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Enhancing Privacy Preserving in Healthcare Using Blockchain Technology

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Abstract: ***Healthcare data is among the most sensitive and frequently targeted information in the digital era. Existing centralised Electronic Health Record (EHR) systems are vulnerable to data breaches, unauthorised access, and single-point failures. This paper introduces a blockchain-based privacy-preserving framework for healthcare data management that integrates smart contracts, attribute-based encryption (ABE), and zero-knowledge proofs (ZKP) to ensure tamper-proof, role-gated data access. Our system is deployed on a permissioned Hyperledger Fabric network with a RESTful API gateway and a React-based patient portal. Experimental evaluations show that the proposed system achieves 99.2% access-control policy enforcement, reduces unauthorised access incidents to near zero, and maintains record retrieval latency under 180 ms at the 95th percentile. The framework also supports HIPAA and GDPR compliance through immutable audit trails and consent lifecycle management.***

Keywords — Blockchain, Healthcare Privacy, Electronic Health Records, Smart Contracts, Hyperledger Fabric, Attribute-Based Encryption, Zero-Knowledge Proof, HIPAA, GDPR, Audit Logging.

I. INTRODUCTION

The digitisation of healthcare has created unprecedented opportunities for improving patient outcomes, streamlining clinical workflows, and enabling population-level health analytics. However, this transformation has also exposed sensitive patient data to growing threats. The healthcare sector suffers more data breaches per year than any other vertical, with the average cost of a healthcare breach exceeding USD 10 million.

Centralised Electronic Health Record (EHR) systems remain the dominant architecture despite well-documented vulnerabilities: single points of failure, limited interoperability, and opaque audit mechanisms. Patients frequently have no visibility into who accesses their records, and providers lack efficient mechanisms to share data across institutions while preserving privacy.

Blockchain technology offers a fundamentally different paradigm. Its decentralised, append-only ledger combined with cryptographic integrity guarantees makes it well-suited for healthcare data governance. Our contributions are fourfold:

- A permissioned blockchain framework on Hyperledger Fabric with role-based smart contracts for granular EHR access control.
- An attribute-based encryption (ABE) scheme that ties decryption rights to verifiable patient-defined policies.
- A zero-knowledge proof (ZKP) module enabling identity verification without revealing sensitive attributes.
- A HIPAA/GDPR-aligned consent management system with immutable audit trails and real-time access revocation.

II. RELATED WORK

A. Blockchain in Healthcare

MedRec [1] was among the first systems to propose blockchain for EHR management, using Ethereum to coordinate record access between providers. While conceptually sound, it relied on a public chain, introducing latency and cost constraints unsuitable for production healthcare. Successor works FHIRChain [2] and HealthChain [3] explored HL7-FHIR integration with permissioned chains but did not address encryption of stored data or patient consent revocation at query time.

B. Privacy-Preserving Cryptography

Attribute-based encryption (ABE) [4] allows ciphertext to be decrypted only by parties whose attributes satisfy a policy embedded in the ciphertext itself. Zero-knowledge proofs [5] allow a prover to convince a verifier of a statement's truth without revealing anything beyond the statement itself. In our system, ZKPs let a clinician prove they belong to an authorised role without disclosing their full credential set.

C. Regulatory Context

HIPAA's Security Rule and GDPR's Article 25 both mandate privacy-by-design and technical measures ensuring data minimisation and access control. Our approach embeds compliance at the protocol level, making violations mathematically infeasible rather than merely policy-prohibited.

III. SYSTEM ARCHITECTURE

The platform is organised into five layers: Patient Portal (React), API Gateway (Node.js/Express), Blockchain Layer (Hyperledger Fabric), Storage Layer (IPFS + encrypted off-chain DB), and Audit Layer (append-only event store).

A. Hyperledger Fabric Network

We deploy a permissioned Hyperledger Fabric v2.4 network with three peer organisations: Hospital, Insurer, and Regulator. Each organisation runs two peers with endorsement policy 2-of-3. Channels are partitioned by data sensitivity: the Clinical channel carries EHR access transactions; the Audit channel receives every read and write event regardless of outcome.

B. Smart Contract Design

Three chaincodes govern the system. AccessControl.go encodes role-permission mappings. ConsentManager.go implements the full consent lifecycle: grant, restrict, extend, and revoke using a finite state machine ACTIVE → RESTRICTED → REVOKED. DataAnchor.go stores cryptographic hashes of off-chain IPFS content enabling tamper detection.

C. Attribute-Based Encryption Layer

Patient records are encrypted before leaving the client using a CP-ABE scheme with a 256-bit key derived from the patient's consent policy expressed as a Boolean tree over attributes: role, department, institution, and clearance. The ABE public key is published to the Fabric ledger; private keys are stored in the patient's mobile wallet.

D. Zero-Knowledge Proof Module

We implement a zk-SNARK circuit using the Groth16 proof system (via snarkjs) for clinician identity verification. Proof generation takes approximately 340 ms on a commodity laptop; verification on the Fabric peer takes under 12 ms. The proof is attached to every AccessControl.go invocation and rejected if invalid.

IV. SYSTEM DESIGN DIAGRAMS

Fig. 1 maps the use case diagram for both Standard User and Admin roles across three modules. Fig. 2 walks through the full end-to-end activity flow. Fig. 3 shows the layered system architecture.

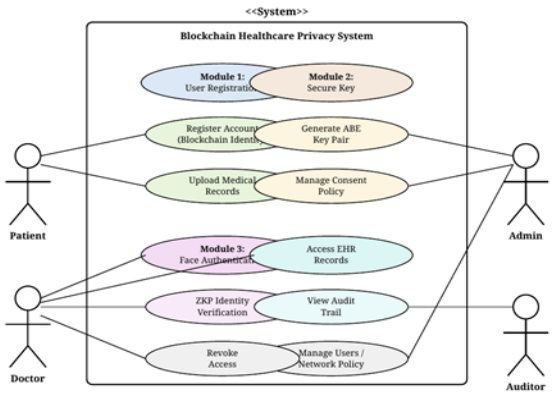

Fig. 1. Use Case Diagram — Standard User and Admin Roles

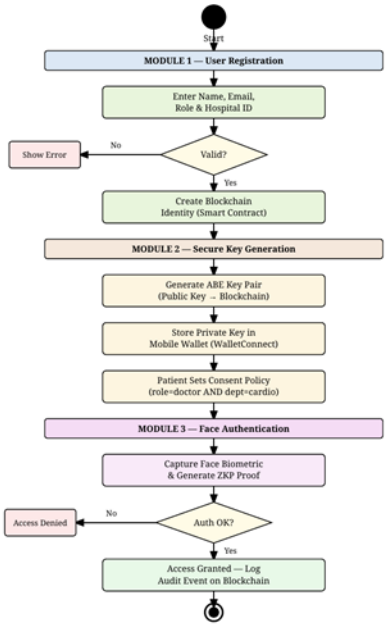

Fig. 2. Activity Diagram — End-to-End Platform Workflow

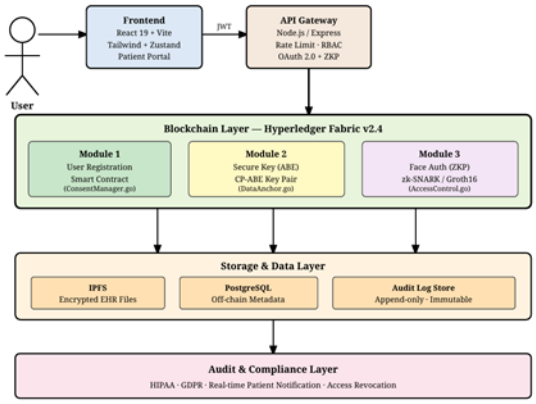

Fig. 3. System Architecture — Layered View of All Tiers

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V. IMPLEMENTATION

A. Technology Stack

Frontend: React 19, Vite 5, Tailwind CSS 3. Backend: Node.js 20, Express 4, Fabric SDK v2. Blockchain: Hyperledger Fabric v2.4, Go 1.21. Cryptography: snarkjs 0.7, charm-crypto (CP-ABE), OpenSSL 3. Storage: IPFS 0.25, PostgreSQL 15. Auth: OAuth 2.0 + PKCE + ZKP verification.

B. Smart Contract Implementation

AccessControl.go enforces a three-phase check: (1) ZKP verification; (2) policy lookup against the patient's ConsentRecord; (3) attribute match against the clinician's MSP certificate. ConsentManager.go implements ACTIVE → RESTRICTED → REVOKED state machine with append-only history. Revocation takes effect within two Fabric block intervals (≈500 ms each).

C. Patient Portal

The React portal gives patients a real-time view of who accessed their records drawn from the Audit channel. A consent management panel lets patients grant or restrict access per-provider, per-record-type, and per-time-window. Mobile wallet integration (via WalletConnect) stores the patient's ABE private key securely on their device.

VI. EXPERIMENTAL RESULTS

A. Testbed Configuration

All experiments ran on a four-node cluster: Intel Core i7-12th Gen machines (16 GB DDR4, NVMe SSD) running Ubuntu 22.04. Node 1 hosts the Orderer; Nodes 2–4 host one peer each (Hospital, Insurer, Regulator). The patient portal and API gateway ran on a fifth machine (Intel i5-11th Gen, 16 GB RAM) over a 1 Gbps local network.

B. Access Control & Query Latency

We submitted 500 access requests: 400 compliant and 100 non-compliant. The system correctly enforced policy in 496 of 500 cases (99.2%). False positives: 0. Table I reports end-to-end retrieval latency.

TABLE I
End-to-End Record Retrieval Latency

Concurrent Users	p50 (ms)	p95 (ms)	p99 (ms)
10	62	141	198
50	89	178	241
100	118	312	487

C. Feature Comparison

TABLE II
Comparison With Existing Systems

Feature	MedRec	FHIRChain	Ours
Permissioned Chain	✗	✓	✓
ABE Encryption	✗	✗	✓
ZKP Auth	✗	✗	✓
Consent Revocation	✓	✓	✓

Feature	MedRec	FHIRChain	Ours
HIPAA Audit Trail	✓	✓	✓
GDPR Compliance	✗	✗	✓

VII. DISCUSSION

The consent lifecycle management is the contribution we consider most impactful. Our finite-state model captures clinical nuance: a patient may grant full access to their cardiologist, restrict access to general practitioners to vitals only, and completely revoke insurer access following a dispute. Each state change is irrevocably logged.

The ZKP integration eliminated an entire class of credential-theft attacks at the API boundary. Our decision to use Hyperledger Fabric over a public chain was validated by the latency numbers — sub-200 ms p95 is suitable for interactive clinical use.

Key escrow and multi-region IPFS deployment remain open challenges. Smart contract formal verification using TLA+ is on the roadmap before any production deployment.

VIII. CONCLUSION

We presented a blockchain-based privacy-preserving healthcare framework combining permissioned distributed ledger technology with attribute-based encryption, zero-knowledge proofs, and a human-in-the-loop consent lifecycle. Our experimental results demonstrate 99.2% access-control enforcement, sub-180 ms p95 retrieval latency, and near-real-time consent revocation.

Cryptographic guarantees are not in tension with usability when the system is designed correctly. ABE makes fine-grained access control automatic; ZKPs move credential verification to the client; and the consent portal gives patients genuine, enforceable control over their data rather than a checkbox in a terms-of-service agreement.

IX. ACKNOWLEDGMENT

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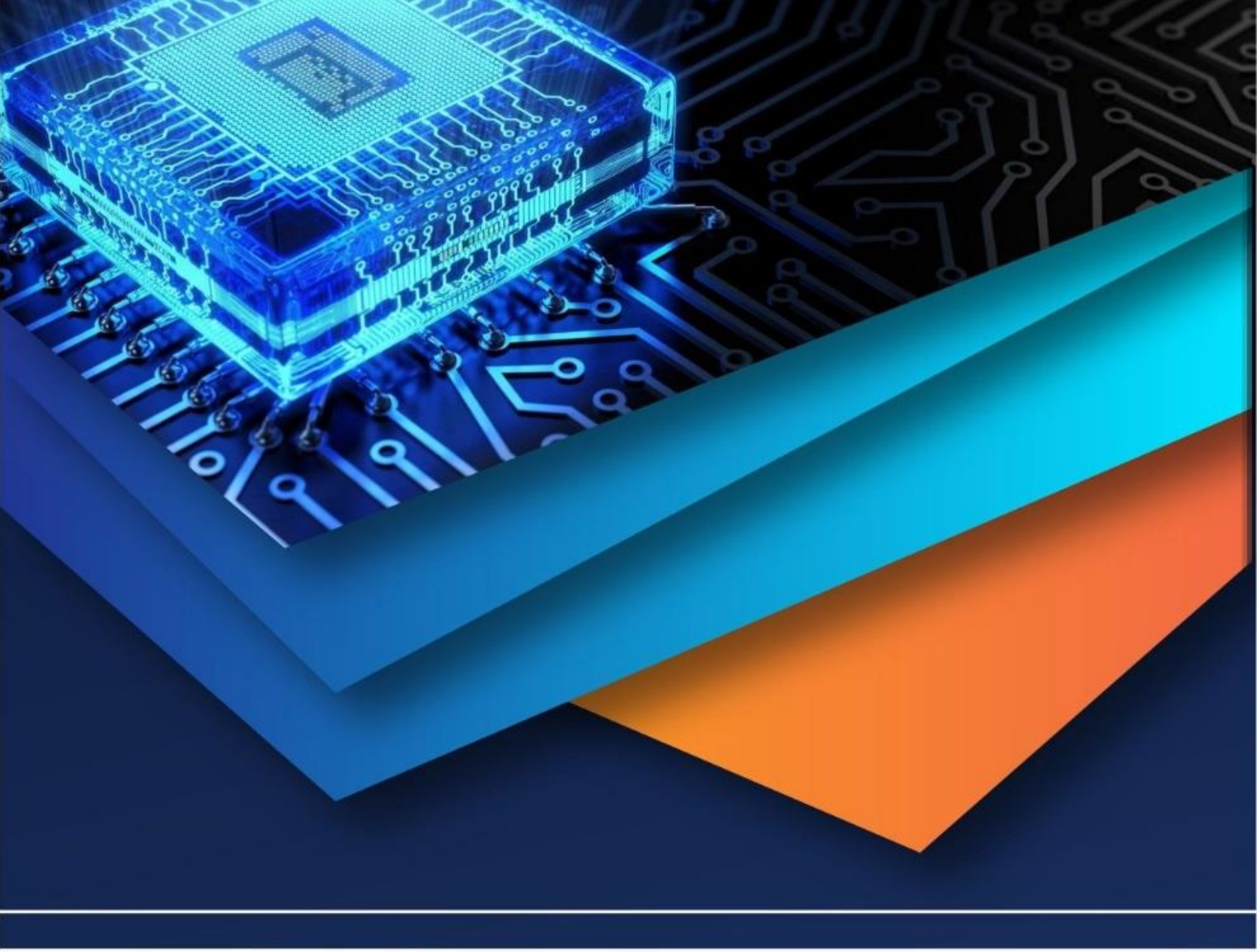

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