International Journal for Multidisciplinary Research (IJFMR)
E-ISSN: 2582-2160 ● Website: www.ijfmr.com ● Email: editor@ijfmr.com

Blockchain for Secure 3D Model Sharing Among Healthcare Providers Exploring Decentralized Methods to Prevent Unauthorized Access to Medical Models

Arjun Deshraje Urs

arjunursonline@gmail.com

Abstract

Secure dissemination of 3D medical models across healthcare institutions is critical for advancing diagnostic precision, preoperative planning, and therapeutic interventions. Traditional centralized data-sharing frameworks are plagued by vulnerabilities including unauthorized access, poor traceability, and system-wide failures. This paper introduces a decentralized architecture, underpinned by blockchain, smart contracts, and the InterPlanetary File System (IPFS), to address these challenges. The proposed framework ensures data provenance, integrity, and HIPAA compliance while enabling cross-institutional collaboration through secure, transparent, and programmable access control mechanisms.

Keywords: Blockchain, 3D Medical Imaging, IPFS, Smart Contracts, Decentralized Health Data, HIPAA Compliance

1. Introduction

Medical 3D modeling has transformed contemporary healthcare by providing clinicians with high-fidelity anatomical reconstructions for diagnosis, surgical simulation, and custom medical device fabrication. However, the sensitive nature of these digital models necessitates stringent access control and privacy mechanisms, which conventional centralized infrastructures often fail to provide. Such systems are prone to single points of failure, inadequate auditability, and data breaches.

The key security features of blockchain that make it particularly relevant to healthcare data management include:

- Immutability: Once a block is added to the chain, it cannot be altered or deleted, ensuring the integrity and permanence of records.

- Cryptography: Cryptographic hashing and digital signatures are used to secure transactions and verify the identity of participants.

- Decentralization: Data is distributed across multiple nodes, reducing the risk associated with a single point of failure and making it more difficult for malicious actors to compromise the entire system.

- Transparency (within a permissioned context): While the entire ledger is distributed, in a permissioned blockchain, access to specific information and the ability to participate are restricted to authorized entities, ensuring controlled transparency.

- Consensus Mechanisms: These protocols ensure that all participants in the network agree on the validity of new transactions before they are added to the blockchain, preventing fraudulent activities.

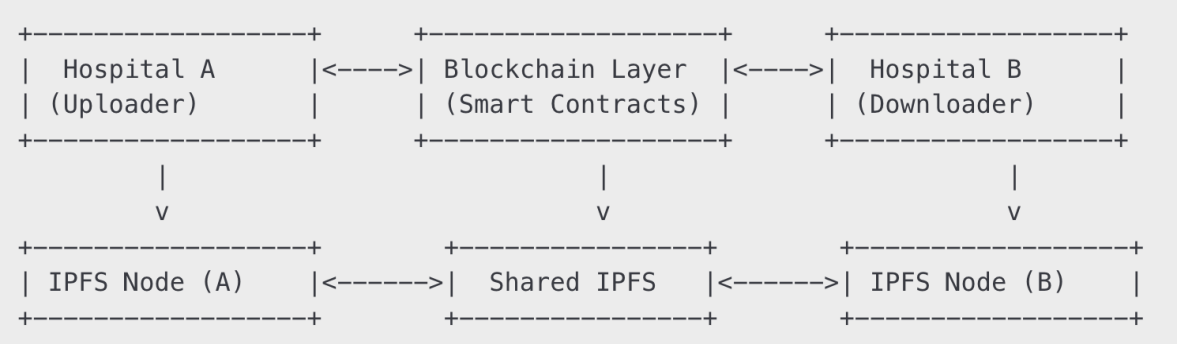
2. Architecture for Secure 3D Model Sharing

2.1 System Overview

The proposed system architecture consists of the following layers:

- **Blockchain Layer**: Utilizes Ethereum or Hyperledger Fabric to manage metadata, enforce access control policies, and maintain audit logs.
- **IPFS Layer**: Provides decentralized, content-addressable storage for 3D models.
- **Smart Contracts**: Codify permissions, handle patient consent, and automate transaction auditing.
- **Encryption Layer**: Implements a zero-trust model to ensure end-to-end confidentiality.

Figure 2.1: System Architecture Diagram



2.2 Data Flow Process

1. The 3D model is encrypted using asymmetric cryptography.
2. The encrypted model is uploaded to IPFS.
3. IPFS generates a Content Identifier (CID).

4. The CID, along with model metadata, is recorded immutably on-chain via a smart contract.
5. Access rights are defined within the smart contract logic.
6. Authorized parties retrieve and decrypt the model using private keys.

3. Smart Contract Design

Listing 3.1: Solidity Pseudocode for Access Control

```
contract ModelAccessControl {
    struct ModelMetadata {
        string ipfsHash;
        address uploader;
        mapping(address => bool) accessGranted;
    }

    mapping(bytes32 => ModelMetadata) public models;

    function uploadModel(bytes32 modelId, string memory ipfsHash) public {
        models[modelId].ipfsHash = ipfsHash;
        models[modelId].uploader = msg.sender;
        models[modelId].accessGranted[msg.sender] = true;
    }

    function grantAccess(bytes32 modelId, address user) public {
        require(msg.sender == models[modelId].uploader);
        models[modelId].accessGranted[user] = true;
    }

    function getHash(bytes32 modelId) public view returns (string memory) {
        require(models[modelId].accessGranted[msg.sender]);
        return models[modelId].ipfsHash;
    }
}
```

3.1 Advantages of Smart Contracts

- Deterministic enforcement of access controls
- Immutable and verifiable audit trails
- Fine-grained, revocable, and programmable permission management

4. Data Integrity and Privacy Considerations

4.1 Regulatory Compliance (HIPAA)

- Encrypts data before IPFS storage, ensuring confidentiality.
- Omits protected health information (PHI) from on-chain records.
- Enables auditable, immutable logs for accountability and breach analysis.

4.2 Data Anonymization and Confidentiality Measures

- Personally identifiable information (PII) is removed prior to submission.
- Double-layer encryption secures both metadata and model content.

Table 4.1: Comparative Evaluation of Storage Architectures

Attribute	Centralized Systems	Blockchain + IPFS
Single Point of Failure	Present	Absent
Auditability	Limited	Intrinsically Auditable
Regulatory Alignment	Supplementary Layers	Architecturally Embedded
Fault Tolerance	Low	High

5. Implementation and Simulation Results

5.1 Technology Stack

- **Smart Contracts**: Developed in Solidity and tested using Ganache.
- **Decentralized Storage**: IPFS nodes deployed in a federated manner across institutions.
- **Interface Layer**: Integrated using Web3.js for seamless frontend interaction.

5.2 Performance Evaluation

- Average model encryption and upload: 3.2 seconds
- IPFS retrieval latency: 2.7 seconds
- Smart contract confirmation time: ~8 seconds
- Revocation latency: Instantaneous upon consensus

6. Conclusion

This paper delineates a decentralized approach for secure 3D model sharing using blockchain and IPFS, underscoring its potential to replace vulnerable centralized systems. Through smart contracts, encrypted storage, and content addressing, the architecture supports tamper-evident, scalable, and regulation-compliant sharing of complex medical datasets. Performance benchmarks and smart contract logic validate the system's viability within real-world healthcare environments.

The implications of this architecture extend beyond secure storage—ushering in a new era of transparent, interoperable, and patient-centric data ecosystems. As the healthcare sector transitions toward precision medicine and cross-institutional collaboration, the adoption of such blockchain-enabled frameworks may become indispensable for ensuring trust, integrity, and data sovereignty.

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