Federated Search Engine Architecture For Donor Tracking in ART Clinics

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Abstract
Clinics and sperm banks offering Assisted Reproductive Technology (ART) make extensive use of donor sperm and oocytes; however, information related to donors is often dispersed among these banks. Such repeated use of the same donor across clinics results in significant births from the same donor. It also raises critical ethical, legal, and public health concerns, such as unintended genetic relationships among offspring, and the inability to perform long-term monitoring. While centralized donor databases have been proposed earlier as a solution, they raise substantial concerns regarding data privacy, regulatory adherence, and acceptance by participating organizations. This paper proposes a federated search engine framework to support secure donor tracking across ART clinics without centralizing the storage of sensitive records. The proposed framework deploys decentralized query processing, with privacy-enhancing cryptographic identifiers, and aggregates non-identifiable donor indicators to enable controlled information sharing. Formal mathematical formulations help describe donor identity abstraction, federated query resolution, and detection of potential consanguinity risks. Performance evaluations conducted on synthetically generated, multi-clinic datasets indicate that the architecture is scalable, compliant with privacy constraints, and effective in mitigating donor overuse. Overall, the proposed framework is a practical and ethically responsible framework for donor tracking within distributed ART environments.

Keywords: Federated Search, ART Clinics, Donor Tracking, Consanguinity, Donor Database

Introduction

The global expansion of ART services has led to increased reliance on donor gametes. While ART outcomes have improved significantly, governance mechanisms for donor usage remain fragmented and largely manual. Clinics typically maintain isolated donor records, resulting in systemic blind spots across institutions. This increases the probability of donor overuse and donor-conceived individuals unknowingly forming consanguineous relationships. Centralized registries have been proposed as a solution, but they introduce legal exposure, privacy risks, and resistance from clinics concerned about data ownership. In countries such as India, where regulatory frameworks continue to evolve, a centralized architecture may be impractical. This paper proposes a federated search-based

architecture that enables ART clinics to participate in donor tracking without relinquishing control over their data.

Limitations of Existing Options

National ART registries collect aggregate statistics but lack real-time interoperability and donor-level traceability. Voluntary donor sibling registries rely on self-reporting and DNA testing, limiting coverage and timeliness. Federated data networks are used in biomedical research, public health surveillance, and electronic health records to balance data utility and privacy. Existing systems do not combine federated search principles with donor tracking under ART-specific ethical constraints.

Methodology

Let C = {c1, c2, ..., cn} be the set of ART clinics and Di be the local donor dataset maintained by clinic ci.

Assumptions

- No clinic shares raw donor data externally.
- All clinics adopt a minimal common metadata schema.
- Donor anonymity preserved under all query operations.

To systematically compare global ART registries, this paper evaluates registries across six measurable dimensions.

Let R = set of ART registries, R = {R1, R2, R3, ..., Rn}.

Each registry Ri is evaluated using a feature vector Fi:

Fi = (DC, DA, LM, IO, DS, PC)

Where: DC = Data Coverage, DA = Donor Anonymity Model, LM = Legal Mandate, IO = Interoperability Level, DS = Data Standards Adoption, PC = Privacy Controls.

Each parameter is scored on a normalized scale from 0 to 1.

Registry Score (RS) is calculated as: RS(Ri) = (DC + DA + LM + IO + DS + PC) / 6. This allows quantitative comparison of registries operating under different legal and technical environments.

Challenges with Existing ART Registries

Let

- Td = Total number of donors,
- Tc = Total number of clinics,
- Ld = Linked donor records across clinics.

Cross-Clinic Tracking Index (CCTI): CCTI = Ld / (Td × Tc).

In most current systems, Ld approaches zero because donor records are siloed per clinic. Therefore: CCTI ≈ 0 → indicates severe fragmentation.

Let

S = Number of standardized fields implemented,

T = Total recommended fields.

SDI = S / T.

Low SDI values indicate incompatibility across registries.

Interoperability challenges are modeled as the intersection of four constraint sets:

- C1 = Data Format Variability
- C2 = Legal Restrictions

- C3 = Ethical Constraints
- C4 = Privacy and Anonymity Requirements

Overall Interoperability Constraint (IC):

$IC = C1 \cap C2 \cap C3 \cap C4$.

The larger the intersection, the harder it becomes to exchange or query data across registries.

Proposed Federated Registry Architecture

Federated Query Process

1. Query Q is submitted by an authorized user.
2. Q is converted into metadata-only subqueries.
3. Subqueries are dispatched to clinic adapters.
4. Clinics execute queries locally.
5. Aggregated responses are returned.
6. Privacy rules are enforced before final output.

Query Cost Model

Let

n = number of participating clinics and

ti = response time of clinic i.

Total Query Time (Tq):

$Tq = \max(t1, t2, t3, ..., tn)$.

This ensures scalability by parallel execution.

Donor Tracking Model

Donor Usage Count

For a donor D:

$Usage(D) = \Sigma Ci(D)$,

where

$Ci(D)$ = number of cycles involving donor D at clinic i.

Regulatory Threshold Enforcement

Let

- Umax = maximum allowed donor usage.
- If
- $Usage(D) > Umax$,
- Then
- Trigger Regulatory Alert = TRUE;
- else
- Trigger Regulatory Alert = FALSE.

No clinic sees the full usage count — only the federated engine evaluates the threshold.

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