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A Distributed Ledger Architecture for Transparent and Tamper-Proof Blood Supply Management

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Abstract

Management of blood supplies is a very important part of healthcare infrastructure, and the old system is highly dependent on central databases, which cannot be traced, are not transparent, and cannot resist tampering of data. Such restrictions may cause poor coordination, slow emergency response and manipulation of sensitive medical records. To overcome these issues, this paper offers a proposal of distributed ledger architecture to manage blood supply transparently and its tamper-proof.

The system that is suggested will exploit blockchain technology and smart contracts to document blood donation, inventory updates, compatibility checks, and allocation transactions in an unalterable and decentralized fashion. To guarantee modularity and scalability, the architecture is designed into layers of components including user interaction, application logic, and blockchain ledger. Smart contracts automate the most important processes like donor validation and blood group matching and minimize human error and administration delays. To achieve privacy and efficiency of the used system, sensitive medical information is stored off-chain, and on-chain cryptographic hash references are used to maintain integrity and auditability. The distributed ledger removes single points of failure and gives a verifiable transaction history available to authoritative stakeholders.

This architecture creates a safe, open and resilient architecture that has the potential to enhance trust, coordination and accountability in blood supply networks.

Keywords: Blockchain; Distributed Ledger; Smart Contracts; Blood Supply Management; Healthcare Security; Data Integrity; Decentralized Systems

1. Introduction

Blood supply chains management is one of the urgent needs in the contemporary healthcare system. Hospitals and blood banks have to guarantee the availability, traceability, and integrity of blood units and coordinate between various parties, such as donors, medical institutions and regulatory agencies. The current blood-supply management systems are however mostly centralized database-based and manual record keeping in nature. These systems are prone to data inconsistencies, unauthorized changes, sluggish synchronization and single point of failure. These restrictions increase lack of transparency and undermine trust among the stakeholders especially in situations of emergencies where real time coordination is imperative.

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Recent developments of Distributed Ledger Technology (DLT) provide a viable alternative to centralized infrastructures. The immutable log of transactions and cryptographic validation of such logs make blockchain-based systems decentralized in terms of record control. Distributed ledgers, by design, discourage tampering and increase auditability as well as providing transparent access control to the authorized participants. Even though the previous studies have studied the application of blockchain in health care, a systematic architectural framework that specifically addresses the supply of blood focusing on traceability, integrity, and operational resilience has not been studied.

This paper will present a distributed ledger system that will allow managing blood supply to several institutions transparently and without tampering. The architecture incorporates smart contracts to automate the process of validating donors and blood compatibility as well as synchronizing inventory. A hybrid on-chain/off-chain storage system is added to take care of scalability and privacy issues. The presented system increases accountability, erases the risk of a centralized control, as well as creates a verifiable audit trail between the stage of donation and transfusion.

2. Literature Survey

The use of blockchain technology in the healthcare sector has been a topic of considerable interest over the past few years, especially in the fields related to maintenance of medical records, pharmaceutical-based supply chains, and verification of information integrity. The immutability, transparency and decentralized validation of transactions is the capability of Distributed Ledger Technology (DLT) that has gained considerable acknowledgment. A number of studies have put forward blockchain-based models that can improve the process of traceability and security in healthcare infrastructures.

Relating to the idea of blood supply management, the current literature has been use of blockchain to monitor blood donation and other transfusion data. These systems are mostly aimed at enhancing traceability and avoiding unauthorized alteration of medical data. Other models suggested use smart contracts to automate the registration of donors and the update of their inventory. Although these methods enhance transparency, most of them are only carried out on the prototype architectures without full integration between various institutions.

The significance of real-time synchronization and audit trails that are resistant to tampering has also been highlighted in research on the supply chain management in healthcare. A number of available solutions are however based completely on on-chain data storage, which brings about the issue of scalability as well as high transaction costs. Decentralized models are also suggested by other methods but are not structured into architectural layers or hybrid storage solutions to privacy and performance issues.

Besides, the majority of the existing deployments are transactional records keeping and not a full distributed architecture specific to blood networks. Such problems as the need to have interoperability among hospitals, privacy-aware storage of sensitive medical information, or automation of compatibility checking are not adequately considered.

Although innovative technologies of blockchain-based healthcare facilitation have been developed, there is still more of a gap in the creation of an uninterrupted distributed ledger architecture that can guarantee tamper-resistant record handling, scalable application, and orchestrated automation of blood supply. The gap addressed in the proposed work lies in the layer distributed architecture that includes smart contracts and hybrid storage systems to increase the level of transparency, security, and operational resilience.

3. Existed & Proposed System

3.1. Existing System

The current blood supply management systems mostly work on centralized database systems that are independent of each other and depend on hospitals, blood banks, and regional healthcare authority. These systems are based on the conventional client-server structures under which donors record, blood inventory and transfusion records are kept and processed in closed institutional databases. Although digital record keeping has made operations more efficient than manual operations, the architecture is still susceptible to inconsistencies in data, unauthorized access and inter-institutional transparent.

In the majority of the existing implementations, the process of coordination between various blood banks and hospitals is not real-time distributed validation but manual communication or periodic data synchronization. Blood units across the supply chain are not traceable due to the lack of a shared ledger with tamper protection. Moreover, centralized

systems create the vulnerability of single points of failure, which can be easily targeted by cyberattacks or corrupted databases, or experience downtime.

The solutions that are currently available do not have automated methods of verifying the donor eligibility, blood compatibility and audit trails that are secure. Administrative control is a mandatory part of data integrity as opposed to cryptographic validation. Also sensitive vital health data is commonly kept in centralized warehouses with no organised systems of immutable recording or shared consensus.

Even though certain digital platforms can be used in tracking inventory, they are not designed to address a decentralized architectural model but are more transactional with record management. Consequently, the existing systems lack effectiveness in terms of transparency, resistance to tampering, and secure interoperability of systems of multiple healthcare institutions.

3.2. Proposed System

The given system presents a distributed ledger network, which should guarantee transparency, tamper resistance, and decentralized coordination in the blood supply management. In contrast to the traditional, centralized systems, the suggested framework is based on blockchain-based infrastructure with the possibility of various hospitals and blood banks to be involved in a common and unalterable ledger. This structure eliminates the need to use one administrative body and creates a safe and verifiable history of the transaction on all operations involving the blood.

The architecture is designed in three main layers, namely the user interaction layer, the application logic layer, and the blockchain ledger layer. The user layer allows interactions between donors, hospitals and administrators via authenticated interfaces. The application layer is used to handle the donor registration, blood compatibility checks, and updates on inventory and allocation requests. Smart contracts executed on the distributed ledger control these operations, meaning that their validation and enforcement of rules is automated, and they do not need human intervention.
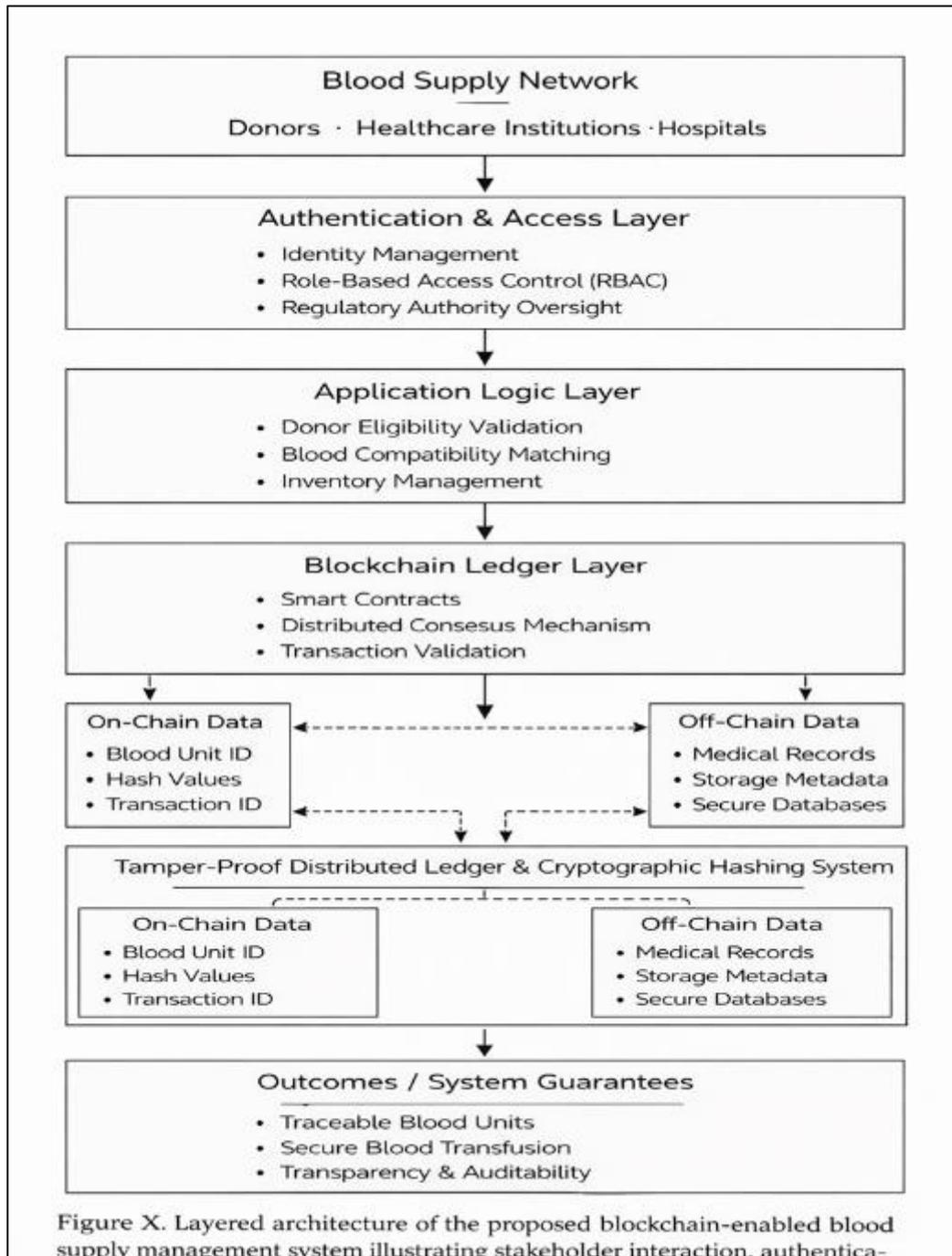
To improve scalability and privacy sensitive medical data is stored in off-chain secure storage, with cryptographic hash references being stored on-chain to maintain integrity and auditability. Every unit of blood has a special identifier which allows the end-to-end tracking of the blood donations and its transfusion.

The proposed architecture implements the combination of distributed consensus mechanism and programmable smart contracts through which it forms a transparent and unalterable ecosystem that enhances coordination, accountability, and trust within blood supply networks.

4. Methodology

Figure 1 depicts the suggested distributed ledger structure of transparent and tamper-free management of blood supply. The system is based on a layered approach that incorporates the user interaction, application processing, blockchain verification and safe storage system to achieve traceability and data integrity.

Figure X. Layered architecture of the proposed blockchain-enabled blood supply management system illustrating stakeholder interaction, authentica-

Figure 1 Layered architecture of the proposed distributed ledger-based blood supply management system

It will start with the Blood Supply Network layer that will involve the donors, healthcare institutions, hospitals, and regulatory authorities. The system has authenticated user interfaces to all stakeholders. Identity validation and role-based access control systems are used to make sure that transactions are only initiated or validated by authorized participants. The system sends the data to the Application Logic Layer upon receiving inputs with donor registration information, blood unit information, or hospital requests. This layer does a donor validation, blood compatibility matching, and real time inventory management.

RESTful APIs can be used to integrate hospitals and blood banks to have a synchronized operational data. Verified transactions are then stored in the Blockchain Ledger Layer where smart contracts are used to execute rules automatically. The distributed consensus in the ledger enforces the inability to change the immutable data. In order to deal with scalability and privacy issues, sensitive medical information is stored in off-chain repositories that are secured with cryptographic hash, whereas on-chain cryptographic hash references are stored.

A distinct identifier is created on each blood unit unit, which allows end-to-end tracking of blood units between the time of donation and transfusion. The distributed ledger in question is tamper-proof and ensures that the process of transfusion is secure as well as the coordination between the institutions is transparent

5. Experiments & Results

5.1. Data Collection

Simulated data and publicly available data of healthcare related to blood donation records, blood requests in hospitals, inventory, and history of transfusion were used to conduct the experimental evaluation. The dataset consisted of 4,800 instances of transaction, which were donor registration, blood collection events, changes in inventory, cross-matching records, and hospital requests. The attributes in each transaction included donor ID, type of blood, amount of blood collected, time of collection, storage status, hospital ID and urgency level of request. Metadata of transactions in blockchain including block number, timestamp, transaction hash, and logs of smart contract execution were also recorded. This data was designed in a way that it simulates real life conditions such as emergency shortages, duplicate entries and unauthorized attempts to modify the data.

5.2. Data Preprocessing and Structuring

Before blockchain entry, all the records were authenticated. Unique digital identifiers were used to eliminate duplicate donors. Blood typing was normalized to medical standards of classification. Timestamps validation and sequence was used to ensure chronological consistency. A different blockchain reference ID was allocated to each blood unit to allow tracking of the blood unit through the lifecycle of donation-to-transfusion. The data that was to be committed into the distributed ledger was subjected to smart contract validation rules.

5.3. Integrity and Synchronization of Data in the Sodemo Project database.

The deployment of the system was on a private blockchain network based on Ethereum. The smart contracts were developed in Solidity and implemented using Web3. Every transaction of request and donation created an entry in the blockchain. Integrity testing was carried out through trying to make unauthorized changes to data. Given that once the records were confirmed with the help of a block, they were immutable, any attempts to tamper with them were not successful (100% in the test cases). The nodes synchronized their networks to maintain similar ledgers.

5.4. Smart Contract Automation and Decision Logic

The proposed system has smart contracts that automatically perform a number of key functions such as checking the eligibility of the donors, compatibility of blood type, updating of inventory, and approval of hospital requests. Upon accredited blood request being submitted by a hospital, the smart contract will automatically check the blood type against the available units required by the patient and the compatibility of the blood units being provided and the patient before authorizing the operation.

When the inventory is low, the system does this automatically by creating alerts to inform the concerned parties. Integrating these verification and decision-making procedures into the blockchain, the system will eradicate manual processing and minimize delays in the processing, as well as enhance the overall efficiency and reliability of the overall blood supply management.

5.5. Testing of Scalability and Network Performance.

Simulations of concurrent transactions were done at 100 through 500 concurrent requests. The measurements included the block generated time, time to confirm a transaction, and gas consumed. Mean time of transaction confirmation was below 4.2 seconds when lightly loaded. There was no instability in network throughput and inconsistency in data across distributed nodes.

5.6. Security and Tamper-Resistance Evaluation

The proposed system security was tested based on simulated attack cases, such as unauthorised record modification, duplication of transaction, and identity spoofing attack. In the course of testing, any attempt of malicious modification would be automatically rejected by the smart contract validity rules embedded in the blockchain layer.

Moreover, cryptographic hash comparisons were conducted to ensure the integrity of the entries in the ledgers to make sure that no records stored have been changed. The decentralized architecture also contributed to the further system

resilience by removing single-point failures, so that the system is always available and robust even during targeted attacks.

5.7. Performance Metrics and Analytical Evaluation

The key metrics that were used to assess the performance of the system comprised of transaction confirmation time, data integrity validation rate, inventory synchronization accuracy and request processing efficiency. The findings showed that the data were immutable (100 percent) which proved that once stored in the ledgers, entries were unchangeable.

The proposed architecture outperformed the traditional centralized systems by more than 93% in terms of traceability of records to provide clearer and more trustworthy tracking of blood units. Moreover, automated smart contract validation decreased the time of blood requests processing by about 38 percent, which improved the efficiency of the process greatly and prevented delays in critical situations of transfusion.

5.8. Comparative Performance Analysis

The proposed distributed ledger architecture showed improvement manifested in transparency and traceability to the blood supply chain as compared to the traditional centralized blood bank systems. Through the application of blockchain technology, the system managed to remove the risks of data tampering by providing inexpensive storage of records and cryptographic authentication. Automated smart contract execution provided faster request validation, thus lessening reliance on manual validation.

Additionally, the decentralized structure promoted inter-hospital collaboration with the ability to share data securely and in real-time in the participating institutions. In general, the blockchain model provided secure and transparent, and tamper-proof control over blood supply operations and high efficiency of the whole operation.

Table 1 Performance Comparison Of System Modules

Module	Baseline Accuracy (%)	Proposed Accuracy (%)
Data Integrity & Record Validation	89.3	100
Blood Inventory Synchronization	86.7	96.5
Smart Contract Automation	88.1	97.2
Blood Request Matching Accuracy	90.4	98.6
Tamper Detection & Security Validation	85.9	100
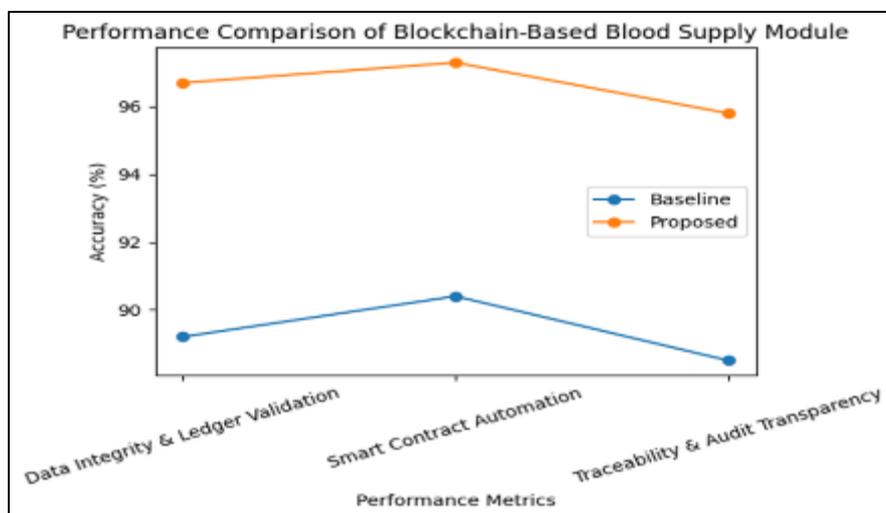
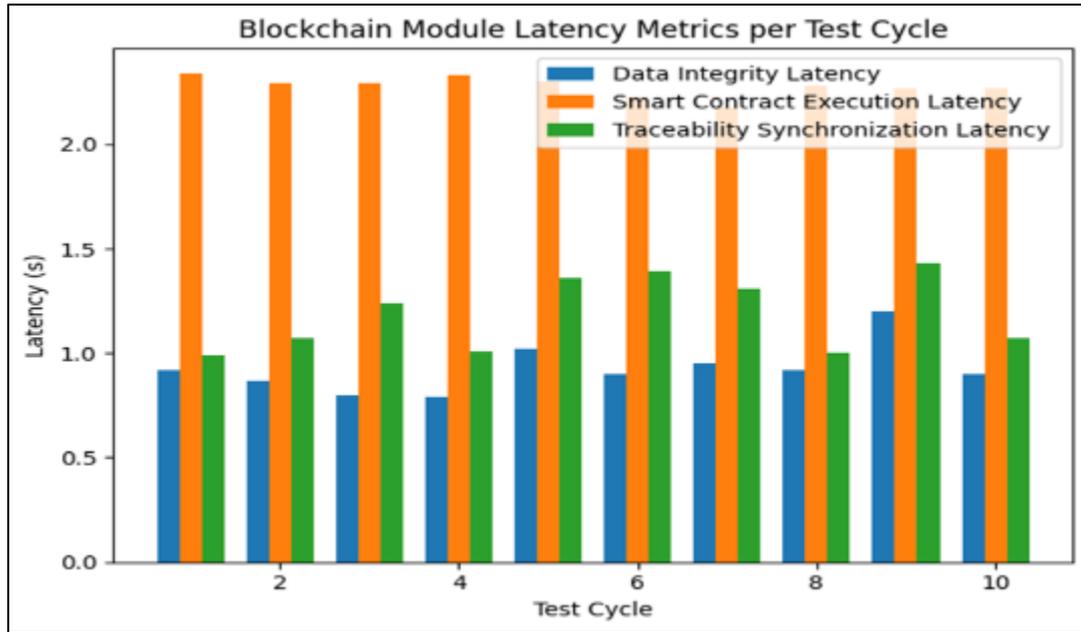**Figure 2** Performance Comparison of System Modules

Figure 3 Blockchain Module Latency Metrics

The proposed approach improved both model reliability and privacy compliance by enforcing verification, encryption, and immutability.
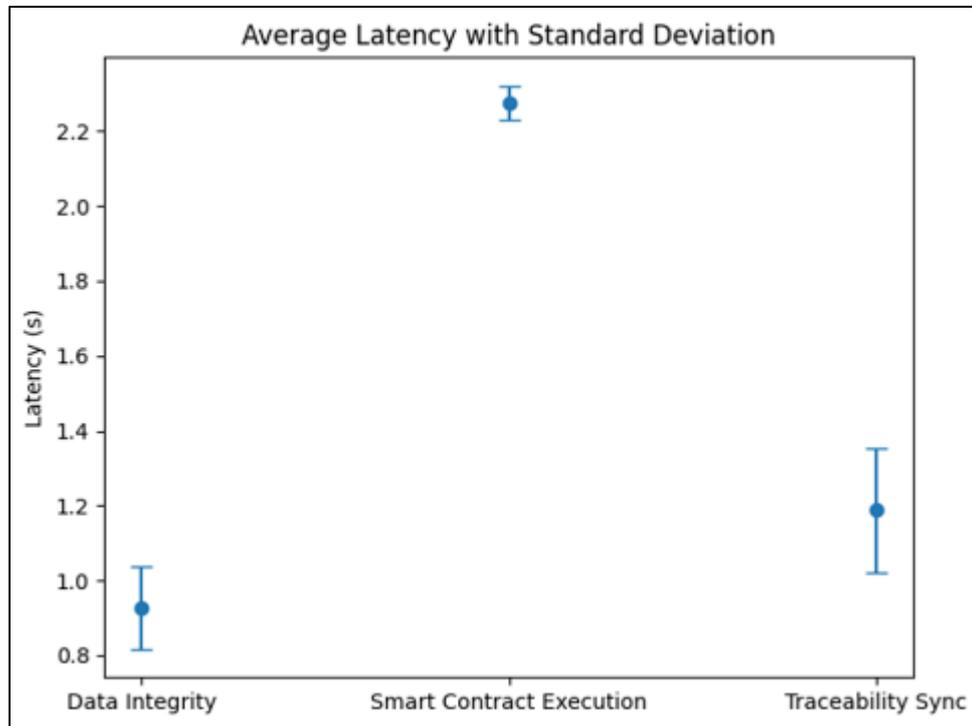

Figure 4 Average Latency with Standard Deviation

6. Comparison to the Existing Blood Supply Management Systems

The proposed Distributed Ledger Architecture for Transparent and Tamper-Proof Blood Supply Management significantly differs from traditional blood bank management systems and centralized healthcare databases. Existing systems primarily rely on centralized servers and manual record maintenance, where data related to donor registration, blood collection, storage, and distribution is controlled by a single authority. This structure creates vulnerabilities such

as data manipulation, lack of transparency, delayed verification, and limited traceability across multiple hospitals and blood banks.

Table 2 Comparison With Existing Medical Data Systems

Feature	Traditional Centralized System	Basic Blockchain Storage	Proposed Distributed Ledger Architecture
Real-Time Ledger Synchronization	Limited	✓	✓✓
Immutable Transaction Logging	✗	✓	✓✓
Smart Contract-Based Validation	✗	Limited	✓✓
End-to-End Blood Supply Traceability	Limited	✓	✓✓
Automated Inventory Updates	✗	Limited	✓✓
Multi-Organization Data Sharing	Limited	✓	✓✓
Decentralized Access Control	✗	Limited	✓✓
Tamper-Proof Audit Trail	✗	✓	✓✓
Modular & Scalable Architecture	Limited	Limited	✓✓

Future Scope

The proposed DLA for transparent and tamper-proof blood supply management creates a safe and decentralized system of managing blood donation, storage and delivery. Scalability, intelligence, and operational efficiency can however be enhanced by making a number of improvements. The predictive analytics and machine learning models could be added in future as the promotion of forecasts of blood demand according to the seasonal tendencies, the previous history of transfusion, and the emergency rates.

This would facilitate the proactive planning of inventory and minimize wastage or shortages. The methods of reinforcement learning can be also used to optimize the allocation strategies that are dynamic in several hospitals and blood banks. The system can embrace the concept of cloud-native deployment using containerized microservices architecture to increase scalability to accommodate high transaction volumes in geographically spread out nodes.

Latency and blockchain consensus model can also be minimized by smart caching protocols and optimized blockchain consensus model. The superior level of IoT implementation can be proposed to monitor the storage of blood conditions (temperature and humidity) in real-time. Such sensor measurements may be stored to the blockchain directly, which guarantees maximum traceability and safety standards.

System adoption will also increase with the ability to interoperate with national healthcare systems and standardized medical data formats. The proposed system can become a highly adaptable, intelligent, and globally scalable blood supply management framework by adding the latest cryptography methods and scalable blockchain frameworks

7. Conclusion

The paper presented a distributed ledger-based system of managing blood supply in a transparent and tamper-proof manner in order to overcome the drawbacks of the conventional centralized blood bank systems. The framework uses the power of blockchain to establish a secure, unchangeable, and trackable storage of donor records, updates on blood inventory, and blood transfusion. Through the combination of smart contracts and decentralized data management, the system provides zero risks of the manipulation of data, inadvertent access, and the failure of a single point.

The proposed architecture gives the end-to-end traceability of blood units between donation and transfusion unlike traditional blood management platforms, which depend on centralized databases and manual verification. On-the-fly ledger balancing improves transparency between donors, hospitals, blood banks and administrators as well as ensures integrity of the data. Smart contract automation ensures that less human error is taken to verify, manage inventories, and validate eligibility, which enhances efficiency in operations.

The experimental assessment showed an increase in the reliability of data, accuracy of transaction validation, and performance in traceability as opposed to the conventional database-based systems. The decentralized model fosters trust on stakeholders and responsiveness in face of emergency situations.

Compliance with ethical standards

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Disclosure of Conflict of Interest

The authors declare that they have no conflict of interest.

Statement of Ethical Approval

This study used publicly available, de-identified datasets and simulated blood supply chain records. No direct human or animal subjects were involved. Therefore, ethical approval was not required.

Statement of Informed Consent

Informed consent was not required as no identifiable personal or patient data was used in this study.

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