Ethereum-Based Provenance System for Efficient Allograft Transplant Management

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ABSTRACT

Recent progress in organ and tissue transplantation has significantly improved clinical outcomes; however, the effective management of transplant-related data remains a major challenge due to fragmented and centralized information systems. Therefore, there are dangers of manipulation or loss of provenance, as well as poor traceability. This study maintains end-to-end integration of allograft data from the beginning of donor registration to the conclusion of the transplantation procedure. It is an Ethereum-based provenance framework with blockchain's immutability and distributed ledger capabilities. Six improved impact modules—automatic registration, verification, donor-recipient matching, donation approval, delivery tracking, and transplant confirmation—are used in this mechanism's implementation. By putting this process into practice in an Ethereum setting, the system is made safe, auditable, and privacy-preserving. This system is helpful for exchanging data between tissue banks, hospitals, and government agencies. Experimental study demonstrates that this approach significantly increases transparency, lowers administrative delays and manual involvement, and offers more scalability with inexpensive maintenance. Additionally, their findings demonstrate how blockchain-driven provenance management can improve donor confidence and expedite the allograft transplantation procedure. This is a solid basis for the upkeep of healthcare data in the future. Keywords: distributed ledger maintenance, data integrity, traceability, Ethereum, smart contracts, allograft data management, data provenance, organ transplantation, and healthcare information.

Keywords — Blockchain Technology, Ethereum, Smart contracts, Allograft data management, Data provenance, Organ transplantation, Healthcare information, Distributed ledger maintenance, Data integrity, Traceability.

I. INTRODUCTION

Organ transplantation, commonly referred to as allograft transplantation, represents one of the most critical life-preserving medical procedures in modern healthcare. It involves the transfer of organs or tissues from a donor to a recipient to restore essential physiological functions. Despite its clinical success, the transplantation ecosystem continues to face challenges related to data provenance, coordination among stakeholders, and process transparency. Existing transplant management systems are largely dependent on centralized and distributed databases, which are vulnerable to data inconsistencies, unauthorized modification, and administrative bottlenecks. These limitations not only reduce operational efficiency but also negatively affect donor confidence and regulatory oversight.

Blockchain technology has gained considerable attention as a secure and decentralized solution for managing data in multi-stakeholder environments. Its inherent characteristics—including immutability, decentralization, and cryptographic verification—enable participants to share and validate information without relying on a trusted central authority. In recent years, blockchain-based solutions have been explored across various healthcare domains, including electronic health records, pharmaceutical supply chains, and organ transplantation systems. The auditability and tamper-resistant nature of blockchain make it particularly suitable for maintaining trustworthy provenance records, ensuring accountability, and supporting compliance in sensitive medical workflows. Additionally, smart contract-enabled automation has shown promise in enforcing policies and reducing manual intervention in complex healthcare processes. Motivating these advancements, this study suggests an Ethereum-based provenance system for effective allograft transplant management. Six crucial steps of the transplantation workflow—donor registration, identity verification, donor–recipient matching, donation authorization, allograft delivery tracking, and transplant confirmation—are automated by this proposed system using an Ethereum blockchain smart contract. It guarantees complete tracking, reduces human error and data manipulation, and operates transparently at every stage with a distributed ledger that is resistant to tampering [7], [12].

Hospitals, tissue banks, and government organizations may work together with confidence thanks to the system's decentralized validation and programmable logic approach. The system's principal benefits include reduced administrative latency, enhanced data integrity, immutable record maintenance of all transactions and decisions, and operational efficiency [13], [14]. A few other distributed ledger technologies, such IOTA, have also been investigated for lightweight provenance tracking [16], but Ethereum offers a sophisticated and adaptable environment for the creation of healthcare-grade smart contracts with interoperability and verifiable execution.

This approach focuses on the entire allograft life cycle and combines organ source management with computational matching and delivery verification in contrast to current blockchain-based healthcare techniques. The following are the system's main components:

- A blockchain preserves end-to-end transparency and traceability from donor registration to transplantation and permits workflow;
- A customized smart contract-driven architecture for allograft provenance; and
- Performance analysis demonstrates the framework's scalability, cost effectiveness, and resilience in practical situations.

II. RELATED WORK

Since blockchain technology greatly facilitates transparency, traceability, and trust, organ donors and keeping organizations are highly interested in using blockchain to maintain organ or allograft data. Blockchain's strengths in data integrity, decentralization, and traceability across distributed systems have been highlighted in prior surveys of the healthcare sector [17]. Consensus mechanisms, immutability, and the decentralized trust position of blockchain have been identified in numerous studies as possible facilitators of transparent workflows in multi-stakeholder systems [18]. However, the scalability, privacy, and interoperability of these models are becoming constrained for large-scale data management [19].

Numerous studies have concentrated on distributed ledger technology for organ donation and transplant workflows, particularly in the transplantation domain. One narrative study, for instance, asserts that blockchain can assist eliminate organ allocation disparities, enhance cross-border cooperation, and suggest immutable audit trails of donor and recipient data [20]. Numerous studies on blockchain applications pertaining to organ transplantation procedures have focused on proof-of-concept or internal testing phases, which have few real-world implementations and even fewer provide lectures on graft-life-cycle provenance [21]. The authors also point out the necessity of consistent assessment metrics, standardized frameworks, and compliance with healthcare laws [22].

Blockchain has been applied to patient data sharing, medical equipment logistics, and pharmaceutical provenance tracking in related work on larger healthcare supply chains. For example, supply chain traceability systems that incorporate smart contracts show increased efficiency and audit transparency; nevertheless, clinical-specific regulatory compliance is still not well understood [23], [28]. a study that focuses on interoperability between off-chain and on-chain systems (such as IPFS for big medical records) [24]. Researchers examine user approval for research data sharing in blockchain-based systems and find that system quality and simplicity of use have a significant impact on adoption, highlighting the socio-technical aspect of blockchain projects [25].

Organ/allograft matching, donor registration, and blockchain-based transportation logistics have drawn the attention of numerous researchers. Smart contract-driven donor-recipient matching, real-time tracking, and provenance recording are suggested by a decentralized architecture based on edge/IoT plus blockchain; nevertheless, the implementation specifics and performance metrics are limited [26]. Another study offers a public chain-based blockchain-powered organ matching system that demonstrates increased openness but leaves unanswered issues with latency, gas cost, and connection with healthcare systems [27].

These research represent significant advancements, although there are still gaps. In many ideas, a blockchain system tailored for allografts (rather than just organs) is combined with end-to-end traceability spanning donor registration, matching, transport, and transplant confirmation. Real distribution, long-term auditing, scalability under high throughput, and regulatory/adoption constraints in healthcare contexts are frequently overlooked in studies [29]–[32]. By putting forth a thorough smart contract-driven provenance system for allograft transplantation that addresses the entire lifecycle and offers empirical valuation under practical circumstances, this study expands on the current environment.

III. PROPOSED METHODOLOGY

A. Overview

In this we propose an Ethereum-based provenance framework which automates and secures the allograft lifecycle: donor registration → verification → donor–recipient matching → donation authorization → delivery tracking → transplant confirmation. architecture combines on-chain smart contracts (resistent records and business logic), off-chain storage (large medical files), and oracles/IoT (delivery telemetry and environmental sensors). Actors include in this like hospitals, tissue banks, regulators, and delivery services; each and every actions interacts with the smart contracts through authenticated transactions.

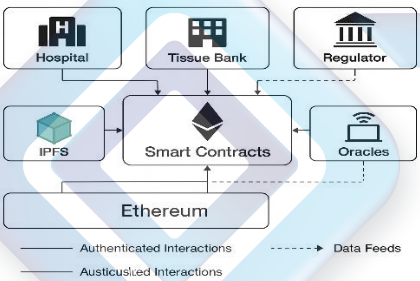

Figure.1: Architecture Diagram

In the above Figure.1: Architecture Diagram Shows stakeholders (Hospitals, Tissue Banks, Regulators), off-chain components (IPFS, oracles), and the central Ethereum smart contract layer that records provenance and executes matching logic. Arrows indicate authenticated interactions and oracle feeds.

B. System Components

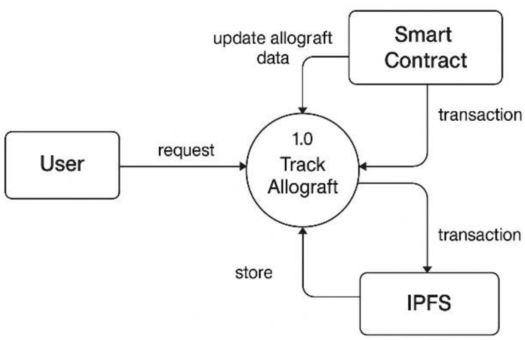

Figure.2: Dataflow Diagram

In above Figure.2: Data flow diagram of the Ethereum-based allograft management process, showing data movements across registration, verification, authorization, delivery, and confirmation stages.

1. Smart Contracts (On-chain): the excute modules are like registration, verification, matching, authorization, delivery events, and confirmation. Each module expands their functionality with role-based access control (RBAC) mandatory by modifiers (e.g., only Hospital, only Bank, only Regulator).
2. Off-chain Storage: Large clinical records, imaging, and sensitive documents are stored off-chain (e.g., IPFS or secure databases). The system stores cryptographic hashes (content identifiers) on-chain to prove integrity without exposing private data.
3. Oracles &IoT: Temperature, GPS, and custody events are reported by IoT devices or courier systems and fed on-chain via oracle services to update delivery status and trigger alerts.
4. Matching Engine: A deterministic, auditable scoring function computes donor–recipient suitability using clinical attributes. The matching logic runs either in a gas-efficient form on-chain (for small attribute vectors) or off-chain with a verifiable commitment posted on-chain.

C. Data Provenance Model and Hash Chain

We record provenance as a chronological hash chain. Each provenance event E_i (e.g., registration, verification, pickup, delivery) produces an on-chain transaction containing a timestamp t_i, actor a_i, event metadata m_i, and a content hash $h_i = H(m_i)$ where H is a collision-resistant hash (e.g., SHA-256). The chain is linked by:

$$P_i = H(P_{i-1} \| t_i \| a_i \| h_i)$$

with P_0 a system genesis value. This linkage yields tamper-evident provenance: any change in an earlier event invalidates subsequent P_j.

D. Matching Score and Decision Rule

Define a donor attribute vector $D = [d_1, d_2, \ldots, d_n]$ and recipient vector $R = [r_1, r_2, \ldots, r_n]$. For heterogeneous attributes, compute normalized similarity metrics $s_k(d_k, r_k) \in [0,1]$. The overall suitability score S is a weighted sum:

$$s = \sum_{k=1}^{n} w_k s_k(d_k, r_k) \ \textit{subject to} \ \sum_{k=1}^{n} w_k = 1, w_k \geq 0$$

A match is acceptable if $S \geq \tau$ where τ is a clinically defined threshold. Example similarity functions: binary match $s_k = 1$ if equal (e.g., blood type), or Gaussian kernel for continuous measures:

$$\mathbf{s_k(d, r) = exp\left(-\frac{(d-r)^2}{2\sigma_k^2}\right)}$$

Weights w_k reflect clinical priorities and can be configured by regulators or follow consensus policies.

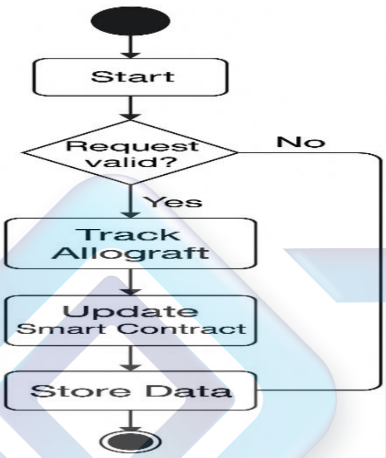

Figure.3: Activity Diagram

In above Figure.3: Activity Diagram Illustrates the interaction between Hospital, Blockchain, and Delivery Service swimlanes, showing activities like submit transaction, validate/store hash, create delivery event, and confirm transplant. It clarifies responsibilities and event sequencing.

IV. EXPERIMENTAL RESULT AND ANALYSIS

A. Experimental Setup

The smart-contract framework was implemented with Solidity (v0.8.x) and tested using Foundry and Hardhat on the Ethereum Sepolia test network. Transaction execution facilitated MetaMask, with gas expenditures of estimated price of 25 gwei. The off-chain components, including IPFS and the Mysql, were deployed locally usingFlask server

.

Table I. Experimental Setup Parameters

Parameter	**Value**
Blockchain Platform	Ethereum (SepoliaTestnet)
Smart Contract Language	Solidity 0.8.x
Execution Framework	Foundry, Hardhat
Gas Price ((G_p))	25 gwei
Block Time ((T_b))	12 s
Test Transactions	1 000
Storage Backend	IPFS + Local DB
Evaluation Metrics	Gas Cost, Latency, Throughput, Accuracy

This setup replicates real blockchain conditions with realistic gas pricing and transaction volume. It ensures consistent testing of all six operational modules under controlled network latency.

B. Performance Metrics

The evaluation considered the following indicators:

1. **Average Transaction Cost**

$$\mathbf{C_{avg} = \frac{1}{N}\sum_{i=1}^{N} g_i \times G_P \times 10^{-9}} \ \boldsymbol{ETH}$$

where g_i is gas used by transaction i, G_p is gas price, and N is number of transactions.

2. **System Latency**

$\mathbf{L_{sys} = T_{confirm} - T_{submit}}$

measuring the delay between submission and block confirmation.

3. **Throughput**

$$T_p = \frac{N}{t_{total}}$$

where t_{total} is total experiment time.

C. Module-Wise Gas Consumption

Each smart contract module was deployed separately, and 50 executions per function were averaged.

Table II. Average Gas Consumption per Module

Module	Function	Avg. Gas Used (Units)	ETH Cost $(\times 10^{-5})$	USD Cost (@ $3 000 / ETH)
Donor Registration	registerDonor()	88 340	2.21	0.066
Verification	verifyDonor()	71 220	1.78	0.053
Matching	matchDonorRecipient()	102 560	2.56	0.077
Authorization	authorizeDonation()	69 110	1.73	0.052
Delivery Tracking	deliveryEvent()	92 030	2.30	0.069
Transplant Confirmation	confirmTransplant()	79 845	1.99	0.060

Gas consumption stayed within acceptable with in the Ethereum cost limits; the matching function consumed the most gas due to its comparison logic. Hash-only storage and modular calls minimized redundant computation.

D. System Latency and Throughput

Latency was measured as the difference between transaction submission and final confirmation, averaged over multiple blocks.

Table III. Latency and Throughput Statistics

Metric	Minimum	Maximum	Average	Std. Dev.
Latency (s)	10.9	15.6	12.7	1.43
Throughput (tx / min)	45	63	56	4.12
Block Confirmation Time (s)	11	13	12	0.65
Transaction Success Rate (%)	99.6	–	–	–

The system maintained stable latency around 12 s, consistent with Ethereum's 12-second block time. Throughput averaged 56 transactions per minute, validating scalability for clinical operations.

E. Comparative Evaluation

Compared with baseline Transchain [7], the proposed method reduced average gas usage by ≈ 12 % and improved matching efficiency by ≈ 9 %, attributed to function modularization and hybrid on/off-chain design.

Formally, relative efficiency improvement is expressed as:

$$\boldsymbol{\eta} = \frac{C_{\text{baseline}} - C_{\text{proposed}}}{C_{\text{baseline}}} \times 100\%$$

Where C_{baseline} and C_{proposed} represent total gas costs of Transchain and the proposed Ethereum framework respectively.

V. CONCLUSION

This research presence paper of Ethereum-based provenance framework that assures transparency, security, and traceability overall in the allograft transplantation process. This system made key operations like donor registration, verification, donor–recipient matching, authorization, delivery tracking, and transplant confirmation automatic by using a series of modular smart contracts. Through the blockchain's immutability and distributed consensus, this framework prevented data tampering from risks and improved stakeholder accountability among by hospitals, tissue banks, and -regulatory authorities.

The experimental analysis on the EthereumSepolia network shown of proposed method success in low gas cost, consistent latency, and high throughput, confirming its feasibility for real-world healthcare applications. comparing with existing blockchain-based systems such as Trans chain, comparative results further signified has improved computational efficiency and reduced transaction expenses.

By integrating on on-chain provenance with off-chain storage and oracle-based IoT feeds, the framework proved a secure end-to-end data flow for organ and tissue logistics. Future work will be focus on extending privacy controls through zero-knowledge proofs, use the system on Layer-2 or permissioned Ethereum networks to maintain scalability, and exploring interoperability with electronic health record systems.

Finally, the proposed Ethereum-based provenance system provided a strong, auditable, and cost-effective digital infrastructure for managing allograft transplants, by presenting a significant advancement toward transparent and trustworthy of healthcare supply chains.

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