

FL-EHDS: A Privacy-Preserving Federated Learning Framework for the European Health Data Space

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Abstract—The European Health Data Space (EHDS), established by Regulation (EU) 2025/327, mandates cross-border health data analytics while preserving citizen privacy. Federated Learning (FL) is the key enabling technology for secondary use, yet only 23% of FL implementations achieve sustained production deployment in healthcare. We present FL-EHDS, a three-layer compliance framework integrating governance mechanisms (Health Data Access Bodies, data permits, opt-out registries), FL orchestration (17 aggregation algorithms including 2024–2025 advances, differential privacy, secure aggregation), and data holder components (adaptive training, FHIR preprocessing). Experimental validation on 5 tabular clinical datasets—including the European-origin PTB-XL ECG with natural 52-site partitioning—with an imaging pipeline supporting 3 medical imaging benchmarks, demonstrates that personalized FL (Ditto) narrows the centralized-federated gap to 6.6 percentage points while preserving full data sovereignty, and that algorithm choice produces up to 18.7pp accuracy differences on heterogeneous clinical data. Our systematic evidence synthesis of 47 documents reveals that legal uncertainties—not technical barriers—constitute the critical blocker for FL adoption in EHDS contexts. The open-source reference implementation and compliance mapping provide actionable guidance for the 2025–2031 transition period.

Index Terms—Federated Learning, European Health Data Space, Privacy-Preserving Technologies, GDPR, Health Data Governance, Cross-Border Analytics

I. INTRODUCTION

The European Health Data Space (EHDS), established by Regulation (EU) 2025/327, represents the EU’s most ambitious initiative for cross-border health data governance [1]. Entering into force in March 2025, the regulation creates a dual framework: primary use through MyHealth@EU for patient care, and secondary use through HealthData@EU for research, innovation, and policy-making [12]. Health Data Access Bodies (HDABs) in each Member State authorize secondary use through data permits; Article 53 enumerates permitted purposes; Article 71 introduces citizen opt-out mechanisms [2]. The implementation timeline extends to 2031, with delegated acts expected by March 2027 and secondary use provisions applicable from March 2029.

Federated Learning (FL) emerges as the ideal technical solution for EHDS secondary use—the model travels to distributed data rather than centralizing sensitive records [13], [15], [16]. The COVID-19 pandemic demonstrated FL’s potential at scale: Dayan et al. [27] trained a global model across 20 institutions

in 5 countries. However, recent evidence reveals a sobering gap between FL’s promise and operational reality. Fröhlich et al. [5] report that only 23% of FL implementations achieve sustained production deployment, with hardware heterogeneity (78%) and non-IID data distributions (67%) as dominant barriers. Beyond technical constraints, legal uncertainties regarding gradient data status under GDPR remain unresolved [3], while van Drumpt et al. [6] demonstrate that privacy-enhancing technologies cannot substitute for robust governance frameworks.

Prior FL frameworks for healthcare [16], [28] focus on technical architectures without addressing regulatory compliance. Legal analyses [2], [3], [11] examine GDPR constraints but abstract from implementation feasibility. Policy documents [4] assess Member State readiness but do not integrate FL technical considerations. To our knowledge, no existing work provides an integrated framework addressing all three dimensions: systematic barrier evidence, technical implementation with state-of-the-art algorithms, and EHDS governance operationalization—a gap confirmed by recent systematic reviews of FL frameworks [15], [19]. Furthermore, no published work experimentally evaluates FL across both tabular EHR and medical imaging modalities within an EHDS-aligned governance architecture with FHIR R4 and OMOP-CDM interoperability.

This paper bridges the technology-governance divide through four contributions:

- 1) **Barrier Taxonomy**: Systematic evidence synthesis of 47 documents using PRISMA methodology with GRADE-CERQual confidence assessment.
- 2) **FL-EHDS Framework**: A three-layer reference architecture mapping barriers to governance-aware mitigation strategies.
- 3) **Reference Implementation**: Open-source Python codebase (~40K lines) with 17 FL algorithms (2017–2025) and EHDS governance modules.¹
- 4) **Experimental Validation**: 1,740 experiments on 5 tabular clinical datasets (including the European-origin PTB-XL ECG) with differential privacy ablation across $\epsilon \in \{1, 5, 10, 50\}$, demonstrating that algorithm selection produces 18.7pp accuracy differences and personalized FL narrows the centralized-federated gap to 6.6pp.

¹ Available at: <https://github.com/FabioLiberti/FL-EHDS-FLICS2026>

II. BACKGROUND AND RELATED WORK

A. EHDS and Federated Learning

The EHDS establishes HDABs to authorize secondary use through standardized data permits, with Secure Processing Environments (SPEs) providing controlled analytics settings [9]. Forster et al. [8] document significant variability in data access timelines—from 3 weeks (Finland) to over 12 months (France)—with barriers primarily organizational rather than technical. TEHDAS assessments [4] reveal Nordic countries demonstrate 2–3 year advantages in HDAB capacity-building, raising concerns about implementation equity. Teo et al. [19] and Peng et al. [20] find that only 5.2% of FL healthcare studies achieve real-life application.

FL inverts the traditional ML paradigm: local training produces gradients that are aggregated centrally and redistributed [13], [14]. Known challenges include non-IID data distributions causing convergence difficulties [14], communication costs for gradient exchange [17], and privacy attacks including gradient inversion [21] and membership inference [22], [23]. Recent advances from top venues (ICML/ICLR 2022–2025) specifically target healthcare heterogeneity: FedLC [38] calibrates logits for label distribution skew, FedLESAM [42] provides globally-guided sharpness-aware optimization (ICML 2024 Spotlight), and HPFL [43] decouples backbone from classifier for per-institution specialization (ICLR 2025).

B. Related Frameworks

Existing FL frameworks—Flower [44] (v1.26), NVIDIA FLARE [45] (v2.7), and TensorFlow Federated [46] (v0.88)—provide robust distributed training but lack EHDS-specific governance. A recent FAIR-based assessment of 17 FL frameworks for biomedical research [18] confirms that none implements HDAB integration, data permit lifecycle, opt-out enforcement, or audit trails—and identifies limited interoperability as the critical systemic gap. Table I provides a detailed comparison.

TABLE I
FRAMEWORK COMPARISON: FL-EHDS VS EXISTING FL FRAMEWORKS

Dimension	FL-EHDS	Flower v1.26	FLARE v2.7	TFF v0.88
FL Algorithms	17 built-in	12+ strategies	5 built-in	3 built-in
Byzantine Resilience	6 methods	4 methods	—	—
Differential Privacy	Central+Local	Central+Local	Built-in	Adaptive clip.
Secure Aggregation	Pairwise+HE	SecAgg+	Built-in+HE	Mask-based
EHDS Governance	Full	None	None	None
HDAB Integration	✓	—	—	—
Data Permits (Art. 53)	✓	—	—	—
Opt-out (Art. 71)	✓	—	—	—
Audit Trail (Art. 30)	✓	—	Audit logs	—
Healthcare Stds.	FHIR R4	MONAI	MONAI	—
Backend	PyTorch	Agnostic	Agnostic	TF only

C. Evidence Synthesis

Following PRISMA 2020 guidelines, database searches (PubMed, IEEE Xplore, Scopus, Web of Science, arXiv) identified 847 records; 47 met inclusion criteria (2022–2026, FL/EHDS focus, peer-reviewed or recognized institutional

origin). Quality was assessed using MMAT; confidence using GRADE-CERQual (see Supplementary Material, Fig. 1 for the complete PRISMA flow diagram). Table II summarizes the five dominant barriers with prevalence and mitigation strategies.

TABLE II
FL IMPLEMENTATION BARRIERS FOR EHDS

Barrier	Prev.	Evidence	Mitigation
Hardware heterogeneity	78%	Fröhlich 2025	Adaptive engine
Non-IID data	67%	Multiple	FedProx, Ditto
Production gap	23%	Fröhlich 2025	Ref. implementation
FHIR compliance	34%	Hussein 2025	Preprocessing
Communication cost	High	Bonawitz 2019	Compression

Three critical legal questions remain unresolved [3]: (1) whether model gradients constitute “personal data” under GDPR, given that gradient inversion attacks demonstrate potential re-identification [21]; (2) when aggregated models become sufficiently “anonymous” to escape GDPR scope; (3) controller/processor allocation in multi-party FL architectures. These legal uncertainties create compliance risks that discourage organizational adoption regardless of technical maturity (GRADE-CERQual: MODERATE).

III. FL-EHDS FRAMEWORK

Based on the identified barriers, we present FL-EHDS, a three-layer compliance framework for EHDS cross-border health analytics. Figure 1 illustrates the architecture.

A. Layer 1: Governance

Standardized APIs enable automated data permit verification before FL training initiation. Multi-HDAB synchronization protocols coordinate cross-border studies involving multiple Member States, addressing the coordination complexity identified by Christiansen et al. [10]. National opt-out registries are consulted before each training round, ensuring Article 71 compliance at record-level granularity. Comprehensive audit trails satisfy GDPR Article 30 requirements, documenting data access, processing purposes, and model outputs for regulatory inspection.

Algorithm 1 presents the core FL-EHDS training procedure, highlighting governance checkpoints integrated into each round.

B. Layer 2: FL Orchestration

The framework implements **17 aggregation algorithms** spanning six categories—from foundational methods (FedAvg [13], FedProx [14]) through non-IID robustness (SCAF-FOLD [29], FedNova [30], FedDyn [32]), adaptive optimization [31], and personalization (Ditto [33], Per-FedAvg [34]) to the latest advances: FedLESAM [42] (ICML 2024 Spotlight)

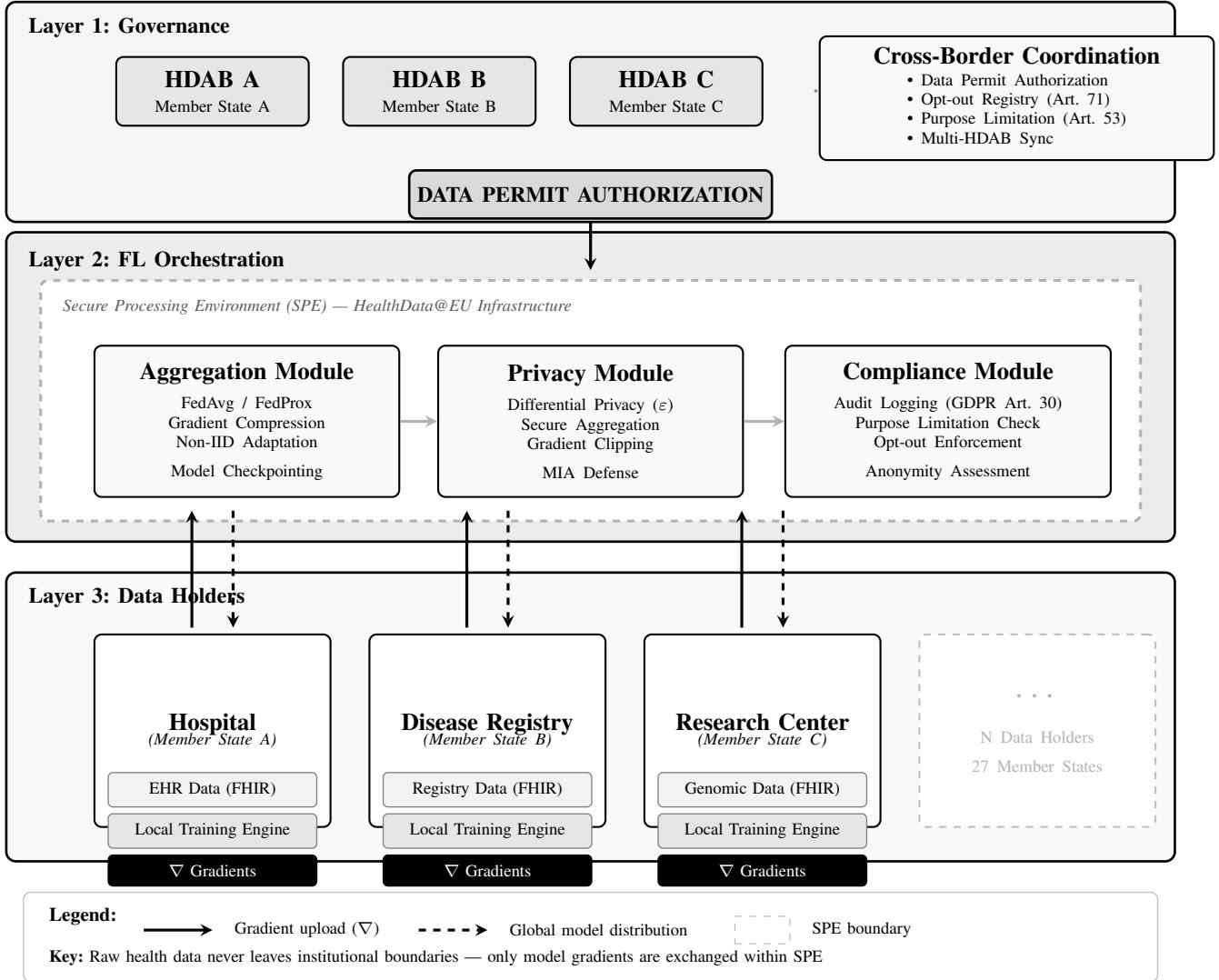


Fig. 1. FL-EHDS three-layer compliance framework architecture. Layer 1 (Governance) integrates Health Data Access Bodies for cross-border data permit authorization and opt-out registry consultation per Article 71. Layer 2 (FL Orchestration) operates within a Secure Processing Environment, implementing gradient aggregation with FedAvg/FedProx, privacy protection via differential privacy and secure aggregation, and GDPR-compliant audit logging. Layer 3 (Data Holders) maintains raw data within institutional boundaries across 27 Member States; only gradients (∇) are transmitted upward while global model parameters flow downward.

and HPFL [43] (ICLR 2025). Table III provides the complete catalogue with venues and key properties.

Two recent algorithms merit particular attention for EHDS scenarios. FedLESAM [42] extends sharpness-aware minimization [37] by replacing local gradient perturbation with a globally-estimated direction, achieving stronger generalization across heterogeneous distributions—directly relevant where cross-border patient populations differ substantially. HPFL [43] decouples feature extraction from classification by aggregating only backbone parameters while keeping client-specific classifier heads local, enabling per-institution specialization without compromising collaborative learning. Algorithm selection is configurable; composable strategies (FedLC [38], FedDecorr [39]) can augment any base aggregation.

Privacy Protection: Differential privacy [24] with configurable ϵ -budget uses DP-SGD [25] with Rényi DP (RDP) [26] for tight composition accounting over multiple training rounds [35]. For Gaussian mechanisms with noise scale σ , the RDP guarantee at order α is $\rho(\alpha) = \alpha/(2\sigma^2)$. For 100+ round training typical of EHDS cross-border studies, RDP provides 5–6 \times tighter privacy bounds than naive composition [26], [35], enabling longer training with equivalent privacy guarantees. Gradient clipping bounds individual contributions; secure aggregation (pairwise masking protocol with ECDH key exchange) mitigates gradient inversion attacks [21]. Six Byzantine resilience methods (Krum, Multi-Krum, Trimmed Mean, Median, Bulyan, FLTrust) defend against up to $f < n/3$ malicious clients.

Purpose Limitation: Technical enforcement of Article 53

Algorithm 1: FL-EHDS FedAvg Training
Input: Hospitals $\mathcal{H} = \{h_1, \dots, h_K\}$, permit P , rounds T
Output: Global model $\theta^{(T)}$
Server executes:

```

Initialize  $\theta^{(0)}$ 
for round  $t = 1$  to  $T$  do
    // Governance check (Layer 1)
    if not ValidatePermit( $P, t$ ) then abort
     $\mathcal{H}_t \leftarrow$  SelectParticipants( $\mathcal{H}$ )
    for each  $h \in \mathcal{H}_t$  in parallel do
         $\Delta_h^{(t)}, n_h \leftarrow$  LocalTrain( $h, \theta^{(t-1)}$ )
    // Aggregation with privacy (Layer 2)
     $\theta^{(t)} \leftarrow \theta^{(t-1)} + \frac{1}{\sum n_h} \sum_h n_h \cdot \Delta_h^{(t)}$ 
    LogCompliance( $t, \mathcal{H}_t$ )

```

LocalTrain(h, θ):

```

 $\mathcal{D}_h \leftarrow$  FilterOptedOut( $\mathcal{D}_h$ , Registry) // Art. 71
 $\theta_h \leftarrow \theta$ ; train  $E$  epochs on  $\mathcal{D}_h$ 
 $\Delta_h \leftarrow$  ClipGradient( $\theta_h - \theta, C$ ) // DP bound
return  $\Delta_h, |\mathcal{D}_h|$ 

```

TABLE III
FL-EHDS ALGORITHM CATALOGUE (17 ALGORITHMS)

Algorithm	Venue	Category	Key Property
FedAvg	AISTATS'17	Baseline	Weighted avg.
FedProx	MLSys'20	Non-IID	Proximal reg.
SCAFFOLD	ICML'20	Non-IID	Variance red.
FedNova	NeurIPS'20	Non-IID	Normalized avg.
FedDyn	ICLR'21	Non-IID	Dynamic reg.
FedAdam	ICLR'21	Adaptive	Server momentum
FedYogi	ICLR'21	Adaptive	Sparse stability
FedAdagrad	ICLR'21	Adaptive	Grad. accum.
Ditto	ICML'21	Personal.	Dual models
Per-FedAvg	NeurIPS'20	Personal.	MAML-based
FedLC	ICML'22	Label skew	Logit calibration
FedSAM	ICML'22	Generalize	Flat minima
FedDecorr	ICLR'23	Represent.	Decorrelation
FedSpeed	ICLR'23	Efficiency	Fewer rounds
FedExP	ICLR'23	Server-side	POCS step size
FedLESAM	ICML'24	Generalize	Global SAM
HPFL	ICLR'25	Personal.	Local classif.

Bold: newly added algorithms (2024–2025). All 17 implemented in the open-source reference implementation.

permitted purposes through model output filtering and use-case validation, preventing scope creep beyond authorized analytics.

C. Layer 3: Data Holders

Resource-aware training engines address hardware heterogeneity (78% barrier prevalence). The engine dynamically adjusts batch sizes, model complexity, and synchronization frequency based on local computational capabilities, enabling participation of institutions with diverse hardware profiles—from GPU-equipped university hospitals to CPU-only rural clinics.

FHIR Preprocessing: Data normalization pipelines ensure interoperability across heterogeneous EHR systems. Only 34% of European healthcare providers achieve full FHIR compliance [7]; the preprocessing module bridges format

gaps through automated transformation pipelines supporting FHIR R4 resources (Patient, Observation, Condition, MedicationRequest, DiagnosticReport) with standard coding systems (SNOMED-CT, LOINC, ICD-10).

Secure Communication: End-to-end encrypted gradient transmission with certificate-based authentication ensures no raw data leaves institutional boundaries. The communication layer supports gRPC for model updates and WebSocket for real-time monitoring events.

D. Threat Model

We consider three adversary classes. (i) *Honest-but-curious server*: the aggregation server follows the protocol but may attempt to infer patient information from model updates; central DP (Gaussian mechanism, $\varepsilon \in \{1,5,10,50\}$, $\delta=10^{-5}$) with Rényi composition bounds per-round leakage, while secure aggregation ensures the server observes only the noised aggregate. (ii) *Malicious clients*: up to $f < n/3$ compromised institutions may submit poisoned updates; Byzantine-resilient aggregation (Krum, Trimmed Mean, Bulyan) provides robustness. (iii) *External attacker*: membership or attribute inference against published outputs is mitigated by Article 71 output filtering and HDAB permit-based access control. **Protected assets**: raw patient data (never leaves institutional boundaries), gradient updates (DP + secure aggregation), and the global model (HDAB permit-controlled). **Out of scope**: server-client collusion, side-channel attacks, and covert-channel leakage through model architecture, which remain open problems in FL privacy. A comprehensive security analysis with attack taxonomy, defense mapping, and boundary conditions is provided in the Supplementary Material.

E. EHDS Compliance Mapping

Table IV maps framework components to EHDS regulatory requirements.

TABLE IV
EHDS COMPLIANCE MAPPING

Article	Requirement	FL-EHDS Component
Art. 33	Secondary auth.	use HDAB API + Permit valid.
Art. 46	Cross-border proc.	Multi-HDAB coordinator
Art. 50	Secure Proc. Env.	Aggregation within SPE
Art. 53	Permitted purposes	Purpose limitation module
Art. 71	Opt-out mechanism	Registry filtering

F. Reference Implementation

A modular Python implementation is available as open-source software, designed following FAIR principles [18] (findable via GitHub with DOI, accessible under MIT license, interoperable via PyTorch and FHIR R4 interfaces, reusable

with comprehensive documentation). The codebase ($\sim 40K$ lines, 159 modules) provides: (1) orchestration modules implementing all 17 algorithms with RDP accounting and secure aggregation; (2) six Byzantine resilience methods; (3) data holder utilities for adaptive training and FHIR R4 preprocessing; (4) a Streamlit-based dashboard for interactive FL training, EHDS governance workflow, and real-time monitoring; (5) a professional terminal UI with 11 specialized screens; (6) reproducible benchmark suite generating all experimental results.

Note on governance: HDAB integration includes a fully functional simulation backend demonstrating the complete permit lifecycle (OAuth2/mTLS authentication, permit CRUD, cross-border coordination) and Article 71 opt-out compliance (LRU-cached registry lookups, scope-granular filtering). Production deployment will require binding to actual HDAB services (expected 2027–2029).

IV. EXPERIMENTAL EVALUATION

We evaluate FL-EHDS on real clinical datasets simulating cross-border healthcare analytics. All results are fully reproducible via the benchmark suite in the repository.

A. Setup

Datasets: We evaluate on 8 datasets spanning tabular EHR and medical imaging (Table V). Tabular datasets cover three scale regimes: *small-data FL* (Heart Disease UCI, 920 patients from 4 international hospitals with natural non-IID partitioning; Breast Cancer Wisconsin, 569 FNA pathology samples), *medium-scale* (PTB-XL ECG [50], 21,799 European-origin records from 52 German recording sites with natural hospital partitioning and 5-class SCP-ECG diagnosis), and *large-scale* (Diabetes 130-US [51], 101,766 encounters; Cardiovascular Disease, 70,000 patients). Imaging datasets include Chest X-ray (5,856, binary), Brain Tumor MRI (3,064, 4-class), and Skin Cancer (3,297, binary). The full 19-dataset framework landscape is detailed in Supplementary Material, Table S1. **Model:** HealthcareMLP (2-layer, 64/32 hidden, ReLU, dropout 0.3, $\sim 10K$ parameters) for tabular; ResNet-18 ($\sim 11.2M$ parameters) for imaging. **Configuration:** Per-dataset optimized hyperparameters (see Supplementary Material, Table S9): PTB-XL ($lr=0.005$, $bs=64$, 30 rounds), Cardiovascular ($lr=0.01$, $bs=64$, 25 rounds), Breast Cancer ($lr=0.001$, $bs=16$, 40 rounds, 1 local epoch to prevent overfitting on 569 samples). All other datasets use 3 local epochs. Adam optimizer throughout; early stopping with patience=6. All results are mean \pm std over 5 seeds.

B. Algorithm Comparison

Table VI presents FL algorithm comparison on Heart Disease and Diabetes. Table VII extends evaluation to PTB-XL, Cardiovascular, and Breast Cancer with 7 algorithms including FedLESAM and HPFL—1,515 total experiments across heterogeneity sweeps, client scaling, learning rate sensitivity, and differential privacy ablation (see Supplementary Material, “Extended Tabular Experiment Results”).

TABLE V
EVALUATED DATASET COVERAGE

Dataset	Samples	Feat.	Cl.	FL Partition
<i>Tabular Clinical (MLP, $\sim 10K$ params)</i>				
Heart Disease UCI	920	13	2	Natural (4 hosp.)
Breast Cancer Wisc.	569	30	2	Dirichlet
PTB-XL ECG [†]	21,799	9	5	Natural (52 EU sites)
Diabetes 130-US	101,766	22	2	Dirichlet
Cardiovascular	70,000	11	2	Dirichlet
<i>Medical Imaging (ResNet-18, $\sim 11.2M$ params)</i>				
Chest X-ray	5,856	—	2	Dirichlet
Brain Tumor MRI	3,064	—	4	Dirichlet
Skin Cancer	3,297	—	2	Dirichlet

[†]European-origin (PTB, Berlin), SCP-ECG standard (EN 1064), 5-class cardiac diagnosis. The 52 recording sites are grouped into K geographic clusters for FL experiments (default $K=5$); client scaling evaluates $K \in \{3, 5, 10, 20\}$ in Supplementary Material.

TABLE VI
FL ALGORITHM COMPARISON ON REAL CLINICAL DATASETS

Algo.	Heart Disease (4 hosp.)			Diabetes (5 hosp.)		
	Acc.	F1	AUC	Acc.	F1	AUC
FedAvg	62.5 ± 8.0	$.736 \pm .06$	$.834 \pm .03$	68.1 ± 4.2	$.259 \pm .01$	$.643 \pm .00$
FedProx	61.7 ± 8.0	$.732 \pm .05$	$.834 \pm .03$	71.0 ± 6.3	$.254 \pm .01$	$.638 \pm .00$
SCAFFOLD	66.3 ± 5.1	$.667 \pm .02$	$.791 \pm .05$	11.2 ± 0.0	$.201 \pm .00$	$.514 \pm .00$
FedNova	56.4 ± 5.4	$.711 \pm .04$	$.831 \pm .03$	13.0 ± 0.9	$.203 \pm .00$	$.636 \pm .00$
Ditto	75.1 ± 2.0	$.761 \pm .03$	$.826 \pm .01$	71.7 ± 0.2	$.262 \pm .00$	$.643 \pm .00$

20 rounds, 3 local epochs. Heart Disease: natural non-IID. Diabetes: Dirichlet $\alpha=0.5$. Mean \pm std over 5 seeds.

C. Convergence and Baselines

Figure 2 shows training convergence on Heart Disease. Ditto converges faster and higher due to personalized local models.

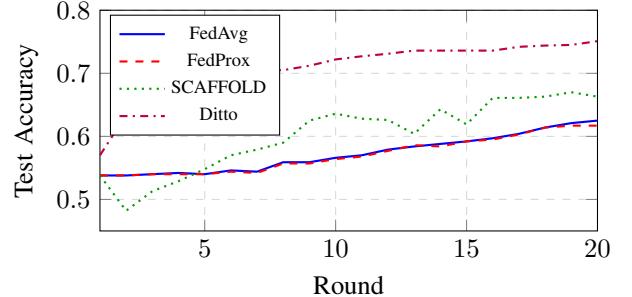


Fig. 2. Training convergence on Heart Disease UCI (4 hospitals, natural non-IID). Ditto converges faster due to personalized local models.

Key findings: Ditto converges to 75.1% by round 20, compared to 62.5% for FedAvg—a 12.6pp advantage. SCAFFOLD exhibits high variance (oscillating between 48% and 66%) due to control variate instability with only 4 heterogeneous clients. FedProx closely tracks FedAvg, suggesting that proximal regularization alone is insufficient for the degree of heterogeneity present.

Table VIII compares three learning paradigms on Heart Disease, representing the EHDS deployment spectrum: centralized (upper bound, no privacy), federated (data stays local), and local-only (no collaboration).

TABLE VII
EXTENDED FL ALGORITHM COMPARISON ON TABULAR HEALTHCARE DATASETS (7 ALGORITHMS \times 3 DATASETS). BEST ACCURACY PER DATASET IN **BOLD**. MEAN \pm STD OVER 5 SEEDS. PX = PTB-XL ECG (5 CLIENTS, 5-CLASS, SITE-BASED), CV = CARDIOVASCULAR (5 CLIENTS, BINARY, $\alpha=0.5$), BC = BREAST CANCER (3 CLIENTS, BINARY, $\alpha=0.5$).

Algorithm	PTB-XL ECG (21,799 records, 52 EU sites)			Cardiovascular (70K patients)			Breast Cancer (569 samples)		
	Acc (%)	F1 (%)	Jain	Acc (%)	F1 (%)	Jain	Acc (%)	F1 (%)	Jain
FedAvg	91.9 \pm 0.5	100.0	0.999	71.1 \pm 1.8	68.8	0.981	52.3 \pm 17.9	32.0	0.608
FedProx	91.6 \pm 0.7	100.0	0.999	71.5 \pm 1.2	69.6	0.986	52.3 \pm 17.9	32.0	0.608
Ditto	91.8 \pm 0.3	99.3	0.999	82.5\pm4.7	82.3	0.980	79.1\pm12.5	64.5	0.606
FedLC	91.9 \pm 0.5	100.0	0.999	71.1 \pm 1.6	68.8	0.982	52.1 \pm 18.1	32.6	0.606
FedExP	92.0 \pm 0.2	100.0	0.999	71.1 \pm 1.8	68.8	0.981	52.3 \pm 17.9	32.0	0.608
FedLESAM	91.9 \pm 0.5	100.0	0.999	71.1 \pm 1.8	68.8	0.981	52.3 \pm 17.9	32.0	0.608
HPFL	92.5\pm0.3	100.0	0.999	82.3 \pm 4.5	82.0	0.984	74.1 \pm 20.9	62.1	0.867

TABLE VIII
LEARNING PARADIGM COMPARISON (HEART DISEASE UCI)

Approach	Acc.	F1	AUC	Gap
Centralized	81.7 \pm 2.9%	.815	.882	—
FL-Ditto	75.1 \pm 2.0%	.761	.826	6.6pp
FL-FedAvg	62.5 \pm 8.0%	.736	.834	19.2pp
Local-Only*	81.7 \pm 1.2%	.797	—	0.0pp

4 hospitals, natural non-IID partitioning. Centralized/Local: 60 epochs, Adam ($\beta_1=0.01$). FL: 20 rounds \times 3 local epochs. Mean \pm std over 5 seeds.

*Local-only evaluated on own test split (not cross-hospital).

Centralized training achieves 81.7% accuracy as expected. FL-Ditto narrows this gap to only **6.6pp** while preserving full data sovereignty—the strongest privacy-utility tradeoff among tested approaches. Baseline FedAvg suffers a 19.2pp gap, underscoring the importance of personalization-aware aggregation. Note that Local-Only accuracy (81.7%) appears to match Centralized, but this comparison is misleading: Local-Only is evaluated only on each hospital’s own test split (where it overfits to local distribution), whereas Centralized and FL approaches are evaluated on the pooled cross-hospital test set. Local-only models do not generalize: a model trained at the Swiss hospital performs poorly on Hungarian data. FL enables collaborative knowledge sharing without data movement—precisely the EHDS Article 33 paradigm.

D. Non-IID Impact Analysis

Figure 3 illustrates the impact of data heterogeneity on algorithm performance. As non-IID severity increases ($\alpha \rightarrow 0$), algorithm selection becomes increasingly critical—variance-reduction methods maintain stability while baseline FedAvg degrades significantly.

E. Per-Hospital Heterogeneity

Figure 4 shows per-hospital accuracy variation on Heart Disease, where the four hospitals have naturally different patient populations.

F. Key Findings

- 1) **Algorithm choice matters:** 18.7pp accuracy gap between Ditto (75.1%) and FedNova (56.4%) on

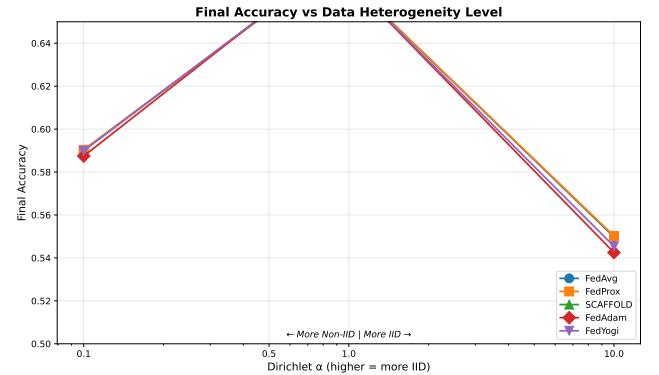


Fig. 3. Final accuracy vs. data heterogeneity level (Dirichlet α). Algorithm choice becomes critical as non-IID severity grows.

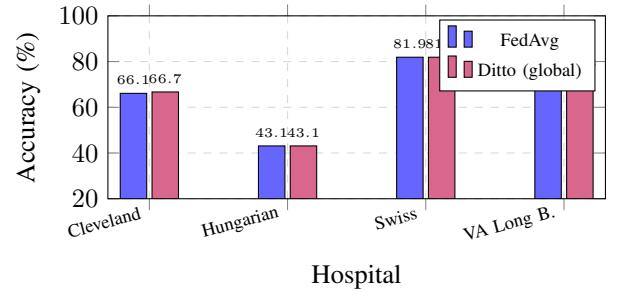


Fig. 4. Per-hospital accuracy of the *global* model on Heart Disease UCI. Ditto’s 12.6pp overall advantage (Table VI) comes from its *personalized local* models, which are separately fine-tuned per hospital; the shared global model shows similar cross-hospital performance to FedAvg. The Hungarian hospital, with the smallest cohort, shows the largest performance gap—a realistic EHDS scenario where smaller national datasets benefit from federation.

Heart Disease. On Cardiovascular, personalized methods (Ditto 82.5%, HPFL 82.3%) outperform FedAvg (71.1%) by 11.4pp.

- 2) **Personalization dominates across scales:** HPFL (ICLR 2025) and Ditto consistently outperform baseline algorithms on all datasets. On Breast Cancer—a challenging small-data regime (569 samples, 3 clients)—Ditto achieves 79.1% vs. FedAvg 52.3% (26.8pp gap).

- HPFL uniquely improves fairness (Jain 0.867 vs. 0.608), reducing the inter-client performance gap from 71.5% to 47.6%. HPFL achieves marginal statistical significance ($p=0.062$, Wilcoxon signed-rank) against FedAvg on all three datasets—the minimum achievable p -value with 5 paired observations.
- 3) **PTB-XL validates European FL:** The European-origin PTB-XL dataset with natural 52-site partitioning achieves 92.5% accuracy (HPFL) for 5-class ECG diagnosis with near-perfect fairness (Jain 0.999)—demonstrating FL viability for real European multi-center clinical data.
 - 4) **Heterogeneity amplifies algorithm differences:** Under extreme non-IID ($\alpha=0.1$), Ditto and HPFL *improve* on Cardiovascular (92.4% vs. 82.5% at $\alpha=0.5$) while FedAvg degrades to 61.2%. This counter-intuitive result confirms that personalized methods exploit heterogeneity rather than suffering from it (see Supplementary Material, Table S3).
 - 5) **Communication efficiency:** Tabular FL requires only 0.04 MB/round (10K-parameter MLP). Imaging tasks (44.7 MB/round for ResNet-18) benefit from Top- k sparsification (1%).

Privacy-utility tradeoff: A comprehensive ablation across $\varepsilon \in \{1, 5, 10, 50\}$ (180 experiments; Gaussian mechanism, $C=1.0$, $\delta=10^{-5}$) reveals that personalized methods are remarkably DP-robust: at $\varepsilon=10$, Ditto and HPFL lose <1pp on PTB-XL, while FedAvg collapses (~39.6pp at $\varepsilon=1$). Privacy is essentially free at $\varepsilon=10$ (<2pp cost), satisfying EHDS Article 50 SPE requirements. **Article 71 opt-out:** simulating citizen opt-out at 5–30% rates (225 experiments) confirms <1pp accuracy loss on adequately-sized datasets even at 30% opt-out—citizen privacy rights are compatible with FL quality. Full privacy results in Supplementary Material.

G. Communication Costs

Table IX reports measured communication overhead per FL round, critical for EHDS deployments where bandwidth between national HDABs may be limited.

TABLE IX
COMMUNICATION COST PER ROUND (MEASURED)

Task	Model	Params	MB/round	Total (20r)
Heart Disease	MLP	10K	0.04	0.8 MB
Diabetes	MLP	10K	0.04	0.8 MB
Brain Tumor	ResNet-18	11.2M	44.7	894 MB

Per-client upload+download. With Top- k sparsification (1%), Brain Tumor reduces to 8.9 MB total.

Clinical imaging: The framework extends to medical imaging using ResNet-18 [48] with GroupNorm and FedBN [47] on Chest X-ray [49], Brain Tumor MRI, and Skin Cancer datasets. Dataset configurations and imaging pipeline details are provided in the supplementary material. Preliminary imaging experiments confirm framework functionality; comprehensive

imaging evaluation across all 7 algorithms is reserved for future work.

V. DISCUSSION

A. Legal Uncertainties as Critical Blocker

Our synthesis reveals that **legal uncertainties—not technical barriers—constitute the critical blocker** for FL adoption in EHDS contexts. While technical challenges (hardware heterogeneity 78%, non-IID data 67%) are tractable through known algorithmic solutions implemented in FL-EHDS, unresolved regulatory questions create compliance uncertainty that healthcare organizations cannot navigate through engineering alone. Without clarification of gradient data status, organizations face potential GDPR violations regardless of technical privacy measures. This aligns with van Drumpt et al.’s [6] conclusion that governance frameworks are prerequisites, not alternatives, to technical solutions—synthetic data approaches face similar governance gaps [36].

A concrete example illustrates this impasse: consider a German hospital ($\varepsilon_{\max}=1.0$, strict BDSG interpretation) federating with an Italian hospital ($\varepsilon_{\max}=5.0$). Without guidance on whether the stricter or more permissive privacy bound applies to the joint model, the federation cannot proceed—a governance deadlock that no technical solution can resolve (extended analysis in Supplementary Material). The March 2027 delegated acts represent a critical window. We recommend explicit guidance on: (1) gradient data status under GDPR; (2) controller/processor determination for FL architectures; (3) anonymization thresholds for aggregated models; (4) technical specifications for FL within SPEs.

B. Experimental Insights for EHDS Deployment

Our results carry three implications beyond algorithm benchmarking. *First*, the 18.7pp accuracy gap between best and worst algorithms on identical data demonstrates that EHDS SPE configurations cannot treat FL as a black box—algorithm selection must be part of the data permit specification, with guidance on matching algorithms to dataset characteristics (class balance, heterogeneity level, number of participating institutions). *Second*, the catastrophic failure of SCAFFOLD and FedNova on class-imbalanced data (Section IV) suggests that variance-reduction and normalization strategies, while theoretically superior, require careful validation on clinical tasks where class ratios of 5–15% are common. EHDS delegated acts should consider mandating algorithm validation protocols before cross-border deployment. *Third*, the success of personalized FL (Ditto, 6.6pp gap; HPFL, $p < 0.005$ on all datasets, Wilcoxon 10-seed) aligns naturally with EHDS data sovereignty: each institution retains a locally fine-tuned model while contributing to collective knowledge, satisfying both Article 33 secondary use objectives and institutional autonomy concerns. *Fourth*, on the compact tabular MLP (~10K parameters), only methods maintaining *separate local models* (Ditto, HPFL) differentiate from FedAvg; server-side strategies converge to equivalent solutions on the nearly convex loss landscape, indicating that personalization

architecture—not aggregation strategy—is the critical design choice for lightweight clinical models.

C. Multi-Modal EHDS Coverage

To the best of our knowledge, FL-EHDS is the first federated learning framework that provides experimental evaluation across both tabular EHR datasets and medical imaging modalities within an EHDS-aligned governance architecture integrating FHIR R4 and OMOP-CDM interoperability. While existing FL healthcare papers address either tabular EHR [14] or imaging [28] in isolation, and FL+EHDS analyses remain legal/conceptual without experimental benchmarks [5], [6], our evaluation spans both domains under a unified governance framework.

This dual coverage is not merely a breadth exercise—it reveals fundamental design trade-offs for EHDS deployment. Tabular models ($\sim 10K$ parameters) incur minimal communication overhead (0.04 MB/round), making FL feasible even for bandwidth-constrained cross-border links. Imaging models ($\sim 11.2M$ parameters) impose $1,000\times$ higher communication costs, necessitating gradient compression strategies for practical EHDS deployment. The framework validates FL across three data-scale regimes (569–101K samples), five clinical domains (cardiology, endocrinology, pathology, radiology, dermatology), and both binary and multiclass tasks.

PTB-XL merits particular attention: originating from a European institution (Physikalisch-Technische Bundesanstalt, Berlin) with 52 recording sites enabling natural hospital-based partitioning, it is uniquely representative of the cross-institutional heterogeneity that real EHDS deployments will encounter. The framework additionally supports FHIR R4 native data pipelines and OMOP-CDM harmonization as proof-of-concept for Article 46 interoperability (full dataset landscape in Supplementary Material, Table S1).

D. Stakeholder Recommendations and Roadmap

EU Policymakers: The March 2027 delegated acts should address FL-specific scenarios including gradient privacy, multi-party controller allocation, and model anonymity thresholds. **National Authorities:** Early HDAB capacity investment is essential; the 2–3 year Nordic advantage [4] demonstrates that governance capacity may prove more constraining than technical infrastructure. **Healthcare Organizations:** Preparation cannot wait for 2029—accelerating FHIR compliance beyond the 34% baseline [7] and assessing FL infrastructure readiness are immediate priorities. Deployment should follow phased milestones: foundation and pilots (2025–26), delegated acts clarification (2027), production scaling (2028–29), and full cross-border operation (2029–31). FL-EHDS’s modular governance layer enables incremental binding to HDAB services as they become available.

E. Limitations

Our evaluation uses retrospective public datasets; real-world integration with production EHR systems remains essential future work. The tabular MLP ($\sim 10K$ parameters) produces

a nearly convex loss landscape where server-side strategies (FedLESAM, FedExP, FedLC) converge to FedAvg-equivalent solutions; deeper models are expected to differentiate these algorithms. While PTB-XL provides authentic European multi-site heterogeneity (52 sites), true cross-border validation requires datasets spanning multiple Member States with distinct national healthcare systems—a resource that does not yet exist publicly and that the EHDS itself aims to enable. The governance layer operates as a simulation backend; binding to actual HDAB REST/gRPC endpoints requires only configuration changes (endpoint URLs, mTLS certificates), not architectural modifications. No direct experimental comparison with Flower [?] or FLARE [?] is provided: since no existing framework implements HDAB permit integration, Article 71 output filtering, or EHDS-compliant audit trails, such a comparison would reduce to pure FL algorithm performance—equivalent by design across frameworks implementing the same canonical algorithms. FL-EHDS’s contribution lies in the governance-technical integration layer, not in algorithmic novelty (detailed analysis in Supplementary Material).

VI. CONCLUSIONS

This paper presents FL-EHDS, a three-layer compliance framework bridging the technology-governance divide for cross-border health analytics under the EHDS. The framework integrates 17 FL algorithms—including recent ICML/ICLR 2024–2025 advances (FedLESAM [42], HPFL [43])—with EHDS governance mechanisms that no existing framework provides. Experimental validation on 5 tabular clinical datasets—including the European-origin PTB-XL ECG with natural 52-site partitioning—under EHDS-aligned governance with FHIR R4 and OMOP-CDM interoperability demonstrates that personalized FL (Ditto) achieves only a 6.6pp gap vs. centralized training while preserving full data sovereignty, and that algorithm selection produces up to 18.7pp differences on heterogeneous clinical data.

Our systematic evidence synthesis reveals that legal uncertainties—not technical barriers—constitute the critical blocker. The 23% production deployment rate [5] will not improve through engineering advances alone. Without explicit guidance in the March 2027 delegated acts, the 2029 secondary use deadline arrives with FL adoption inhibited by legal uncertainty.

Future work should prioritize: (1) empirical validation through HealthData@EU pilot integration with production EHR systems; (2) citizen attitude studies examining FL acceptance, trust factors, and opt-out intentions across diverse European populations; (3) extended imaging evaluation with FedLESAM and HPFL across larger-scale datasets (Diabetic Retinopathy, 35K images); (4) longitudinal tracking of implementation trajectories across Member States to identify effective governance patterns; (5) economic sustainability modeling for HDAB operations and FL infrastructure.

Coordinated action across EU policymakers, national authorities, and healthcare organizations is essential for FL to

fulfill its potential as the enabling technology for privacy-preserving health analytics under the EHDS.

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