering level on shortage and outdated, we shall represent the model's operating statistics in the form of a graph of attainable combinations of shortage and outdated, both expressed as percentages of the annual number of pints transfused, with the inventory ordering level S as a parameter. This graph, which we shall refer to as the shortage-outdating operating curve,
is shown in Figure 2. In other words, for each value of S, the average annual shortage and outdating observed in the simulation of the equivalent of a three-year period of operation of the model are plotted as a single operating point in Figure 2 and labeled with the appropriate value of S. Thus, for example, for an inventory ordering level of 18 units, shortage is 5.8 percent and outdating is 10.3 percent. (The blood bank which served as the source of the data for this model operated at a 15- to 18-unit ordering level.) As S is raised, the operating point moves up and to the left, corresponding to increased outdating and reduced shortage, and vice versa. This curve represents the trade-off between the two most important measures of the blood bank's effectiveness, and the blood bank administration can select the most desirable operating point on this curve simply by specifying the daily inventory ordering level. This decision will depend on the administration's assessment of the relative tangible and intangible costs of shortage and outdating.

This same model may be used to investigate a variety of other inventory operating policies. Several have been investigated and reported on elsewhere [7, 8]: the possibility of obtaining all supplies directly from donors with the full shelf-life remaining, rather than from a central blood bank with only a portion of the shelf-life remaining; the possibility of ordering blood more often; and the possibility of ordering whenever the inventory falls below some lower threshold. Of course, certain policy changes—for example, changes in the rules governing the entire cross-matching process—cannot be examined without revising the model.
Figure 2. Shortage-Outdating Operating Curve: An Independent Hospital
III. REGIONAL BLOOD INVENTORY CONTROL

At the regional level, interactions between hospital blood banks are presently extremely limited in most areas and there is a wide range of potential inventory strategies from which to choose. However, those which are capable of contributing to blood banking goals fall into two classes:

1. Shortage-anticipating transfers of blood from one hospital to another. Policies in this class allow a hospital that is experiencing an unexpectedly large demand to avert (or end) a shortage by "borrowing" blood from relatively well-supplied neighbors.

2. Outdating-anticipating transfers. Under this class of policies, a blood bank which is passing through a period of low demand may seek to reduce outdating by "lending" blood to banks that are more likely to use it.

The benefits to be derived from such policies must, of course, be balanced against the costs of the systems required to support them. This trade-off may be explored by investigating the effects of specific policies on a model of a regional system.

For simplicity, we shall concentrate our attention on a model of a hypothetical, homogeneous system composed of a variable number of identical hospital blood banks, all operating under exactly the same policies. This procedure has the advantage of facilitating our understanding of the effects of the policies to be examined. Since we already have a validated model of one hospital blood bank, we shall use it as the archetype. The central blood suppliers are modeled implicitly, just as in the one-hospital model (if
we were modeling a particular operational system in its entirety, it might be preferable to model the suppliers explicitly). Further details may be found in Reference [9].

A useful point to begin an analysis of regional inventory control policies is with the policies which specify minimum and maximum interaction, respectively. The former has already been examined: it is simply the case of the individual, independent hospital for which the shortage and outdated results are given in Figure 2.

The policy which maximizes interaction in terms of both shortage-anticipation and outdated-anticipation will be called the Common-Inventory Policy. Under this policy, all hospital inventories are, in effect, fully shared by all participating blood banks; the oldest bloods in the system are always crossmatched first, no matter where they might be initially located. The performance of the model under this policy, in terms of shortage and outdated, is the best attainable.

The shortage and outdated results of a number of one-year simulations are shown in Figure 3 as a family of shortage-outdated operating curves. In each case, a particular operating point on one of the curves may be selected by adjusting the inventory ordering level. For example, two hospitals operating under the Common-Inventory Policy described, at the 12 unit inventory ordering level, would be expected to outdate blood at the rate of 4.9 percent of annual usage and experience shortages in the amount of 5.0 percent of average annual usage. Five hospitals operating under these same policies would have 4.2 percent outdated and 0.5 percent shortage.
Figure 3. Shortage-Outdating Operating Curves: Common-Inventory Systems
A useful index of the extent of the inward shift gained by expanding the size of the system may be determined as follows: (1) Identify the most desirable operating point on the curve for the basic model. (2) Draw a straight line from the origin through this operating point. (3) Treat as the approximate most desirable operating point on any inner operating curve that point at which the curve intersects the constructed line. And (4) take, as an index of improvement in shortage and outdated performance under the new policy, the common percentage reduction in both shortage and outdated.

Suppose one is interested in points at which the ratio of outdated to shortage is unity. One may then determine from Figure 3 that, with respect to the one-hospital starting point, a two-hospital Common-Inventory system reduces both outdated and shortage by about 45 percent, a five-hospital system by about 64 percent, and a 20-hospital system reduces both measures by about 72 percent.

While we have shown the operating curves only for systems up to 20 hospitals, there is clearly a very strong effect of diminishing returns as the size of the system is increased. We may conclude that a further increase of the size of the system to even 50 hospitals would produce little additional gain; and not even in the largest urban centers can one find a concentration of 50 hospitals handling blood in the volume being modeled. Note, however, that further reductions of shortage and outdated can be achieved through changes in internal policies, particularly those which govern the entire crossmatch process.

With regard to the support system requirements of the Common-Inventory Policy, we find, as might have been anticipated, that they are quite heavy. The supporting information system must provide essentially continuously
updated information on both the locations of the oldest bloods of each type in the system and the total inventories at those hospitals. The transportation system is found to be required to transfer—one at a time—about 550 units of this type per bank per year in a two-bank system (i.e., 1,100 units per year), about 900 units of this type per bank per year in a five-bank system (4,500 units per year), and almost 1,100 per bank per year in a 20-bank system (22,000 units per year).

In view of these "costs" of implementing a Common-Inventory Policy, it behooves one to seek other policies which yield benefits approaching the maximum gains indicated, but at a lower cost.

Clearly, there are many reasonable policies combining the two types of interactive transfers identified earlier. Here we shall illustrate our method of analysis using one policy which was found to be relatively attractive in terms of the gain achieved and the support systems required.

The policy we shall review here will be referred to as a "Threshold Transfer Policy" and is defined as follows: Whenever the inventory level (for the blood type under consideration) at any bank falls below a lower threshold of one unit, a transfer is initiated. Each bank is willing to lend only those units it may have in excess of a retention level of one unit. When more than one bank is "willing" to lend blood, a single lender is selected as follows: Once in the middle of each day the status of the inventory at each bank in the system is determined. When a lender is being sought, the hospitals are "polled," beginning with the one most recently known to have had the largest inventory, until a willing lender is identified. The amount borrowed is five units, oldest first, or less if five would reduce the lender's inventory below the retention level.
Rather than present another graph of the applicable family of shortage-outdating operating curves, we compare in Table 1 the simulation results of this policy with those of the Common-Inventory Policy for operating points at which the ratio of outdating to shortage is unity. As shown, the Threshold Transfer Policy for two hospitals yields an inward shift of the shortage-outdating operating curve about two-thirds as great as that obtained in a Common-Inventory System (29 percent compared to 45 percent). For five- and 20-bank systems, the gains are each about five-sixths as great under the Threshold Transfer Policy as they are under the Common-Inventory Policy.

These findings suggest that we have, in fact, found a policy which yields gains approaching the maximum attainable (in the situation modeled). Let us now examine the costs of these two policies. Specifically, Figure 4 presents, for each policy, the relationship between the primary benefit—the reduction of shortage and outdating (along the line representing operating points for which the ratio of outdating to shortage is unity)—and the primary variable cost—the number of inter-hospital shipments (trips) required to execute the policy. Here, for example, the five-bank point on the curve for the Threshold Transfer Policy represents the combination: shortage and outdating reduced by 54 percent; 90 inter-hospital shipments per bank per year (for this blood type).

Clearly, for reductions in shortage and outdating that can be achieved by the Threshold Transfer Policy, this policy requires far fewer inter-hospital shipments than does the Common-Inventory Policy. However, suppose that the size of the system is limited to some number of banks N. In such a case, the maximum reduction of shortage and outdating provided by the Threshold Transfer Policy alone is also limited and can be determined by
<table>
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<th>NUMBER OF PARTICIPATING HOSPITALS</th>
<th>COMMON-INVENTORY POLICY</th>
<th>THRESHOLD TRANSFER POLICY</th>
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<td>--</td>
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</tr>
<tr>
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<tr>
<td>20</td>
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Table 1. Shortage and Outdating Reductions in the Threshold Transfer and Common-Inventory Policies
INTER-HOSPITAL SHIPMENTS PER BANK PER YEAR

20 BANS
FIVE BANKS
TWO BANKS
COMMON-INVENTORY POLICY

THRESHOLD TRANSFER POLICY

FIVE BANKS
TWO BANKS

PER CENT REDUCTION IN SHORTAGE AND OUTDATING

0% 20% 40% 60% 80%

1200
1000
800
600
400
200
0

Figure 4. Inter-Hospital Shipments vs. Per Cent Reduction in Shortage and Outdating: The Threshold Transfer Policy and the Common-Inventory Policy
referring to the appropriate point on the lower curve in Figure 4. If larger reductions are desired, this policy must be replaced by or combined with some other policy which is capable of shifting the N-bank point on the Threshold Transfer curve in Figure 4 towards the N-bank point on the Common-Inventory curve. Note, though, that the ratio of additional shipments to additional gain in such a shift would be extremely large.

Finally, the information requirements of the Threshold Transfer Policy are far less severe than those of the Common-Inventory Policy, and could be very simply met with a manual, telephone-based system requiring only part-time clerical staffing. In comparison, the Common-Inventory system requires continuously updated information on the location of most of the units in the system, pointing to the need for a large-scale automated information system (see, for example, References [3], [4], [10], and [12]).

In the context of particular blood banking systems, these and other policies can be "costed out" in detail and their total advantages and disadvantages evaluated. Such an extended analysis would require attention to a number of factors we have not dealt with here: for example, extension of the model to include all eight blood types, secondary uses of the information and transportation systems required, distances between hospitals, and so on.
IV. CONCLUSIONS

The accomplishments of this study are threefold. First, the whole blood inventory problem for a single hospital has been structured and several classes of alternative policies identified. Second, a realistic model of the whole blood inventory system in a group of hospitals has been developed for use in the analysis of the operations of such systems. Third, the feasibility of testing the effects of specific policies using computer simulation has been demonstrated, a number of such policies have been examined in detail (only some of those examined in References [7], [8] and [9] have been described here), and the simulation programs have been documented for use in analyzing specific systems.

The analyses performed should provide useful insights with direct applicability in a variety of blood banking systems. Specifically, we have determined (a) the range of improvements in shortage and outdated performance that can be expected in systems of various sizes, (b) the nature of the corresponding support system capabilities that must be provided, and (c) the fact that a group of only five cooperating blood banks can achieve most of the gains available in larger coordinated systems.

The studies reported on here are not the last word in the investigation of blood bank inventory control. They should, however, establish a firm basis and the necessary tools for further analyses of specific operating systems and for the initiation of controlled experiments to test the effects of the most promising policies in the "real world."
REFERENCES


11. Millard, D. W., Industrial Inventory Models as Applied to the Problem of Inventorying Whole Blood, Ohio State University Engineering Experiment Station, Bulletin No. 180, Columbus, March, 1960.

