CSCI 531

Applied Cryptography

Semester Project

Designing a Secure Decentralized Audit System for healthcare

Submitted by

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Problem statement

The aim of the project is to design and analyze a secure decentralized audit system for the healthcare department. The implementation of the system should meet the following goals:

- *Privacy:* Patient records cannot be viewed by any unauthorized entity.
- *Identification and authorization:* Access to all data should follow the step of authentication. Only authorized and identified entities can access the patient's records.
- *Queries:* An authorized, identified auditor can query the audit logs
- *Immutability:* All modifications to the medical records should be detectable
- *Decentralization:* A trusted third-party can vouch for the integrity of the data in the medical records.

1. Introduction

Audits are a useful tool for an organization. They provide credibility for the data that thrive in the organization and give other organizations the confidence that the records are fair and true. It helps build trust between the organizations and between the organization and the public. Audits in the healthcare department aim to bring forth the discrepancies between the actual medical practice and the ones written in books. This enhances the quality of healthcare the patients receive. To make auditing easier and more trustworthy, the process of auditing has become decentralized.

This project aims at implementing such a decentralized auditing system for the healthcare department to meet the aforementioned goals. Section 2 talks about the proposed system architecture and Section 3 discusses the cryptographic components that are incorporated in the proposed architecture. The implementation details are given in Section 4. Section 5 provides a conclusion to the thesis, noting its assumptions and limitations and provides scope for future work.

2. Proposed system architecture

The proposed system consists of three participants: doctor, patient and auditor. The roles of each of the participants are:

- A patient can book an appointment, print the medical records, give access to a doctor to view the medical records, give access to an audit to view the medical records and delete an appointment.
- A doctor, who has been authorized by the patient, can view the medical records of the patient, copy the records, make changes to the records and delete the records
- An auditor, who has been authorized by the patient, can query the audit logs of the record he/she/they selects and also view the medical records if the audit logs don't tally.

The main component of the system is the audit logs. Every action performed on a medical record by the participants of the system generates an audit log. It consists of:

- Recorded message: It tells about the action that was carried out. Depending on the action performed, the message in the audit log vans also the status of the record varies.
- Date and time: A timestamp of when the action was performed
- Patient account address: Address of the patient whose record is viewed
- Doctor account address: Address of the doctor who looked after the patient
- Auditor account address: Address of the auditor who views the audit logs

The proposed system contains a front-end for easy user interaction with the system and uses a Flask development web server. The whole system is built over a Blockchain. It uses smart contracts to execute the actions performed on the medical records and also stores the transactions on the blockchain. The smart contract is also written to emit the actions into an event log. This log will be rendered in the front-end for the auditor's approval.

2.1 System Goals Satisfaction

Privacy:

Patient is the sole participant who can grant access to his/her medical records for a doctor or an auditor. This way no unauthorized entity will be able to view, modify or delete the patient's records. Any attempt to access the records without authorization, the system redirects to a page showing exception.

The patient also has the right to revoke access to a doctor or an auditor. On top of this, all the activities are monitored and put in the blockchain.

Identification and authorization:

All the participants of the system are required to signup, providing their credentials, in order to be able to use the system. Each participant is given a blockchain address and a patient is given a contract address for login purposes. The information is stored as a database in an encrypted form. The passwords are stored using salted-hash-encryption. More on this later. All registered users pass through a login page. This guarantees identification and authentication.

The system does not deal with authorization per se in any form like Access Control Lists(ACLs), policies etc. It is the patient who grants access to the records for other participants. In this system, the patient acts as an authority who authorizes.

Queries:

A patient can book an appointment specifying the feasible date and time. Booking an appointment creates a medical record with unique ID. A patient can give access to a doctor and auditor and also revoke access. The patient can also delete a medical record. Deleting a medical record by the patient is considered equivalent to cancelling a doctor's appointment.

A doctor, authorized by the patient, can view, modify, copy or delete the records. When a doctor's access is revoked, he/she will no more be able to do any of those actions on the record.

An auditor, given access by the patient, can view all the audit logs. On the worst case, the auditor can view the medical records if he/she finds any discrepancies with the logs. A record has a feature called record status. It is a numerical value that maps to the event performed on the medical record.

All actions performed by any of the participant is recorded as a Blockchain transaction. So anyone will be able to see the changes and verify the correctness of the data.

Immutability:

Blockchain is an immutable ledger. All the actions are recorded in the Blockchain as individual transactions. Each transaction block is internally chained using cryptographic hashes. A record cannot be changed without altering the cryptographic hash as well as all hashes in subsequent blocks. So anyone in the network can check the integrity of the data and no changes will go undetected.

Decentralization:

The proposed system takes advantage of two main technologies: Blockchain and Smart Contracts.

There are two major categories of implementing a Blockchain technology: permissioned and permissionless. Because a patient's privacy is at concern here, the system is implemented as a permissioned blockchain technology. Participants of the blockchain network are given permission by agreed upon administrators. For this system, the administrator is the designer of the system.

The system uses smart contracts which contain code on what should be done under specified circumstances. For example, the smart contract will tell what action should be taken when a doctor tries to view a patient's record. The contract will first check if the doctor has been authorized by the patient; then it checks if the record exists only then further steps are carried out. Smart contracts ease the process of monitoring and enforcement of actions by automating the whole process.

The system is completely decentralized and any trusted third party will be able to detect the changes in the system.

2.2 Cryptographic components of the proposed system

Ethereum Blockchain

Blockchain is the backbone of the system. It is used to preserve and exchange patient data in a secure manner. It satisfies the requirement of decentralization. A transaction is requested to write a new block of data to the blockchain. Every participant in the blockchain checks hashes to validate the transaction., thus making it a secure and immutable mode of storing data.

Smart contracts

The smart contract in the system is Patient.sol written using Solidity. It takes care of the following actions:

- ➔ Contains the declaration of a medical record
- ➔ Creates a new medical record
- ➔ Deletes a medical record
- ➔ Prints a record
- ➔ Lists all the records of a patient
- ➔ Updates a record
- ➔ Changes the status number of the record depending on the action performed on the record like queried, copied, printed, deleted etc..
- ➔ Checks permission for the doctor and auditor
- ➔ Logs every event and writes it as a transaction on the blockchain.
- ➔ Lets the doctor or auditor to perform the queries
- ➔ Grants / revokes access for the doctor/ auditor

After every patient registers into the system, individual contracts are created for each of the patients. Patients are assigned a unique contract address along with the blockchain address. To distinguish the participants, doctors and auditors dont have a contract address for these participants. They are asked to input the value 0 during Login.

SSL/TLS certificates

The system uses Flask-based web server in the development environment. The development webserver runs on HTTPS using SSL certificate. Because its is a development web server, the certificate is self-signed. The SSL certificate acts as identification for the server, containing the server name and domain details.This helps in establishing a trusted and secure connection between the server and the client.

The code snippet that implements this component is :

```
if __name__ == "__main__":
    app.run(ssl_context='adhoc')
```

This adds encryption to the Flask application by creating an SSL certificate on-the-fly.

Hashing passwords

Passwords should never be stored or sent in clear. If an attacker finds a database of plaintext passwords, they can easily be matched with the usernames (mostly emails) to log in to a system. A common method used today is to use salted hashing when a password is providedto the system. The salt is stored along with the salted-hashed password in the database.

Hashing algorithms like SHA-256 are very easy to try and match with a particular hash using brute-force approach with the computation power we have now. Another tactic to matching hashes is using rainbow tables, which implements the process of randomly generating passwords in a grouped fashion.

Due to the above reasons, the system is implemented using HMAC with a combination of salting. HMAC is a slower hashing method. In technical terms, it takes in a password, random salt and number of iterations to produce a certain key length. The larger the number of iterations the longer it is to get the result.

All the salted-hashed passwords are stored in the database (.csv) file along with the salt that was used in the process. The verification step goes like this: Get the salt and the hashed password from the database. Carry out salted hashing using the salt from the database for the password that the user has supplied in the login page. Grant access if the hashed values are same. Else, the user cannot get into the system.

AES256(CTR) Encryption and Decryption

Not only passwords, all data about the users of the system are stored in encrypted form in the database. The system uses AES256 in CTR mode for encryption and decryption purposes. During SignUp, the data is encrypted and stored in the file. During Login and while querying the audit logs, the data is first decrypted for further processing.

AES in CTR mode is chosen considering the factor of scalability (in terms of hardware) and parallelization. The parallel nature of CTR mode where the blocks are encrypted independently of each other can help speed things up in a multicore processor setting. Also, unlike CBC, CTR mode can perform certain calculations offline to prepare the key stream thereby reducing the latency of the system.

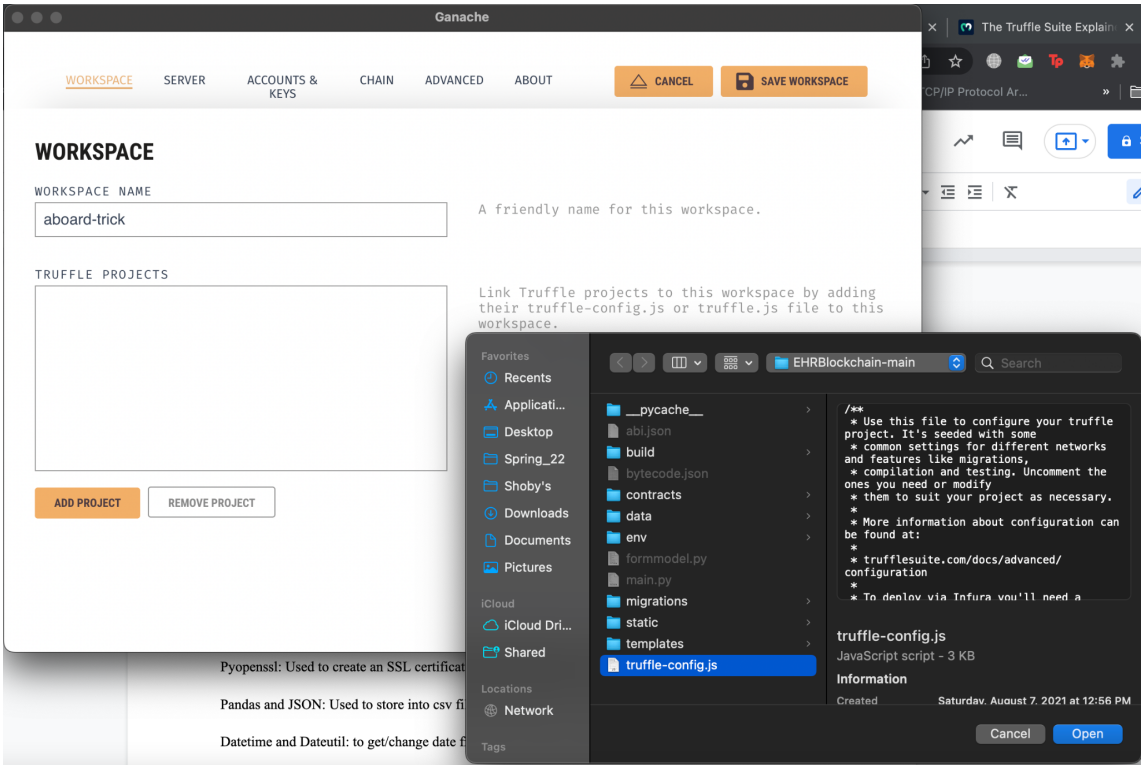
3. Prototype Implementation

To implement the Ethereum Blockchain, Truffle and Ganache are used.

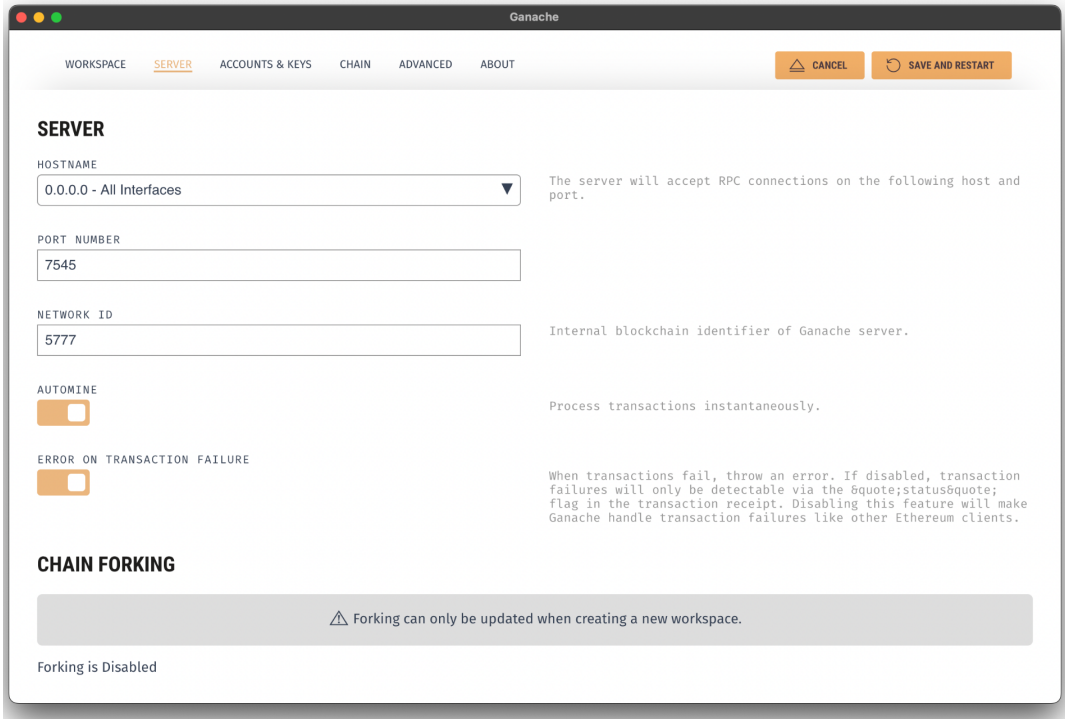
- Truffle: Truffle is the development environment, testing framework, and the dApp pipeline for an EVM blockchain.(https://github.com/trufflesuite/truffle)

- Ganache GUI: Ganache is a personal Ethereum Blockchain used to deploy smart contracts, develop applications, run tests and perform other tasks free of cost. (https://trufflesuite.com/ganache/)

In the Ganache GUI, create a new workspace and add the truffle-config.js file from the project folder as shown below



Make sure the server settings are as shown below:



To run the system, create a python virtual environment.
Using the commands: (Unix/MacOS)

```
python3 -m venv env
source env/bin/activate
```

After activating the environment, download the following packages using 'pip install' :

- Web3.py (https://web3py.readthedocs.io/en/stable/): It is a Python library for interacting with Ethereum. It's commonly used in decentralized apps (dapps) for sending transactions to the Blockchain, interacting with smart contracts, and many more.

- Flask (https://flask.palletsprojects.com/en/2.1.x/quickstart/): Flask is a small and lightweight Python web framework for creating web applications in Python. It is easy to create a web application with Flask because you only need a single Python file.

- Eth_utils(https://github.com/ethereum/eth-utils): Used for access the event logs generated by the smart contract from the Blockchain.

Hashlib: Used to hash passwords and file names in /data/

Cryptography: Used for fernet encryption/decryption and generation of key.

- JSON(https://docs.python.org/3/library/json.html): Contract ABI is represented in JSON format. The Contract Application Binary Interface (ABI) is the standard way to interact with contracts in the Ethereum ecosystem, both from outside the blockchain and for contract-to-contract interaction.

- Pyopenssl(https://pypi.org/project/pyOpenSSL/): Used to create SSL certificate for the webApp.

- Pandas(https://pandas.pydata.org/): Used to store and retrieve the encrypted data in .csv file.

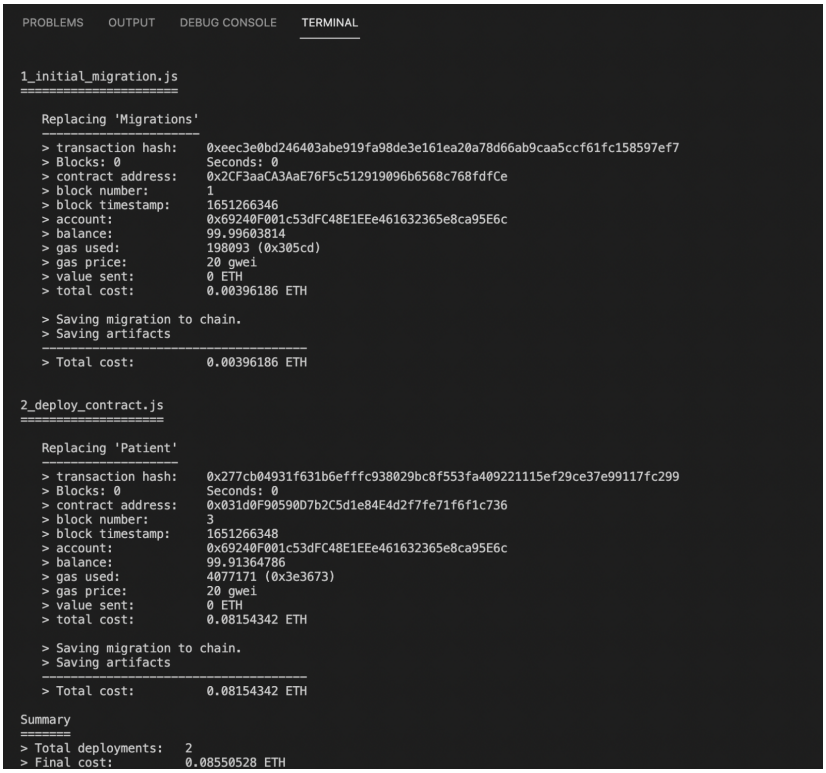
- Datetime(https://docs.python.org/3/library/datetime.html) and Dateutil(https://dateutil.readthedocs.io/en/stable/): to convert human readable time to unix timestamp and vice-versa

- Clipboard(https://pypi.org/project/clipboard/): Used in the copy query. It copies a unique patient record into clipboard.

Once all the packages are imported, you are all set to run the application. Do the following:

```
truffle compile && migrate
```

in your terminal to migrate all the contracts into the blockchain. You output will look like this:



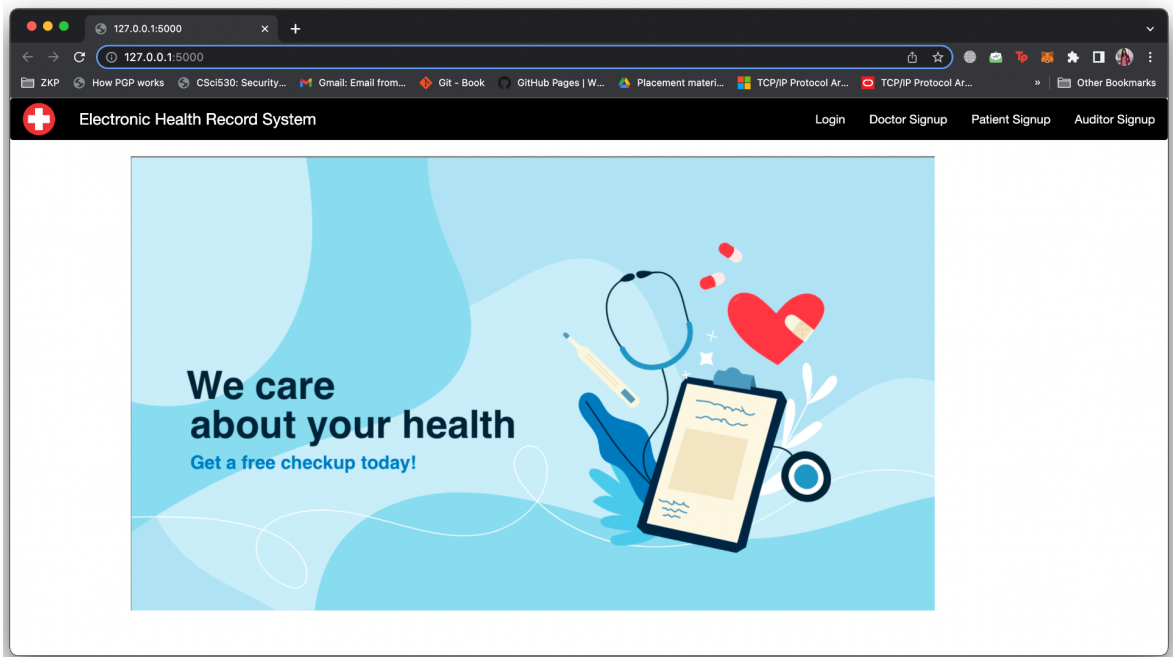
Then:

```
FLASK_APP=main.py FLASK_ENV=development flask run
```

This will start the web application at https://127.0.0.1:5000. As you can see the application uses HTTPS.

```
PROBLEMS  OUTPUT  DEBUG CONSOLE  TERMINAL
^C%
(env) shoby@Shobanas-MacBook-Air EHRBlockchain-main % FLASK_APP=main.py FLASK_ENV=development flask run
 * Serving Flask app 'main.py' (lazy loading)
 * Environment: development
 * Debug mode: on
Web3 is connected = True
 * Running on http://127.0.0.1:5000 (Press CTRL+C to quit)
 * Restarting with stat
 * Debugger is active!
 * Debugger PIN: 377-143-775
Web3 is connected = True
```

The homepage of the website is as follows:



3.1 File description

- Python files:
  - *main.py:* This is like the main() function in C++. When you run this program, a series a of activities gets triggered. It deploys the smart contracts, reads the symmetric key for encryption and decryption purposes. It links all the HTML files by telling what code to be executed when a particular action is performed (like patient signup). It also defines all the actions that can be performed by each participant and talks to the smartcontact at the backend to perform the query. The file is deployed using a Flask development web server.

  - Formmodel.py: This file contains Flask forms i.e. it defines the components of a form in a specific html page. For example, in the patient signup form, the flask contians the components : first name, last name, address, zip code, email, password etc.

- Json files:
  - abi.json: As mentioned above, ABI is the way to interact with the smart contract and the ABI comes in JSON format. It contains the functions, events, variable definitions that are in the smart contract.
  - bytecode.json: The contracts written using Solidity, after running "truffle compile" gets converted into Ethereum Virtual Machine (EVM) bytecode. It is this bytecode that gets deployed on the blockchain and not the .sol files.

- Smart Contracts: (Found in the contracts directory)
  - Migrations.sol: This file is not that useful during the development phase but it comes into play when the app is for production. It keeps track of the changes in the network which is helpful when there is a situation to modify only the current deployment.
  - Patient.sol: This is the main contract in the system. It creates and assigns a unique contract address for each patient in the system. It also defines the structure of the medical record and the events that occur on the medical record. There are functions which takes care of rendering the record details to the front-end and also the function of granting and revoking access to the participants of the system.

Once you compile the contracts, they get converted into a JSON file and gets stored in the build directory.

- build/contracts/Migrations.json: JSON file of Migrations.sol
- build/contracts/Patient.json: JSON file of Patient.sol

- Database: (Database directory)
  - 3f91fb273e0c… .csv: Participants' (doctor, auditor, patient) signup
  - data is stored in the enrypted format. The reason that the filename is also hashed is to not reveal any information about the data stored in the file.
  - enc_key.key: This file contains the symmetric key for all the encryption and decryption purposes. It should be kept safe.
  - f415ea3131a... . csv: Medical record ID and patient's contract address is stored here after encrypting with the symmetric key.

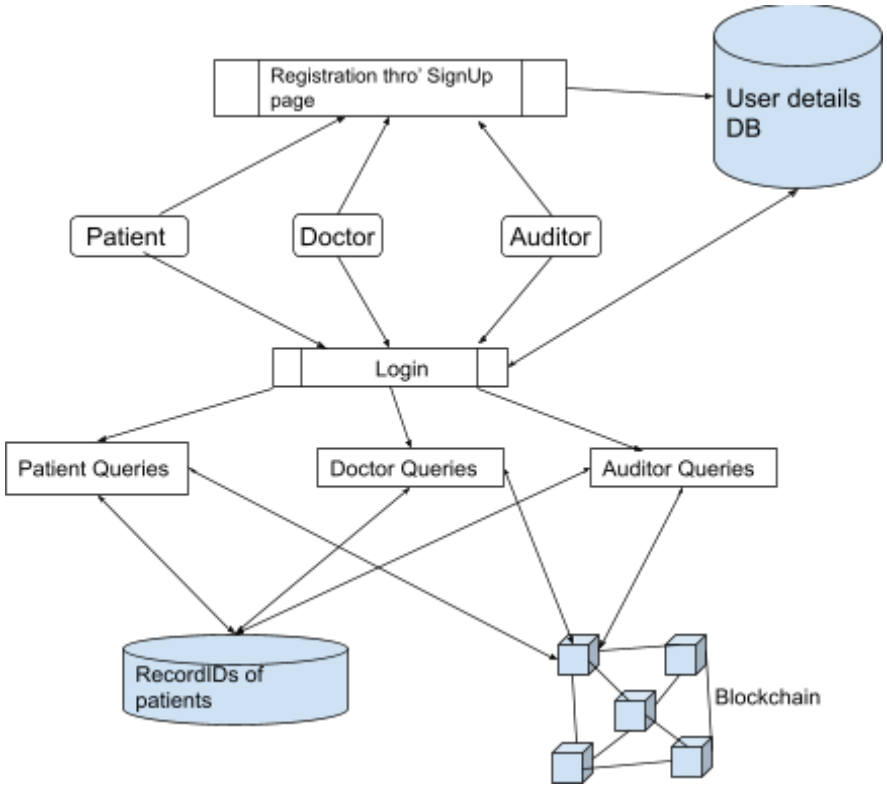
- JavaScript:(Present in the migrations folder)
  - 1_initial_migration.js: Part of the truffle implementation. It keeps track of the record on the Ethereum network.
  - 2_deploy_contract.js: Creates a sample Patient contract for testing purposes and deploys to the Ethereum Blockchain.

- CSS: (present in the static directory)
  - Contains all the images and .css files for the DApp website.

- HTML: (Can be found in the templates directory)
  - index.html: This is the landing page of the website. Has navigation to Login,patient signup, audito signup and doctor signup.
  - auditsignup.html: Auditors enter their details to signup. After signup, the user is redirected to result.html page
  - doctorsignup.html: To set up the account, doctors provide the required data in the Flaskform displayed on the webpage. After signup, the user is redirected to result.html page
  - patientsignup.html: Patients enter their details to get registered into the system. After signup, the user is redirected to result.html page
  - result.html: After signup, users get a blockchain address which they have to keep note of. On top of it, patients also get a contract address.
  - login.html: Requires blockchain address and password to login. Additionally patients are required to provide their contract address.
  - auditor.html: Audit actions are shown in the webpage.
  - auditquery.html: Displays the audit logs of the particular record of the particular patient.
  - patient.html: Queries of the patients are taken care in this page.
  - Doctor.html: Doctors can perform their actions on the record.

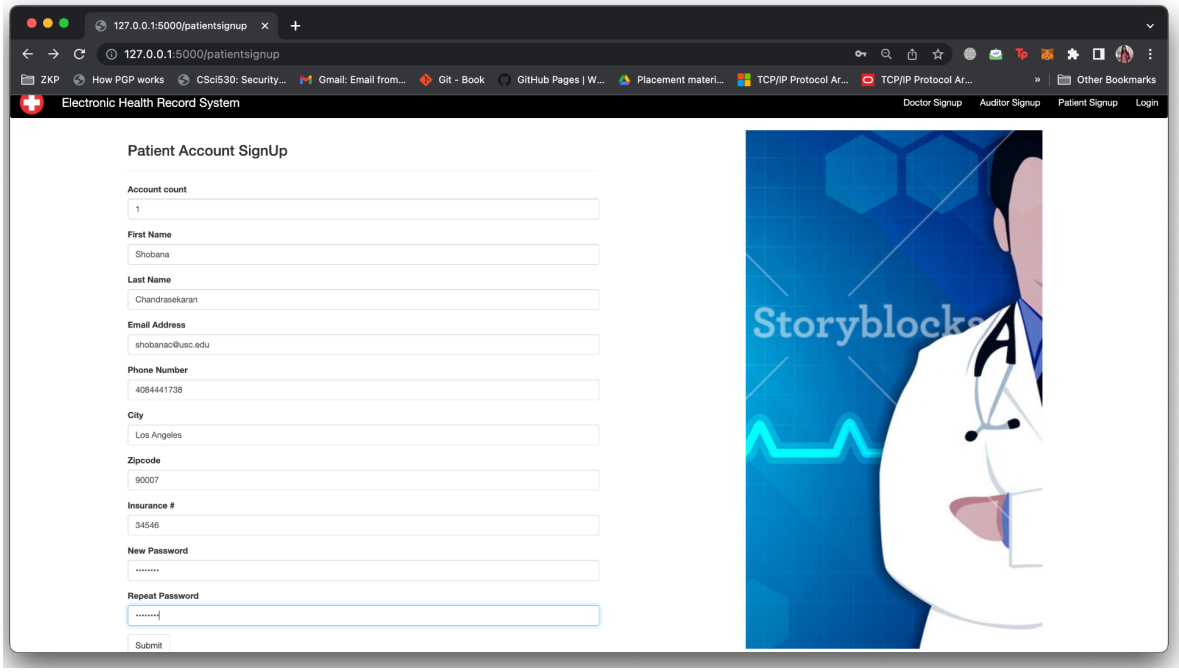
- Truffle Configuration file:
  - truffle-config.js: Configuration file to connect Ganache GUI to truffle. Contains details of interface address and port address

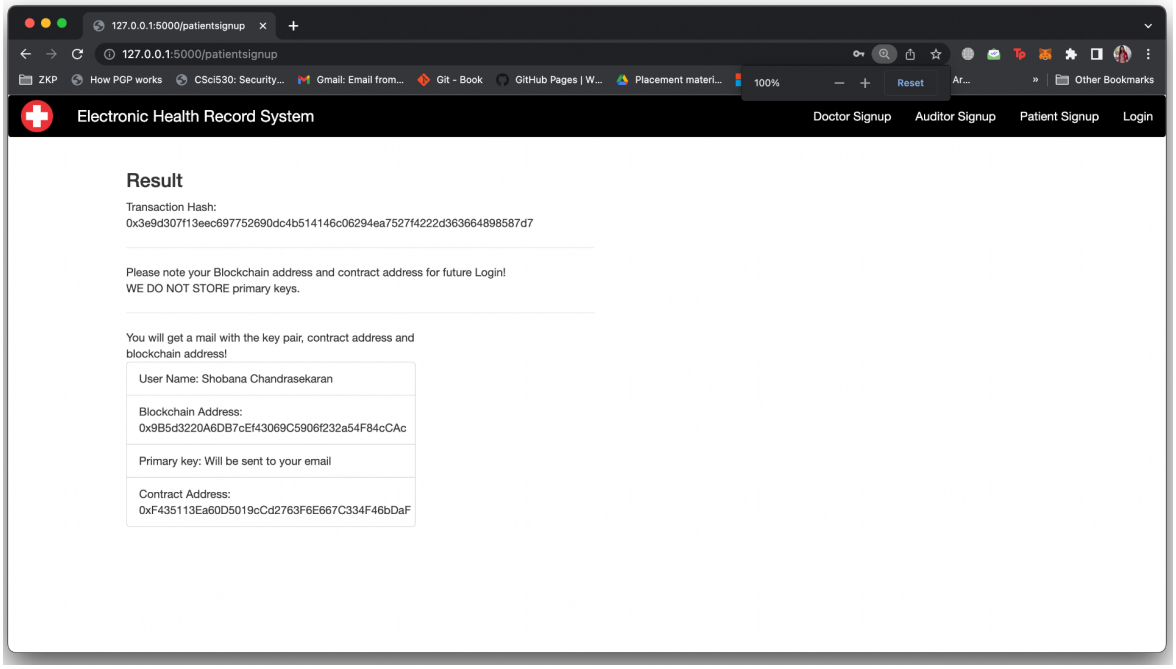
3.2 System Workflow

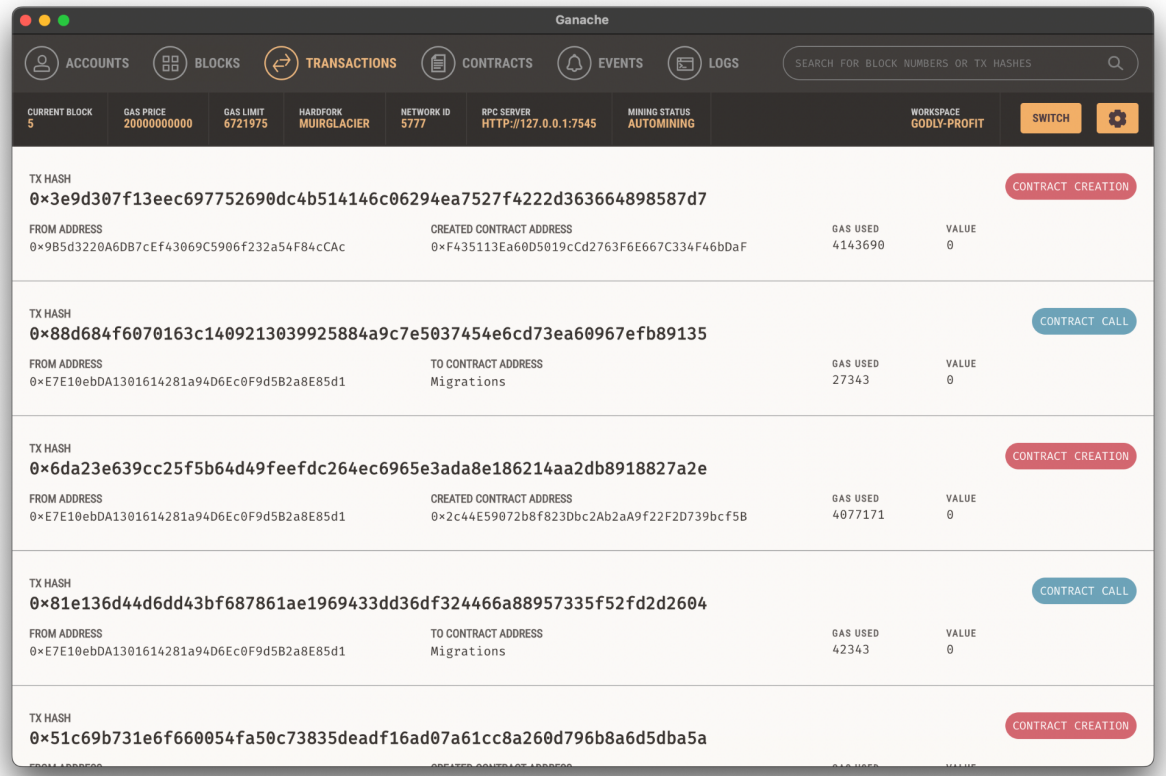


The Registration step:

Patient registration






Ganache
ACCOUNTS
BLOCKS
TRANSACTIONS
CONTRACTS
EVENTS
LOGS
SEARCH FOR BLOCK NUMBERS OR TX HASHES
CURRENT BLOCK 5
GAS PRICE 20000000000
GAS LIMIT 6721975
HARDFORK MUIRGLACIER
NETWORK ID 5777
RPC SERVER HTTP://127.0.0.1:7545
MINING STATUS AUTOMINING
WORKSPACE GODLY-PROFIT
SWITCH
TX HASH
0×3e9d307f13eec697752690dc4b514146c06294ea7527f4222d363664898587d7
CONTRACT CREATION
FROM ADDRESS
0×9B5d3220A6DB7cEf43069C5906f232a54F84cCAc
CREATED CONTRACT ADDRESS
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GAS USED
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VALUE
0
TX HASH
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CONTRACT CALL
FROM ADDRESS
0×E7E10ebDA1301614281a94D6Ec0F9d5B2a8E85d1
TO CONTRACT ADDRESS
Migrations
GAS USED
27343
VALUE
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CONTRACT CREATION
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CREATED CONTRACT ADDRESS
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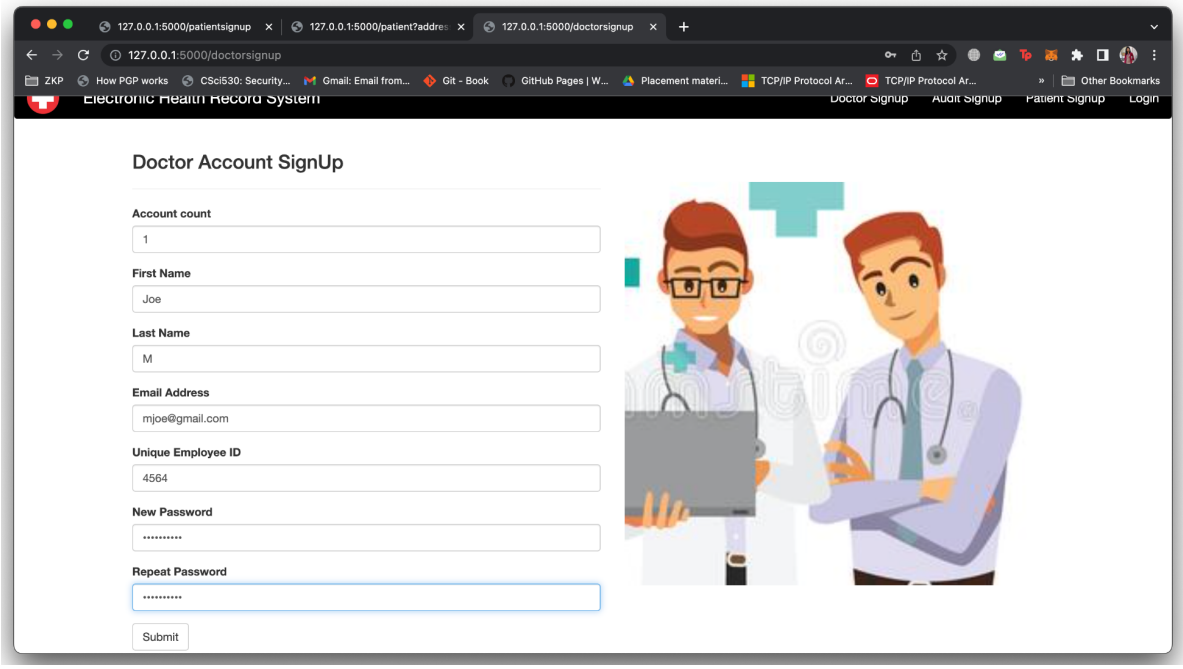
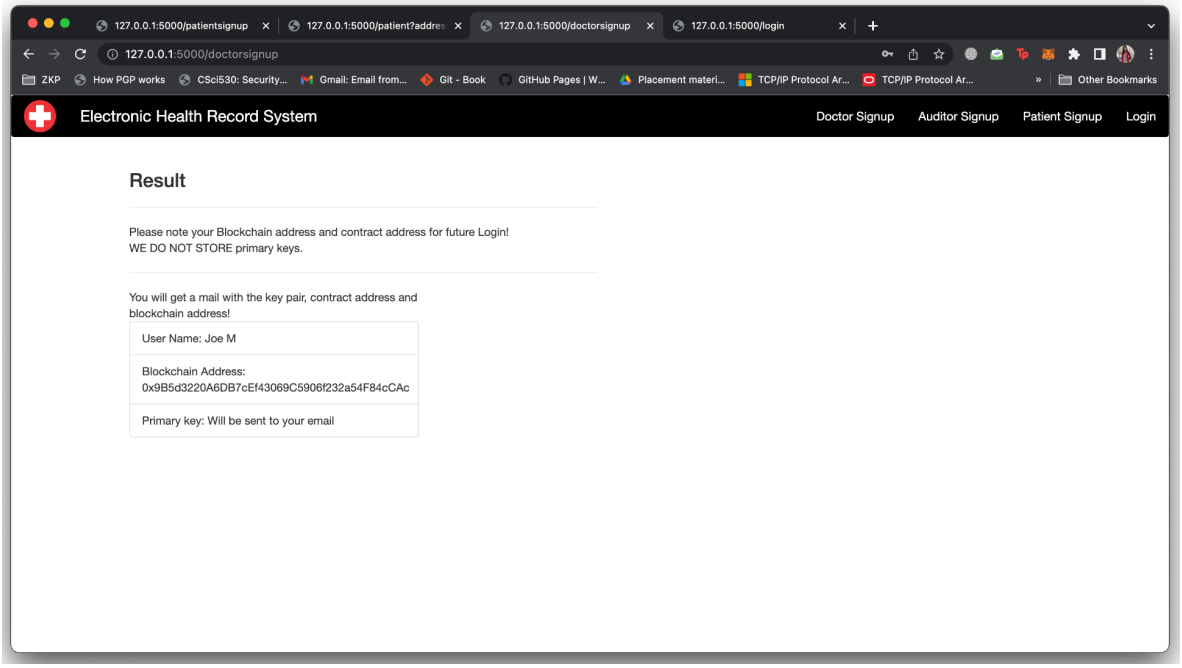
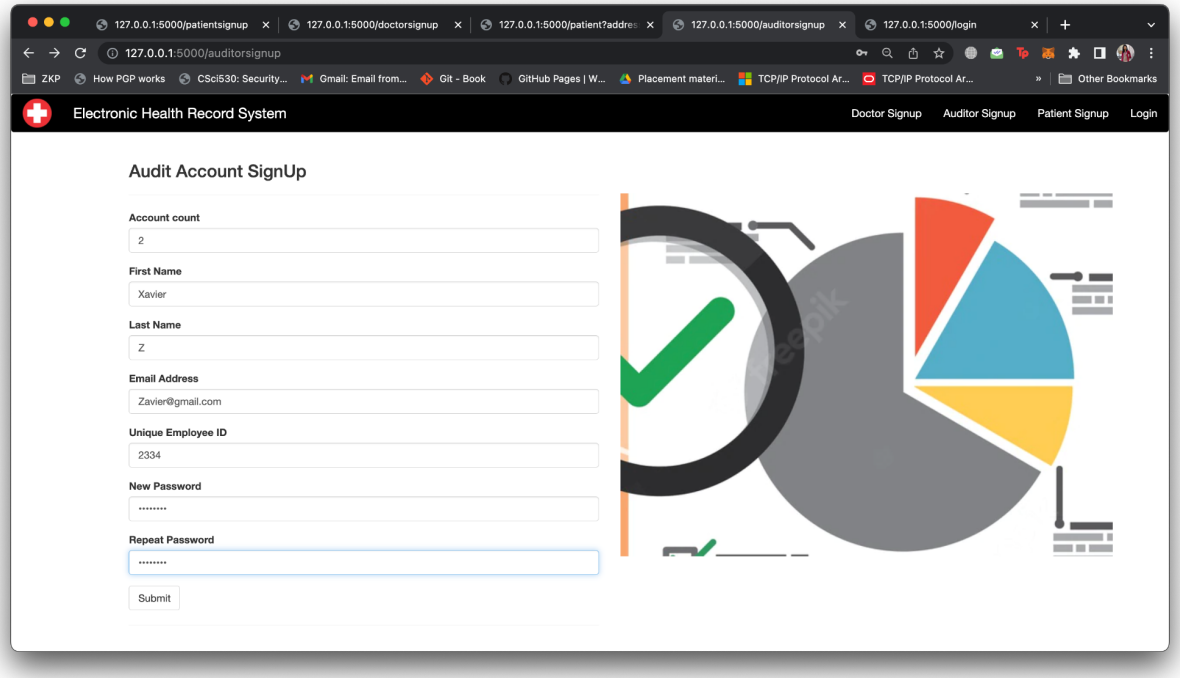
CONTRACT CREATION

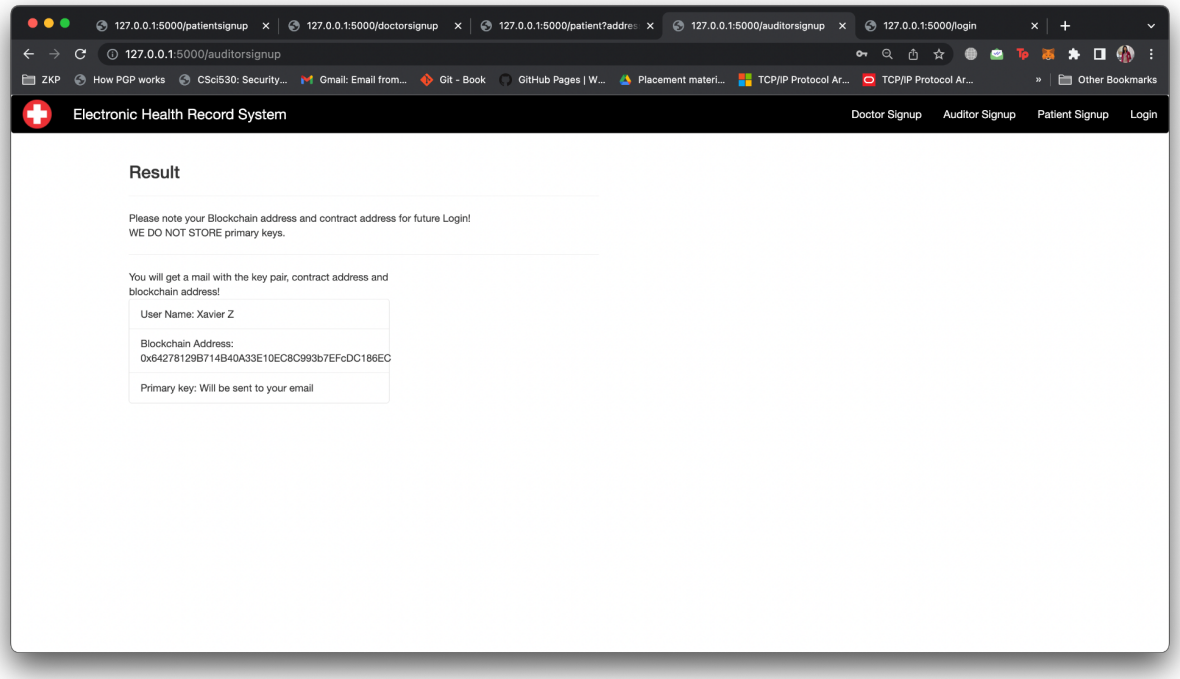
Doctor registration





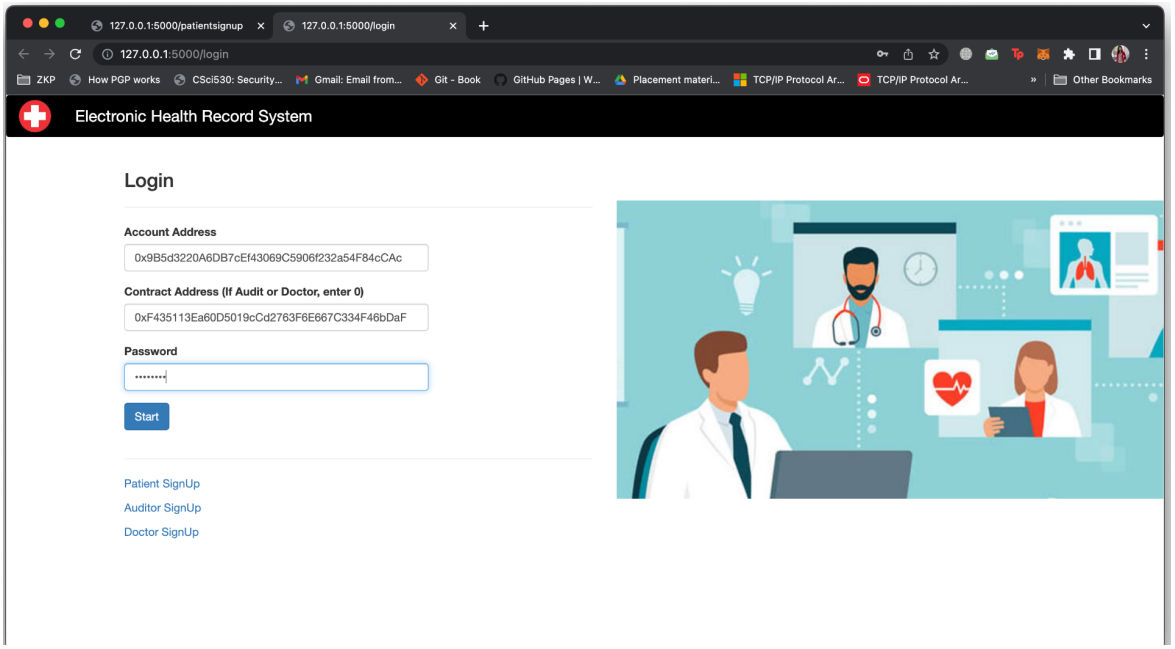
Auditor Registration

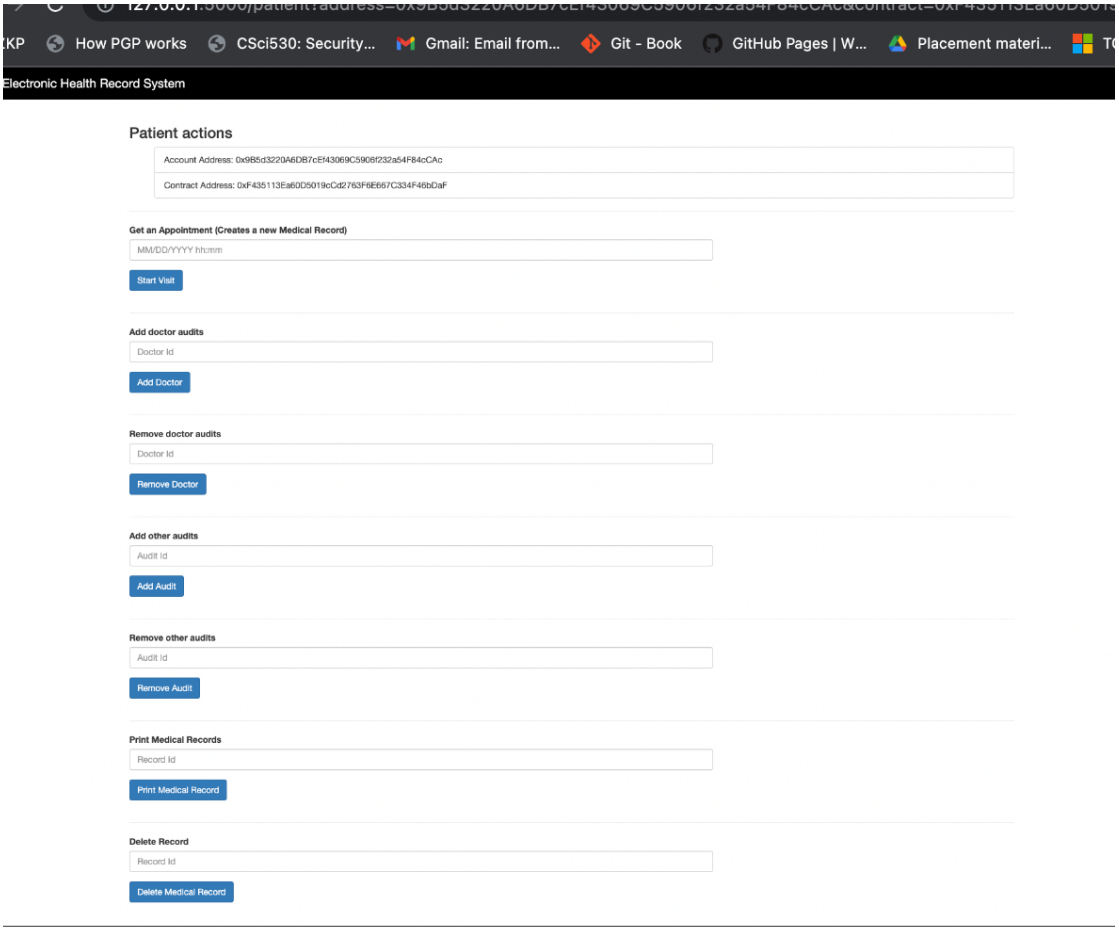




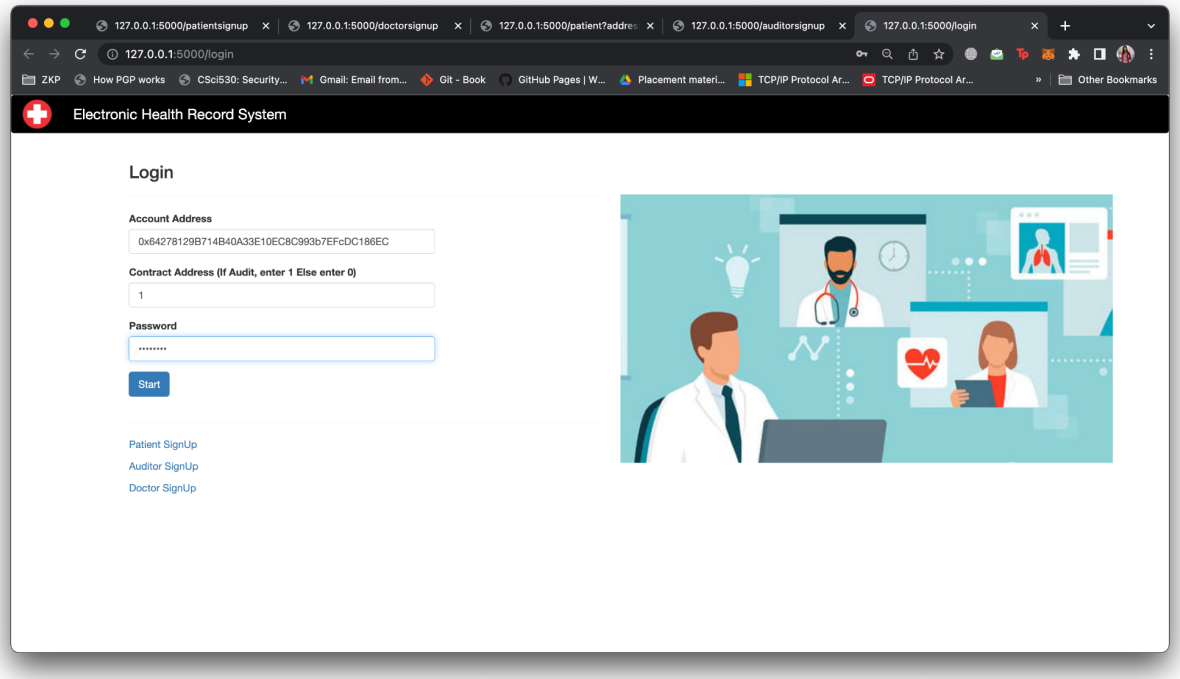
The Login step:

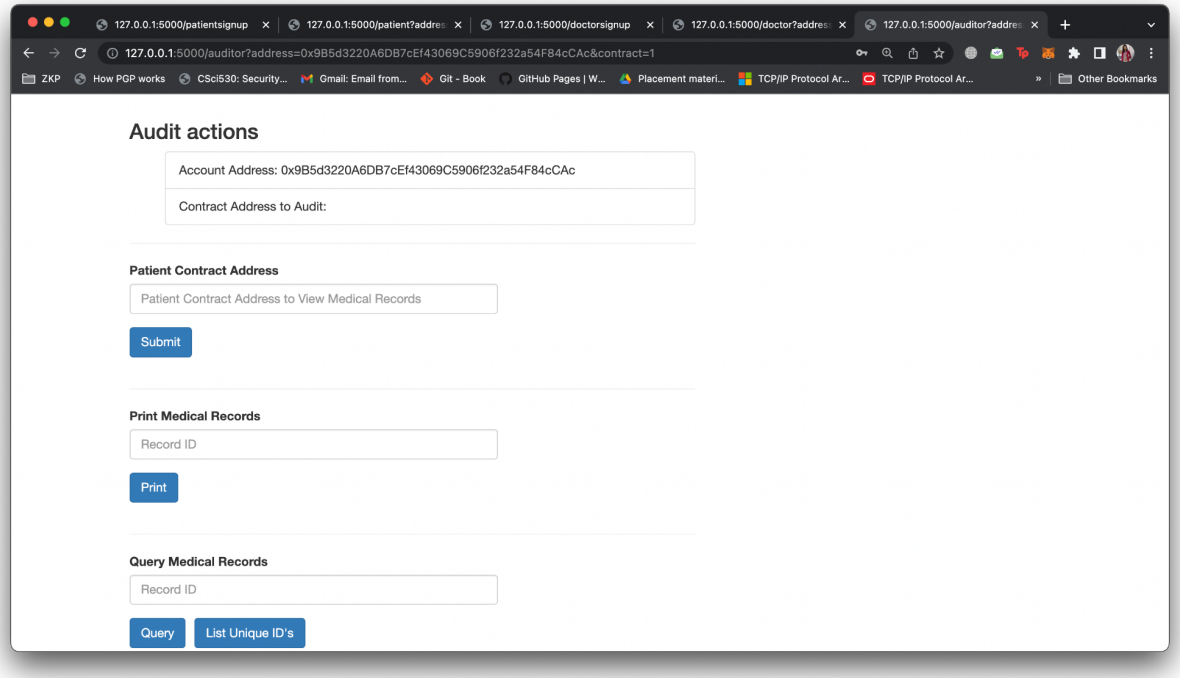
Patient: Once a patient logins to their account, their interface looks as follows:



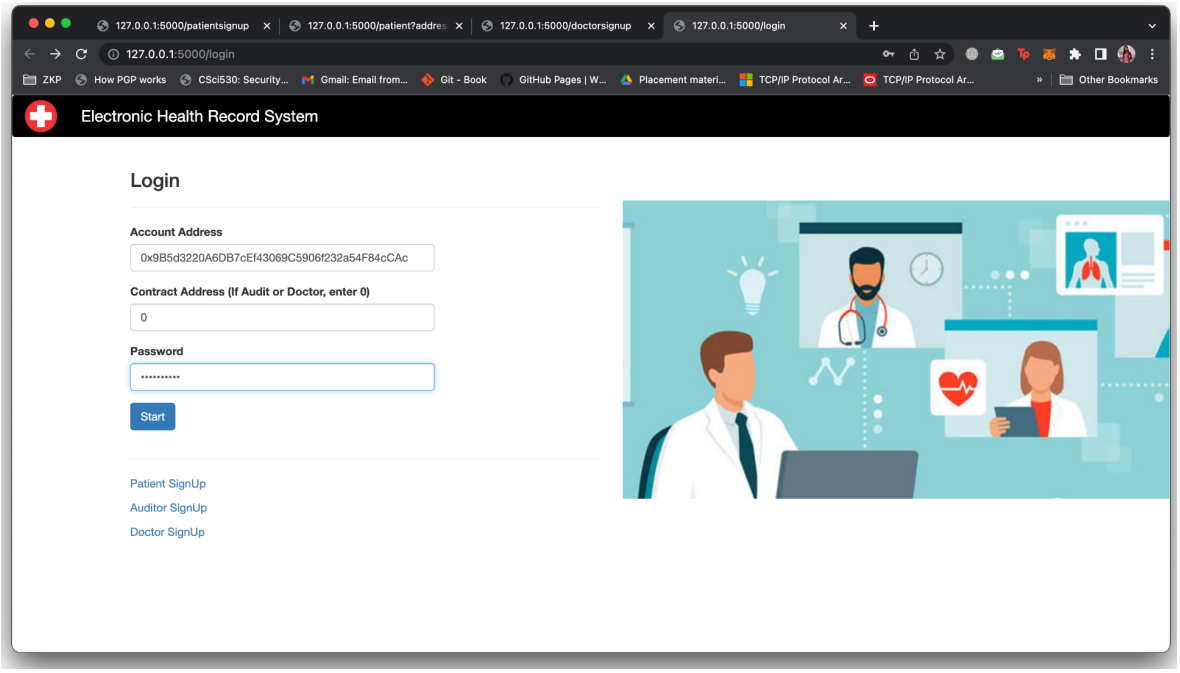


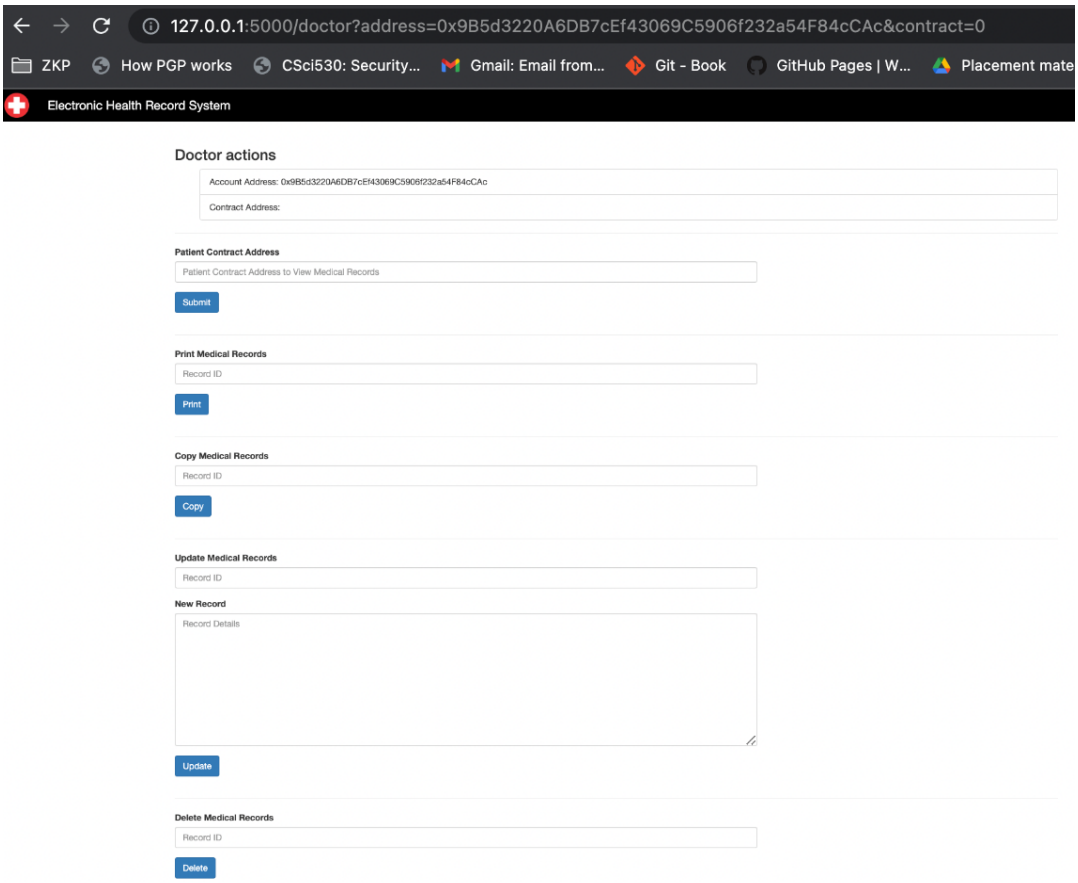
Auditor: The auditor's actions are as follows once he logins to the system.





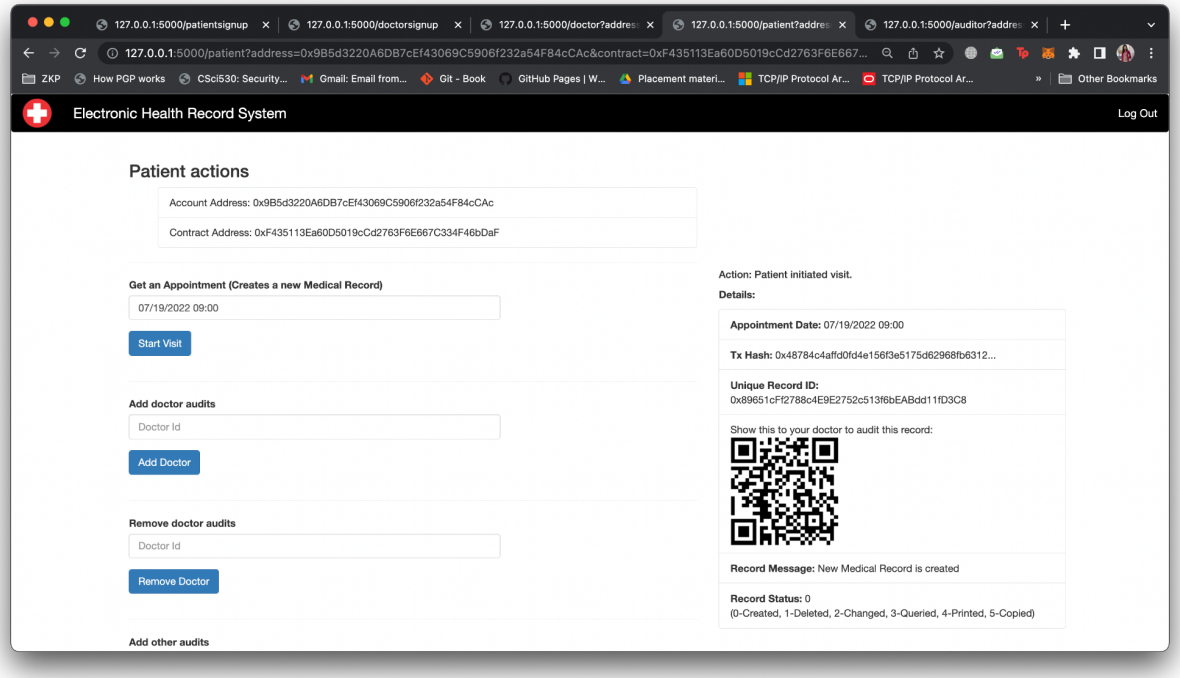
Doctor: The doctor's actions that are possible once he logins to the system and also provided the access by the patient.



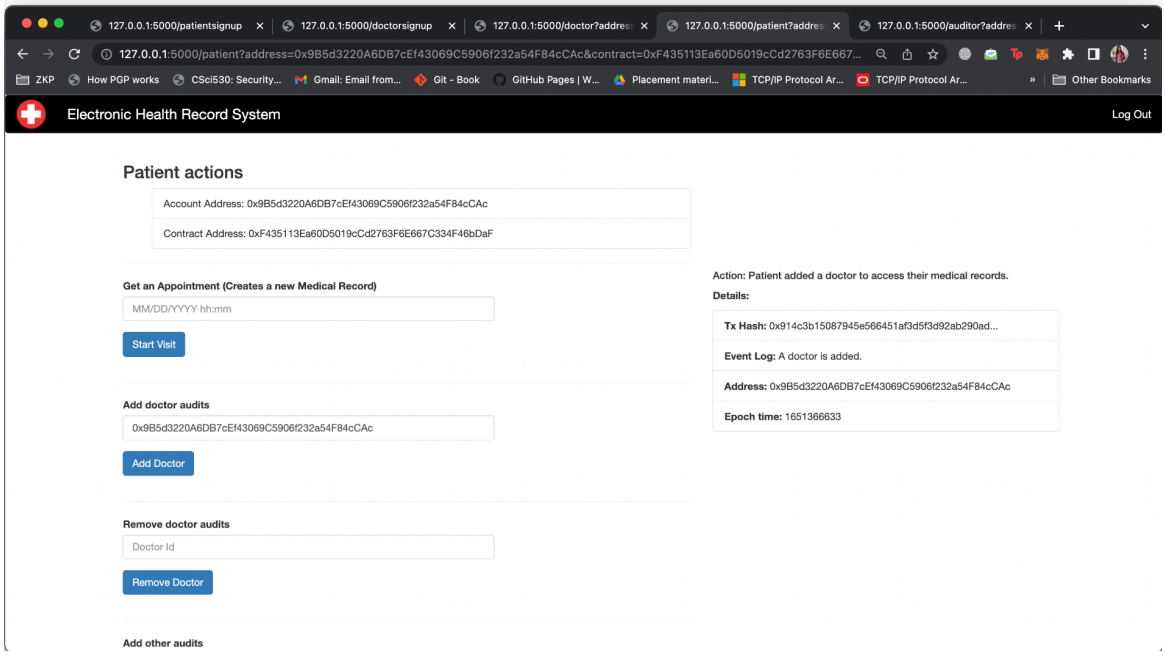


Patient Queries

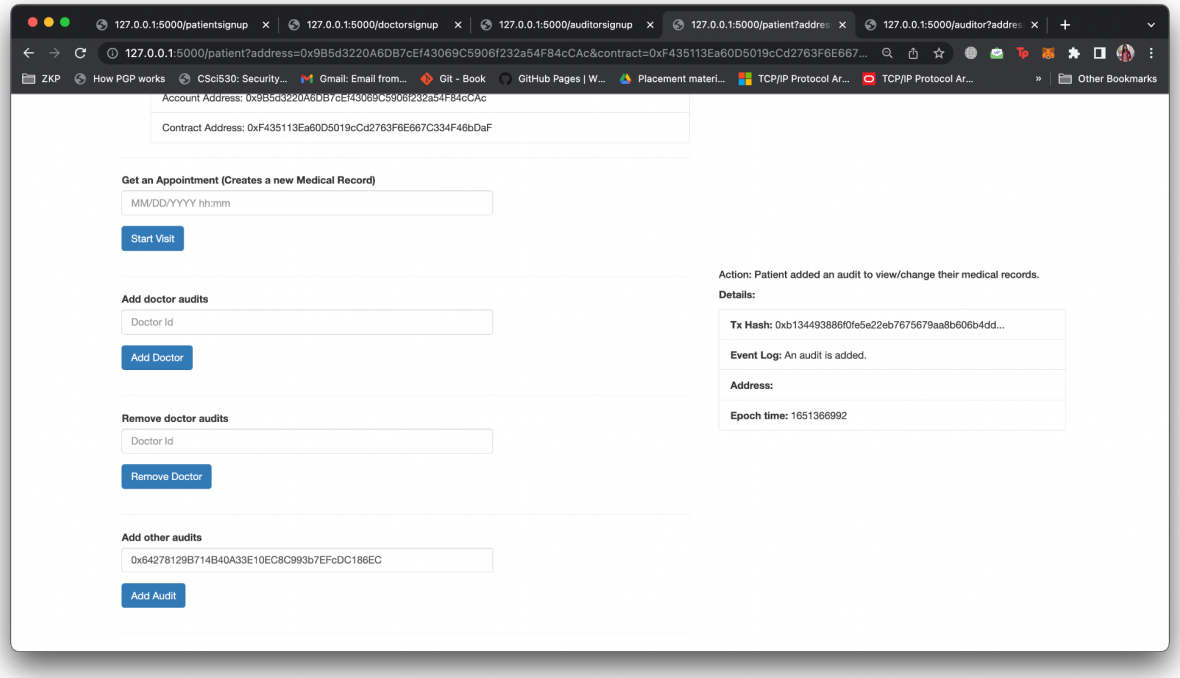
1. Booking appointments (Creates a record)



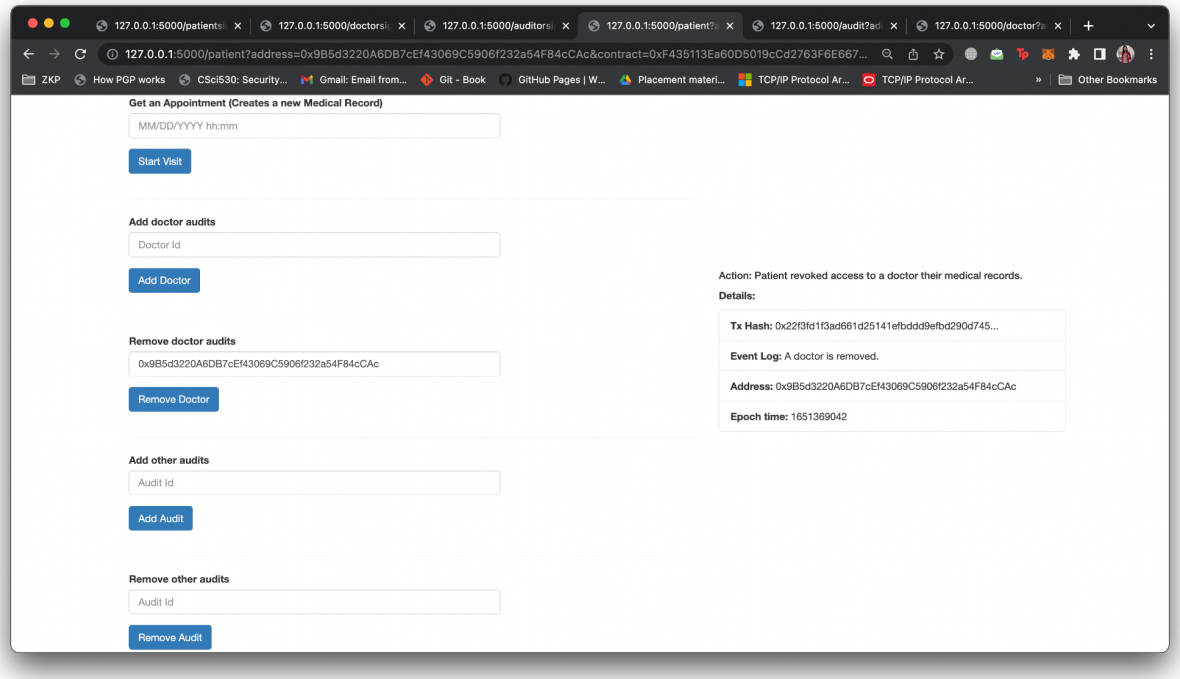
2. Grant access to a doctor



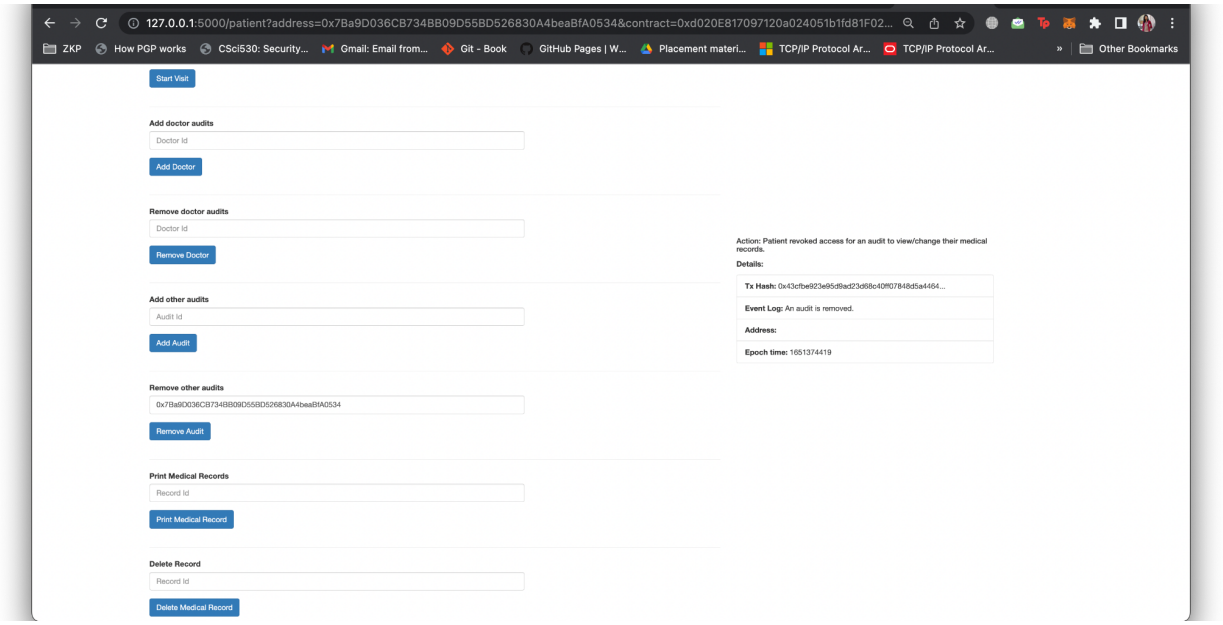
3. Grant access to an audit



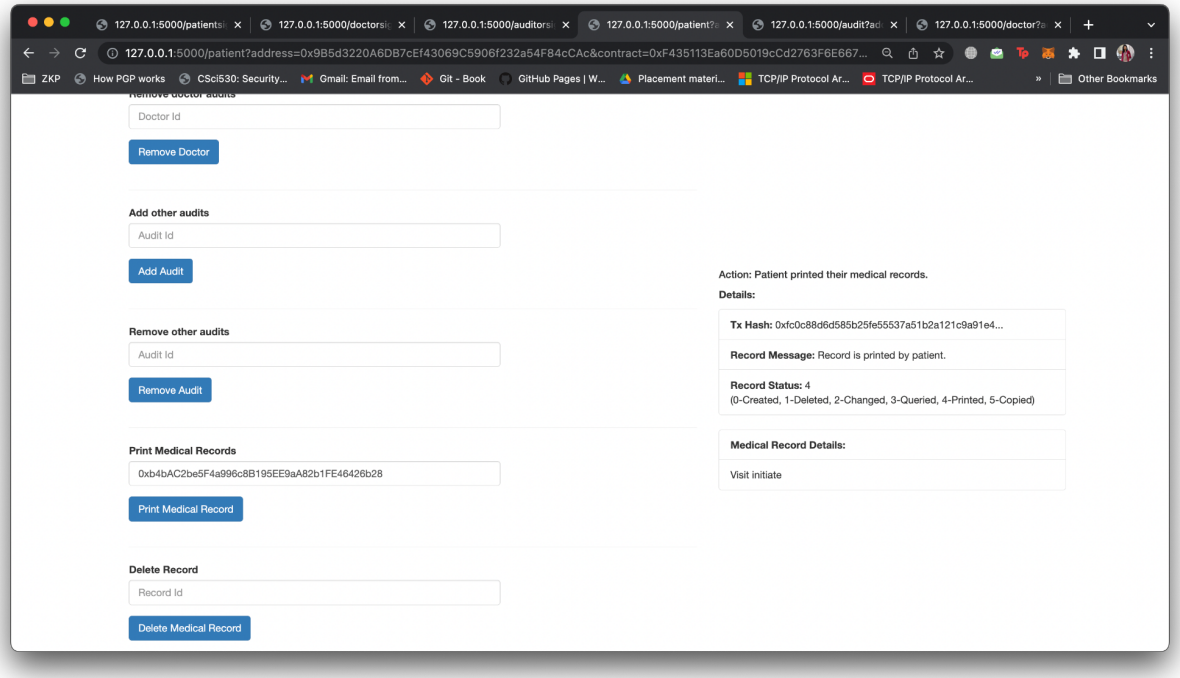
4. Revoke access of a doctor



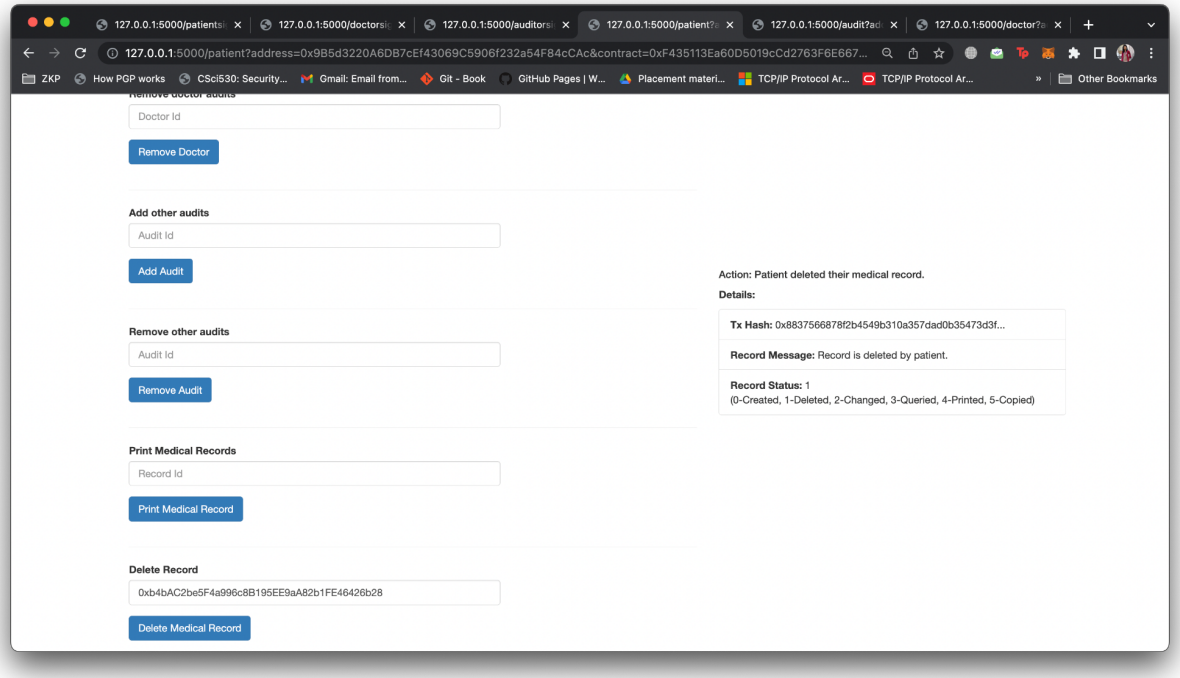
5. Revoke access of an audit



6. Print record details

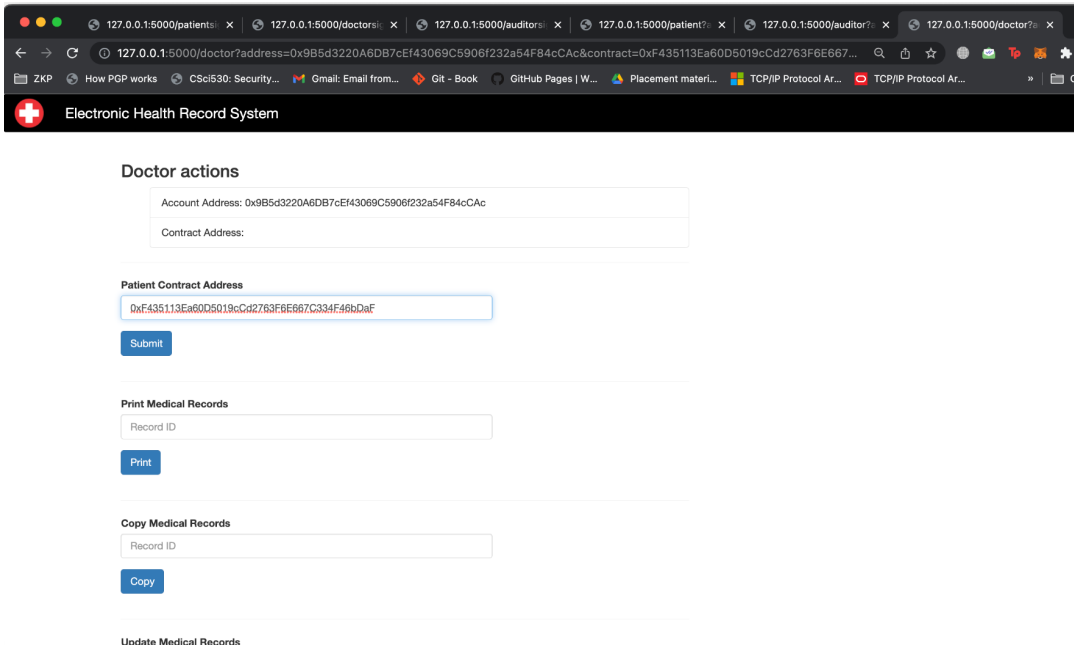


7. Delete an appointment (deletes the record)

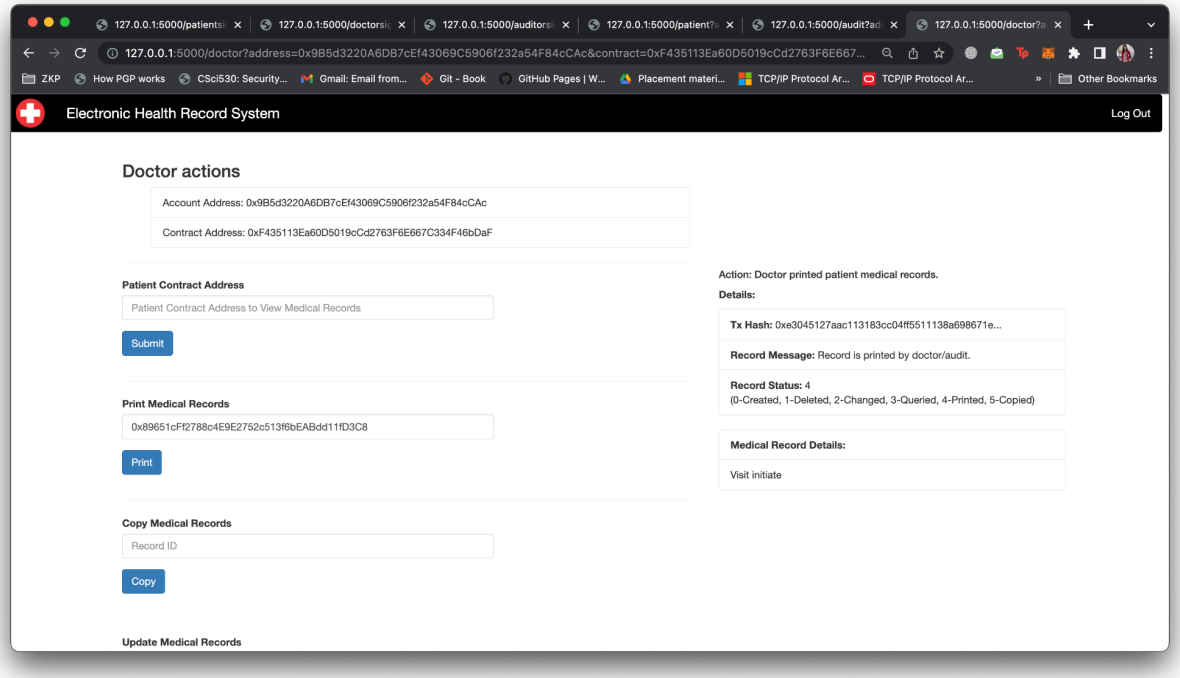


Doctor Actions:

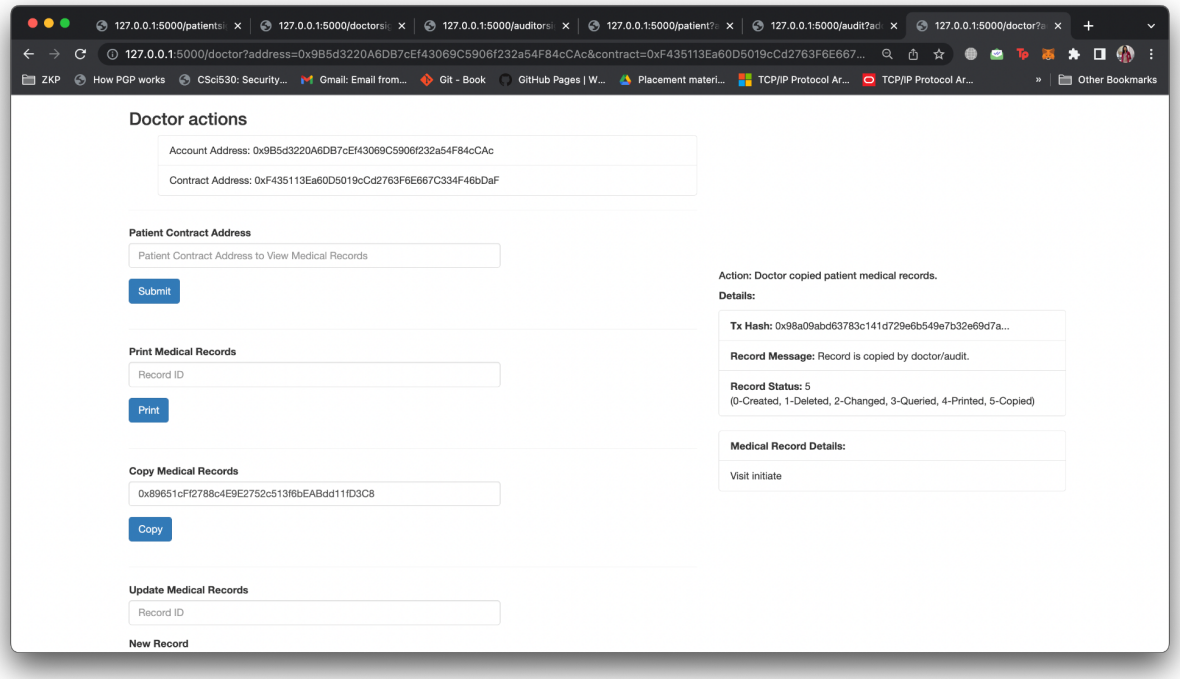
1. Submit the contract address of the patient to view the records



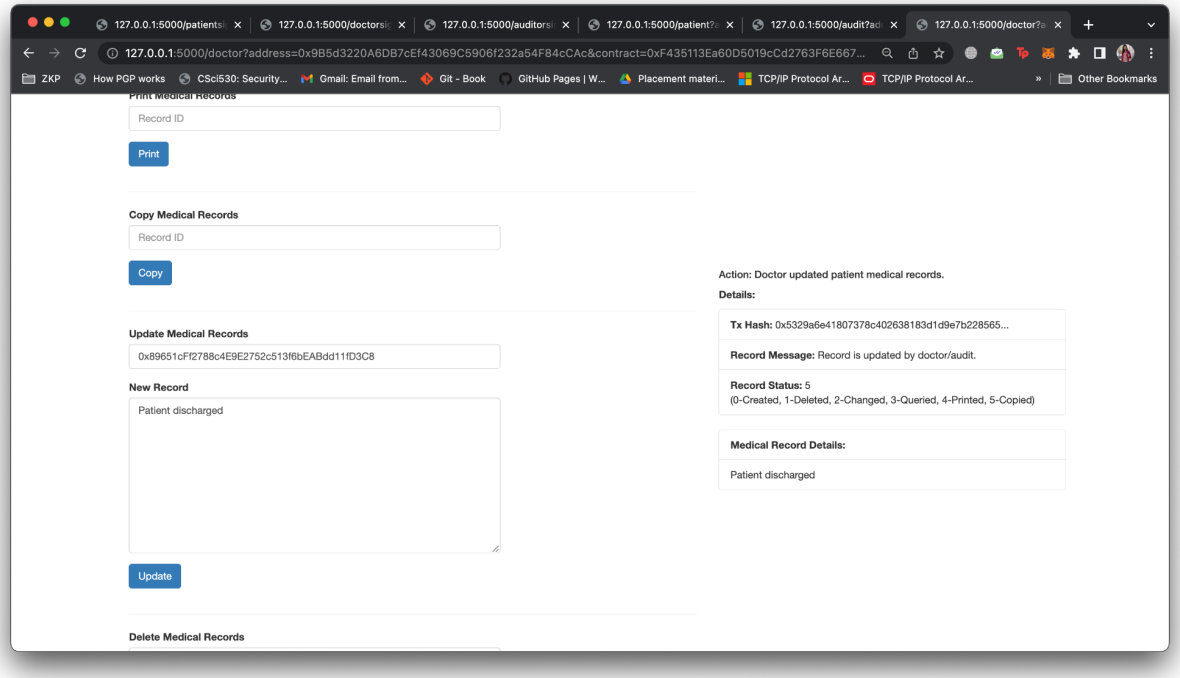
2. Display the record details



3. Copy the record

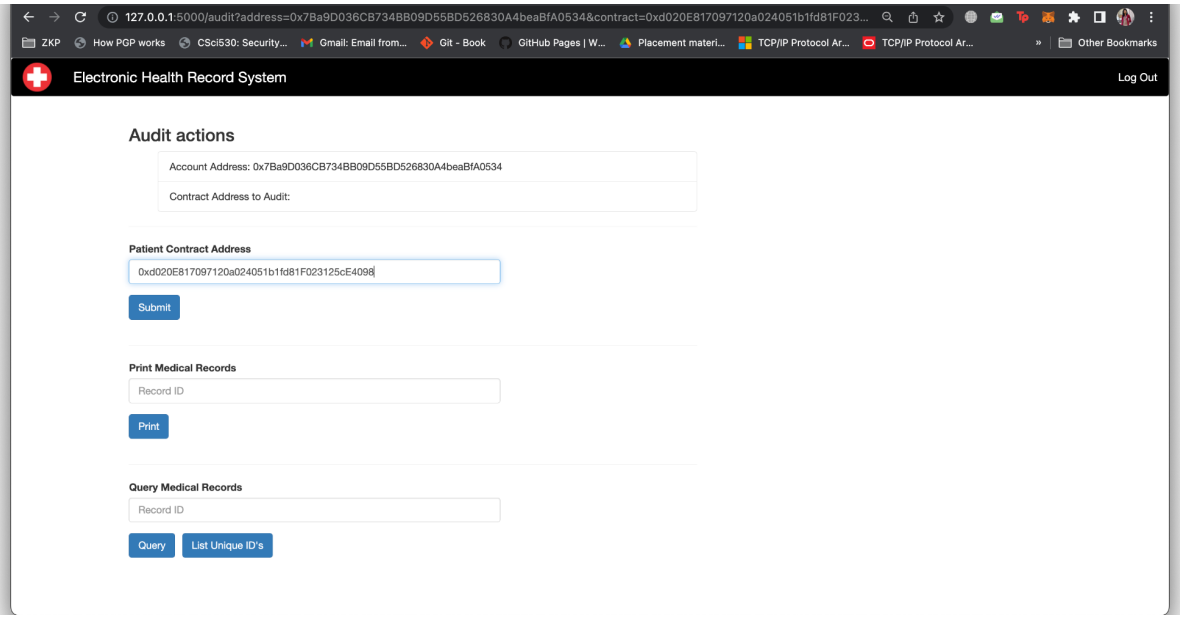


4. Update the record

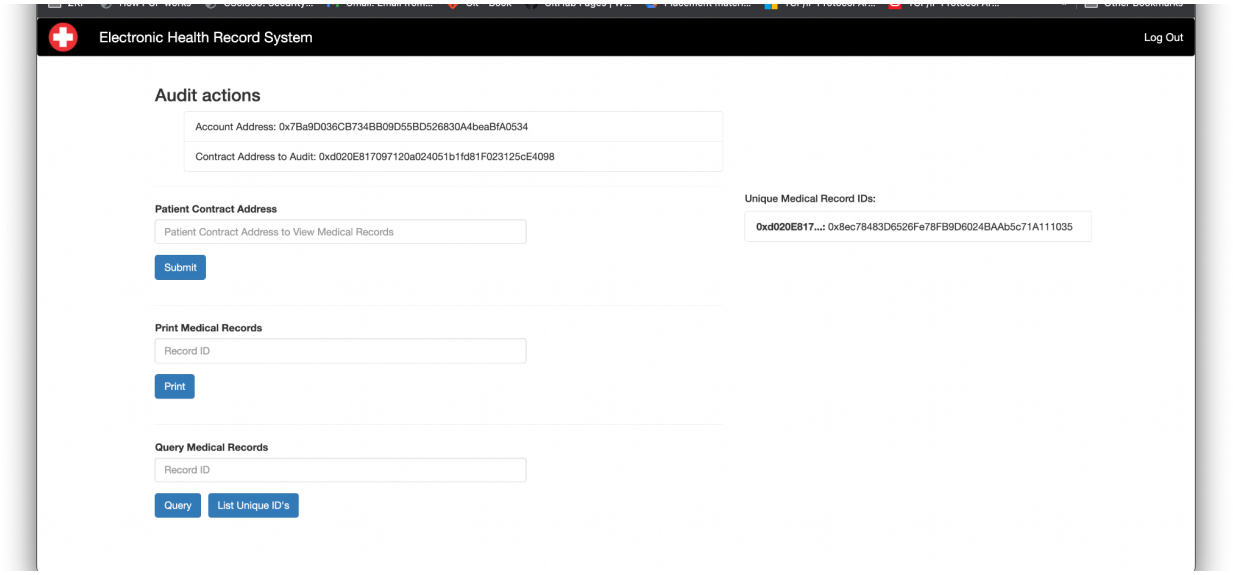


Auditor Queries

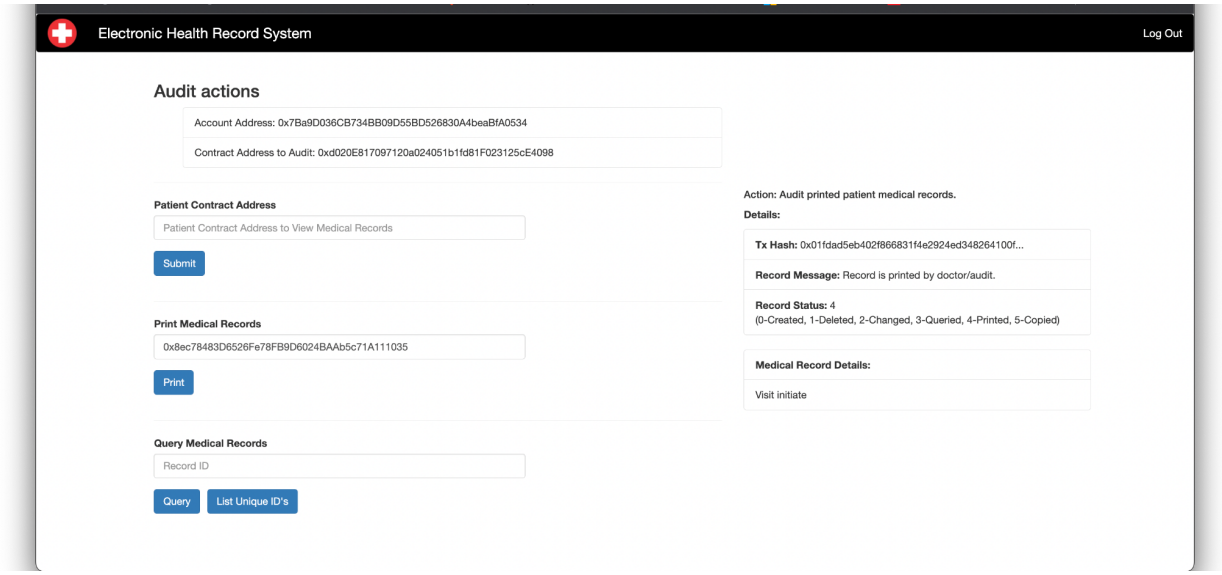
1. Submit the contract address of the patient to view the logs



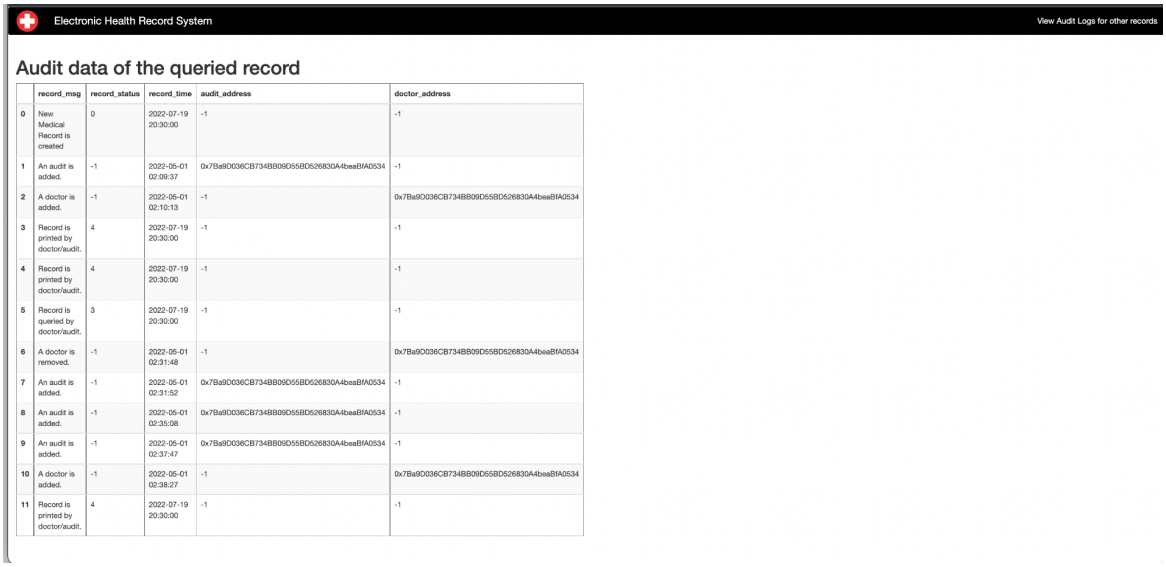
2. List all the medical records of that patient



3. Print the records



4. Query the audit log of that record



	record_msg	record_status	record_time	audit_address	doctor_address
0	New Medical Record is created	0	2022-07-19 20:30:00	-1	-1
1	An audit is added.	-1	2022-05-01 02:09:37	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534	-1
2	A doctor is added.	-1	2022-05-01 02:10:13	-1	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534
3	Record is printed by doctor/audit.	4	2022-07-19 20:30:00	-1	-1
4	Record is printed by doctor/audit.	4	2022-07-19 20:30:00	-1	-1
5	Record is queried by doctor/audit.	3	2022-07-19 20:30:00	-1	-1
6	A doctor is removed.	-1	2022-05-01 02:31:48	-1	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534
7	An audit is added.	-1	2022-05-01 02:31:52	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534	-1
8	An audit is added.	-1	2022-05-01 02:35:08	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534	-1
9	An audit is added.	-1	2022-05-01 02:37:47	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534	-1
10	A doctor is added.	-1	2022-05-01 02:38:27	-1	0x7Ba9D036CB734BB09D55BD526830A4beaBfA0534
11	Record is printed by doctor/audit.	4	2022-07-19 20:30:00	-1	-1

3.3 Assumptions

The following assumptions were made during the design and development of the system:

- Patient as the authorizer of the system who grants and revokes access to the doctor or auditor for access the medical records.
- An auditor or doctor is first required to submit the contract address of the patient to view the audit logs or record details respectively.
- Record status number :

  -1 → Record doesn't exist
  0 → Record created
  1 → Record deleted
  2 → Record modified
  3 → Record logs queried
  4 → Record printed
  5 → Record copied
- The audit logs displayed is for a particular record of a particular patient. If the auditor wants to view a different record, he has to go back and submit the ID of that record. Or if the auditor wants to view a different patient's record, he has to submit the contract address of the patient he wants to view the records of.
- To distinguish the participants, patients are given a contract address to login and the auditors and doctors are required to enter 0 in place of contract address to login.
- It is assumed that the user will be sent the contract address and the details about the registration (key details) to their mail.

4. Conclusion

The proposed system satisfies all the requirements mentioned in the problem statement. However, the system suffers certain limitations. It doesnot address the criteria of authorization in its whole. It is assumed that the patient takes the role of authorizer. Also, the system stores all the encrypted data in a file. A sophisticated database system could be used for this purpose. All the address required during Login action are not user friendly. As these addresses are a bunch of numbers, it will be difficult for the users to remember their username. This can be further improved by converting the address into some human readable format. The UI of the system can be improved. When the record is not present in the DB, the UI takes the user to an exception page. This can be converted to display proper error messages.
In conclusion, the system can be further improved by taking care of the above mentioned limitations.

References

The project template was inspired from https://github.com/shamil-t/ehr-blockchain and https://github.com/cumbul/EHRBlockchain. I have used the same tech stack and tools as this project. The format and some functionalities of the patient contract and 2_deploy_contract.js was taken from
https://github.com/NFhbar/Ethereum-Medical-Records
Some other references:
https://github.com/samia17/Medical_Records_Miniproject
https://github.com/yDeepak1889/Electronic-Medical-Record-management-using-Blockchain

I have implemented the front-end of the project, the auditor queries, cryptographic components (Symmetric encryption, hashing of passwords) and the roles of a Doctor.

Web references

1. **https://blog.miguelgrinberg.com/post/running-your-flask-application-over-https**
2. **https://www.techtarget.com/searchitoperations/tip/Blockchain-An-immutable-ledger-to-replace-the-database#:~:text=Every%20block%20links%20to%20the,create%20secure%20and%20immutable%20records.**
3. **https://us.aicpa.org/content/dam/aicpa/interestareas/frc/assuranceadvisoryservices/downloadabledocuments/blockchain-technology-and-its-potential-impact-on-the-audit-and-assurance-profession.pdf**
4. **https://www.sciencedirect.com/science/article/pii/S266660302100021X**
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7. **https://academy.moralis.io/blog/the-truffle-suite-explained-what-is-truffle**