International Journal of Hospital Research 2017, 6(3): x-x
http://ijhr.iums.ac.ir
doi 10.15171/ijhr.2017.xx
Research Article
IJHR
Open Access

A Collaborative Blood Distribution System in a Network of Hospitals Based on their Normal and Emergency Requests: A Mathematical Model and Solution

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Abstract

Background and Objectives: A blood distribution network orchestrates distribution of safe blood products to hospitals. Blood shortage and blood wastage are two important factors affecting efficiency of blood distribution network. Service delivery time is another factor that refers to the time interval between blood request by a hospital and transfusing it to the patient. Collaboration between hospitals can mitigate the three mentioned factors.
Methods: Mixed integer non-linear programming (MINLP) was used to model both current blood distribution network and collaborative blood distribution network mathematically. Two types of collaboration, including preventive and reactive, and two types of blood requests, including normal and emergency, were considered in modeling. The proposed model had been put into effect by considering platelets as blood product and applying real data of three high usage, medium-usage and low-usage hospitals in Tehran, Iran, during a planned horizon of 7, 14 and 30 days using IBM ILOG CPLEX solver.
Findings: Preventive collaboration led to decrease in blood wastage at low-usage hospital and decrease in blood shortage at high-usage one. Reactive collaboration led to a decrease in blood shortage at all types of hospitals. Moreover, service delivery time of emergency requests was decreased using collaboration.
Conclusions: Determining the effect of preventive and reactive collaboration on blood shortage, blood wastage and service delivery time regarding both normal and emergency requests is the contribution of this paper. Managers of blood organizations and hospitals can save patients' life and reduce costs of the whole blood distribution network by defining groups of hospitals which collaborate with each other under predefined protocols. The proposed model can be used to predict improvement in blood distribution network by implementing collaboration between hospitals.
Keywords: Blood distribution network, Collaboration, Blood wastage, Blood shortage, Normal request, Emergency Request, Service delivery time

Background and Objectives

Blood is a scarce resource which can be assumed as a perishable product due to its limited shelf-life. Patients with thalassemia, hemophilia, chronic anemia, blood-related cancers, on dialysis, and patients in need of major surgery or organ transplant need blood products to survive. Blood distribution network is one of the healthcare networks which has been studied mostly as a perishable supply chain in the medical field.[1-8] Beliën and Forcé reviewed the literature of blood supply chain and categorized researches in this field into eight categories fields including type of blood product, solution method, hierarchal level, type of problem, type of approach, exact versus heuristics, performance measures and practical implementation.[9] Blood supply chain consists of four major elements: donors, blood centers (BC), hospitals and patients.[10,11]

Many researches have been done with the subject of blood supply chain management and blood inventory management and different methods have been used to solve them such as Integer Programming,[12-15] Linear Programming,[16,17] Dynamic Programming,[18,19] Data Mining techniques,[1] and Generalized Network Theory.[6] Blood shortage and wastage which have been considered in frequent researches[1,3,6,8,13,20-22] are two important factors in managing blood supply chains.

Collaboration in supply chain has been referred in the literature using different terms such as lateral transshipment, horizontal collaboration, stock rotation

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and redistribution.[23-29] Three types of blood transshipment between hospitals have been considered in the literature including (a) preventive transshipment where an emergency need at a hospital cannot be met by the BC, (b) shortage-anticipated transshipment and (c) outdate-anticipated transshipment.[7]

Denesiuk et al implemented a redistribution model in which near outdated red blood cells (RBCs) would be transshipped from a low-usage hospital to a high-usage one in Canada during a two-year period.[23] Lang used preventive transshipment concept in order to improve blood inventory management at hospitals in a blood supply chain.[28] Hosseinifard and Abbasi proposed a blood network structure to improve outdate and shortage rate at the hospitals in which some hospitals shared their blood bank as a centralized inventory to satisfy demands of other hospitals which are forced to have no inventory.[25]

Hospitals send their blood requests to the BC in two types: first, normal requests in which hospitals usually try to fill their stock and second, emergency requests in which some blood products are requested for a specific patient whose life is in danger. Emergency requests should be satisfied in the shortest time through transfusion network. The flowchart of managing normal and emergency blood requests in the hospital blood banks has been prepared based on interviews with managers of the Iranian Blood Transfusion Organization (IBTO) and related documents, as shown in Figure 1. To the best of our knowledge, considering both blood order types has been raised only in the research done by Kopach et al in which they proposed a queuing model considering two types of urgent and non-urgent demand at one hospital in order to determine optimal policy to blood inventory levels at the hospitals using simulation method.[30] The focus of this paper was to benefit from collaboration among hospitals as demand points in blood distribution network with the aim of (1) applying reactive collaboration to decrease blood shortage and increase patient safety when emergency requests occur at the hospitals and (2) applying preventive collaboration to reduce blood wastage by transshipping unused blood products from low-usage hospitals to high-usage ones.

Methods

A mixed integer non-linear programming (MINLP) was used to model collaboration in blood distribution network mathematically in this research. First, the current blood distribution network was formulated considering two types of normal and emergency requests without collaboration among hospitals. Then the collaborative blood distribution network with two types of preventive and reactive collaboration has been introduced. Schema of the two proposed models has been shown in Figure 2. As shown in Figure 2a, the first model consisted of a BC and three types of hospitals including low-usage hospital (H_L), medium-usage hospital (H_M) and high-sage hospital (H_H). Hospitals could send two types of requests to the BC. Thus two kinds of arcs have been considered: black

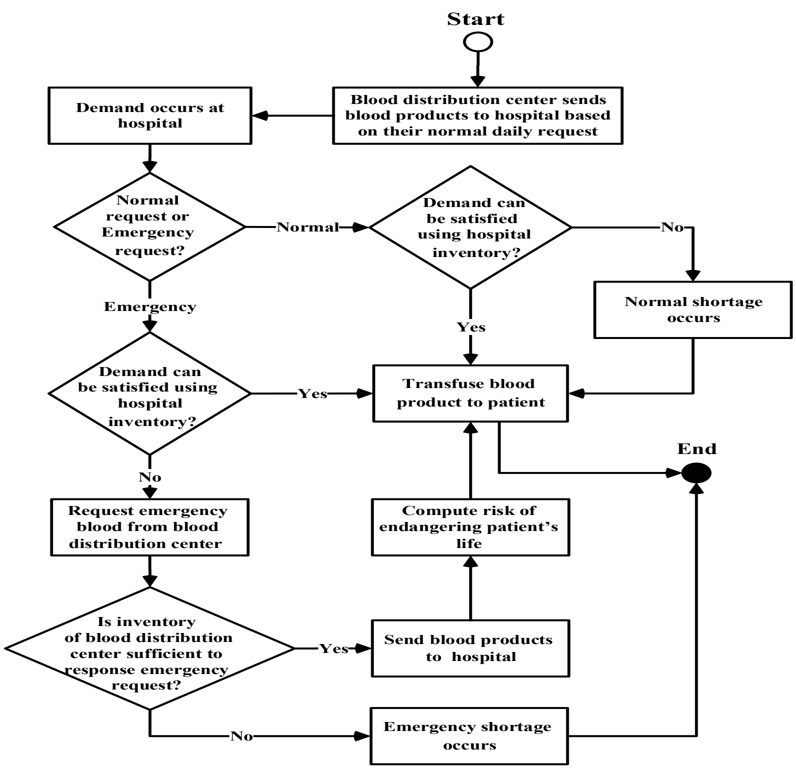

Figure 1. Flowchart of Normal and Emergency demands at Hospital.

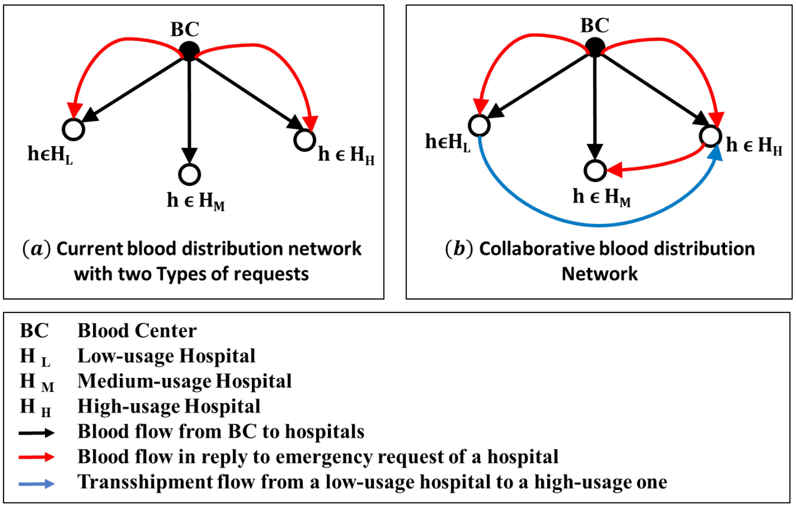

Figure 2. Schema of the Proposed Models.

arcs, which show flow of blood products sending from the BC to a hospital with normal blood request, and red arcs, which show flow of blood products from the BC or other hospitals to a hospital with emergency blood request. Collaborative blood network has been shown in Figure 2b, in which hospitals collaborate with each other to (1) reduce shortage cost and increase patient safety by helping each other to fulfill emergency requests and (2) reduce wastage cost by transshipping flow of unused blood products reaching a certain age from the low-usage hospitals to the high-usage ones, presenting by blue arcs.

It had been assumed that our blood product is platelet with a lifetime of five days. The day in which platelets are trans-shipped/redistributed from the low-usage hospital to the high-usage one is considered to be the third day of platelet lifetime as suggested by Fontaine et al.[24] The planning horizon has been assumed to be 7, 14 and 30 days.

Blood distribution network in Tehran consists of a blood center, called Vesal center, which serves almost 154 hospitals. The proposed model has been applied to a small part of Tehran blood distribution network, including Vesal center and three hospitals. The hospitals were selected based on their blood usage: a high-usage hospital, a medium usage one, and a low-usage one. The high-usage and medium-usage hospitals were teaching hospitals and the low-usage one was a private hospital. The real data of platelet usage in July 2017 of the selected hospitals has been used as illustrated in Table 1.

Shortage cost and wastage cost used in the model are shown in Table 2. Emergency shortage cost had been considered equivalent to blood money which should be paid regarding Iranian insurance law.

The travel time to get from one node to another one had been retrieved from Google Maps based on the average time throughout the day as illustrated in Table 3. It should be mentioned that time travel from node n to node h was not necessarily the same as time travel from node h to n due to constraints such as one-way routes and traffic lights.

The proposed models were run using IBM ILOG CPLEX 12.6.0.0 on Fujitsu Lifebook S series with 2.30 GHz and 4 GB of RAM.

Mathematical Modelling

In the following, mathematical modelling was presented in two parts: (1) modeling current blood distribution network considering two types of requests, and (2) modeling the

Table 1. Demand Data of Normal and Emergency Request

Parameter	Type of Hospital	First Week	Second Week	Last 2 Weeks
Normal requests (Number of platelet bag)	High-usage	90-74-74-73-98-67-77	72-77-49-44-38-16-46	56-65-71-86-81-25-89-84-81-105-62-82-47-82
	Medium-usage	9-5-12-9-7-5-19	6-0-0-0-9-21-0	8-6-11-17-12-15-15-8-6-0-16-28-9-18
	Low-usage	4-7-0-9-0-0-0	5-5-0-7-2-0-2	4-2-0-4-3-0-0-0-0-0-0-0-0-0
Emergency requests (Number of platelet bag)	High-usage	5-15-5-18-4-10-11	16-20-10-11-13-10-16	10-11-10-27-8-10-12-23-10-20-13-8-9-13
	Medium-usage	4-1-0-3-0-1-7	3-4-3-3-0-3-2	9-0-1-1-4-3-1-4-1-3-0-3-3-4
	Low-usage	0-1-0-0-0-0-0	0-1-0-2-0-2-0	0-0-0-0-0-0-0-0-0-0-0-0-0-0

Table 2. Cost Parameters

Parameter	Value	Unit	Reference
Normal shortage cost	1500	$/bag	(31)
Emergency shortage cost	70,000	$/bag	(32)
Wastage cost	150	$/bag	(18)

Table 3. Time Travel Between Blood Centers and Hospitals

	Low-Usage Hospital	Medium-Usage Hospital	High-Usage Hospital
Vesal blood center	5	7	10
Low-usage hospital	0	7	10
Medium-usage hospital	3	0	11
High-usage hospital	10	13	0

collaborative blood distribution network considering two types of preventive and reactive collaboration.

(1) Modeling Current Blood Distribution Network Considering Normal and Emergency Requests

Following assumptions were considered in modeling current blood distribution network:

- The model was assumed to be deterministic and single-product.
- The blood product had specific lifetime and would be expired at the end of the product lifetime.
- It had been assumed that emergency demand occurred after normal demand.
- The BC and the Hospitals followed FIFO policy to distribute blood products to the hospitals and to transfuse blood products to the patients who need them. Based on FIFO policy, older blood products should be transfused first.
- If normal demand had not been fulfilled at a hospital, a normal shortage penalty should be considered. If emergency demand could not be fulfill using hospital inventory, the hospital sends emergency request to the BC. But if the BC did not have enough inventory to fulfill emergency request of the requested hospital, an emergency shortage penalty would be incurred to the network because it means lack of blood in the network has put patient's life in danger.
- If a blood product had not been transfused till its expiration date, a wastage penalty occurred at the hospital. If a blood product had not been distributed by blood center till its expiration date, a wastage penalty occurs at the BC.
- The BC and the hospitals had no safety-stock.
- It has been assumed that interval between emergency blood requests and blood transfusion to the related patient should not be more than 30 minutes regarding IBTO policy.[33]
- It has been assumed that probability of endangering patients' lives regarding service delivery time of emergency blood requests could be calculated based on Exponential Cumulative distribution function with rate parameter (λ) of 4.

(2) Modeling Collaborative Blood Distribution Network Considering Preventive and Reactive Collaboration

In this part, the previous model has been extended to a collaborative one. Two types of collaboration between hospitals, including preventive and reactive collaborations, have been considered. In preventive collaboration, the low-usage hospitals sent their blood product of a certain age group to the predefined high-usage hospitals. Thus, wastage would not occur at low-usage hospitals. In reactive collaboration, hospitals could send their help request to all network nodes including BC and other hospitals to fulfill their emergency demands. In this case, nodes which (a) had stock and (b) were closer to the demand point, would have higher priority compared to the other nodes to respond the emergency request.

The details of mathematical models including indexes, parameters, decision variables and formulation are provided in online Supplementary file 1.

Results

In order to evaluate efficiency of collaboration model proposed in this paper, two scenarios have been considered. It was assumed that hospital blood banks have been filled up with an average volume at the first scenario and with an overestimate volume at the second scenario. The first scenario helps us to evaluate reactive transshipment in order to reduce blood shortage and service delivery time and the second one helps us to evaluate preventive transshipment in order to reduce blood wastage at low-usage hospitals. Important factors including blood wastage and blood shortage as well as service delivery times are compared in different charts based on three period of demand data.

Figures 3-5 show blood wastage and blood usage as well as service delivery time of emergency blood requests for both current and collaborative models. Blue, red and green colors have been used to show results related to low-usage, medium-usage and high-usage hospitals respectively in Figures 3-5. It could be inferred from Figure 3 that preventive collaboration made blood wastage in the low-usage hospital to zero. Although blood wastage in high-usage hospital has been increased, blood wastage in the whole blood distribution network has been decreased with the aid of collaboration. Figure 4 showed

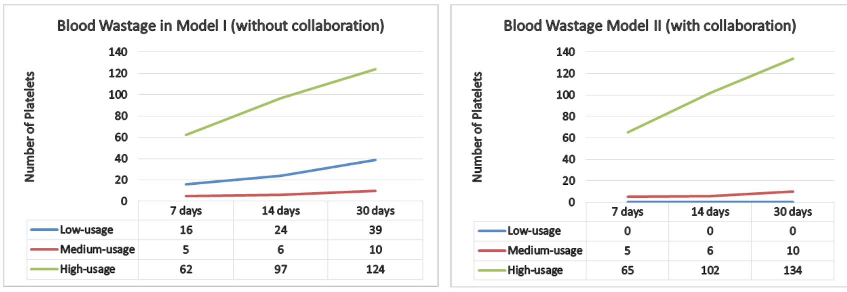

Figure 3. Blood Wastage in Both Current and Collaborative Models.

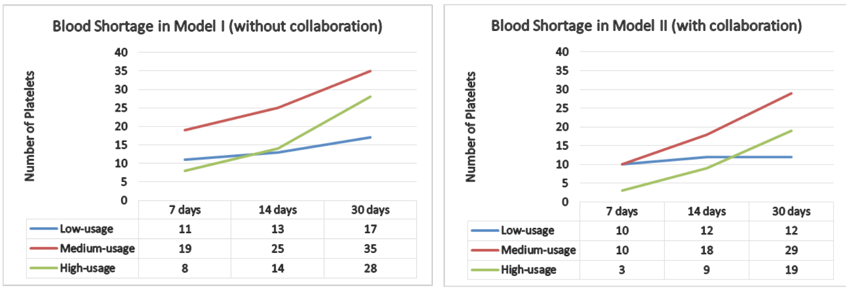

Figure 4. Blood Shortage in Both Current and Collaborative Models.

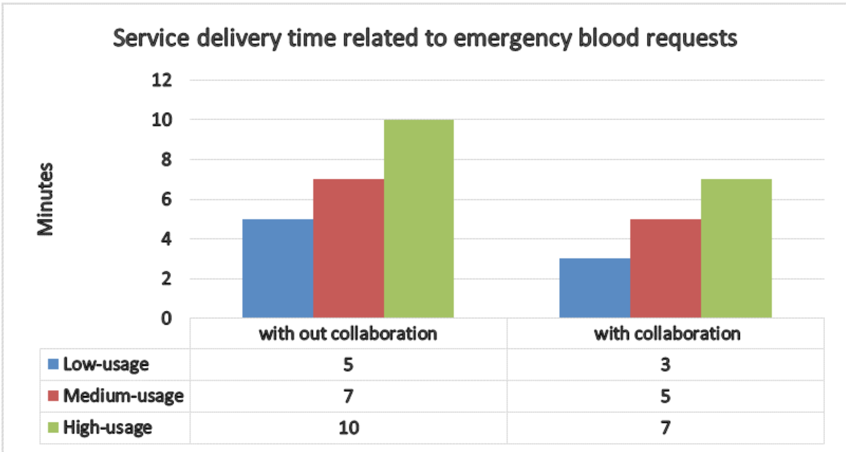

Figure 5. Service Delivery in Both Current and Collaborative Models.

that collaboration led to decrease in blood shortage in all three hospitals especially the medium-usage and the high usage ones. And finally, Figure 5 showed that service delivery time had decreased in all three hospitals due to collaboration between them.

Discussion

The aim of this research was to highlight impacts of collaboration between hospitals in a blood distribution network using mathematical modelling. Two mathematical models were proposed. The first one modeled the current situation of blood distribution network considering two types of normal and emergency blood requests. Hospitals have been categorized based on their blood usage to low, medium and high usage ones. The second model added two types of preventive and reactive collaboration between hospitals to the first proposed model. In preventive collaboration, the low usage hospitals transshipped their blood products that reach a certain age, to the high-usage ones. In reactive collaboration, hospitals can help each other to satisfy blood emergency request. Three factors including blood shortage, blood wastage and service delivery time have been considered in this research as the objective function. The proposed models have been applied to a small cut of Tehran blood distribution network consisting of Vesal center and three hospital with low, medium and high usage of platelet. Using preventive collaboration, unused platelets with age of 3 days old were transshipped from the low-usage hospital to the high-usage one. The results show that preventive collaboration reduced blood wastage in low-usage hospital to zero. Although blood wastage at high-usage hospitals had been increased by preventive collaboration, the total blood wastage at whole network has been decreased. Blood shortage has been decreased in all three hospitals using reactive collaboration. It should be mentioned that preventive collaboration had effect on decreasing blood shortage at high-usage hospital due to platelets which has been transshipped from low-usage hospital to it. Moreover, service delivery time has been decreased remarkably using reactive collaboration between hospitals.

This research showed that collaboration between blood banks of hospitals can mitigate blood shortage and blood wastage in the whole blood distribution network which is in line with other following research. Denesiuk et al showed that transporting near-outdate RBC units to a high-usage hospital site decreased discard rate to at least 20%.[23] Hosseinifard and Abbasi showed that reducing the number of hospitals that hold inventory from 7 to 3 decreased wastage and shortage in the supply chain by 21% and 40% respectively considering inventory centralization in blood supply chain.[25]

This research showed that preventive collaboration would mitigate blood wastage and blood shortage because blood units would be transshipped from hospitals with low possibility of usage to hospitals with high possibility of usage. Moreover, hospitals would help each other to satisfy emergency blood requests as soon as possible using reactive collaboration policy which led to decrease in both blood shortage and service delivery time.

Conclusions

This research showed that collaboration between hospitals could improve performance measures of blood distribution network including blood shortage, wastage and service delivery time. The proposed models could help both blood network administrators and hospital managers as described in the following. Blood network administrators could categorize hospitals based on their blood usage. Then by defining collaborative groups of hospitals in a neighborhood, they could implement both preventive and reactive collaboration using predefined processes and protocols. The more hospitals get involved in the collaborative groups, the higher performance improvement can be achieved in the blood distribution network. Since collaboration made decrease in blood shortage, hospital managers would be able to save more patients' lives. Although collaboration between hospitals could reduce blood wastage and shortage in the modelling world, implementing it in real world encounters serious challenges. Management and validation of blood cold chain, transportation issues, pricing of transshipped blood bags and setting up an acceptable SLA are some challenges which should be addressed by blood network administrators and policy makers.

Authors' Contributions

PKS, MMS and AAP jointly designed the study. PKS has the major contribution to formulating the mathematical model, analysing the data and writing the paper. PKS and AAP contributed to collecting the data. MMS contributed to interpreting the results and revising the manuscript. All authors read and approved the final manuscript.

Competing Interests

We confirm that there has been no known conflicts of interest associated with this publication and there has been no significant financial support for this work that could have influenced its outcome.

Acknowledgements

We thank Iran Blood Transfusion Organization (IBTO) who provided data of Tehran blood distribution network.

Supplementary Materials

Supplementary file 1 contains mathematical models including indexes, parameters, decision variables and formulation.

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Please cite this article as:
Khakshour Saadat P, Sepehri MM, Pourfathollah AA. A collaborative blood distribution system in a network of hospitals based on their normal and emergency requests: a mathematical model and solution. Int J Hosp Res. 2017;6(3):x-x. doi:10.15171/ijhr.2017.xx.