HapiChain: A Blockchain-based Framework for Patient-Centric Telemedicine

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***Abstract*—Given the exploding number of the elderly and patients with chronic diseases and the uneven distribution of clinicians, it is economically impossible to continue traditional medicine. Hence, the healthcare sector has been gradually gravitating towards telemedicine, which applies intelligent systems for more comprehensive medical services with minimum costs. The criticality of data and process involved in telemedicine raise various concerns in terms of reliability and security. To this end, in this paper, we propose *HapiChain*, a blockchain-based framework for patient-centric telemedicine. HapiChain exploits blockchain technology to improve security, scalability, and reliability of medical workflows. Although HapiChain is patient-centric, it also helps the clinicians to save time and prevent unnecessary trips without improvising the level of treatment. In HapiChain, we embed two primary telemedicine services, namely telemonitoring and teleconsultation. For the former service, Hapicare, an existing healthcare monitoring system with self-adaptive coaching using probabilistic reasoning, is used. HapiChain then completes this service by adding teleconsultation services exploiting blockchain technology. The HapiChain framework includes three main layers: (i) interface layer, (ii) DApp layer, and (iii) blockchain layer. In the first layer, Hapicare is used to communicates with the users, i.e., patients and doctors. DApp layer includes the required procedures for security and scalability of HapiChain, namely smart contracts and distributed storage. The latter is achieved using the InterPlanetary File System (IPFS). In the blockchain layer, Ethereum blockchain is used as a platform of DApps. We evaluate the HapiChain framework and the proposed teleconsultation services in a use-case.**

***Index Terms*—Blockchain, Telemedicine, Teleconsultation, Medical Workflow, Ethereum, IPFS.**

I. Introduction

Each aged person has averagely about 0.6 medical consultations per year [1]. Based on the predicted global aged population [2], there will be more than two million consultations on each day of the year 2030 for the elderly. Moreover, most aged persons live in developing countries [2], where the clinicians are not evenly distributed. The elderly and the patients with chronic diseases are often advised for frequent checkups, which mostly consist of checking of symptoms, reading of vital signs, and medicine renewals. Given the aforementioned challenges in managing the elderly and patients with chronic diseases, it is vital to provide a teleconsultation framework for remote access to clinical experts.

Teleconsultation enables remote treatment of patients with reduced costs. Moreover, teleconsultation can be a healthier solution in comparison with face-to-face consultations; as in the latter, doctors' offices or clinics put patients prone to infections, particularly in outbreaks of viral diseases or seasonal influenza. As the elderly form more than two-third of mortality of seasonal influenza [3], minimizing their exposure to possible infected people is critical.

Teleconsultation is also appealing to patients due to reduced costs and increased comfort. The pilot run of a teleconsultation for specialist radiotherapy services received 100% satisfaction from the patients [4]. During the six months of the pilot, 36.5% of patients selected teleconsultation; and those who have chosen face-to-face consultation averagely spent an additional 66 minutes to travel the 49km distance to the doctors' offices [4]. In the aforementioned study, the hidden costs are also discussed, namely traveling costs and absence from work for the persons accompanying patients. Similarly, TELEDIABE [5], which is a teleconsultation system for patients with diabetes, has received positive feedback from the patients; they have saved averagely 115 minutes and 80 euros per each visit using TELEDIABE.

Although teleconsultation is a promising tool to reduce the direct and indirect costs of traditional consultation, the criticality of data, and the process involved in teleconsultation raise various concerns on security and reliability. From the point of view of doctors and patients, confidentiality and integrity of medical data is the main concern when all the data are transmitted through the internet. From a governmental point of view, fraud in fiscal aspects is one of the leading security concerns. Because of the intrinsic features of blockchain technology, such as security, reliability, consistency, and transparency, it has gained interests for use in various domains, including healthcare. Blockchain is a decentralized data structure consisting of a chain of blocks of data that are linked with each other using cryptography algorithms. Blockchain is resistant to tampering by design [6].

The existing blockchain-based approaches in healthcare can be arguably classified into two main categories: (1) Secure Storage and (2) Secure Workflow. The former approaches focus on improving existing healthcare services in terms of se-

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curity and scalability, mainly by focusing on Electrical Health Records (EHRs), as EHRs are the most critical information in healthcare. For instance, the approach proposed in [7] is in *Secure Storage* category; it provides a balance between patients' privacy and data confidentiality by encrypting the records over the network. Furthermore, FHIRChain [8] is another *Secure Storage* approach, integrating blockchain technology in the implementation of HL7 Fast Healthcare Interoperability Resources (FHIR). The latter is a standard for exchanging EHRs [9]. Thanks to blockchain technology, FHIRChain achieves improvements in modularity, integrity, access-controls, and trust. Similarly, in [10], blockchain technology is used to aggregate patients' EHR from various sources and provide content-based access control for patients.

Currently, many medical centers and clinicians store medical files electronically; hence, the *Secure Storage* approaches are promising and useful for current medical systems. However, in contrast to the *Secure Workflow* approaches, they do not benefit from other aspects of blockchain technology, e.g., transparency and modularity of medical workflows. *Secure Workflow* approaches focus on securing telemedicine services as a whole unit. These approaches have an eye for future innovative telemedicine solutions. For instance, numerous teleconsultation project descriptions are as Initial Coin Offering (ICO) initiatives [11]. ICO is a type of funding using cryptocurrency and is commonly for fundraising the projects using blockchain technology. However, most ICOs in the fields of teleconsultation are discontinued. Another example of *Secure Workflow* approach is DermoNet [12], which is a teleconsultation project for dermatology. The use of blockchain technology in DermoNet enables patients to manage and access their data and access more specialists while ensuring the security and integrity of data. Although DermoNet is a promising approach for telemedicine for dermatology, it lacks the requirements for the elderly and patients with chronic diseases, including the need for telemonitoring.

In this paper, we propose *HapiChain*, a blockchain-based framework for patient-centric telemedicine; which is categorized as a *Secure Workflow* approach. In this framework, we use our previous work, *Hapicare* [13], as a telemonitoring service and also an interface for communication of patients and doctors for teleconsultation. Hapicare is a healthcare monitoring system with self-adaptive coaching using probabilistic reasoning. It is targeted for the elderly and patients with chronic diseases to help them to live healthy on their own. Hapicare uses ontology-based reasoning to add contextual information about the readings of vital signs; later, sensor data and their contextual information are processed to diagnose patients' medical conditions and provide a suitable reaction for them. One of the suitable reaction in the case of serious health problems is visiting a doctor. The elderly and patients with chronic diseases are advised to periodically visit their doctors for checkups to verify their treatments, including the medical rules in Hapicare. In such cases, teleconsultation is a promising service to provide medical supervision with minimum costs, which is not applicable in Hapicare. To this end, in HapiChain, we propose a blockchain-based framework integrating telemonitoring services with teleconsultation ones for telemedicine. The proposed teleconsultation service includes traditional aspects of consultations, such as agenda management, measurements, and prescriptions, as well as additional services targeting Hapicare, i.e., customizing Hapicare rules for patients based on the diagnosis. The main contribution of our works are as follows:

- A telemedicine framework with modularity, security, reliability, and transparency using blockchain technology
- Scalable storage for medical files using IPFS
- Customizable content-based access controls to medical files
- An innovative teleconsultation service in cooperation with telemonitoring: in HapiChain, we introduce teleconsultation services to add doctors' supervision to complete the remote medical care of Hapicare.

The rest of this paper is structured as follows: in section II, the used methodology is provided, then our proposed framework, HapiChain, is described. A use-case is presented and discussed in section III to evaluate the HapiChain framework. Conclusion and future works are given in section IV.

II. Methodology

We propose HapiChain as a blockchain-based framework for patient-centric telemedicine. Since telemonitoring is already covered in our previous work [13], in this paper, we propose a teleconsultation service in the continuity of telemonitoring. The security and reliability in teleconsultation are critical as it concerns multiple agents, e.g., patients, doctors, and laboratories; and all the data are transmitted through the internet network. In this section, we briefly review blockchain technology and also our proposed teleconsultation workflows; then, we discuss how we use blockchain technology to ensure security aspects in teleconsultation services.

A. Blockchain Technology

Blockchain technology is considered from the group of Decentralized Ledger Technology (DLT) [14]. The latter is a consensus of replicated, shared, and synchronized data, which can be distributed across multiple sites without having a central administration nor a centralized data storage. Blockchain, as a data structure, consists of a linked list of blocks. Each block holds a copy of data while they are shared across a peer-to-peer network. The blocks are chained to the previous ones using hash values and digital signatures, such that a previous block is not modifiable without modifying all the blocks in the chain structure since that block [15]. Blockchain was brought in the spotlight by Bitcoin [16], a peer-to-peer anonymous cash system using blockchain technology.

After the fame of blockchain technology, it was introduced in various fields. Consequently, structured scripting for application development is increasingly required. Hence, in the second generation of blockchain technology, *smart contracts* have been introduced, which are the scripts executed upon the occurrence of specific transactions. Smart contracts can

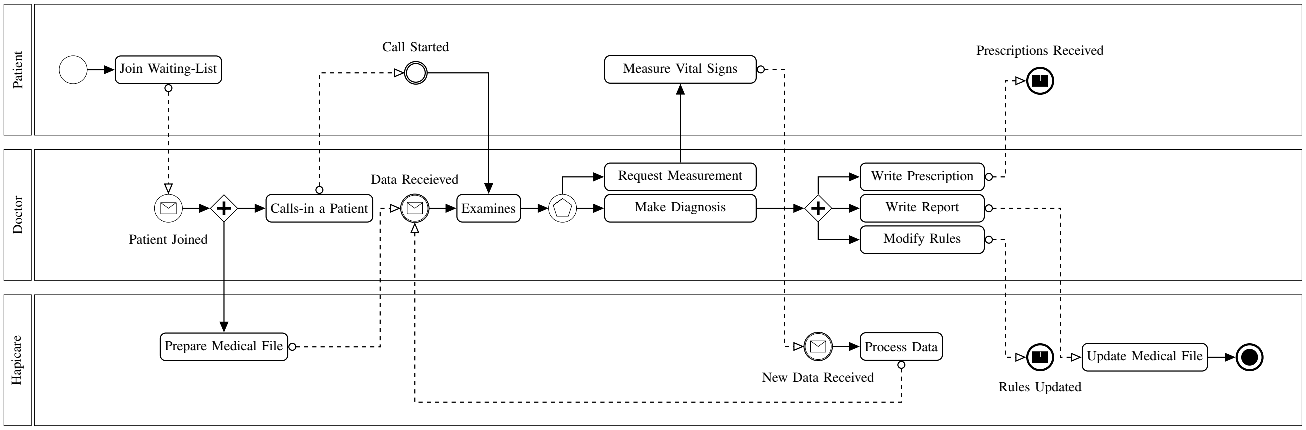

Fig. 1. The simplified process model of a teleconsultation session

be used to enforce additional transactions once a transaction has happened, e.g., enforcing transaction of tax-paying upon the transaction of a purchase. Ethereum [17] is an open-source blockchain-based platform, in which smart contracts are featured. It uses a modified version of the blockchain; it consists of a state machine while any transaction passes through a state transition. Hence, the next state relies on the data in the previous state and the current transaction. For example, in a cash system, the states are balance data of different entities, and they are updated by a transaction "transfer amount X from sender A to receiver B;" such that, in the next state, the balance of entity A is deducted by X while the balance of entity B has been increased the same amount. In Ethereum, there is also a dedicated language for composing smart contracts, namely *Solidity*. The methods of Solidity code can be called via transactions. Although there is no limitation of the size of contents in Ethereum, it is not efficient to use it for the storage of extensive data [17]. InterPlanetary File System (IPFS) [18] is common practice to deal with this limitation. IPFS is a distributed file system that allows easy and transparent access to the extensive contents of data. While the data are stored distributively among a peer-to-peer network, each data instance has a unique address to make the retrieval straight-forward.

B. Teleconsultation

Teleconsultation typically concerns two actors, namely a doctor and a patient, while the shared resources are agenda, waiting room, video channel, prescription, and consultation report. However, in the HapiChain teleconsultation service, we include Hapicare as an additional actor, and consequently, its rules, sensor data, contextual information, and diagnosis reports as additional resources.

Teleconsultation workflow starts by patients looking for an appointment, which can be the result of a suggestion from Hapicare. Patients select an available time-slot from those provided by doctors to book an appointment. The main workflow occurs during the teleconsultation session, which starts at the time of the appointment. The simplified process model of this workflow is depicted in Figure 1. The teleconsultation session starts with the patient logging into the system to join the doctor's virtual waiting room. The doctor will select one patient at a time from his virtual waiting room to start the video consultation. It is worthy to note - similar to a face-to-face consultation- the doctor should have the option to call-in a patient a few minutes around the appointment time. It allows them to examine previous patients peacefully. The doctor can view some primary information about the patients in the waiting room to prepare for their consultation. During this video consultation, the doctor can access the patient's EHRs as well as Hapicare sensor data, contextual information, and reports. In the video consultation, the patient discusses his concerns, and the doctor can pose questions to make a diagnosis or even ask for additional measurements before making a diagnosis. The patient can provide live measurements using IoT sensors and transfer it to the doctor via Hapicare. Once the doctor concludes the consultation, he will issue an invoice and prescription to the patient. Prescriptions are not limited to medications; they might also include additional diagnostic steps such as laboratory examination or referring to a specialist. Moreover, the doctor can update Hapicare rules based on his new observations.

The workflow of teleconsultation is not necessarily similar in all cases. Firstly, the procedures and methods of medical care are ever-evolving, e.g., in the near future, it might be required to directly send the prescriptions to the pharmacy, instead of giving it to the patient. Secondly, in different cases, medical consultations might consist of different actions, e.g., in some cases, a doctor might need to get a second opinion on a diagnosis. Therefore, it is essential to consider the dynamicity of workflow in designing.

Moreover, one of the concerns in teleconsultation is the security of data. Even with traditional consultation, many clinicians store the medical files of patients electronically; but because of security concerns, they use isolated systems and avoid sharing medical files between various centers. Nevertheless, in teleconsultation, all the data are transmitted through the internet; hence, the data are prone to manipulation

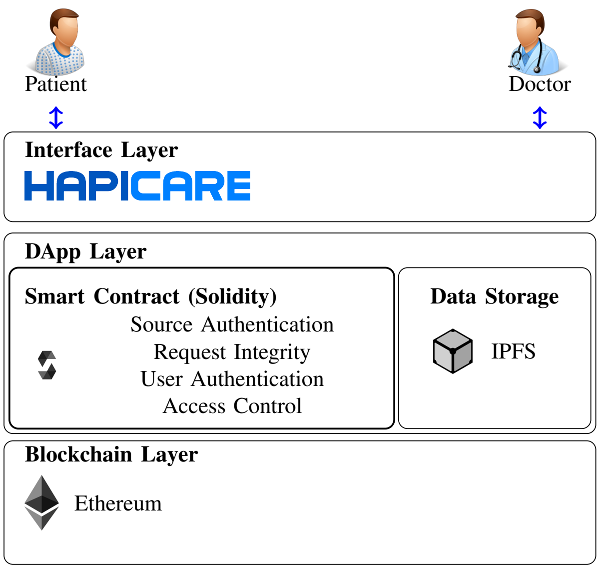

Fig. 2. Structure of HapiChain Framework

and interception. To this end, we use blockchain technology to address these concerns in HapiChain.

C. HapiChain

Given the discussed concerns on modularity and security, we introduce HapiChain, a blockchain-based framework for patient-centric telemedicine. An overview of its structure is depicted in Figure 2. We opted for Ethereum [17] blockchain as it provides simplicity and modularity in developing Distributed Applications (DApps). It is used in the platform layer to support smart contracts and distributed storage. Smart contracts are the core of HapiChain; they contain Solidity codes for managing access to the storage and assuring the process of the workflow. In HapiChain, there are two types of roles: (1) users, which include doctors, patients and Hapicare system; and (2) administrators, who can configure HapiChain. The smart contracts of HapiChain are classified in the following categories:

- Source Authentication: HapiChain is designed to be used via a dedicated interface layer; hence, in order to avoid any unauthorized requests, it is crucial to allow only predefined sources of requests. In the Ethereum platform, there is no limitation of execution by default, so to avoid the process of requests from unauthorized sources, this should be explicitly programmed. The administrator of HapiChain is the only person who authorizes a request source. For instance, in our proof-of-concept, we use Hapicare as the interface layer. Hence HapiChain ignores any requests unless it comes from Hapicare.
- Request Integrity: HapiChain needs to make sure that the received request is an authentic request from the authorized source. In other words, it needs to know that requests have not tampered, e.g., the identification of doctor or patient has not been modified in the request. This integrity validation is achieved by using digital signatures. In Hapicare, the parameters of the request are hashed before transmission. Then in HapiChain, the hash value is again computed and compared with the provided hash. In the case of tampering, the hash values will not match, and HapiChain will drop the request.
- User Authentication: Prior to access control, ensuring the identity of the user is vital; hence, the user of Hapicare is identified and authenticated in this set of smart contracts. Hapicare performs the initial authentication, as a doctor logins to its application. In HapiChain, before processing requests from a doctor, his identification is searched within a list to ensure that he is a registered doctor in HapiChain. The HapiChain administrator can update this list or delegate it to the Hapicare administrator.
- Access Control: The medical files are the most critical information in the medical system. Hence, a set of Solidity codes is dedicated to ensuring confidentiality and also the integrity of the medical files. Access control can be customized for each patient. In general, the access control codes are classified into two sub-categories:
  - Read Medical File: For instance, Hapicare consistently uses a medical file for diagnosis of patients' condition during telemonitoring; however, it may not need to access to all of the medical files. Moreover, during a teleconsultation, a doctor should be able to access all the medical file of the patient.
  - Modify Medical File: For example, the medical file of a patient can be limited to be modifiable only by his caregivers during allowed time.

  The dynamic access control is one of the added values of HapiChain. For the implementation of access controls regarding read and modify medical files, a mapping is defined in HapiChain, from an identification number of an entity to the list of allowed requests of that entity. Prior to any requests, the entity and the request are verified using this mapping. The request, in the simplest case, contains the patient's identification number, type of medical file (monitoring or consultation), type of request (read or modify), and access period. For example, for telemonitoring, the Hapicare system is allowed to access only *monitoring* medical files of *all* patients for an *infinite* time. Hapicare administrators can define these access controls.

Because medical files can grow huge, it is hardly possible to store them in the blockchain; hence they are stored using IPFS [18] to ensure better scalability. For the confidentiality and the privacy of these data, they are anonymized and encrypted before storage. When the smart contracts verify that the "modify" request is allowed, IPFS will store the new data in a storage node, and the address is kept for future accesses. Unless Hapicare has explicitly labeled the type of new data as *monitoring*, the type will be *consultation*. In the case of retrieval, the contents are loaded from the stored addresses.

The Hapicare system is used as an interface for communication with doctors and patients. This layer interacts with smart

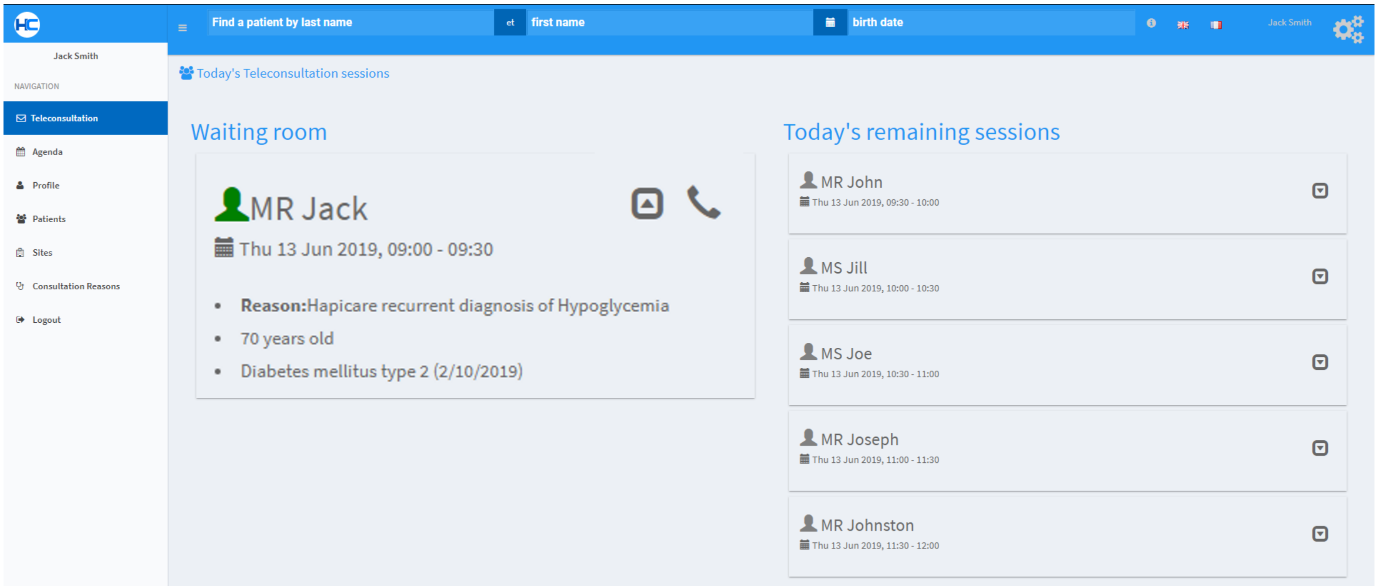

Fig. 3. A view of virtual waiting room

contracts through the provided Application Programming Interfaces (APIs).

III. Use-case

The focus of the HapiChain framework is teleconsultation service in complementary to telemonitoring. The use-case of Hapicare [13] is continued with teleconsultation to depict how HapiChain completes the remote treatment. In this use-case, doctors and patients use Hapicare as a telemonitoring system as well as an interface for HapiChain.

A. Scenario

Jack has diabetes mellitus type 2 and takes two units of insulin injection prior to each meal. He uses Hapicare for self-monitoring. Using the existing information and sensing actions, Hapicare diagnoses Jack with *hypoglycemia* and advises him to *eat carbohydrates (some biscuits)*[1]. However, if Jack is often diagnosed with hypoglycemia, it means his insulin intake is not suitable for his lifestyle. Hence, his insulin needs to be adjusted. However, this modification is too critical to be done automatically, so Hapicare suggests that Jack take a teleconsultation.

Jack's Doctor, Dr. Smith, has provided a list of time slots for teleconsultation; Jack can book one of them using the Hapicare interface. In the time of the appointment, the process will be followed, similar to Figure 1. Jack joins the virtual waiting room of Dr. Smirth and waits until Dr. Smith starts his consultation session. As shown in Figure 3, Dr. Smith can see the online patients who are waiting to start their consultation, as well as some additional information, namely his reason for the consultation, age of the patient, and his chronic diseases. For instance, the reason for Jack's teleconsultation is "Hapicare recurrent diagnosis of Hypoglycemia", while his age is 70, and his chronic condition is diabetes mellitus type 2, which is diagnosed in 2/10/2019. Such information helps the doctor to prepare for the consultation. Once, Dr. Smith calls-in Jack, the video call is established. In the meantime, Dr. Smith requests for Jack's medical file via Hapicare application. The request is forwarded to HapiChain. The smart contracts process the request to have the following conditions: (1) the request comes from Hapicare (Source Authentication), (2) the digital signature of the request matches the computed hash value (Request Integrity), (3) The doctor is registered in HapiChain (User Authentication), and (4) The doctor is allowed to access the requested file on the current time (Access Control). If the conditions are met, HapiChain will allow access and sends the encrypted medical file to Hapicare, where the medical file is decrypted and shown to Dr. Smith. Based on analyzing the medical file and considering the reason for appointment, which is frequent diagnoses of hypoglycemia, Dr. Smith asks Jack to measure his blood sugar. Jack measures it using his IoT-based glucometer, and then the measurement is processed and transferred to Dr. Smith via Hapicare. Dr. Smith notes that his blood sugar is currently regular, so in general, his insulin intake is suitable. Dr. Smith investigates the time of recurrent hypoglycemia and notes that most of them happened at nights. He concludes that Jack probably takes light dinners, and his dosage of insulin before dinner is too much and causes him hypoglycemia; therefore, he prescribes Jack to take only one unit of insulin before dinner. To ensure that the new prescription is well suited for Jack, Dr. Smith configures Hapicare rules to remind Jack to measure his fasting blood sugar for the next seven days and book another appointment if it is more than 131 mg/dL on average. As the teleconsultation session ends, the new medical file consisting of the new prescription, and a new measurement is encrypted and stored

[1]The video of this scenario is accessible through https://youtu.be/KPvWQYZcUhs

using HapiChain. The access of Dr. Smith to the medical file is also then terminated. Afterward, Hapicare continues monitoring of Jack.

B. Discussion

The added values of HapiChain can be discussed in two main categories: (1) the benefits of *teleconsultaion* and (2) the benefits of *blockchain technology*. In the given scenario, Dr. Smith has examined Jack and has adjusted his insulin dosage. At the same time, neither of them has to leave their comfort at home. Hence, teleconsultation saves time and money on both sides of doctors and patients. The elderly and patients with chronic diseases are usually at high risks of many communicable diseases, seating in a waiting room alongside other patients increases the chance of infection. Hence, using teleconsultation is a healthier option for the patient.

Moreover, blockchain technology ensures the confidentiality and privacy of the patient. The medical file of the patient is encrypted and can be as limited as only accessible by his doctor at the time of appointment. The use of smart contracts in blockchain ensures that the medical files are not tampered nor compromised. Moreover, blockchain technology enables high scalability and interoperability as the process of data management is uniform and transparent, which is coded in smart contracts. Additionally, because all the reports of consultations are stored in HapiChain and are tamper-proof, fiscal management is transparent, and the chance of health frauds are minimized.

IV. Conclusion

Due to longevity, societies are facing a massive number of the elderly and patients with chronic diseases. In our previous work, we covered the management of them at their living location using Hapicare, telemonitoring of patients at their living location is covered. It helps the patients to diagnose their medical condition and provides them suitable suggestions. Nevertheless, in many situations, the intervention of an expert, i.e., a doctor, is required. Teleconsultation has been proven to be more economically efficient, as it removes unnecessary trips; moreover, it is a healthier option as it reduces the chance of contamination. The challenge is the security and the reliability of teleconsultation. To this end, we have proposed HapiChain, a blockchain-based framework for patient-centric telemedicine. It embeds Hapicare and completes it by providing teleconsultation services. The use of blockchain technology ensures the security, reliability, and scalability of the service. We have discussed a use-case to show how HapiChain is beneficial as an innovative teleconsultation service. We have completed a cycle of remote treatment; Hapicare continuously monitors the patient and provides suggestions. When an expert's intervention is required, HapiChain provides a secure framework for teleconsultation. However, for future work, it is essential to model the attacks and verify the security of the HapiChain framework against the attacks. Moreover, another prospective work is deploying HapiChain for a pilot project to receive feedback from patients and clinicians.

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