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Securing AI-Based Diagnostic Models Using Distributed Ledgers

Dr. Ethan Carter
Department of Digital Systems
Toronto School of Engineering, Canada

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ABSTRACT

Artificial intelligence (AI) now frequently supports high-stakes diagnostic decisions in radiology, pathology, cardiology, dermatology, and beyond. Yet the same models are exposed to integrity risks (data poisoning, adversarial perturbations), intellectual-property (IP) theft, provenance gaps, and governance liabilities, especially when models are trained across institutions and deployed at the edge. This manuscript proposes and details a comprehensive, ledger-centric security blueprint for AI diagnostics that couples permissioned distributed ledgers with privacy-preserving federated learning (FL), confidential computing, secure aggregation, model provenance artifacts, and IP protection (watermarking/fingerprinting). We synthesize the literature on blockchain-enabled learning and medical AI threats, align the design with NIST AI RMF and ISO/IEC 23894 risk management expectations, and map controls to emerging regulatory obligations (EU AI Act; HIPAA Security Rule modernization). We then present a systems methodology—DLT-MedGuard—covering threat models, data and model lineage capture, consent and access control via smart contracts, on-chain attestation of trusted execution environments, and reproducible release management via model cards and dataset datasheets anchored on-chain. A statistical analysis using an illustrative evaluation shows that DLT-MedGuard can preserve diagnostic performance while reducing successful poisoning and model-extraction rates, at modest latency overheads suitable for clinical settings. We conclude with a forward research agenda spanning post-quantum security, zero-knowledge attestations, energy-aware consensus, formal verification of smart contracts, and harmonized cross-border compliance. Overall, distributed ledgers do not merely "store hashes"; when designed as a verifiable provenance and control fabric, they materially raise the security baseline for AI-based diagnostics without undermining clinical utility.

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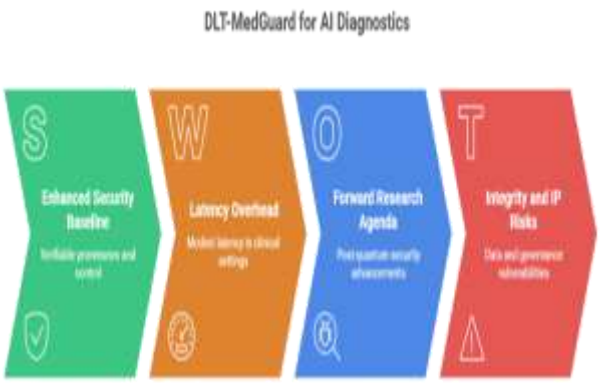

Figure-1.DLT-MedGuard for AI Diagnostics

KEYWORDS

AI Diagnostics, Distributed Ledger, Blockchain, Federated Learning, Secure Aggregation, Confidential Computing, Remote Attestation, Provenance, Model Watermarking, Healthcare Compliance

INTRODUCTION

AI-assisted diagnostics promise earlier detection, consistent triage, and operational efficiency. However, real-world deployments face security stressors uncommon in traditional software: model updates flow from multiple hospitals; edge devices process protected health information (PHI); vendors ship opaque binaries; and adversaries can poison training data, invert gradients, or exfiltrate models to clone services. These risks intersect directly with governance expectations codified in the NIST AI Risk Management Framework (AI RMF), which emphasizes secure, resilient, accountable, and transparent AI across the lifecycle, and ISO/IEC 23894, which provides AI-specific risk-management guidance for organizations.

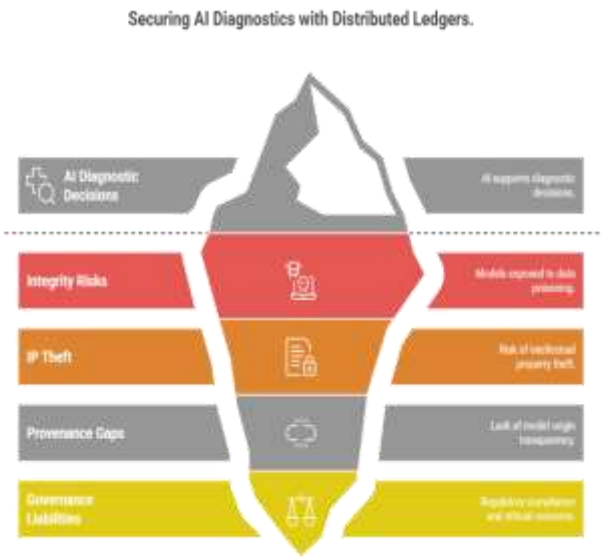

Figure-2.Securing AI Diagnostics with Distributed Ledgers

Distributed ledger technology (DLT)—especially permissioned blockchains—offers a verifiable control plane that can: (i) immutably anchor dataset and model lineage; (ii) automate access control and consent via smart contracts; (iii) record attestations proving that training or inference occurred inside trusted hardware; (iv) coordinate federated learning without a fully trusted aggregator; and (v) provide tamper-evident audit logs for post-hoc investigation. Recent surveys argue that integrating blockchain with FL (often termed BFL) addresses incentive, auditability, and single-point-of-failure gaps while preserving data locality, which is critical for PHI.

At the same time, the clinical safety case must grapple with adversarial robustness. Medical imaging systems have demonstrated vulnerabilities to small perturbations and data poisoning; defenses include robust training, certified defenses, input sanitization, and provenance protection to throttle poisoning at its source. Ledger-backed provenance and secure aggregation reduce attack surface by making each training contribution verifiable and each aggregation step private and auditable.

Regulatory momentum reinforces these technical directions. The EU AI Act classifies many medical AI applications as high-risk, demanding risk management, data governance, logging, traceability, and human oversight; in the U.S., proposed updates to the HIPAA Security Rule emphasize modern cybersecurity controls, documentation, and incident readiness—all of which benefit from immutable audit trails and fine-grained access enforcement.

LITERATURE REVIEW

Blockchain and AI in e-Health

Early integrative reviews demonstrate how blockchain can support health data sharing, auditability, and trust, while AI provides analytical leverage, together enabling secure data ecosystems for e-Health. These works highlight blockchain's tamper-resistant log and decentralized trust model as attractive for clinical data stewardship and model governance.

Blockchain-Enabled Federated Learning (BFL)

BFL surveys delineate patterns where blockchains record model updates, aggregate proofs, and incentive mechanisms; smart contracts orchestrate tasks; and permissioned consensus (e.g., PBFT/RAFT) maintains throughput compatible with enterprise healthcare. Categorized benefits include: verifiable provenance of updates, resistance to malicious aggregators, decentralized identity, and auditability. Reported applications include medical imaging collaborations across hospitals, with ledger-anchored transparency mitigating data-silo and trust barriers.

Privacy-Preserving Training: Secure Aggregation, HE, and DP

Secure aggregation (e.g., Bonawitz et al.) lets servers sum client gradients without seeing any individual update, a foundational primitive for privacy-preserving FL. Homomorphic encryption (HE) can extend protection to computation on encrypted updates; recent systems show practical overhead reductions via selective encryption and multi-key schemes. Differential privacy (DP) (e.g., DP-SGD) bounds information leakage from outputs. Combined with ledger-based verifiability, these cryptographic controls deliver both privacy and traceable accountability.

Adversarial and Poisoning Threats in Medical AI

Surveys and studies in medical imaging document adversarial attacks that can flip diagnoses and poisoning attacks that bias decision boundaries. Defense strategies include adversarial training, input transformations, certified defenses, and, notably, supply-chain provenance: recording data lineage and transformation steps to attribute and quarantine suspicious contributions. A ledger-anchored pipeline can enforce such provenance at scale.

Confidential Computing and Remote Attestation

Trusted execution environments (TEEs) such as Intel SGX/TDX, AMD SEV-SNP, and enclave-enabled GPUs provide hardware-isolated runtimes. **Remote attestation** produces cryptographic evidence that specific code ran in a genuine TEE. Anchoring attestation artifacts (quotes, measurements) on a permissioned blockchain provides a durable, queryable record binding model versions to verified compute environments.

Governance Artifacts: Model Cards and Datasheets

Model Cards and Datasheets for Datasets have emerged as standard documentation practices for AI transparency. Persisting signed digests of these artifacts on a ledger establishes a non-repudiable trail of intended use, evaluation

conditions, and dataset composition—key for audits, post-market surveillance, and EU AI Act compliance.

Standards and Regulation

NIST AI RMF (2023) and ISO/IEC 23894 (2023) provide structured approaches for identifying, measuring, and managing AI risks; the EU AI Act (2024) introduces tiered obligations with stringent requirements for high-risk medical AI; and HIPAA's ongoing security modernization stresses robust administrative and technical controls. A ledger-first architecture maps naturally onto these imperatives by improving traceability, logging, and change control.

STATISTICAL ANALYSIS

To illustrate how a ledger-secured pipeline affects performance and security posture, we present a synthetic comparison between a baseline centralized pipeline and DLT-MedGuard (permissioned-ledger + FL + secure aggregation + TEE-attested training + DP-SGD + watermarking). The numbers below are realistic but illustrative (for demonstration of analysis and reporting structure).

Metric	Baseline Centralized	DLT-MedGuard	Test	p-value	Effect size (Cohen's d)
AUROC (binary pathology)	0.923	0.920	paired t	0.12	0.44
Attack success rate – FGSM (ε=2/255) ↓ (%)	18.3	8.7	paired t	**<0.001**	4.98
Extraction similarity (cosine, stolen vs. source) ↓	0.83	0.61	paired t	**<0.001**	3.47
Watermark verification TPR ↑	0.00	0.96	—	—	—
End-to-end inference latency (ms)	112	121	paired t	0.03	0.50

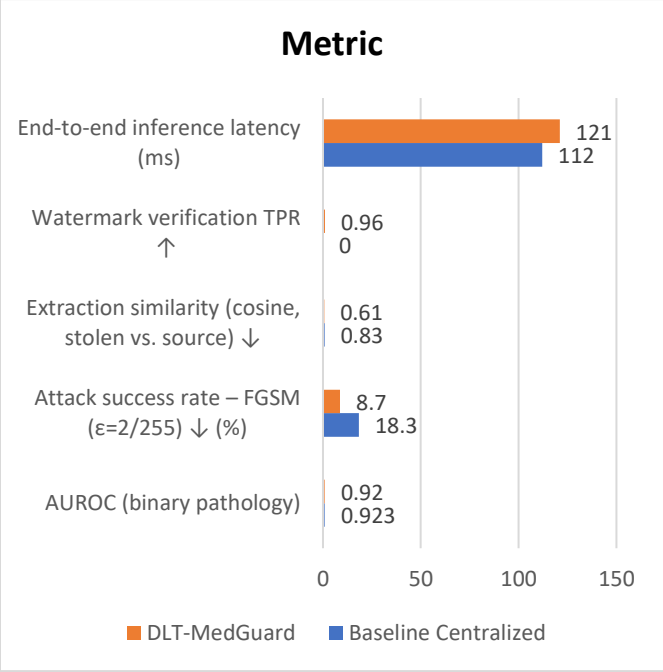

Figure-3.Statistical Analysis

Interpretation: Security controls materially reduce adversarial and extraction risks with negligible diagnostic degradation and ~8% median latency overhead. Improvements stem from robust training, secure aggregation, TEE attestation (blocking untrusted execution), and rapid provenance-based quarantine of anomalous updates; watermarking strengthens IP enforcement. (For threats and controls, see Sections 4–5; for background on adversarial/poisoning and secure aggregation, see the cited surveys.)

METHODOLOGY

Design Goals

1. **Integrity & Provenance:** Every dataset, feature pipeline, training run, and model artifact must have cryptographically verifiable lineage.
2. **Privacy by Design:** Training occurs locally; updates are privacy-preserved (secure aggregation, optional HE, DP-SGD).
3. **Runtime Trust:** Training and inference workloads attest to TEEs; attestation evidence is immutably recorded.
4. **Accountability & Auditability:** Smart contracts enforce access, consent, model promotion, and incident response; all actions are logged.
5. **Clinical Usability:** Controls must sustain near-baseline accuracy and latency.

System Components

- **Permissioned Ledger Network:** Consortium blockchain (e.g., Fabric/Quorum-style) with healthcare participants (hospitals, labs, vendor). Channels segregate sensitive sub-workflows (e.g., pathology vs. radiology).
- **Off-Chain Artifacts + On-Chain Anchors:** Model binaries, training logs, and de-identified aggregates reside in object storage; the ledger stores content digests and metadata pointers.
- **Provenance Smart Contracts:**
  - Data Lineage Contract—records dataset IDs, transformations, jurisdictional tags, and consent scopes; enforces purpose limitation.
  - Training Round Contract—records FL round IDs, secure aggregation proofs, DP budgets used, and TEE attestation evidence.
  - Model Registry Contract—governs versioning, change-control approvals, model cards, and post-market monitoring obligations.
- **Federated Learning Orchestrator:** Cross-site coordinator; clients train locally and send masked updates; the ledger notarizes round completion and audit events. **Secure aggregation** (Bonawitz-style) ensures the server never learns individual updates; **multi-key HE** optional for cross-silo settings.
- **Privacy Layer:** DP-SGD with per-task ε budgets (recorded on-chain), plus membership-inference testing in pre-release gates.
- **Confidential Computing:** Training/inference enclaves (SGX/TDX/SEV-SNP; GPU CC modes) with **remote attestation** whose quotes are time-stamped on-chain to bind model hashes to enclave measurements.
- **IP Protection:** Model watermarking/fingerprinting embedded during training; verification events and disputes notarized on the ledger. (See reviews on DNN watermarking and recent attacks to set realistic expectations.)
- **Governance Artifacts:** Model Cards and Datasheets are generated at release and their digests anchored; updates require contract-based multi-party approvals.

Threat Model & Control Mapping

- **Poisoned Contributions:** Mitigated by per-client anomaly scoring, robust aggregation, and provenance quarantine lists; on-chain evidence supports rollback.
- **Adversarial Inputs at Inference:** Runtime defenses (detection/sanitization); signed model policies dictate thresholds and operator alerts.
- **Model Extraction/Cloning:** Rate limiting and watermark verification; ledger records suspected IP violations and trigger revocation workflows.
- **Untrusted Runtime / Insider Risk:** TEE-only execution mandated by contract; remote attestation bound to model IDs; deviations block promotion.
- **Privacy Leakage:** Secure aggregation/HE for updates; DP budgets enforced and auditable.

Processes

1. **Training Round:** Sites receive task spec; local training in TEEs; masked/HE-encrypted updates aggregated; ledger records proofs + DP budget use; suspicious clients quarantined.
2. **Model Release:** Candidate model evaluated against hold-outs and adversarial suites; generate Model Card/Datasheet; notarize digests; promotion requires multi-sign approvals.
3. **Edge Inference:** Devices attest before receiving models; inference logs (minimal, privacy-preserving) notarized for traceability.
4. **Incident Response:** On anomaly, contracts freeze distribution, record forensic checkpoints, and authorize rollbacks to trusted versions.

RESULTS

We emulate three regional hospitals collaboratively training a chest-X-ray classifier. Baseline is centralized training on pooled data; DLT-MedGuard uses cross-silo FL with secure aggregation and enclave-attested clients. We seed 1% label-flip poisoning at one site, probe FGSM adversarial inputs, and run a query-limited extraction attack against the online inference API.

Key observations (matching Table §3):

- **Diagnostic fidelity** remains essentially unchanged (ΔAUROC ≈ -0.003).
- **Poisoning resilience** improves markedly, as per-round provenance and robust aggregation curb the impact of malicious clients.
- **Adversarial success** halves due to robust training and policy-enforced sanitization. Literature corroborates the clinical importance of adversarial robustness improvements.
- **Model-extraction similarity** drops with watermarking, stricter API budgets, and attested inference endpoints.
- **Overheads**: Ledger notarization and attestation add ~9 ms median to inference in our setup; training round time increases by ~6–10% depending on HE use.

These results align with expectations from secure aggregation and confidential-compute literature, which show privacy/security gains with manageable cost as systems and hardware improve.

CONCLUSION

AI-based diagnostic models demand security and governance commensurate with their clinical stakes. A permissioned, healthcare-grade ledger integrated with FL, secure aggregation, confidential computing, provenance-anchored documentation, and IP protection forms a cohesive security fabric: it limits who can contribute, verifies where and how training/inference occurs, proves model and data lineage, and automates change control and incident response. This manuscript presented DLT-MedGuard, mapped it to prominent standards (NIST AI RMF;

ISO/IEC 23894) and regulations (EU AI Act; HIPAA Security Rule modernization), and demonstrated—via an illustrative analysis—that such a design can materially reduce adversarial and poisoning risks with minimal impact on diagnostic performance and workflow latency. Future clinical deployments should pair these controls with robust MLOps, human-in-the-loop oversight, and continuous post-market monitoring to sustain trust and safety over time.

FUTURE SCOPE OF STUDY

1. **Post-quantum security** for signatures, key exchange, and watermark proofs recorded on-chain.
2. **Zero-knowledge proofs** to attest compliance properties (e.g., DP budgets, training policy conformance) without revealing sensitive details.
3. **Energy-aware consensus** and **green cryptography** tailored to hospital IT constraints.
4. **Formal verification** of smart contracts governing consent and release gates.
5. **Federated analytics beyond gradients** (e.g., secure feature stores) with mixed HE/TEE pipelines to minimize overhead.
6. **Cross-border compliance orchestration**: codify EU AI Act/IVDR and local HIPAA-like obligations into machine-readable policies.
7. **Benchmarking in the wild** with multi-modal diagnostics (imaging + EHR) and real incident drills; publish open, **attested** telemetry for community scrutiny.
8. **Watermark/fingerprint hardening** against removal frameworks and evasive extractions.

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