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PAPER

Electronic Health Record Interoperability System in Peru Using Blockchain

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ABSTRACT

In Peru, there is currently no integrated electronic health record (EHR) system that can be automatically shared between healthcare facilities. This leads to increased service costs due to duplicated examinations and records, as well as additional time required to manage patients' clinical information. One alternative for ensuring the secure interoperability of EHRs while preserving data privacy is the use of blockchain technology. However, existing works consider a pre-established format for exchanging EHRs, which is not applicable when systems have different formats, as is the case in Peru. This work proposes an architecture and a web application for exchanging EHRs in heterogeneous systems. The proposed system includes the homologation of an EHR with rapid interoperability resources for medical attention using FHIR HL7, and vice versa, to achieve interoperability. Additionally, it utilizes blockchain technology to ensure data security and privacy. The web application was tested using a case simulation to demonstrate EHR interoperability between clinics in a clear, secure, and efficient manner. In addition, a survey was conducted with 30 patients regarding adoption, and another survey was conducted with 10 doctors from a public hospital in Peru regarding usability. The results demonstrate a very high level of adoption and usability for them all. Unlike other studies, the proposal does not necessitate alterations to existing EHR systems for interoperability. In other words, the proposal presents a feasible and cost-effective alternative to addressing the EHR interoperability issue in clinics and hospitals in Peru.

KEYWORDS

interoperability, electronic health record (EHR), blockchain-FHIR, HL7, IPFS

1 INTRODUCTION

The electronic health record (EHR) offers numerous benefits for clinical practice, but it also presents several challenges that must be addressed to ensure effective implementation and optimized use of the EHR [1]. These challenges include integrating with other medical information systems, ensuring information security

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and privacy, providing accessibility for all healthcare providers, managing the cost of implementation and maintenance, training healthcare providers, and keeping up with the constant evolution of technology [2]. In Peru, access to the EHR has increased in recent years. However, many healthcare providers do not have access to EHR information systems (EHRIS), especially in rural areas, making continuity of care difficult for patients who move or change providers [3]. Furthermore, the security and privacy of medical information are major concerns for patients. Therefore, it is essential that the EHR be designed and implemented securely to protect sensitive information [4]. However, EHR can be vulnerable to cyberattacks [5]. Therefore, it is essential to take appropriate measures to ensure information security.

Currently, many systems worldwide use EHR. However, these systems present significant gaps, such as EHR incompatibility between systems and the digitization of patient medical files [6]. EHR incompatibility means that doctors and other healthcare professionals are often unable to access or transfer a patient's EHR if it is on a different or incompatible system than the one they are using, delaying diagnosis and treatment, and putting patients' health at risk [7]. The interoperability of EHRs between healthcare facilities is essential for improving efficiency in their use and in delivering health services. However, in many countries, this goal has not been fully realized. In the Latin American region, Uruguay leads in EHR interoperability at 34%, followed by Argentina at 21%, and Chile and Colombia at 11%. Peru occupies one of the last positions with less than a 10% maturity level in interoperability [8]. On the other hand, there is a significant weakness in the security and privacy of EHR because health centers do not employ adequate techniques to safeguard a patient's data [9]. Additionally, most health centers store patient data locally, and some do not have backup data [10]. The numerous instances of attacks on healthcare data, such as those in the US and England, where there have been significant losses of sensitive data [11], have underscored the critical importance of EHR security and privacy.

In Peru, Law No. 30024, enacted in 2013, establishes the national EHR registry. This law is an interoperability platform and a repository for clinical information for every patient registered in the medical institution chosen by the patient [12]. It is a fact that private medical institutions in Peru operate a private system for storing and managing EHRs. Ensuring the integrity and security of this data requires a highly secure system to prevent patients' personal information from falling into the wrong hands. The Peruvian Ministry of Health (Minsa) has implemented measures to address this issue by introducing various electronic record solutions, now collectively known as Electronic Health Record Information Systems (SIHCE in Spanish). However, there are still challenges in implementing and complying with these systems nationwide. Specifically, there is a lack of standardization and compatibility between the various systems used by health centers at the national level. In addition, many health centers still use paper-based EHR systems, which means they do not have access to real-time information and may experience delays in receiving results from tests and exams.

There have been numerous studies on the interoperability of EHRs. In [7], a system called OmniPHR is proposed for EHR interoperability, incorporating the HL7 FHIR and openEHR standards. The study extends to include blockchain and MIMIC-III, along with artificial intelligence using natural language processing (NLP), achieving an F1 score of 87.9% in integrating various standards into a single format, as presented in [13]. In [14], Hyperledger Fabric is utilized to create a secure interoperability system known as MedHypChain. Each transaction is protected by a signature encryption scheme, and tests show confidentiality, anonymity, traceability, and authenticity.

In reference [15], the SHealth system is proposed to be blockchain-based, utilizing multiple layers to define the privileges and permissions of health entities without compromising their authenticity. In reference [16], HonestChain was developed. It utilizes blockchain technology to securely share patient data and employs digital signature algorithms to ensure the authenticity of the data.

Despite the abundance of literature on EHR interoperability, no studies on EHR interoperability have been identified in Peru. In Peru, the law [17, 18] does not mandate a clear implementation route for the EHR, making interoperability even more challenging. This also means that the studies identified cannot be directly applied to the Peruvian case, where centralized or isolated systems are generally managed.

This paper proposes an EHR interoperability system that facilitates the transfer and transformation of patients' EHR using the FHIR (fast healthcare interoperability resources) standard and blockchain technology. This system aims to make individuals' medical histories available across various clinical facilities. In addition, the user is assisted in maintaining a unique record and expediting care across various health facilities, ensuring efficient, safe, and prompt treatment. Blockchain technology works as a decentralized network without a central authority. Data is continuously added in the form of blocks and validated by the network itself, ensuring transparency and security [19]. It offers a wide range of applications and functions in the healthcare sector [20, 21] and is known for its resistance to attacks. Additionally, it provides easy access control methods and preserves data privacy [22]. Moreover, it has been successfully applied to EHR exchange systems [23].

The primary contributions of this work include:

- Develop an interoperability architecture for her to facilitate communication between healthcare facilities using diverse formats and systems.
- Provide a web-based system for exchanging EHR and demonstrate its functionality.
- Please provide a synthesis of 16 EHR exchange systems that utilize blockchain technology.

This paper is organized into six sections. In Section 2, a review of health systems for exchanging EHR between different health centers is presented. The technological proposal model and its implementation are described in Sections 3 and 4, respectively. Section 5 presents the validation and results. Finally, the conclusions are presented in Section 6.

2 REVIEW OF EHR SYSTEMS WITH BLOCKCHAIN

Electronic health record interoperability systems with blockchain are designed in the health sector to facilitate the exchange and management of EHRs with enhanced accessibility and security. These systems aim to improve the efficiency of medical care by reducing time and costs per patient. In general, they consider the following factors:

- *Information exchange standards*: They ensure that interoperable systems can communicate and share information efficiently and securely. Some of these standards include HL7 FHIR [24], DICOM [25], SNOMED CT [26], and other related standards [27].
- *System type*: This refers to the front end of the system, which can be web or mobile.

- *Security and privacy technology*: This is provided by blockchain technology, as well as the signature algorithm (encryption) used for authentication and authorization.
- *Access levels*: Patient, doctor, manager, and medical center

Below are 14 blockchain-based EHR interoperability systems that were identified in the indexed journals Scopus, Web of Science, IEEE Access, and PubMed (refer to Table 1).

Table 1. Blockchain-based interoperable EHR systems

System	Type of System	Standards	Blockchain	Access Level	Reference
OmniPHR	Web	openEHR, HL7 FHIR and MIMIC-III	Ethereum and Chord algorithm	Patient and doctor	[13]
MedHypChain	Web	Standard proposed by authors	Hyperledger Fabric and consensus algorithm	Administrator, patient, and doctor	[14]
HonestChain	Web	HIPAA	Hyperledger and proof-of-information algorithm	Administrator and doctor	[16]
Cloud-Assisted EHR System	Cloud Service	Standard from the same health entity	Hyperledger Fabric, consensus algorithm and PBFT	Patient and doctor, medical centers, administrator	[28]
SHealth	Web	Standard from the same health entity	Hyperledger Fabric, SHA-256 algorithm, ECC algorithm and AES algorithm	Doctor, patients, health centers	[15]
EC-ACS	Cloud Service	Standard from the same health entity	Blockchain and 17 different algorithms	Doctor, patients, auditor	[29]
MCPS	Consortium Blockchain	Standard from the same health entity	Blockchain and encryption algorithm	Patients and doctors	[30]
Distributed EHR	Cloud Service	OmniPHR	Ethereum, Hyperledger and Chord algorithm	Patients, doctors, and health services	[7]
EHR System – Cryptosystem	Rest-API Service	HL7 FHIR	Hyperledger + C-AB/IB-ES	Patients, doctors, and health services	[23]
PHR System	Mobile and Web application	FHIR	Ethereum and Smart Contract (IPFS)	Patient, doctor, administrator, and medical center	[31]
Wireless sensor networks	Web	–	Blockchain, wireless sensors and Smart Contract	Patient and administrator	[32]
MedChain	Web	–	Blockchain (ECC)	Medical Center	[6]
Health Wizz	Mobile and Web application	FHIR	Ethereum (IPFS)	Patient and medical center	[2]
Secure Cloud-Based EHR	Web	–	Cryptosystem and blockchain (C-AB/IB-ES)	Patient and medical center	[33]

3 INTEROPERABLE EHR MODEL

A model is proposed to enable the interoperability of EHRs for patients across different healthcare facilities. The purpose of this model is to enable each patient to easily access their clinical history, regardless of the healthcare facility where they received treatment. To achieve this, the EHR of a healthcare facility is converted into the standardized HL7 FHIR format. This format is then shared with other healthcare facilities, enabling the sharing of patient data, including comprehensive characteristics and clinical details. The model is based on blockchain, smart contracts, and the HL7 FHIR format. It consists of five modules: medical history consultation, external management, patient authorization, HL7 FHIR transformation, and EHR search.

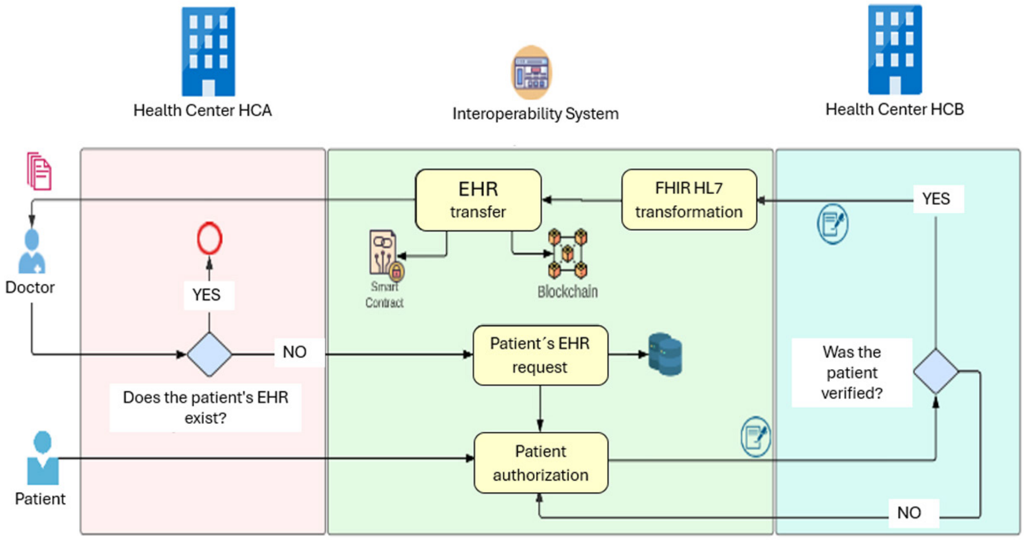


Fig. 1. Interoperable EHR model with blockchain

In the model (see Figure 1), initially, the patient visits a doctor at an HCA health center, who then searches for the patient's EHR in the system. If it exists, interoperability will not be necessary. Otherwise, the doctor proceeds to initiate a process to obtain the EHR from the previously visited health center (HCB health center). This process, known as "external management of the EHR," requires the patient's authorization for the transfer of their data. When the request arrives at the HCB health center, the patient's data will be verified. If the request is denied, the EHR will not be shared. Otherwise, the search history will be conducted within the system, and a copy will be created to be sent via the web application. The web application will convert the patient's medical history into the FHIR HL7 format, store it in the blockchain, and then decrypt the history using a smart contract. Finally, the patient's information will be accessible at Center A, where the doctor can directly review the patient's medical history.

Patient's EHR request: The purpose of this module is to request a patient's EHR from one or more healthcare centers. Once entered into the system, the patient's identifying data, such as their ID, the reason for the request, and the clinic from which the EHR is requested, is entered.

Patient authorization: When the doctor requests a copy of the patient's EHR, an authorization from the patient. This authorization must be signed by the patient to give consent for the sharing of their data, thereby accepting the terms and conditions of the document. Once the authorization has been granted, it will be sent together with the EHR request.

FHIR HL7 transformation: This module is responsible for reading and transforming the EHR that has been sent from the HCB health center into the HL7 format. For this purpose, each text item in the EHR is transformed into the items of the HL7 standard (see Figure 2). For example, the text "Fever, Cough" under the item "symptoms" is transformed into [{"symptoms": "Fever, Cough"}]. In addition, the information will be stored on a blockchain to enhance security during the transfer. Smart contracts will be utilized to decrypt the medical history and transmit it to Health Center A. Once this process is completed, the doctor will be notified that the transfer has been successfully completed and will be accessible to him.

a)

Name: Piero Cossio
Dni: 45986257
Birth Date: 23/12/1999
Address: Av. las camelias 189
Marital Status: Soltero
Alergies: Penicilina
Attention Date: 11/05/2022
Medications: Paracetamol
Observations: Ingerir después de comida
Symptoms: Fiebre, tos
Gender: Masculino
Phone Number: 999563584
Contact Relationship: Madre
Contact Name: Roxana Jara
Contact Phone Number:
Contact Address: Av. las camelias 189
Diagnosis: Covid-19
Diagnosis Date: 12/05/2022
Has Insurance: NO
Doctor Name: Dr. Alfredo Molina

b)

{"resourceType":"Patient","name":[{"family":"Piero Cossio"}],"dni":[{"dni":"45986257"}],"birthDate":[{"birthDate":"23/12/1999"}],"address":[{"address":"Av. las camelias 189"}],"maritalStatus":[{"maritalStatus":"Soltero"}],"alergies":[{"alergies":"Penicilina"}],"attentionDate":[{"attentionDate":"11/05/2022"}],"medications":[{"medications":"Paracetamol"}],"observations":[{"observations":"Ingerir después de comida"}],"symptoms":[{"symptoms":"Fiebre, tos"}],"gender":[{"gender":"Masculino"}],"phoneNumber":[{"phoneNumber":"999563584"}],"contactRelationship":[{"contactRelationship":"Madre"}],"contactName":[{"contactName":"Roxana Jara"}],"contactPhoneNumber":[{"contactPhoneNumber":""}],"contactAddress":[{"contactAddress":"Av. las camelias 189"}],"diagnosis":[{"diagnosis":"Covid-19"}],"diagnosisDate":[{"diagnosisDate":"12/05/2022"}],"hasInsurance":[{"hasInsurance":"NO"}],"doctorName":[{"doctorName":"Dr. Alfredo Molina"}]}

Fig. 2. EHR: a) HCB format; and b) HL7 format

EHR transfer: The request is received at the HCB health center, where the patient's data is verified. If the information is not correct, the request will be denied, and the clinic that submitted the request will be notified. Otherwise, the patient will be looked up in the HCB health center system. Once the EHR of the requested patient is located, a copy will be created and sent via the EHR management system.

4 HNC SYSTEM

Next, the proposed interoperability model is implemented in a web system called health net chain (HNC).

4.1 Architecture

Figure 3 depicts the high-level technology architecture for transferring an EHR from the clinical system (HCA) to the clinical system (HCB). The architecture incorporates blockchain technology, smart contracts, an IPFS server, and the FHIR HL7 format. Blockchain technology ensures decentralized and tamper-resistant storage. Smart contracts establish rules and automate operations. The IPFS server facilitates the storage and distribution of files, while the FHIR HL7 format standardizes the representation and exchange of medical data, ensuring the integrity and interoperability of each patient's clinical information. The project uses SQLite as the database, which enhances portability and scalability. Additionally, it is lightweight and can be stored on the same server.

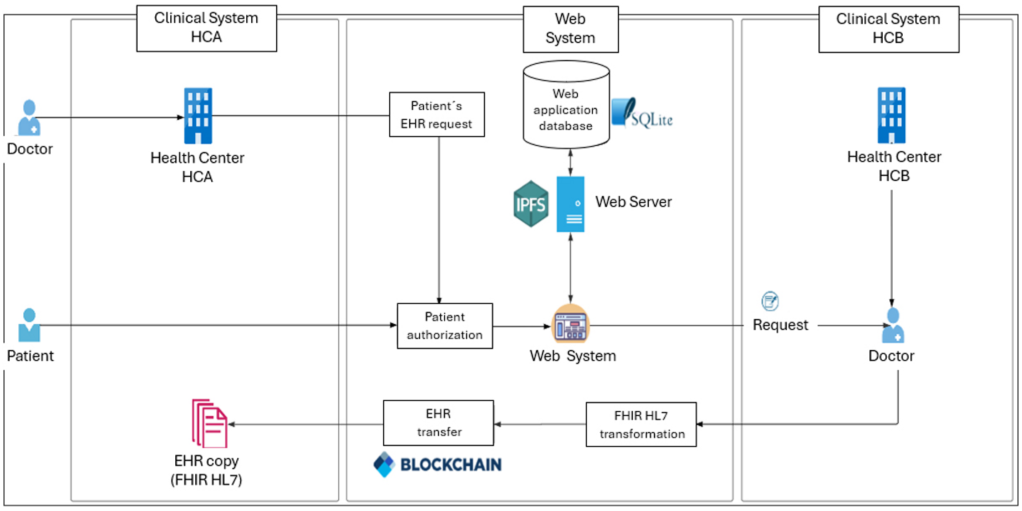


Fig. 3. Technological architecture of the HNC interoperability system

4.2 Database diagram

The database model focuses on the operation of the web system and will not store any documents (EHR). Similarly, the model below enables us to organize accurate and fundamental patient data for easier retrieval, along with clinic information and the corresponding request.

4.3 Implementation

The HNC was developed using Node.js on the backend and technologies such as HTML, CSS, and JavaScript on the frontend. To enhance the website, we utilized plugins and libraries. The "Sash" UI component was implemented to enhance the usability of the application's administrative design. Additionally, it includes a local IPFS server to generate hashes for the uploaded files. The blockchain will be executed locally, enabling the partial processing of file hashes. When necessary, a smart contract will be used to provide access to documents. For the conversion of PDF files to the FHIR HL7 standard format, the FHIR standard format of HL7 International (http://hl7.org/fhir/) in JSON format was utilized [34].

Patient request module: A form is completed with basic details including the patient's name, date of birth, and ID. It also explains the reason for needing to access their records.

Patient authorization module: The patient authorizes the EHR request by submitting a signed document, known as an authorization, which is then attached to the documents in the request module. Once the request is authorized, the individual responsible for the requested clinic (HCB) will verify the request for accuracy. If the request is not in order, it will be rejected with reasons provided. If the request is in order, it will be accepted, and a copy of the EHR will be sent in PDF format.

FHIR HL7 transformation module: This module involves generating an HL7 FHIR from an EHR. This is carried out through a procedure that takes into account:

The EHRs, such as FHIRs are organized into field categories. Consider the categories d $R^1, R^2, \ldots, R^c$ and $H^1, H^2, \ldots, H^c$ for FHIR and HCE respectively. For example, Patient and Medication for FHIR and Patient and Medication for HCE. Each category

R^j is given as $R^j = \{(a_1^j, b_1^j), \ldots, (a_n^j, b_n^j)\}$, where a_1^j is a FHIR field and b_1^j represents its corresponding field in HCE. For example, "name" in FHIR corresponds to "nombre" in HCE. It should be noted that each EHR category is defined by a set of fields and their associated data (if any), denoted as, $H^j = \{(b_1^j, d_1^j), \ldots, (b_n^j, d_n^j)\}$, where d_1^j represents the data corresponding to the b_1^j field.

The transformation is described by the following algorithm:

Transformation Algorithm

1. $O \leftarrow \{\}$
2. $for\ j = 1, c$
3. $\quad O = O + "R^j":\{$
4. $\quad for\ i = 1, n$
5. $\qquad d_1^j \leftarrow texto(a_1^j, b_1^j)$
6. $\qquad O \leftarrow O + "a_i^j" : "d_i^j"$
$\quad end - for$
7. $\qquad O \leftarrow O + \}$
$\quad end - for$
8. $FHIR \leftarrow O$

Notes: (1) The temporary file O is initialized as empty; (2) Each category R^j is started in O; (3) The R^j category is opened, adding "{" to the O file; (4) Each field of a category is counted; (5) For each field a_i^j the data d_i^j is obtained. This is done using the function $texto(.,.)$, which determines the HCE text that is on the right side of b_i^j. If this does not exist, it will return "" (empty); (6) The record $"a_i^j" : "d_i^j"$ is added to the O file; (7) The R^j category is closed, adding "}" to the O file; and (8) The algorithm is finished.

The transformation algorithm is implemented in a code from the JavaScript library called pdf2json. This code transforms a text (see Figure 2a) to the FHIR HL7 format (see Figure 2b).

EHR transfer module: The EHR in the FHIR HL7 format, produced by the transformation module, is uploaded to the IPFS server for storage and to generate a unique hash for the file. The file is then transferred to a blockchain, where its integrity and security are guaranteed. Finally, a smart contract is utilized to decrypt the file and retrieve it in the HCA. Ethereum was used for the implementation.

5 VALIDATION

Following this, the proposal is validated through a simulation of a case study involving two clinics and expert judgment.

5.1 Case study simulation

Case. The case study examines the interoperability of EHR in two health centers (HCA, HCB) that use different EHR formats and lack standardization. However, their medical staff is familiar with the FHIR HL7 standard. The patient "Jesus Alberto Gonzales Duarez" (a fictitious patient) is at HCA, a facility that does not have his EHR. On the other hand, HCB does have the patient's EHR in its system, so HCB is required to transfer the patient's EHR to HCA.

Production start-up. To achieve interoperability between HCA and HCB clinics, the following preparatory activities must be completed with the clinics: 1) Introduce the HNC system, explaining its purpose, functionality, and benefits; 2) Formalize EHR transfer agreements between the clinics; 3) Enroll clinics and users in the system; 4) Provide training on the system and the HL7 FHR standard to user personnel (administrators, doctors).

Simulation. For the simulation, Truffle and Ganache were used as development and simulation tools. They facilitate the creation and testing of smart contracts without interfering with the main blockchain network.

Patient EHR request: Since the HCA does not have the patient's EHR, the doctor submits a request for it in the NCE through the patient's EHR request module, completing a form (see Figure 4a).

Patient authorization: Next, the patient is informed that he needs to provide authorization for the sharing of his EHR with the HCB clinic. This is done under informed consent, allowing the doctor to request access to the EHR. If this is the case, the patient will authorize the order through the patient authorization module interface (see Figure 4b).

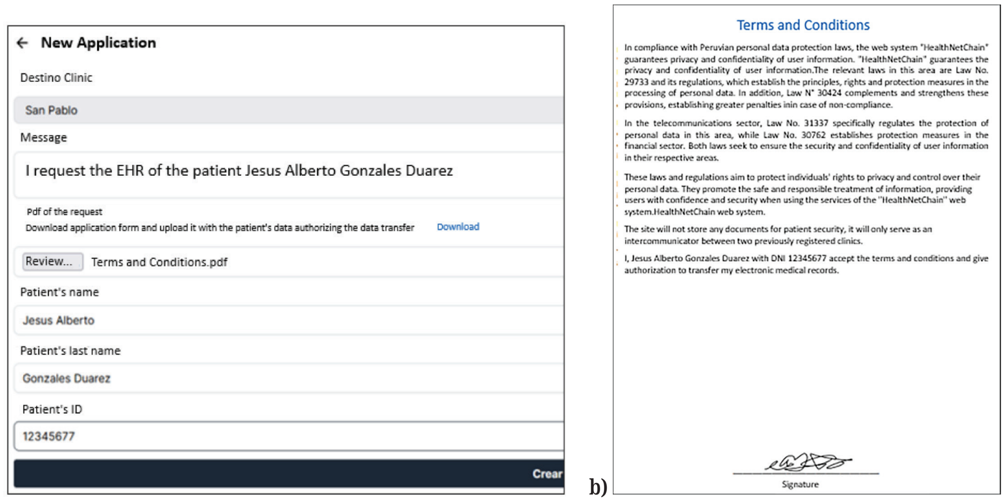


Fig. 4. EHR request: a) Request; and b) Patient authorization

Request submission: After obtaining the patient's authorization, HNC sends the request to HCB along with the patient's authorization as evidence of consent.

Verification: Upon receiving the EHR transfer request (see Figure 5), the HCB clinic user verifies the validity of the patient's authorization. This process is not carried out by the HNC system; however, it is essential to ensure that the privacy and security requirements for medical information are met. Once the request is validated, HCB sends the EHR in PDF format through the HNC system.

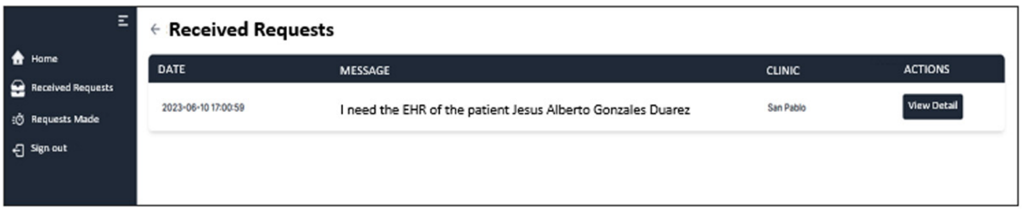
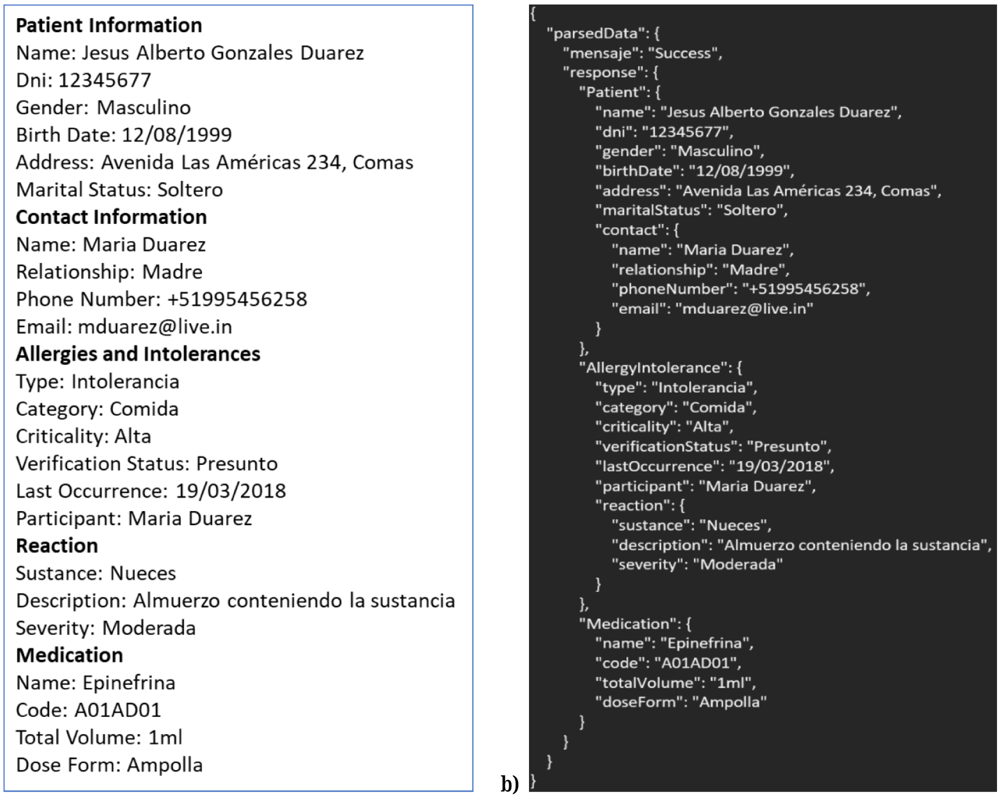


Fig. 5. EHR requests received

FHIR HL7 transformation: Next, HNC automatically converts the patient's EHR (see Figure 6a) to the FHIR HL7 format (see Figure 6b) using the FHIR HL7 transformation module.

EHR transfer: Next, HNC automatically sends the patient's EHR to HCA through the EHR transfer module in the FHIR HL7 format.



Patient Information
Name: Jesus Alberto Gonzales Duarez
Dni: 12345677
Gender: Masculino
Birth Date: 12/08/1999
Address: Avenida Las Américas 234, Comas
Marital Status: Soltero
Contact Information
Name: Maria Duarez
Relationship: Madre
Phone Number: +51995456258
Email: mduarez@live.in
Allergies and Intolerances
Type: Intolerancia
Category: Comida
Criticality: Alta
Verification Status: Presunto
Last Occurrence: 19/03/2018
Participant: Maria Duarez
Reaction
Sustance: Nueces
Description: Almuerzo conteniendo la sustancia
Severity: Moderada
Medication
Name: Epinefrina
Code: A01AD01
Total Volume: 1ml
Dose Form: Ampolla

a)


```
{
  "parsedData": {
    "mensaje": "Success",
    "response": {
      "Patient": {
        "name": "Jesus Alberto Gonzales Duarez",
        "dni": "12345677",
        "gender": "Masculino",
        "birthDate": "12/08/1999",
        "address": "Avenida Las Américas 234, Comas",
        "maritalStatus": "Soltero",
        "contact": {
          "name": "Maria Duarez",
          "relationship": "Madre",
          "phoneNumber": "+51995456258",
          "email": "mduarez@live.in"
        }
      },
      "AllergyIntolerance": {
        "type": "Intolerancia",
        "category": "Comida",
        "criticality": "Alta",
        "verificationStatus": "Presunto",
        "lastOccurrence": "19/03/2018",
        "participant": "Maria Duarez",
        "reaction": {
          "sustance": "Nueces",
          "description": "Almuerzo conteniendo la sustancia",
          "severity": "Moderada"
        }
      },
      "Medication": {
        "name": "Epinefrina",
        "code": "A01AD01",
        "totalVolume": "1ml",
        "doseForm": "Ampolla"
      }
    }
  }
}
```


b)

Fig. 6. HCE: a) Original format; and b) FHIR HL7 format

The case simulation demonstrates that the proposal ensures compatibility and understanding of EHRs among clinics that use different formats, thereby ensuring safe and efficient EHR interoperability between clinics.

Performance and latency: The simulation was conducted on a PC with an 11th Gen Intel(R) Core (TM) i7-11700 @ 2.50GHz (16 CPUs), 2.5GHz, 32 GB RAM, and Windows 11 Pro 64-bit operating system (10.0, build 22621). The results show that the average time for 10 transactions was 0.6452 ms and 0.2963 ms when using and not using the blockchain, respectively. This indicates that the throughput is reduced from 3.3750 to 1.5499 transactions per second when using the blockchain. It should be noted that performance can be improved by increasing the processor's power.

Considering that the hashed file is similar in size to its original file, the sending time of this file will be comparable whether blockchain is used or not. Therefore, the latency difference when blockchain is used or not is determined by the transaction time. In the simulation, the difference was 0.3489 (0.6452–0.2963), indicating that the latency increases by 0.3489 ms for each transaction when blockchain is used. It should be noted that this transaction cost is offset by the security that blockchain provides, and it can also be reduced by increasing the processing power.

5.2 Expert judgment

Participants. A survey was conducted to assess the usability and satisfaction of the HNC system. Ten doctors with experience ranging from 4 to 30 years (refer to

Table 2) participated in the survey, and 30 patients aged 19 to 44 years were surveyed to evaluate its adoption (refer to Table 3).

Table 2. Profile of surveyed doctors

Id	Genre	Age	Years of Experience
M01	Female	63	25
M02	Female	29	4
M03	Female	34	5
tavM04	Female	28	5
M05	Female	55	28
M06	Female	30	3
M07	Male	35	8
M08	Male	59	30
M09	Male	38	10
M10	Male	40	12

Table 3. Profile of surveyed patients

Id	Age	Genre	Id	Age	Genre	Id	Age	Genre
P01	22	Male	P11	22	Male	P21	28	Female
P02	19	Female	P12	33	Female	P22	33	Female
P03	23	Male	P13	29	Female	P23	26	Male
P04	20	Male	P14	34	Male	P24	35	Male
P05	18	Male	P15	27	Male	P25	29	Male
P06	25	Male	P16	32	Female	P26	31	Female
P07	24	Male	P17	26	Male	P27	43	Female
P08	21	Male	P18	31	Male	P28	36	Male
P09	18	Female	P19	35	Male	P29	39	Male
P10	22	Male	P20	30	Male	P30	44	Female

Experiment. A survey was conducted to assess the usability, satisfaction, and adoption of the HNC system.

- The perception of usability and satisfaction was assessed through surveys distributed to doctors (refer to Table 4).
- The perception of adoption was assessed through surveys given to patients (refer to Table 5).

Doctors received individual training on using the HNC for 30 minutes, which included exercises to interact with the system and test its functionalities (see Figure 7). Next, the usability and satisfaction surveys were administered. Patients received a brief five-minute explanation about the benefits and limitations of a system that enables secure sharing of EHRs between clinics, followed by the administration of the adoption survey. All surveys were conducted at a level 3 hospital in Lima, Peru, with anonymous identification.

Fig. 7. Training of doctors in the use of HNC

Survey. Two surveys have been conducted: a usability survey targeting doctors (refer to Table 5), who are the primary users of HNC, and an adoption survey targeting patients (refer to Table 6). It should be noted that patients do not interact directly with HNC. However, their consent is required for their EHR to be shared between the different health centers where they are treated. Therefore, it is necessary to evaluate their perception of adoption. The usability questionnaire addresses the two main functionalities: the transfer of EHR (QU1, QU2, QU3) and the conversion of her to FHIR HL7 (QU4, QU5), as well as its adoption (QU6, QU7, QU8). The adoption questionnaire considers the security provided by blockchain (QS1) and the usefulness of the system (QS2, QS3). On the other hand, the responses to the questions were evaluated using the Likert psychometric scale (1: nothing; 2: low; 3: moderate; 4: high; 5: very high).

Table 4. Usability questionnaire (doctors)

Id	Questions
QU1	How easy is it to generate an EHR transfer request in the application?
QU2	How easy is it to download the patient's authorization to request a copy of his EHR?
QU3	How easy is it to successfully send a patient's EHR to another clinic?
QU4	How easy is it to correctly receive a request for a copy of a patient's EHR from another clinic?
QU5	How much is a patient's EHR understood in the FHIR HL7 format?
QU6	Are the design of the web system interfaces adequate?
QU7	How easy was it to learn how to use the application?
QU8	Would you recommend using HNC for EHR transfers?

Table 5. Adoption questionnaire (patients)

Id	Questions
QS1	Do you agree that the system can safely share your EHR between healthcare facilities (where you receive care) to support your healthcare?
QS2	Do you consider that the use of HNC reduces the cost and time in the consultation, because your EHR is shared between health centers?
QS3	Would you recommend using HNC for secure and fast EHR exchange?

Results. Considering that the Likert scale includes integer values and that the average results can be fractions, the interpretation for the values has been defined as follows: [1, 1.8): nothing; [1.8, 2.6): little [2.6, 3.4]: moderate, (3.4, 4.2]: high (4.2, 5]: very high; scheme used in several works such as [35].

Table 6 represents the results obtained from the survey conducted on patients. In this table, the value 1 in row QS1 indicates that a patient answered the question with a value of 1, Similarly, the value 15 in the same column indicates that 15 patients responded with a value of 5. The average column indicates the average of the responses for each question, which can be obtained by adding the values of each row by its corresponding Likert scale, thus the average for QS1 is $4.30 = \frac{(1\times1+2\times0+3\times3+4\times11+5\times15)}{30}$.

The results obtained from the survey conducted with patients indicate "totally agree" (very high) that the system can safely share their EHR between health centers where they are treated (QS1) and that I would recommend using HNC for secure and fast EHR exchange (QS3). Furthermore, it has been demonstrated that patients "strongly agree" (high) that using HNC will reduce the cost and time required for consultations (QS2). These results show a very high perception (4.29) that this type of system can be adopted.

Table 6. Patient adoption survey results

Questions	Response – Likert Scale					Average
	1	2	3	4	5	
QS1	1	0	3	11	15	4.30
QS2	1	1	6	10	12	4.03
QS3	1	0	2	6	21	4.53
Average						4.29

Table 7 presents the results of the system usability surveys administered to doctors. The values in columns M01–M10 represent the responses on the Likert scale, and the values in the "average" column indicate the average score of each question (on the left side) and the average of the dimension (on the right side). For example, the value 4.6 in the average column for the row corresponding to QU1 is the average of the answers to this question. The value 4.29, on the other hand, is the average of answers for the transfer dimension, which includes the answers to questions QU1, QU2, and QU3.

The results presented in Table 7 indicate that doctors "totally agree" (very high) with the EHR functionalities: transfer, as it demonstrates success in transferring between health centers; and transformation, as the system correctly transforms from HCE to FHIR HL7. Furthermore, doctors highly rate the system's interfaces and ease of use, and they also recommend its use. Therefore, there is a high probability of EHR adoption.

Table 7. System usability survey results in doctors

Dimension	Id	Specialists										Average	
		M01	M02	M03	M04	M05	M06	M07	M08	M09	M10		
Transfer	QU1	5	5	5	4	4	5	5	5	4	4	4.6	4.29
	QU2	5	5	5	5	3	5	5	5	5	4	4.7	
	QU3	5	5	5	5	4	5	5	5	4	4	4.7	
Transformation	QU4	5	5	5	5	3	5	5	5	4	4	4.6	4.65
	QU5	5	5	5	4	5	5	5	5	4	4	4.7	
Adoption	QU6	5	5	5	4	3	5	3	5	5	5	4.5	4.63
	QU7	5	5	5	5	3	5	5	5	4	5	4.7	
	QU8	5	5	5	5	4	5	4	5	4	5	4.7	

6 CONCLUSION

This work proposes an architecture and a web application for securely interoperating EHRs from different health facilities by transforming them into the standard FHIR HL7 format and utilizing blockchain technology. Unlike other proposals that necessitate substantial alterations to the clinics' EHR systems to achieve interoperability, this proposal does not require changes to existing systems. Its high usability would result in widespread adoption.

The architecture was implemented in a web application using Node.js for the frontend and Express.js for the backend. As for the database, since it does not contain a large amount of data, SQLite is being used. It was then tested using a case simulation to demonstrate EHR interoperability between clinics in a clear, secure, and efficient manner.

In addition, a survey was conducted with 30 patients regarding adoption, and another survey was conducted with 10 doctors from a public hospital in Peru regarding usability. The results demonstrate the very high adoption and usability of all of them. This indicates that the proposal is a feasible, cost-effective, and secure alternative for addressing the issue of EHR interoperability in clinics and hospitals in Peru.

A limitation of the system is that health personnel must be familiar with the standard FHIR HL7 format. Although this is taught in university health programs, additional training is desirable, as many clinics use their own formats in practice. In future work, the introduction of fingerprint, signature, and/or face recognition algorithms could automate the authorization of EHR use, thereby facilitating the use of the proposed system.

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