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PULSE-FHIR: Platform for Unified Labeled Signals of Electrocardiograms in FHIR

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Abstract This work presents PULSE-FHIR, an open-source web platform that integrates Fast Healthcare Interoperability Resources (FHIR)-compliant electrocardiogram (ECG) recordings with temporally synchronized visualization of clinical and AI-generated annotations. PULSE-FHIR supports multi-lead display, including 12-lead ECG recordings, flexible temporal navigation, and the overlay of beat-level annotations from reference databases, such as MIT-BIH, or neural network outputs. Additionally, it interfaces with FHIR servers, such as HAPI-FHIR, using SMART on FHIR when authentication and authorization are required. Precise alignment of raw signals and annotation markers enables direct comparison of AI classifications with reference labels, supporting ECG review and validation workflows in Internet of Medical Things (IoMT) ecosystems. The manuscript details the system architecture, FHIR representations for ECG signals and annotations, the implementation of the visualization interface, and experimental validation using MIT-BIH recordings. Results demonstrate effective temporal synchronization and rendering latencies below 200 ms for complete one-minute ECG records. The evaluation also indicates the importance of incremental retrieval strategies for handling long-term ECG recordings. A QR code links to a demonstration video and the project source code on GitHub.

Keywords: HL7 FHIR, Interoperability, Electrocardiography (ECG), IoMT, Health Information Systems, Web-based Visualization, Data Standardization

1 Introduction

Cardiovascular diseases (CVDs) are the leading cause of death worldwide. In 2022, they accounted for an estimated 19.8 million deaths, corresponding to approximately 32% of all global deaths. Most of these deaths were associated with heart attacks and strokes [World Health Organization, 2025].

Periodic cardiovascular evaluation, including targeted genetic assessment and routine screening of risk factors, is important because congenital and heritable conditions may affect cardiac health even in individuals with otherwise healthy lifestyles [Musunuru *et al*., 2020]. Among diagnostic procedures, the electrocardiogram (ECG) is one of the main tools for identifying cardiac abnormalities. It records the electrical activity of the heart and supports the detection of rhythm disturbances and conduction anomalies [Cascino and Shea, 2023]. Wearable biosensors have expanded the possibilities for continuous monitoring by enabling signal acquisition outside clinical environments [Assaad *et al*., 2025].

These wearable devices operate within the Internet of Things (IoT) paradigm, in which sensors and devices exchange data through communication networks. In healthcare, the Internet of Medical Things (IoMT) refers to connected medical devices and wearables that collect and transmit physiological data for remote monitoring, clinical analysis, and diagnostic workflows [Vishnu *et al*., 2020; Mathkor *et al*., 2024]. However, devices and platforms from different vendors often rely on heterogeneous data models and communication mechanisms, which can limit integration across systems [Azad *et al*., 2025].

The growth of connected health devices increases the need for standardized protocols to support interoperability, security, and data integrity across heterogeneous health information systems. This remains a challenge at both platform and network levels, especially in medical applications [Jaleel *et al*., 2020]. Fast Healthcare Interoperability Resources (FHIR) [HL7 International, 2019] is one of the main international standards for health data interoperability and is supported by more than 1600 members in over 50 countries [National Library of Medicine, 2025]. FHIR stands out compared with other healthcare interoperability standards because data exchange is designed to occur through Hypertext Transfer Protocol (HTTP) requests using RESTful methods such as GET, POST, PUT, and DELETE. [Saripalle *et al*., 2019].

In parallel with advances in data standardization, artificial intelligence (AI) methods have been increasingly applied to the automated detection of arrhythmias, with some models reporting performance comparable to that of human specialists [Demolder *et al*., 2023]. However, their use in clinical workflows depends not only on classification performance, but also on the ability to inspect and validate the results. In ECG analysis, annotations are temporal markers that indi-

Table 1. List of Abbreviations and Acronyms

Abbreviation	Description
AI	Artificial Intelligence
API	Application Programming Interface
BPM	Beats Per Minute
CSS	Cascading Style Sheets
CVD	Cardiovascular Disease
ECG	Electrocardiogram
EHR	Electronic Health Record
FHIR	Fast Healthcare Interoperability Resources
GUI	Graphical User Interface
HL7	Health Level Seven
HTML	HyperText Markup Language
HTTP	Hypertext Transfer Protocol
IoMT	Internet of Medical Things
IoT	Internet of Things
JSON	JavaScript Object Notation
LOINC	Logical Observation Identifiers Names and Codes
MIT-BIH	Massachusetts Institute of Technology – Beth Israel Hospital
REST	Representational State Transfer
SLR	Systematic Literature Review
SMART	Substitutable Medical Applications and Reusable Technologies
UI	User Interface
URL	Uniform Resource Locator

cate cardiac events and their classifications, such as "normal beat", "premature ventricular contraction", or "atrial fibrillation". Reference databases such as the MIT-BIH Arrhythmia Database [Moody and Mark, 2001; Goldberger *et al.*, 2000] provide specialist-validated annotations that are commonly used as gold-standard labels. AI models, in turn, can generate predicted annotations that need to be compared with these references. However, many web-based ECG visualization tools do not provide native support for displaying annotations synchronized with the raw ECG signal. This limits the ability of specialists to review model outputs in their temporal context.

To address these visualization and interoperability challenges, this work presents PULSE-FHIR (Platform for Unified Labeled Signals of Electrocardiograms in FHIR), a software system with a Graphical User Interface (GUI) designed to connect FHIR-compliant data repositories with clinical ECG visualization and review. The platform processes ECG data from FHIR-compatible cloud sources and provides synchronized visualization of signals with temporally aligned annotations, supporting both manual specialist markings [Moody and Mark, 2001; Goldberger *et al.*, 2000] and AI-generated classifications [Freire *et al.*, 2024]. This visualization approach allows healthcare professionals and researchers to inspect computational outputs, compare algorithmic annotations with gold-standard labels, and review ECG events in their temporal context. By combining FHIR interoperability with annotation rendering, PULSE-FHIR supports the review of AI-driven arrhythmia detection outputs while maintaining compatibility with existing health data infrastructures.

The main contribution of this work is the integration of FHIR-based ECG representation with synchronized visualization of beat-level annotations in a web platform designed to support ECG review and AI-assisted ECG review workflows. PULSE-FHIR provides four specific contributions:

(i) retrieval, decoding, and visualization of ECG signals represented as FHIR *Observation* resources using *SampledData*;
(ii) a FHIR-compatible representation for MIT-BIH-based beat annotations;
(iii) an interactive multi-lead interface with temporal navigation, annotation overlay, and beat-type filtering; and
(iv) an experimental evaluation based on FHIR server access, comparison with established ECG viewers, annotation rendering assessment, and front-end performance measurements.

Accordingly, this work evaluates whether ECG signals and beat annotations encoded as FHIR-compatible resources can be retrieved, decoded, temporally aligned, and rendered in an interactive web-based environment. Table 1 summarizes the main abbreviations and acronyms used throughout the manuscript.

2 Related Work

A systematic literature review (SLR) was conducted to identify current approaches to ECG visualization and interoperability in IoMT environments. The review was organized using the Parsifal tool [Simple Complex, 2021] and followed the PICO strategy [Arizona State University Library, 2025] to define the search terms. The review question was: "Which software tools or platforms have been proposed for ECG visualization in IoT/IoMT or web-based environments, and how do they address multi-lead visualization, interoperability standards, and annotation support?"

The final search string used in the systematic search was:

```
("ECG" OR "electrocardiogram")
AND ("dashboard" OR "front-end" OR "data visualization" OR
"interface")
AND ("IoT" OR "IoMT")
AND ("HTML" OR "JavaScript" OR "web")
AND ("protocol" OR "FHIR")
AND NOT ("machine learning" OR "exploratory study" OR
"systematic review" OR "deep learning")
```

The search was conducted in five scientific databases where a total of 35 papers were identified, distributed as follows: IEEE Digital Library contributed the largest number of studies (11 papers), followed by Scopus (8 papers), EI Compendex (7 papers), ACM Digital Library (5 papers), and SpringerLink (4 papers). Web of Science and ScienceDirect were not included due to institutional access restrictions and search-interface limitations regarding the number of Boolean connectors, respectively.

The exclusion criteria were duplicated records, unavailable full-text articles, studies published before 2020, books, review papers, and documents without sufficient implementation details. When supported by the database, the search was restricted to open-access articles, publications from 2020 onward, and article-type documents. Conference articles were retained because a preliminary screening indicated that they were aligned with the software-oriented scope of this work.

Table 2. Comparative analysis of the SLR results.

Work	Leads	GUI tech stack	Interface	Validation	Annotations	Interoperability
Kubov *et al.* [2020]	1	JavaScript, HTML5, Canvas	Mentions the interface, without a focus on design	Graph in Excel	No	None
Hasan *et al.* [2024]	2	JavaScript, React, Plotly	Prototyping	Comparison with the certified device Kenz Cardico 1210	No	None
Matos *et al.* [2024]	3	JavaScript, Angular	Interviews with professionals	Contec MS400 Simulator	No	None
Meftah *et al.* [2024]	–	Mobile application	Different layouts	None	No	None
Adochiei *et al.* [2024]	3	HTML, Grafana	Intuitive GUI	None	No	None
Faisal *et al.* [2022]	3	HTML, JavaScript, Bootstrap, jQuery, Ajax, Plotly	Clean, responsive, dynamic, and user-friendly UI	Biocare ECG-300G	No	None
This work	Multi-lead	TypeScript, React, Plotly	Status visibility, real-world compatibility, and minimalist design	LightWAVE and MIT-BIH Web Visualizer graphical consistency assessment	FHIR-compatible annotations	FHIR

The remaining studies were assessed using eight quality questions: whether the work (Q1) presents ECG visualization, (Q2) supports detailed navigation such as zoom or temporal scrolling, (Q3) derives information from the ECG such as beats per minute - BPM, (Q4) presents the interface layout, (Q5) identifies the front-end technology, (Q6) compares the visualization output with a reference, (Q7) implements an interoperability protocol, and (Q8) addresses usability aspects. Each question was scored as yes (1), partially (0.5), or no (0). Studies with a total quality score below 6 were excluded from the comparative analysis.

After applying the exclusion criteria and quality assessment procedure, six studies were retained and compared with PULSE-FHIR, as summarized in Table 2. The analysis of these studies reveals two primary trends in system design: mobile-centric solutions and web-based dashboards. Regarding mobile approaches, Kubov *et al.* [2020] developed a lightweight ECG viewer using JavaScript and HyperText Markup Language (HTML) 5 Canvas, validated via prototyping, while Matos *et al.* [2024] focused on a native mobile application with varying layouts. Although these solutions offer portability, they often lack the extensive analytical capabilities required for clinical review on larger displays.

In the domain of web-based monitoring, several authors have leveraged modern frameworks to create dashboards. Faisal *et al.* [2022] used a stack of HTML, jQuery, and Plotly to build a responsive interface, which was validated with a Biocare ECG-300G device. Similarly, Adochiei *et al.* [2024] employed Grafana and HTML for IoT-based real-time monitoring. More recently, Hasan *et al.* [2024] and Matos *et al.* [2024] adopted component-based architectures using React and Angular, respectively. Matos *et al.* [2024] validated their system using a Contec MS400 simulator, whereas Hasan *et al.* [2024] focused on a cost-effective design with minimal validation.

Despite these advancements, the comparative analysis highlights three main limitations across the selected studies:

1. **Restricted Multi-Lead Visualization:** As shown in Table 2, the majority of existing platforms are designed to render only a small subset of leads simultaneously (typically 1 to 3 leads) [Kubov *et al.*, 2020; Hasan *et al.*, 2024; Matos *et al.*, 2024; Faisal *et al.*, 2022; Adochiei *et al.*, 2024]. This limitation restricts their applicability in scenarios that require broader multi-lead ECG inspection, such as standard 12-lead review.
2. **Lack of Interoperability Standards:** None of the reviewed works reported implementation of HL7 FHIR for ECG data exchange, and no explicit use of other standardized health interoperability protocols was identified. Most approaches rely on proprietary formats, direct database connections, or application-specific data flows, which may limit integration with broader healthcare ecosystems and Electronic Health Records (EHRs).
3. **Absence of Clinical Annotation Support:** None of the works listed in Table 2 reported support for synchronized visualization of diagnostic beat annotations. The reviewed systems focus mainly on rendering ECG waveforms and do not display beat-type classifications, such as "Normal" or "Premature Ventricular Contraction", aligned with the ECG trace.

PULSE-FHIR addresses these limitations by supporting interactive multi-lead ECG visualization, retrieving ECG data from FHIR-compliant repositories, and providing a FHIR-compatible mechanism for rendering synchronized beat-level annotations. In this way, the platform supports not only ECG visualization but also the inspection and comparison of clinical and AI-generated annotations in interoperable health data environments.

3 Methodology

Figure 1 illustrates the ecosystem considered by PULSE-FHIR, which comprises three layers: ECG devices, cloud-based FHIR APIs, and web applications. Different ECG acquisition devices, such as wearable sensors and electrocardiographs, may generate the ECG signals. The acquisi-

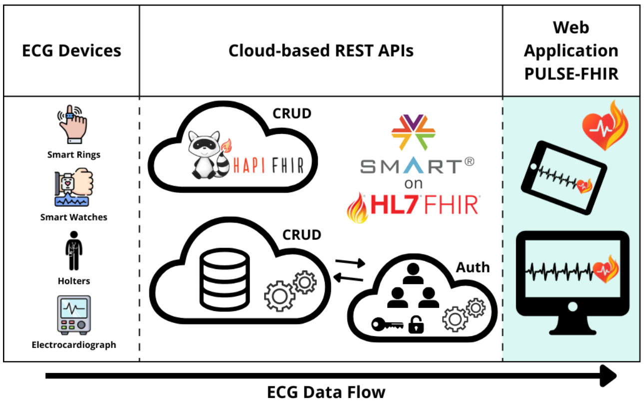

Figure 1. Overview of the health ecosystem from ECG acquisition to visualization. PULSE-FHIR is device-agnostic and retrieves ECG signals and annotations from FHIR-compatible repositories, regardless of the underlying acquisition device.

tion, transmission, and storage mechanisms are outside the scope of this work. PULSE-FHIR operates at the web application layer and retrieves ECG signals and annotations from configurable FHIR-compliant repositories through RESTful endpoints. Once the data are available as FHIR *Patient* and *Observation* resources, PULSE-FHIR can retrieve, decode, and render them in the user interface. The application also supports SMART on FHIR authentication when required by the selected repository.

The methodology was organized into five steps: definition of system requirements from the limitations identified in the related work, specification of the PULSE-FHIR ecosystem and data flow, implementation of the web-based visualization interface, modeling of ECG signals and beat annotations as FHIR-compatible resources, and preparation of the experimental configuration used to evaluate FHIR access, navigation, graphical visualization, and front-end performance.

3.1 System Requirements

Based on the limitations identified in the related work, the following functional and interoperability requirements were defined to guide the development of PULSE-FHIR:

1. display ECG signals;
   (a) show different leads from the same ECG examination;
   (b) support ECG signals with different sampling frequencies;
   (c) allow temporal navigation along the ECG recording;
   (d) display ECG signals with a grid background similar to traditional ECG paper;
2. display beat annotations associated with different heartbeat types;
3. support visualization on small screens through a responsive interface;
4. retrieve and represent ECG data using FHIR-compatible resources;
5. support authentication and authorization using SMART on FHIR;
6. integrate the web application into the ecosystem shown in Figure 1.

3.2 User flow

The user flow of PULSE-FHIR, illustrated in Figure 2, is organized into three main stages: data-source connection, examination configuration, and interactive ECG visualization. These stages summarize the transition from FHIR-compatible data-source access to patient and examination selection and, finally, to interactive ECG inspection. This organization reflects the separation between FHIR-compatible repositories, patient and examination selection, and the ECG visualization interface.

In the first stage, the user establishes the data-source connection. As shown in the upper part of Figure 2, the user selects one of the configured FHIR servers, such as HAPI-FHIR or FASS-ECG, and starts the login process. If the selected server requires authentication, the user is redirected to the corresponding authentication and authorization flow. After authentication, or directly in the case of servers without authentication, PULSE-FHIR performs the required connectivity steps and enables access to the dashboard.

In the second stage, the user configures the ECG examination to be visualized. This stage corresponds to the transition from the server/user data page to the dashboard page in Figure 2. From the dashboard and side configuration panel, the user selects a patient, chooses one of the available ECG examinations, and defines the visualization parameters. These parameters include the ECG leads to display, the time interval or visualization window, and the beat annotation types to inspect.

The third stage corresponds to interactive ECG visualization and analysis. After the configuration is completed, PULSE-FHIR renders the selected ECG leads and enables temporal navigation, synchronized multi-lead visualization, annotation filtering, navigation between annotated beats, and access to summary information about the distribution of beat types. This final stage, represented in the lower part of Figure 2, allows the user to move from FHIR-based data access to detailed ECG inspection within a single web interface.

3.3 Technologies and Interface Design

The PULSE-FHIR web application was developed using HTML, Cascading Style Sheets (CSS), and JavaScript (specifically TypeScript). TypeScript was adopted to implement the application logic with static typing, thereby improving code organization and reducing inconsistencies when manipulating ECG samples, FHIR resources, and annotation structures. The React framework was used to organize the interface into reusable components, including server selection, patient and examination selection, lead visualization, annotation filters, and navigation controls.

For ECG visualization, the Plotly library was selected because it supports interactive plotting, temporal navigation, zooming, custom markers, and graphical elements over the plotted signal. These features are important for supporting ECG inspection workflows in a web environment, especially when multiple leads and beat annotations need to be displayed simultaneously.

The visualization interface was designed to represent ECG waveforms with a grid background similar to traditional ECG

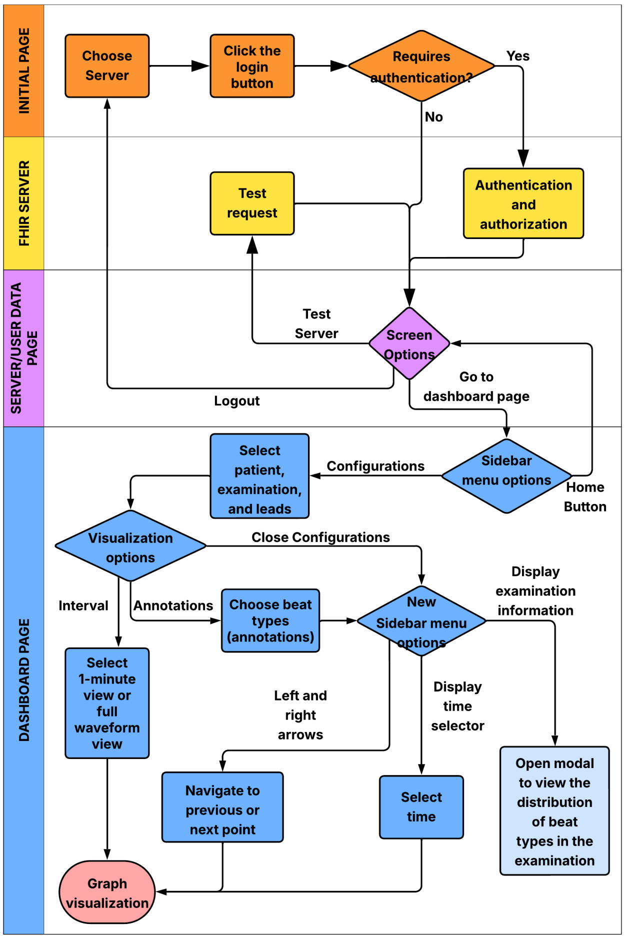

Figure 2. User flow in PULSE-FHIR, organized into data-source connection, examination configuration, and interactive ECG visualization stages.

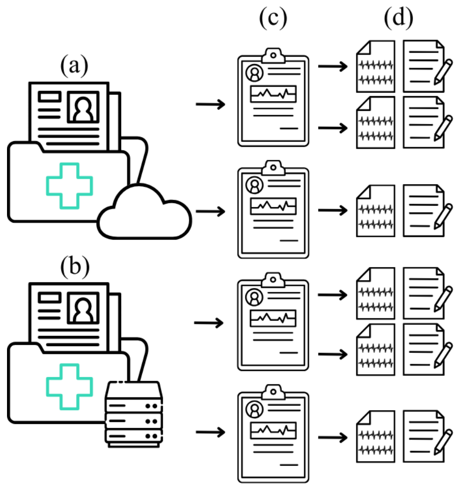

Figure 3. Hierarchy of FHIR resources: (a) remote repositories; (b) local storage; (c) patient list; (d) observation resources with ECG and annotations.

paper. To approximate this representation, the graph uses smaller grid intervals of 0.04 s on the x-axis and 0.1 mV on the y-axis, while larger grid intervals are spaced at 0.2 s and 0.5 mV, respectively. This configuration corresponds to five smaller divisions per larger square, following the visual organization commonly used in ECG interpretation.

In addition to waveform rendering, the same time axis is shared across displayed leads, allowing synchronized navigation and comparison between waveforms. The interface also uses markers and background regions to represent beat annotations over the ECG trace. The annotation markers are generated from the sample indices stored in the corresponding FHIR-compatible annotation resources and are temporally aligned with the decoded ECG signal. Additional graphical elements, such as interval selection regions and temporal navigation controls, were implemented to support detailed inspection of ECG events and comparison between leads.

3.4 Data structures, SMART, and FHIR

PULSE-FHIR adopts a hierarchical configuration of FHIR resources, as shown in Figure 3. Data can be retrieved from remote repositories via web servers (Figure 3(a)) or from files stored locally (Figure 3(b)). For each repository, a predefined hierarchy is configured using previously defined resource identifiers, starting with a patient list (Figure 3(c)). Each patient record links to a set of FHIR Observation resources (Figure 3(d)), which encapsulate the ECG signals and their corresponding beat annotations, following the MIT-BIH classification [Moody and Mark, 2001; Goldberger *et al.*, 2000]. In the current implementation, resources are accessed using previously configured identifiers; however, their internal structures must comply with the HL7 FHIR interoperability standard [HL7 International, 2019].

To support secure access when the repository is associated with a protected FHIR server, authentication and authorization can be configured using SMART on FHIR [Mandel *et al.*, 2016]. In such cases, PULSE-FHIR acts as a client application and does not manage user credentials directly. Authentication and authorization are delegated to the configured FHIR server or identity provider. After the user authorizes access, PULSE-

FHIR uses the resulting authorization context to request the resources required for visualization.

In the current implementation, PULSE-FHIR requires read access to patient-related resources used by the platform, particularly Patient and Observation resources containing ECG signals and beat annotations. Access tokens are handled only within the authenticated browser session and are used to authorize requests to the selected FHIR endpoint; they are not persisted by PULSE-FHIR as application data.

No directly identifiable patient information was used in this study, as ECG signals and annotations were obtained from publicly available MIT-BIH records [Moody and Mark, 2001] and represented as FHIR-compatible resources. Therefore, the validation presented in this manuscript should be interpreted as a research-oriented evaluation of ECG visualization, FHIR-based retrieval, and annotation rendering. In clinical deployments, privacy, authorization scopes, audit logging, consent management, and institutional security policies should be configured and enforced by the underlying FHIR infrastructure and healthcare organization.

3.4.1 Patient

Patient data are represented as a FHIR *Patient* resource [HL7 International, 2019]. In PULSE-FHIR, the *Patient* resource serves as the entry point for accessing the corresponding ECG examinations. The current implementation uses the patient's name only as a visual identifier in the graphical interface, while the ECG signals and annotations are retrieved from linked *Observation* resources.

3.4.2 ECG

ECG samples are represented as FHIR *Observation* resources [HL7 International, 2019] using the *SampledData* structure, following the Sample Array Observation profile [HL7 International – Devices Work Group, 2023]. An example ECG record in JSON format is shown in Figure 4. Some keys are omitted for the sake of readability.

```
{"resourceType": "Observation",
"subject": {"reference": "Patient/abc1234"},
"effectivePeriod":
 {"start": "2025-11-11T18:21:50.436228"},
"component": [{
 "code": {"coding": [{
  "code": "131330",
  "display": "MDC_ECG_ELEC_POTL_II"
 }]},
 "valueSampledData": {
  "origin": {
   "value": -2.16,
   "unit": "mV"
  },
  "period": 2.7777777777777777,
  "factor": 0.001,
  "data": "1785 1770 ... 1945 1935"
 }
}, ... ]}
```

Figure 4: Snippet of a FHIR Observation resource in JSON format describing an ECG [HL7 International – Devices Work Group, 2023]

The definitions and roles of the keys shown in Figure 4, as applied in PULSE-FHIR, are as follows:

1. `resourceType`: mandatory key that identifies the type of the FHIR resource.
2. `subject.reference`: unique identifier of the patient associated with the examination. `Patient/id` indicates the referenced resource type.
3. `effectivePeriod.start`: indicates the start time of the ECG. In the user interface, it serves as the visual identifier of the examination and is used to order them chronologically, grouped by patient.
4. `component`: a list of objects, each describing one ECG lead.
   (a) `code.coding`: a code that identifies each lead, used as the visual identifier of the lead in the user interface.
      i. `display`: textual representation of the lead.
      ii. `code`: numeric identifier based on the IEEE standard [IEEE 11073 Standards Committee, 2020], serving as an alternative to `display`.
   (b) `valueSampledData`: represents the waveform signal of the ECG lead.
      i. `origin.value/unit`: defines the reference/origin value and the measurement unit of the signal. It serves as the reference point for decoding the values into millivolts.
      ii. `period`: temporal interval between consecutive samples, in milliseconds. This value corresponds to a sampling frequency of 360 Hz ($1000/360 \approx 2.778$ ms) and is used to reconstruct the signal's temporal axis.
      iii. `factor`: scale factor used to convert the encoded integer values into real amplitude values.
      iv. `data`: compact representation of the time series of samples through integer values.

The decoding process of the signal for each lead (elements of item 4) follows Equations 1 and 2 below. Note: *sample_int* (Equation 1) and *sample_index* (2) represent each sample integer contained in item 4(b)iv.

$$amplitude_{mV} = (sample\_int \times \texttt{factor}) + \texttt{origin.value} \quad (1)$$

$$time_{ms} = sample\_index \times \texttt{period} \quad (2)$$

The result of this decoding process is a pair of time and amplitude vectors for each ECG lead. These vectors are used by the visualization interface to render the ECG waveform and to support morphological inspection of cardiac events. The same time reference is also used to align beat annotations with the ECG trace, as described in the next subsection.

3.4.3 ECG Annotations

Unlike ECG samples, ECG annotations do not have an established representation standard in FHIR. In the MIT-BIH Arrhythmia Database, annotations indicate the temporal position of relevant events in the ECG signal and may represent different types of information, including beat classes, rhythm changes, and signal quality changes. Beat annotations identify individual labeled beats, such as normal beats, atrial premature beats, and premature ventricular contractions, whereas other annotations indicate rhythm transitions or changes in signal quality. These annotations were produced as reference labels by expert annotators and are commonly used as gold-standard data for evaluating ECG interpretation and arrhythmia classification methods [Moody and Mark, 2001; Goldberger *et al.*, 2000].

Based on this annotation scheme, this work proposes a FHIR-compatible representation that combines FHIR Observation resources with MIT-BIH annotation types. In this representation, each annotation type is encoded as a component of the Observation resource, and the corresponding sample indices indicate where these events occur in the ECG signal. Examples of the annotation types used in this work are shown in Table 3.

Table 3. Examples of MIT-BIH ECG annotation types.

Symbol	Annotation type
N	Normal beat
A	Atrial premature beat
V	Premature ventricular contraction
+	Rhythm change
~	Change in signal quality
...	...

To support beat-level annotation rendering in a FHIR-compatible workflow, we modeled ECG annotations as a companion FHIR Observation resource structured similarly to the ECG signal Observation. An example of an ECG annotation record in JSON format is shown in Figure 5 and contains all the necessary keys.

The `resourceType` and `subject` keys are the same as those previously mentioned for the ECG. The meaning and use of these keys in PULSE-FHIR are as follows:

1. `code.coding`: coding structure that identifies the resource as part of an electrocardiographic study.
   (a) `system`: Logical Observation Identifiers Names and Codes (LOINC) system [Huff *et al.*, 1998], used to provide a standardized clinical terminology for the electrocardiographic study. LOINC is commonly used with FHIR resources [Gimah and Eli, 2025].
   (b) `code`: numeric identifier based on the LOINC system [Regenstrief Institute, 2025].
   (c) `display`: textual representation of the coding.
2. `component`: a set of objects in which each component represents the annotations associated with a specific ECG annotation type.
   (a) `code.coding`: coding structure that identifies the annotation type associated with the stored sample indices.
      i. `system`: annotation coding system based on the MIT-BIH classification [Goldberger *et al.*, 2000].
      ii. `code`: a single character identifying the annotation type or class.
      iii. `display`: textual representation of the coding.
   (b) `valueSampledData.data`: similar format to that of the ECG, but here the values represent the indices of the ECG samples where the beat types indicated in `code` occur.

```
{"resourceType": "Observation",
"code": {"coding": [{
 "system": "http://loinc.org",
 "code": "11524-6",
 "display": "EKG study"
}]},
"subject": {"reference": "Patient/abc1234"},
"component": [{
 "code": {"coding": [{
  "system": "http://physionet.org/...",
  "code": "V",
  "display": "Premature ventricular
      contraction"
 }]},
 "valueSampledData": {"data":
  "551928 552615 553386 554109"
 }
}, ... ]}
```

Figure 5: Snippet of a FHIR Observation resource in JSON format describing MIT-BIH annotations of an ECG

In the proposed representation, the annotation *Observation* acts as a companion resource to the ECG signal *Observation*. The top-level `code.coding` key uses the LOINC code `11524-6` (*EKG study*) to identify the resource as part of an electrocardiographic study. This code was adopted because the resource represents annotations associated with the ECG examination as a whole, rather than a standalone clinical measurement or an individual beat-level event. Therefore, `11524-6` provides a standardized clinical context for the annotation resource, while the beat-level semantics are represented within the `component` elements using MIT-BIH annotation codes, such as `N`, `A`, and `V`. Thus, LOINC identifies the clinical observation context, whereas the MIT-BIH coding identifies the specific annotation class. While the ECG *Observation* stores waveform samples in `valueSampledData.data`, the annotation *Observation* stores the sample indices at which each beat type occurs. This design preserves the temporal relationship between the ECG waveform and the beat-level labels without modifying the original ECG signal resource, enabling annotations from reference databases or AI models to be retrieved, filtered, and rendered on the ECG trace within a FHIR-compatible workflow.

To graphically represent these annotations, we use the indices in item 2b to retrieve the XY coordinates, time, and amplitude from the ECG signal vectors computed by Equations 1 and 2. This process generates vectors corresponding to the annotations, which are then used to plot the points on the graph.

After the patient and ECG examinations are selected, the system filters the annotations based on the annotation types selected in the graphical interface. It then creates point markers at the corresponding sample positions and adds semitransparent colored regions to highlight annotated beat intervals. The interface also enables navigation between markers, zooming, and dynamic filtering of annotation types, supporting the inspection of cardiac events in the ECG.

4 Experimental Results

This section presents four complementary evaluations of PULSE-FHIR. First, we validate interoperability by retriev-

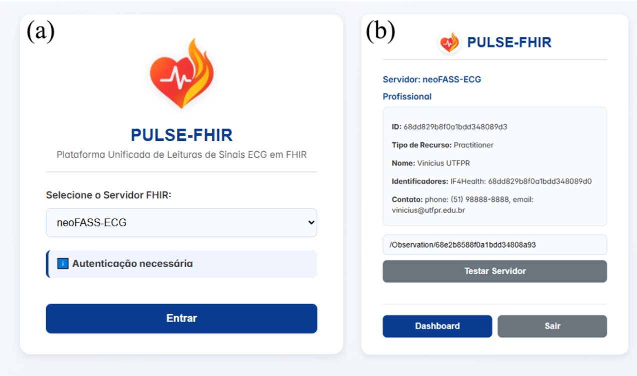

Figure 6. (a) Initial PULSE-FHIR page for selecting the server and performing login; (b) redirection page after login for viewing the server/user data.

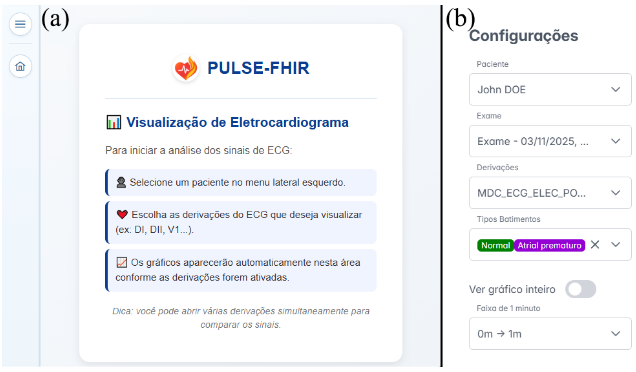

Figure 7. (a) Initial dashboard page with navigation information; (b) side configuration panel with options for Patient, Examination, Leads, and the selected ECG minute.

ing and processing ECG data from different FHIR-compliant APIs. Next, we analyze the application's navigation flow from authentication to ECG visualization. We then compare PULSE-FHIR with existing ECG visualization tools regarding waveform fidelity and annotation support. Finally, we evaluate front-end performance under different ECG sizes and configurations to assess client-side responsiveness, rendering limitations, and scalability.

4.1 FHIR Validation

PULSE-FHIR is primarily a front-end visualization application, as illustrated in Figure 1. Therefore, validating the platform requires verifying whether it can retrieve ECG signals and annotations from FHIR-compliant APIs and process the corresponding FHIR resources without changes to the front-end architecture.

Among the available FHIR servers and APIs used for testing interoperability, two different FHIR implementations were selected for the experiments:

- HAPI-FHIR [Smile CDR, 2014] is a public test server where developers and researchers check if their solutions are compatible with FHIR standard since HAPI-FHIR provides endpoints for all FHIR resources.
- FASS-ECG [Pereira *et al.*, 2023] provides specialized FHIR endpoints for retrieving segments of long-term ECG recordings and requires SMART on FHIR authentication.

To conduct the experiments, ECG signals and ECG annotations from the MIT-BIH Arrhythmia Database [Moody and Mark, 2001; Goldberger *et al.*, 2000] were converted into FHIR-compatible resources and stored in both APIs. Interoperability was validated by dynamically selecting different ECG data sources within PULSE-FHIR. Since the application was designed to interact with configurable FHIR endpoints, PULSE-FHIR was able to retrieve data from both APIs without requiring modifications to the front-end architecture.

When accessing PULSE-FHIR, the user is redirected to the server selection page, shown in Figure 6(a). Two predefined FHIR-compatible options were configured for the experiments: HAPI-FHIR and FASS-ECG. When FASS-ECG is selected, the user is redirected to the corresponding authentication page to authorize data access. After authentication, or directly in the case of servers without authentication, the

Figure 8. ECG visualization page showing synchronized multi-lead visualization, selected beat annotations, the interval measurement tool, and the temporal navigation selector.

user is redirected to the server/user data page shown in Figure 6(b). This page displays the selected server information and provides access to the dashboard.

4.2 System Navigation

After selecting the "Dashboard" button from the server information page shown in Figure 6(b), the user is redirected to the main visualization environment. As shown in Figure 7(a), this page provides access to the ECG dashboard and to the configuration panel used to define the examination to be displayed.

The configuration panel, shown in Figure 7(b), allows the user to select a patient, choose one of the available ECG examinations, define the leads to be visualized, and select the beat annotation types of interest. The examinations associated with each patient are listed in descending chronological order, from the most recent to the oldest. Once an examination is selected, the available leads and annotation types are loaded according to the selected ECG record.

After more than one lead is selected, the corresponding ECG waveforms are displayed simultaneously, as shown in Figure 8. The plots share the same temporal axis, so navigation in one lead is automatically synchronized with the others. This behavior supports multi-lead inspection of cardiac events occurring at the same time instant. Leads can also be temporarily collapsed and reopened without requiring the data to be loaded again, supporting interactive exploration of the examination.

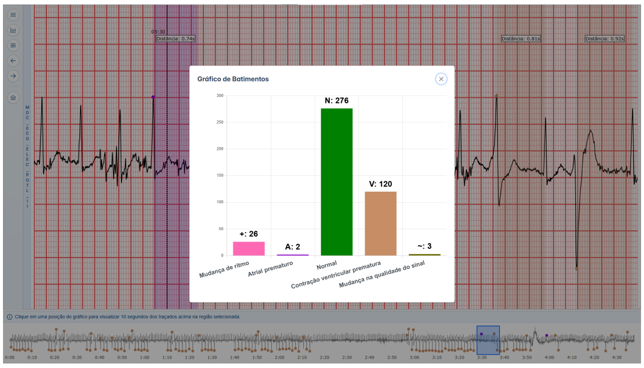

Figure 9. Modal window showing the distribution of beat annotation types in the selected ECG examination.

Beat annotations can be filtered according to the annotation types available in the selected examination, such as Normal, Atrial Premature, and Ventricular Premature Contraction. When one or more annotation types are selected, the corresponding beats are displayed as markers over the ECG trace. In addition to the markers, highlighted regions are added to the plot background to indicate the annotated beat intervals, as illustrated in Figure 8. This visualization supports the inspection of clinical or AI-generated beat-level annotations in their temporal context, enabling reviewers to relate classification outputs directly to the underlying ECG morphology.

The interface also includes temporal navigation and measurement tools. The time selector indicates the currently visible portion of the waveform and allows navigation across fixed visualization windows. The measurement tool allows the user to select two points on the ECG plot; the selected interval is highlighted with boundary lines, and the time difference between the points is displayed in seconds. Additional controls allow navigation to the previous or next annotated beat of the selected type, supporting focused inspection of specific cardiac events.

Finally, PULSE-FHIR provides a summary view of the selected examination by displaying the distribution of beat annotation types, as shown in Figure 9. This functionality complements waveform inspection by providing an overview of the annotation classes present in the ECG record.

To support reproducibility and external inspection, a demonstration video showing navigation within the PULSE-FHIR platform and the project's GitHub repository are publicly available.[1] These resources can also be accessed through the QR code shown in Figure 10.

4.3 Graphical Visualization Validation

The systems identified in Section 2 and summarized in Table 2 were used to contextualize existing approaches to ECG visualization and to derive the functional and interoperability requirements of PULSE-FHIR. However, they were not adopted as graphical validation benchmarks because most of them do not provide public access to the same ECG records, do not expose comparable annotation visualization features, or depend on specific acquisition devices and simulators.

[1] Source code: GitHub repository. Demonstration video: YouTube video.

Figure 10. QR Code that leads to the Link Tree of the project, in which there is the GitHub link of the project and the YouTube link to the video of the demonstration of the project. Url: `https://linktr.ee/pulse_fhir`

For this reason, graphical visualization was evaluated by comparing PULSE-FHIR with two established ECG visualization tools: the MIT-BIH Arrhythmia DB Web Visualizer [Silva, 2025] and LightWAVE [Moody, 2013]. These tools were selected because they provide direct access to MIT-BIH ECG records and annotations, allowing comparison of waveform morphology and annotation placement using the same reference data.

Although these viewers are useful for inspecting ECG records and annotations, they are not designed to operate as FHIR-based visualization clients within interoperable health data ecosystems. Thus, this comparison evaluates whether PULSE-FHIR preserves waveform morphology and annotation placement while adding FHIR-based retrieval, configurable repository access, SMART on FHIR support when required, and synchronized multi-lead annotation visualization.

Figure 11(a) shows the visualization in the PULSE-FHIR platform of a segment of record 100 from the MIT-BIH Arrhythmia Database. At this specific point in the signal, the annotation corresponding to the beat type present in the official MIT-BIH annotation set is displayed, indicating the occurrence of an atrial premature beat. The point shown on the platform corresponds to an amplitude of 0.845 mV at 5.678 s, consistent with the value reported by the reference tool.

For comparison purposes, Figure 11(b) shows the same region of the record using the MIT-BIH Arrhythmia DB Web Visualizer [Silva, 2025]. In this tool, the same beat is likewise annotated as "A", the code that identifies atrial premature beats in both systems, and it is also displayed with an amplitude of 0.845 mV at the equivalent time of 5678 ms. In addition to the specific highlighted point, the preceding and subsequent beats exhibit the same classifications, including two atrial premature beats and normal beats, demonstrating the consistency between the two representations, despite differences in unit notation.

Figure 11(c) presents the equivalent visualization in the LightWAVE viewer [Moody, 2013], which also retrieves record 100. A slight vertical zoom was applied to facilitate visual comparison with the other images. As in the other representations, the beat is annotated as "A" (atrial premature beat) and is identified at approximately 5.67 s.

Overall, the ECG waveform remains visually consistent across the three tools, and the selected annotation is rendered at the expected temporal position and beat class. This result indicates that PULSE-FHIR correctly decodes the FHIR-compatible representation of the MIT-BIH ECG signal and

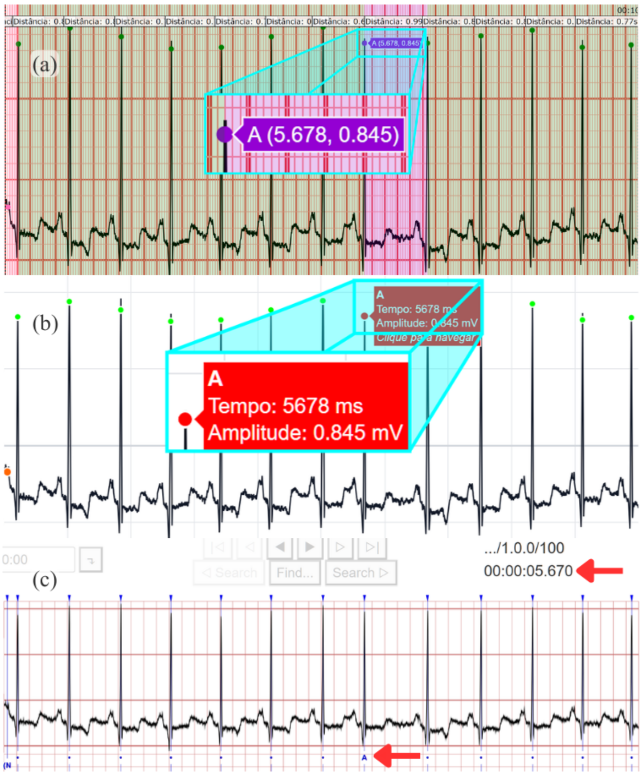

Figure 11. Record “100” from the MIT-BIH Database rendered in (a) PULSE-FHIR, (b) MIT-BIH Arrhythmia DB Web Visualizer, and (c) LightWAVE.

annotations, preserving waveform morphology and beat-level annotation placement. Unlike the reference viewers, however, PULSE-FHIR performs this visualization from configurable FHIR-compatible repositories and supports synchronized multi-lead inspection with annotation filtering in an interoperable health data context.

4.4 Front-End Performance Evaluation

The experiments were conducted on a MacBook Pro equipped with an Apple M5 processor and 16 GB of unified memory. We evaluated PULSE-FHIR using Core Web Vitals metrics [Edgar, 2023] as a reference to identify critical browser-level performance indicators in Google Chrome. Besides, CPU and network throttling features are available in Chrome Developer Tools to reduce the influence of the specific hardware used in the experiments and to evaluate the application under different user conditions.

The first step of the experimental methodology was to identify the most relevant performance indicator for PULSE-FHIR. We navigated through all PULSE-FHIR pages with the Performance tab enabled to identify potential bottlenecks related to loading, interactivity, and visual stability. The ECG visualization page, shown in Figure 8, was identified as the most performance-sensitive component because it concentrates data retrieval and graphical rendering operations triggered by user interactions. In this experiment, rendering latency was defined as the elapsed time between the user request for ECG visualization and the moment when the waveform was fully rendered in the browser.

In the next step, we prepared three 1-lead ECGs and three 12-lead ECGs, each lasting 1, 5, and 30 minutes, since the size of an ECG record described as a FHIR resource increases proportionally with signal duration and the number of leads. PULSE-FHIR allows minute-by-minute visualization in the panel shown in Figure 7(b), so this evaluation includes the ECG visualization page while rendering one minute of ECG data and the full ECG record concerning FASS-ECG endpoints.

Table 4 summarizes the rendering latency of PULSE-FHIR for ECG records with different durations, numbers of leads, and resource sizes. The first three columns describe the ECG dataset characteristics, while the fourth column indicates whether the visualization was limited to a one-minute segment or included the complete ECG record. The last column reports the average rendering latency and standard deviation measured across ten executions.

For complete one-minute ECG records, rendering latency remained below 200 ms, even for 12-lead recordings. The increase in latency was smaller than the increase in resource size, suggesting that PULSE-FHIR scales efficiently for short-duration ECG segments. For five-minute ECG records, rendering latency increased substantially, particularly when the complete recording was displayed. In the worst successful scenario (12 leads, full 5-minute record), the average latency (3.65 s) indicates that rendering performance becomes increasingly dependent on the volume of graphical elements processed by the browser.

According to Nielsen’s usability guidelines [Nielsen, 1994], delays above 1 second become progressively noticeable for the user. The results indicate that PULSE-FHIR provides a responsive experience for up to 1 minute ECG segments and remains usable for up to 5 minute recordings. The experiments also revealed a practical limitation of the current implementation. PULSE-FHIR was unable to render 30-minute ECG records, regardless of the number of leads. Rendering failures included loss of graphical consistency and React stack overflow exceptions caused by the large number of elements generated simultaneously.

The results suggest that PULSE-FHIR benefits from the specialized FASS-ECG endpoints [Pereira *et al.*, 2023], which enable large ECG recordings to be visualized incrementally by retrieving and rendering one-minute segments from long-term recordings while maintaining interoperability through standard FHIR resources.

Table 4. PULSE-FHIR render times for loading the ECG visualization page (Fig. 8) using different ECG records.

#Leads	ECG Time	Record size	View	Render Latency
1	1 min.	23 KB	–	37.4 ± 1.34 ms
	5 min.	498 KB	1 min. Full	91.9 ± 8.08 ms 286 ± 12.27 ms
	30 min.	3.2 MB	1 min. Full	Rendering error React error
12	1 min.	267 KB	Full	187 ± 9.62 ms
	5 min.	6.0 MB	1 min. Full	1073.2 ± 439.72 ms 3652.8 ± 387.75 ms
	30 min.	36.5 MB	–	Error

5 Conclusion

The development of PULSE-FHIR demonstrates the feasibility of integrating FHIR-compatible ECG representations with web-based visualization of synchronized beat-level annotations. The experimental results show that the platform can retrieve and render ECG resources from different FHIR-compatible APIs, including a generic FHIR server and a specialized ECG-oriented FHIR API, without requiring changes to the front-end architecture. The performance evaluation also shows responsive visualization for complete one-minute ECG records, with rendering latencies below 200 ms in the evaluated configurations, while larger records highlight the importance of incremental retrieval strategies for long-term ECG visualization.

Another contribution of this work is the proposed FHIR-compatible representation for ECG beat annotations. By preserving waveform morphology and annotation placement compared with established ECG viewers, PULSE-FHIR shows that diagnostic classifications produced by human experts or AI models can be displayed directly on the ECG time axis within an interoperable visualization workflow. This functionality supports research-oriented validation of arrhythmia detection outputs and provides a foundation for future integration with clinical ECG review workflows.

The proposed FHIR-compatible annotation representation may also support broader use in interoperable healthcare ecosystems. By representing beat-level labels as structured resources associated with ECG signals, the same visualization workflow can be used to compare expert annotations, reference database labels, and outputs generated by AI-based arrhythmia detection models. This can facilitate research-oriented validation, auditability of computational classifications, and longitudinal review of ECG events across systems that adopt FHIR-compatible data exchange. In future clinical integration scenarios, this approach could support decision-support workflows by enabling annotations to be retrieved, filtered, and reviewed alongside the underlying ECG signal, provided that the healthcare infrastructure meets the institutional requirements for validation, privacy, consent, and authorization.

Future work includes extending the platform to additional biosignals, presenting data derived from the selected ECG (e.g., BPM), and including demographic elements, such as patient photos and lists of examinations. Additional developments may include integration with other cloud and web ecosystems, such as neural network-based classifiers [Freire *et al.*, 2024] or servers that transform signals into other types of information [Vieira *et al.*, 2024], which could support clinicians during patient analysis.

Declarations

Authors' Contributions

Adriano Paulichi and Vinícius Coradassi contributed to the conception of this study, developed the methodology, implemented the PULSE-FHIR platform, performed the experiments, analyzed the results, and wrote the manuscript. André L. D. Martins contributed to the experimental design, supported the execution and analysis of the experiments, and reviewed the manuscript. Daniel F. Pigatto contributed to the research planning, methodological refinement, technical discussion, and manuscript review. Fábio Pires Itturriet contributed to the conception and coordination of the study, methodological definition, analysis of the results, and writing and review of the manuscript. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests related to the research, authorship, and/or publication of this article.

Availability of data and materials

The software developed in the current study is publicly available at the project repository: `https://github.com/if4health/pulse-fhir`. A demonstration video of PULSE-FHIR is available at: `https://www.youtube.com/watch?v=2S6v8qEFMQc`. The ECG signals and annotations used in the experiments were derived from the publicly available MIT-BIH Arrhythmia Database. The FHIR-compatible resources generated for the experiments are available from the corresponding author upon reasonable request.

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