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Using Interactive Visual Analytics to Optimize Blood Products Inventory at a Blood Bank

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Abstract

Blood products and their derivatives are perishable commodities that require an efficient inventory management to ensure both a low wastage rate and a high product availability rate. To optimize blood product inventory, Blood Transfusion Services (BTS) need to reduce wastage by avoiding outdates and improving availability of different blood products. We took a blood product lifecycle approach and used advanced visualization techniques to design and develop a highly interactive web-based dashboard to audit retrospective data and consequently, to identify and learn from procedural inefficiencies based on analysis of transactional data. We present pertinent scenarios to show how the blood transfusion staff can use the dashboard to investigate blood product lifecycles so as to probe transition sequence patterns that led to wastage as a means to discover causes of procedural inefficiencies in the BTS.

Keywords:

Data Visualization; Blood Transfusion; Inventories, Hospital

Introduction

Blood product inventory management is a highly complex operation that relies on interpretation of multi-dimensional data including lifecycle-dependent variables such as real-time transaction states of the units, age of the units, discard reasons and lifecycle-independent variables such as blood types, special attributes (e.g., irradiation and phenotyping) and the suppliers [1]. Currently, hospitals and blood suppliers employ a mixture of non-standardized methodologies including paper reporting, spreadsheets and ad-hoc laboratory information system queries. This month-end reporting consists only of the summarized data and therefore it cannot be used for auditing the causes of procedural inefficiencies that lead to wastage. Although the raw blood transfusion data gives a high resolution of the blood product inventory, the interpretive richness and timeliness of the raw data is lost, and quality improvement, such as waste reduction and efficient utilization, is not possible given current methods.

Reducing wastage has been proved to be promisigly effective to improve the efficiency of transfusions [2]. To achive this goal, BTS need to audit the retrospective data to identify the transactional patterns within a blood unit's evolving lifecycle that led to a discard (i.e., wastage due to operational reasons rather than being outdated). This audit is done manually and hence is tedious, not in real-time and prone to missing out underlying inefficiency patterns that are low in frequency and previously unknown. Therefore, new data analytics complemented by interactive data visualization methods are needed to analyze, visualize and interpret blood unit transactional data to optimize blood unit inventory and to detect underlying wastage patterns.

Operational dashboards are being used in various domains to provide an easy-to-interpret overview of on-going processes, activities, users and inventories for system management, diagnostics and optimization. In the recent years, there have been studies around blood product inventory dashboards [3]–[5]. Sharpe et al. [5] developed a real-time dashboard that displays the Red Blood Cell (RBC) unit inventory in a tabular format which is color-coded based on unit's closeness to expiry. Comparing the pre-implementation and post-implementation situations of the inventory proved that utilizing the dashboard reduced the outdate rates significantly. Gomez et al. [3] implemented a dashboard to manage a large platelet inventory, resulting in reducing outdate rates. Woo et al. [4] introduced a similar real-time dashboard suitable for multiple blood products. On examination of the current dashboard solutions for blood inventory management, we note that the existing blood inventory dashboards are cumbersome with limited interactivity and filtering criterion, whilst lacking the ability to audit retrospective blood transfusion log to identify operational causes that lead to wastage due to discards.

Interactive Visual Analytics (IVA) provides a suite of data visualizations to interpret and interact with high-volume and high-dimensional data. IVA's significant ability in taking part to solve complex problems in various domains has been proved [6]. Chishtie et al. [7] comprehensively reviewed the application of Visual Analytics methods in healthcare areas, specifically population health and Health Services Research (HSR). According to their research, there has been a huge demand in implementing and utilizing IVA in the last decade as the promising power of effective data visualization to discover knowledge in data has been understood. Notwithstanding, only 4% of the literature is dedicated to address the problem of health system resource planning using IVA approaches [7].

In this paper, we present the design and workings of an innovative Blood Inventory Dashboard (BID) using advanced IVA methods to visualize lifecycle patterns of all the blood units to understand both typical and atypical lifecycles, which, in turn, helps to identify reasons/processes leading to inefficiencies and wastage. BID analyzes streams of blood transaction data, from a Laboratory Information System (LIS), that constitutes the unit's lifecycle, characteristics/product type and location within the hospital. BID has been developed for the Central Zone-BTS (CZ-BTS) servicing Halifax, Canada, providing the monitoring of three blood products—i.e., Red Blood Cells (RBC), Platelets and Plasma. Our work advances the optimization of blood bank inventories from various aspects, which has a direct impact on blood inventory optimization which affects the reduction of healthcare costs.

Methods

Blood Unit Transactional Data

The transactional data represents the different states a blood unit went through during its lifecycle. Note that the lifecycle of a blood unit consists of a number of transaction states, from its collection to its transfusion/discard. The list of transaction states is [Received, Unconfirmed, Confirmed, Available, Transferred, Assigned, Issued, Crossmatched, Quarantined, Destroyed, Discarded, Transfused], where a unit can go through cycles of these states till transfused/discarded. The detail of the transaction states is provided in [1].

The raw dataset comprises event logs depicting a series of time-stamped transactions experienced by a blood unit during its lifecycle. Figure 1 shows a snapshot of the event log in the order of the time that the transactions were recorded in the LIS. The data is integrated from multiple blood transfusion sites.

Unit number	Blood type	Supplier	State	Inventory location	State date-time	Expiry date-time
⋮	⋮	⋮	⋮	⋮	⋮	⋮
C057119691252	O Pos	CBS - Dartmouth ISBT	Transfused	VG BTS	2019-11-12 18:08:59	2019-11-24 23:59:00
C057119686134	O Pos	Hospital IWK	Issued	VG BTS	2019-11-12 18:21:59	2019-12-03 23:59:00
C057119684940	O Pos	CBS - Dartmouth ISBT	Issued	DG BTS	2019-11-12 18:31:14	2019-11-27 23:59:00
C057119680292	O Neg	CBS - Dartmouth ISBT	Crossmatched	VG BTS	2019-11-12 19:22:34	2019-11-26 23:59:00
C057119684498	A Pos	Prince Edward Island	Crossmatched	HI BTS (Main)	2019-11-12 19:47:11	2019-11-28 23:59:00
C057119684940	O Pos	CBS - Dartmouth ISBT	Transferred	DG BTS	2019-11-12 19:48:14	2019-11-27 23:59:00
C057119680292	O Neg	CBS - Dartmouth ISBT	Issued	VG BTS	2019-11-12 19:49:02	2019-11-26 23:59:00
C057119692521	A Pos	CBS - Dartmouth ISBT	Crossmatched	HI BTS (Main)	2019-11-12 19:50:11	2019-11-29 23:59:00
C057119680292	O Neg	CBS - Dartmouth ISBT	Discarded	VG BTS	2019-11-12 19:54:02	2019-11-26 23:59:00
C057119680287	O Neg	Aberdeen Hospital	Crossmatched	VG BTS	2019-11-12 20:10:07	2019-11-26 23:59:00
C057119680287	O Neg	Aberdeen Hospital	Issued	VG BTS	2019-11-12 20:10:31	2019-11-26 23:59:00
⋮	⋮	⋮	⋮	⋮	⋮	⋮

Figure 1 - A snapshot of the raw dataset showing the log of the transactional events in the Blood Transfusion Services (BTS) in the order of event time. This snapshot only shows Red Blood Cell (RBC) units. The rows are color-coded to distinguish the transaction states for each RBC unit. Not all the attributes are included in this snapshot.

The raw dataset is pre-processed to transform from the event log format to a lifecycle format which will be used to visualize and analyze patterns of blood product lifecycles. As the new format, a transition sequence is developed for each blood unit based on the transaction states that the unit went through; Each transition sequence consists of a number of transitions between subsequent transaction states (i.e., transition step).

In this study, we have taken a 5-year timeframe (January 2015 – December 2019) of the RBC transactional dataset from CZ-BTS in Halifax, Canada as proof-of-concept. This gives us access to 723,623 transaction states for 71,065 RBC units.

BID Design and Implementation

We take an IVA approach to implement BID. Figure 2 shows the overall architecture of BID in functional terms. We collect real-time transactional data from the LIS, which is a distributed system among all the blood transfusion sites. The BID's backend is developed incorporating Java Spring framework to have a RESTful web service. The REST architecture gives a light-weighted service which increases the responsiveness of the server through the provided APIs. The frontend is a combination of React and D3 which are JavaScript-based libraries, optimized for fast interactive multi-dimensional visualizations. The BID's interface is separated into two different views: (1) BID-Live for visualizing live streams of data; (2) BID-Audit for visualizing the retrospective data. BID-Live is updated every 30 minutes by sending an HTTPS GET request to the REST APIs—the update rate can be adjusted based on the transaction frequency in the blood product supply chain. BID-Audit takes into account the record of the last five years and presents the historical transactions in the transition sequence format. BID-Audit retrieves data from the long-term cache storage which records the processed real-time data for auditing purposes.

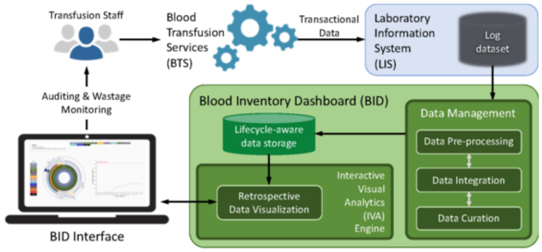

Figure 2 - The functional architecture of Blood Inventory Dashboard (BID)

BID Interface Design and Functionality

We have designed and developed BID for retrospective data visualization to help the staff to identify abnormal patterns of lifecycles which were not readily apparent from the transactional data and to see how much frequent it was to fall into such patterns. Studying blood unit's lifecycle patterns that lead to discard can contribute to discovering operational inefficiencies in the BTS. Towards this goal, BID provides a high-level overview of the transition sequences of blood units, highlighting the sequences that led to a discard. Filterability of the visualization allows the staff to dig into even less frequent transition patterns, thus allowing in-depth analysis of the lifecycle patterns at the level of institutional processes and users involved in the transactions leading to wastage.

For this research, we considered a five-year timeframe as the targeted period of our audit study as this gives an extensive history of the transactions to probe the lifecycle patterns of the blood products to identify the sequence patterns that lead to discards. Some of the potential questions that are intended to be answered utilizing BID are as following:

- What are the typical sequence patterns that lead to a successful transfused state?
- What is the distribution of the different transfused patterns?
- What is the distribution of the different discard patterns?
- What sequence patterns did lead to an outdate of a blood unit?
- What are critical markers of the sequence patterns that points to a potential discard?
- Which sequence patterns did lead to discard more frequently over the last 5 years?
- After a certain sub-sequence of transaction state, what were the most prevalent patterns to be followed?
- What were the rare wastage patterns (e.g., frequency less than 0.05%), and what did mainly cause the wastages for the longest patterns?

To study how the BTS performed in the last five years, especially to identify procedural inefficiencies, we are relying on lifecycle patterns that the blood products went through. Hence, BID is designed to effectively visualize patterns of transition sequences that were developed for each blood unit during the pre-processing phase. Due to the way the human brain processes information, there should be a solid relevance between the concept of transition sequence pattern and the way the data is visualized [8].

There is a selection of visualization techniques that can visualize transition sequences effectively. This category of visualization techniques falls into two general sub-categories [9]: (i) Node-Link diagrams such as trees and dendrograms. They consist of nodes and connections which define parent-child relationships among the nodes, and (ii) Space-Filling diagrams where the focus is on the relative sizes of the nodes within the hierarchy. The size of each node reveals its relative quantity, and its location in the diagram stands for its position in the hierarchy. The visualization techniques in this sub-category use either containment or adjacency to represent hierarchy; The former are called Enclosure diagrams which are plotted as treemap commonly, and the latter are called Adjacency Diagrams which have various layouts such as sunburst, and circle packing.

While Node-Link diagrams are focused on the structure of the hierarchy, they fail to effectively show valuable information about the relative quantity of a node among all the other nodes on the same level in the hierarchy. Additionally, these diagrams are not space-efficient as the size of the diagram has a positive polynomial relationship with the number of the nodes. For these reasons, we chose Space-Filling Diagrams since we need a compact easy-to-understand diagram which not only shows the sequence of transaction states from the time a blood unit is provided until it is either transfused or discarded but also brings into attention the magnitude of the transition patterns.

Among the mentioned visualization techniques in the Space-Filling sub-category, we chose Adjacency diagrams because it is closer to human comprehension of hierarchy than Enclosure diagrams which are cumbersome to interpret precisely [10]. Also, among Adjacency diagrams, sunburst layout tends to use space more economically than circle packing layout where there is a lot of empty space within the circles. Therefore, an interactive sunburst diagram is considered to visualize the lifecycle patterns within the dataset via aggregating all the transition sequences.

Results

BID interface has a modular design, comprising interconnected information modules. As the core of BID interface, Lifecycle Pattern Sunburst (LPS) (Figure 3) consists of rings as transition steps. The first step is the innermost ring, and as we move outward from the center, we approach to the final transaction state which can be either "Transfused" or "Discarded". The angle of each segment shows how much frequent the occurrence of the corresponding state is, and in each level of the hierarchy, states are sorted in descending order clockwise by transaction state frequency. LPS is interactive such that mouse hovering on the diagram reveals more details about the highlighted sub-sequence. Figure 4 shows BID interface where the staff interacted with LPS (module 1) and selected a sequence pattern leading to discard. In this view of the data, sequences with less than 0.05% pattern frequency are excluded which gives us an overview of the BTS over the last five years.

Statistical values related to the highlighted sub-sequence are shown in module 2—i.e., length of the transition sub-sequence, frequency ratio of the highlighted sub-sequence pattern.

To clearly demonstrate the lifecycle trend that is highlighted in LPS via mouse hovering, a breadcrumb trail of the sub-sequence is shown in module 3.

Since time duration between the transaction states give complementary information about the highlighted sequence pattern, average amount of time it takes to transit from a transaction state to its subsequent states is shown as a line chart in module 4; it is noteworthy that there is no direct correlation between lifecycle duration and length of lifecycle in terms of number of transaction states—i.e., a long transition sequence can happen in a relatively short time. This module also compares the trend to the average expiry time which is essential to study the wastage reason—i.e., not reaching the expiry threshold means there is a high risk of wastage due to operational inefficiencies for the blood units that follow the sequence pattern.

Besides the big picture of the prevalent lifecycle patterns that LPS shows, it is important to explore infrequent patterns since a wide variety of uncommon sequence patterns exist that led to discard. To this intend, module 5 filters LPS based on the outcome of lifecycle patterns (i.e., discarded/transfused) and sequence pattern frequencies.

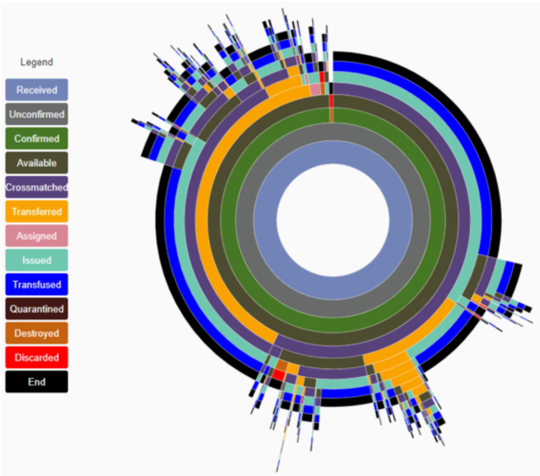

Figure 3 - Lifecycle Pattern Sunburst (LPS) giving an overview of the transactions by excluding the patterns that have frequencies less than 0.05%. Starting from the innermost ring, each ring represents a transition step towards the final transaction state of a lifecycle (the outermost segments) that can be either Transfused or Discarded. The frequency of a transition step is displayed by the angle of the corresponding segment. In each level of the hierarchy, transition steps are sorted clockwise from most to less frequent.

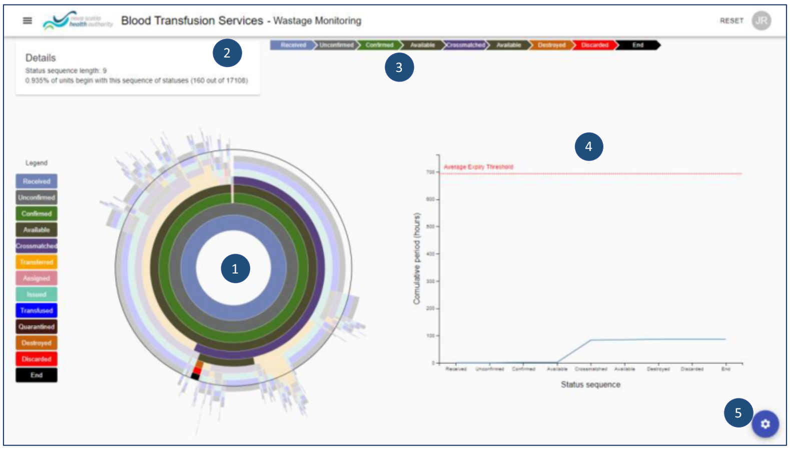

Figure 4 – BID interface showing a highlighted transition sequence by hovering the mouse on LPS. The other modules are updated upon the interaction with LPS. Module 2 shows the statistical detail about the highlighted sub-sequence. Module 3 shows the corresponding sequence breadcrumb. Module 4 shows time durations for each transition step in a cumulative format and compares the trend with the average expiry time. Module 5 opens filtering on LPS based on the outcome and frequency of lifecycle patterns.

Discussion

Investigating the lifecycle patterns not only facilitates performance assessment of the BTS in long term but also helps to learn how likely it is that a blood unit will be discarded from its evolving lifecycle. In order to answer to the potentially pertinent questions, we present scenarios to highlight the staff's interactions for auditing the RBC data accordingly.

- The staff want to identify the most prevalent discard patterns over the last five years. A quick look at LPS where uncommon patterns are filtered out (Figure 3) reveals three frequent discard patterns ('Discarded' states are shown in red). Mouse hovering on the most frequent discard pattern among the three identified patterns (Figure 4) shows that 0.94% of the RBC units (160 out of 17108) were discarded right after going through the following sequence of transaction states.

  $Received \rightarrow Unconfirmed \rightarrow Confirmed \rightarrow Available \rightarrow Crossmatched \rightarrow Available.$

  The line chart shows that there were not significant delays in processing these units compared to their average expiry time. Considering that the units were discarded after being crossmatched for once, it can be inferred that there was a potential inefficiency in the collection and screening process—i.e., Received, Unconfirmed and Confirmed states.

- The staff need to know what the frequent patterns were if an RBC unit was transferred right after being crossmatched for the first time. Towards this goal, they look for the following transition sequence in LPS where uncommon patterns are filtered out (Figure 3).

  $Received \rightarrow Unconfirmed \rightarrow Confirmed \rightarrow Available \rightarrow Crossmatched \rightarrow Transferred.$

  Mouse hovering on the adjacent outer segments (i.e., possible subsequent transition steps) shows that 61.68% was the chance to be issued and 31.37% was the chance to be transferred again. Also, interacting with more outer segments (i.e., farther transition sequences) reveals that 4.5% of these units were transfused in around eleven days on average after being transferred for six times consecutively to various hospitals.

- The staff want to investigate the rare wastage patterns and see which relatively long sequences emerged potentially from operational inefficiencies in the BTS. Figure 5 shows a screenshot of the LPS as the staff has filtered out the common sequences (i.e., sequences with greater than 0.05% pattern frequency) that led to transfusion. Mouse hovering on the patterns reveals the potential inefficiencies in the transfusion process for that particular pattern. For example, one blood unit followed the highlighted pattern in the screenshot in Figure 6 and was expired as the unit went through several transitions to the "Transferred" state. Figure 7 shows an example of a unit that had a quite long transition sequence yet was wasted due to a reason other than expiry. LPS reveals that among the patterns longer than 20 steps, 67.74% of the units (21 out of 31) were discarded due to an operational reason.

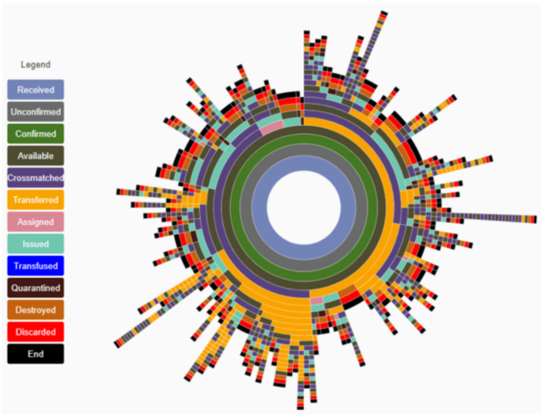

Figure 5 - In this view of LPS, transfused RBC units with greater than 0.05% sequence pattern frequency are filtered out which gives an overview of the discarded units that experienced uncommon lifecycle patterns.

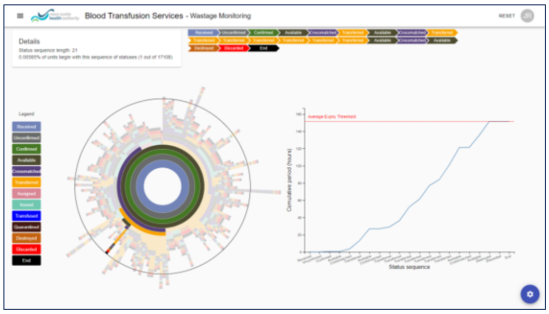

Figure 6 - BID interface showing the uncommon sequence patterns of discarded RBC units. Mouse hovering on LPS has highlighted a sequence transition pattern that happened to one RBC unit and led to being outdated.

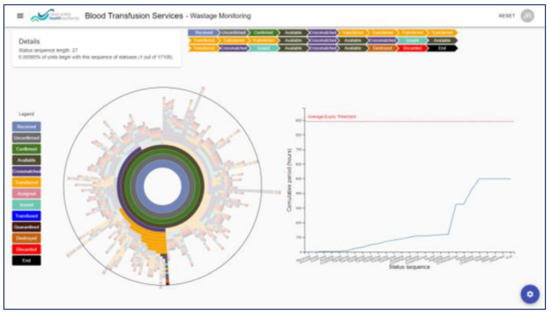

Figure 7 - The same data view as Figure 6. This time, mouse hovering on LPS has highlighted a pattern that happened to one RBC units and led to discard due to a reason other than expiry although the unit went through a long sequence of transitions especially being transferred several times to different hospitals.

BID is designed to be scalable to any BTS. It is being implemented within CZ-BTS where it will handle live data streams. We plan an efficacy and usability evaluation study to investigate the impact of BID on BTS operations.

Conclusions

In our work, we investigated the use of interactive visual analytics to optimize inventory of blood banks by presenting a 360^0 view of the inventory. Our approach is innovative and effective, as current inventory management approaches are typically manual thereby resulting in high wastage and inefficient cross-matching practices. Incorporating the blood unit lifecycle concept and visualizing the blood product lifecycle patterns are novel approaches to study and analyse the retrospective transactional data of BTS to identify procedural inefficiencies in the blood product supply chain.

Acknowledgements

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