Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

Blockchain applications for the healthcare sector: Uses beyond Bitcoin

4

Rabab Jafri and Shikha Singh
Department of Computer Science and Engineering, Amity School of Engineering and Technology, Amity University, Lucknow, Uttar Pradesh, India

1 Introduction

Medicine is an inevitable part of our lives, making medical data such as prescriptions, patient medical history, etc., an essential part of treatment. Traditionally, medical data was written on paper, which was vulnerable to damage or human modifications. Therefore, to mitigate this impairment, it became necessary to safely store this data in an electronic format. Even after this, the medical database is still prone to tampering or even permanent deletion. Information blocking is another issue that occurs when someone from the outside wants to access data without the permission of the patient or hospital. Sharing medical data securely without any modification is necessary, as one disease could be the result of a prior one. This data may be needed when monitoring a patient or when the practitioners need to know the medical history of the patient for treatment. Furthermore, there are numerous issues with time, speed, storage, and protection when data are transmitted on paper or via email. Relying on a centralized database for keeping sensitive data is also not an option. Also, it is believed that cyberattackers are prone to medical data as it has huge revenue potential. So, access to a distributed instead of a centralized ledger for sharing medical data can ensure data security. There should be a patient-centric model to give priority to patients. The patient should be aware of data provided to an insurance company, data provided to a blood bank, etc., to provide flexibility. Therefore, researchers began using blockchain in medical healthcare. Frost and Sullivan highlighted tagging medical equipment with useful identification, and integrating confidence in device identification and tracking as a critical problem. When a gadget fails, tracking it can disclose the source of the problem and save wasteful repurchasing in the case of lost devices. These dangers are expected to be reduced by a strong trust infrastructure based on the identification of medical equipment. Due to security and privacy concerns, just 20%–30% of medical equipment is connected within hospitals, according to the survey. As a result, blockchain can assist the pharmaceutical business in overcoming the rising risks of counterfeit and unapproved pharmaceuticals. There are numerous areas of healthcare and well-being where blockchain technology could be beneficial, including device tracking, clinical trials, pharmaceutical tracing, and

Blockchain Applications for Healthcare Informatics. https://doi.org/10.1016/B978-0-323-90615-9.00022-0

health insurance. Hospitals can use a blockchain infrastructure to track the entire lifecycle of their assets through device tracking. Following that, the data gathered can be used to improve patient safety and give an aftermarket analysis to save money. In today's digital age, academics are concerned about another issue: how to deal with data of a specific size. Applications such as big data, data analysis, image processing, and data mining help in processing an enormous amount of data in gigabytes and terabytes today. Digitalizing systems in the healthcare sector is evidenced by increasing interest and various initiatives taking place in different sectors worldwide. The aim of doing so is to benefit patients and society through the adoption of electronic health records (EHR). The ability of EHR systems includes public healthcare management and online patient access, which has become of interest to various research communities. This can also be seen in the novel coronavirus (COVID-19) pandemic, where remote patient monitoring and other remote healthcare deliverables are used to tackle the situation in the most secure way possible. The medical sector is looking for newer technology to detect and control the COVID-19 pandemic in this global health disaster. As a result, accurate and trustworthy data are required to track and manage the spread of any virus. However, contemporary technology lacks reliable data that could provide correct information regarding the transmission of a novel coronavirus in the current setting. Although public hospitals and clinical laboratories can provide information on COVID-19 patients, the information may not be valid because it is not properly managed, preserved, or collected according to approved processes. Blockchain technology (BT) can assist in tracking the spread of the coronavirus, identifying high-risk individuals, and controlling the infection in real time to address these challenges. BT is a digital database that holds information that can be utilized and shared in a huge decentralized and publicly accessible network at the same time. Blockchain's properties of immutability, transparency, and decentralization can be leveraged to provide security and trust in the healthcare domain.

1.1 Motivation and contribution

Compared to the previously published articles, this work provides a comprehensive assessment and analysis of BT's application in healthcare. The goal of this study is also to demonstrate the obstacles of blockchain research as well as the potential applications of blockchain in healthcare. Only research that presents a novel solution, algorithm, method, methodology, or architecture for the topic of healthcare is included in this systematic review. Research of the review type, discussions of possible blockchain uses and applications, and other irrelevant publications are not included. The remainder of this chapter is organized as follows. In Section 1 we present background information on blockchain technology and EHR systems and its concepts and the current implementation of blockchain in healthcare. A deeper insight into the importance of mobile health, remote monitoring, and the motivations for using blockchain-based EHR systems is listed in Section 2. Section 3 covers the details of a patient-centered blockchain model along with its promising features. Furthermore, a discussion on the present pandemic and how blockchain is striving to help

in this ongoing situation is in Section 4. The chapter is summed up in Section 5 where conclusions are drawn to support the entire contents of the chapter.

1.2 Fundamentals of blockchain

A software system is said to have typically two main architectural approaches: the centralized approach and the distributed approach [1]. Currently, trading and exchanging goods over the Internet depends on financial institutions that monitor any electronic payments and act as a trusted third party to process these payments. There is a cost to these intermediary parties, which increases the transaction cost, thus limiting small casual transactions. This system may work well but still suffer from various hindrances such as the inherited trust-based model drawbacks. The possibility of nonreversible transactions is almost negligible because the intermediary disputes cannot be overlooked and cannot be neglected. This is the basic working of a "centralized system." In a centralized approach, the nodes are distributed and connected with one central node acting as a coordinator. The distributed approach, in contrast, has several nodes connected to each other directly but not centrally. Fig. 1 illustrates the comparison of these two approaches.

Blockchain is a distributed ledger technology with the potential to drastically transform many industries globally. The term "blockchain" was first introduced by Satoshi Nakamoto in his published white paper, which was a technical manifesto released in October 2008 under an MIT public license. He introduced this peer-to-peer, no intermediary system that helped in the electronic cash system by introducing the first digital currency, named Bitcoin. Security in this system is ensured as the nonmalicious nodes collectively control more than 50% of CPU power, which is more than any other group of hoax nodes [2]. This distributed ledger technology is a time-stamped chain of blocks containing the transactions and encoded with a cryptographic hash function and a digital signature, which helps in enabling a trustless protocol. Fig. 2 depicts how each block is associated with the one prior via the previous hash, thus forming

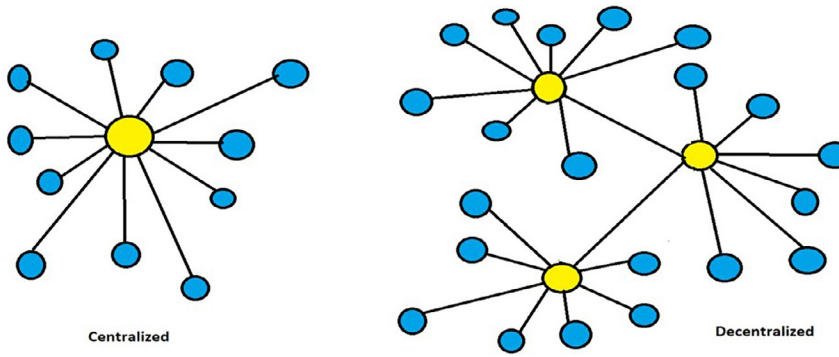

Fig. 1 Centralized vs. decentralized network architecture.

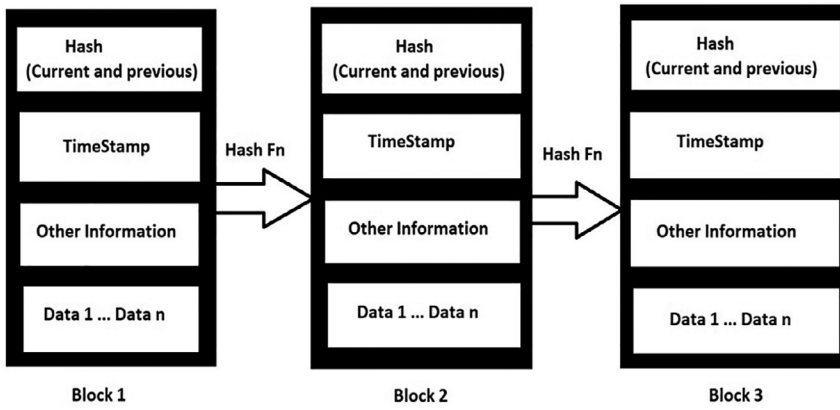

Fig. 2 A blockchain structure.

a chain. The block prior to the present one is called its *parent block* and the first-ever mined block is known as the *genesis block* or *the 0th block*. Data are stored and verified across the entire network of computers. Blockchain verifies, secures, confirms, and records each transaction. Data are stored in a decentralized way across a wide network, saving it from a single point of failure and hence ensuring less fraud and tampering with greater security. There is an effective limit on the speed of new transactions being added. Right now, each new block in the chain must be 1 MB or smaller. A typical Bitcoin transaction is about 250 bytes, so that means 1 MB/250 bytes equal to 4000 transactions that can fit in each new block. Once a block is added to the chain, then anyone who tries to alter it would need to recompute the altered block as well as all the other subsequent blocks, thus making blockchain permanent. This in return demands an enormous amount of computation power. The trust among nodes is obtained by solving mathematical puzzles and cryptography instead of a central bank. As data are stored in an encrypted form, this ensures the preservation of data privacy. Smart contracts were introduced to support different functions for different application scenarios to work toward robustness, as the terms of this smart contract can be preset by users and will only be executed if the conditions are fulfilled. Hence, this hands over control to the owner of the data. The blockchain is a decentralized network that has no central authority and thus all nodes should agree on the validity of the transactions occurring. This is achieved with consensus. A special peer node known as a "miner" validates the transaction and facilitates the consensus process. These are the powerful computers executing software defined by blockchain protocols. The miners are in competition with each other to add their block to the chain first. This is done by a consensus algorithm that makes sure all the nodes agree on the same state of the blockchain. They use proof of work (POW), which is a consensus protocol that confirms transactions and produces new blocks. Miners compete with each other to validate the transaction and whichever node adds a new block to the chain by solving a mathematical puzzle wins a reward. In addition encryption and decryption, one more concept is associated with it, called hashing. Hashing along with

encryption provides security. Hashing basically refers to the process that takes an input of varied length and gives an output of a fixed length. This fixed-length output is called a "hash." Tracing a hash makes it easier to track a transaction. The basic function of a hash is to verify the integrity of the block and form a chain link by including the previous hash block in the current block header. If another node tampers with the block, the hash value changes, causing a hash value mismatch and rendering the local chain invalid. Bitcoin's secure hashing algorithm 256, also known as SHA-256, is a good example. It also ensures the anonymity, immutability, and compactness of the block. This gives a fixed output of a length of 256 bits. The consensus process determines how the miners are chosen and what data are included in the block. The blocks are then broadcast to the network, where the validation nodes verify that the received block contains valid transactions and that it references the previous block in the chain by using the corresponding hash. If both requirements are fulfilled, the nodes add the block to the blockchain. The block is discarded if the prerequisites are not met. The function of network nodes is defined by this. In the blockchain network, each node has its own copy. The same blockchain is disseminated across the whole network in multiple copies. Even if each copy is identical, the fact that it is dispersed throughout the network makes it harder for the wicked node to change it. Thus, a hacker would need to manipulate each and every copy on the entire network, making it a distributed ledger [3].

These properties make blockchain seem ideal for healthcare data management. Although blockchain in healthcare is relatively new, more research is becoming available each day. There are many real-world blockchain healthcare systems such as Gem, Guardtime, and Healthbank, to name a few. The application of blockchain in healthcare transforms the ecosystem in a variety of ways that benefit patients and improve treatments, outcomes, security, and prices. Blockchain has the potential to revolutionize healthcare delivery by putting patients at the center of healthcare ecosystems and increasing healthcare data security, privacy, and interoperability. By making electronic medical records more efficient and secure, this technology can establish a new model for health information exchanges. Its immutable, time-stamped, tamper-proof ledger, accessible by all or preapproved participants, is one of blockchain technology's key offerings, making it a no-brainer for supply chains across industries [4]. Because of its numerous qualities, blockchain can handle many real-world health science goals and criteria, which is a compelling justification for its adoption. Decentralized administration, for example, is extremely valuable for organizing digital assets created by diverse entities. There is no one point of permission, ownership, or control as a result of this. When users don't want to rely on a single central authority, or when patients (users) wish to double-check their data and records, this is advantageous. In clinical and surveillance systems, for example, data provenance is vital. This is ensured because blockchain generates an immutable trail that records transactions in perpetuity, ensuring that crucial records are always available in the network to be inspected if necessary. A block could be used to record transactions in healthcare or research. The actual patient data as well as access records such as requests for and receipts of records are recorded as transactions in blocks on a chain. An example of a health informatics exchange would be: Patient P1 requests that

clinician C use data, institution I1 grants access, and the transaction is visible to the patient P1 or primary care clinician C2. Again, consider a human subject research scenario: researcher R1 requests trial data, institution I2 grants access, and participant P2 and/or principal investigator R2 can view the transaction [5]. Researchers and businesses are growing increasingly interested in the Internet of Things (IoT) cybersecurity and blockchain technology due to its ability to bring answers to a variety of difficulties, most notably those relating to traditional centralized design. Blockchain technology provides a single source of truth that is permanent, verifiable, and immutable. About $1.4 billion was invested in blockchain-related start-ups back in 2016 and the hype cycle shows no sign of slowing anytime soon. Much of the focus on blockchain has been on cryptocurrency, particularly Bitcoin, and the impact that blockchain is expected to have on the financial sector. Despite the focus on financial services, many other areas, including voting, real estate, supply chain management, and healthcare, are vulnerable to upheaval. Healthcare is ripe for disruption because it faces a slew of issues that blockchain can address with its immutability, fraud prevention, and ability to transfer data between institutions without the requirement for third-party trust. Current issues within the modern healthcare industry are:

1. **Healthcare data interchange:** Data must be shared between healthcare providers, necessary third parties, insurers, and patients while adhering to data privacy regulations.
2. **Nationwide interoperability:** Having a uniform standard for patient data sharing makes it easier to transfer data between healthcare providers, which is something that outdated systems often lack.
3. **Medical device tracking:** From supply chain to decommissioning, medical device tracking provides for quick device retrieval, avoidance of wasteful repurchasing, and fraud analytics.
4. **Drug tracking:** As with medical devices, blockchain allows for frictionless recalls and the prevention of counterfeit medications by tracking the chain of custody from the supplier chain to the patient.

1.3 Types of blockchains

There are basically three types of blockchains depending on the managed data, the availability of such data, and the actions that can be performed by the user, namely:

1. **Public blockchain:** As the name suggests, this blockchain is publicly accessible and there are no restrictions on the participants or the validator. The main advantage is that nobody will have complete overall control of the network. There is no central authority, which assures that the data are secure and that the records are immutable. Bitcoin, Ethereum, and Litecoin are some examples of this type of blockchain.
2. **Private blockchain:** To become a member of this blockchain network, participants must be invited. Only persons who are members of the network may see what's going on here. These are primarily used in private organizations to store the organization's sensitive information.
3. **Consortium/hybrid blockchain:** This blockchain network is divided into two different types where some nodes are private while the other nodes are public. As a result, only some nodes will be allowed to participate in transactions while the others will be in charge of the consensus protocols. This is a type of hybrid blockchain consisting both of private and public blockchain. Table 1 states various examples of each of the three kinds of blockchains.

Table 1 Summary of types of blockchain.

	Public blockchain	Private blockchain	Consortium blockchain
What is it?	Anyone anywhere can read and write on the network. Data are validated by every node in the network, thus making it very secure	There is a highly trusted organization (owner of the blockchain) that provides permission to read and write data onto the blockchain	Permissions to verify, read, and write onto the blockchain are controlled by a few predetermined nodes
Benefits and challenges	It is secure and transparent as all transactions made are public with individual anonymity It can be inefficient as all nodes need to verify the transaction	It is efficient and private as the owner has the power to control who can read/write on the blockchain This also gives controlling power to a single consolidated entity	Efficient as fewer nodes verify transactions. It is also private as read/write access can be controlled by predetermined nodes. There is no consolidation of controlling power
Example	Bitcoin, Ethereum, Litecoin, etc.	Ripple and Hyperledger	Corda and quorum

2 Implementations of blockchain in healthcare

Many medical services and blockchain-oriented organizations have successfully delivered blockchain frameworks to improve these medical services for both doctors and patients. By decentralizing patient wellbeing history, following drugs, and improving choices, blockchain is turning into an important instrument for medical services, changing the business around the world. Nonetheless, there are various exploration and operational difficulties trying to integrate blockchain technology with existing EHR systems. Research about blockchain's applications to medical care is presently restricted, yet more exploration opens up consistently. Blockchain apparently is one of the hottest programming research topics right now. It can change medical services by returning ownership over clinical information to the patient. This is advantageous from a patient-focused perspective. Current medical care frameworks are described as being exceptionally complex and exorbitant. This can be diminished through improved health record management, utilization of insurance agencies, and blockchain technology. Healthcare accounts for a significant portion of the gross domestic product (GDP) in developed countries. Hospital costs, on the other hand, are continuing to climb, as are unnecessary operations and data breaches. This is one area in which blockchain technology has the ability to make a difference. It has the ability to a wide range of tasks, including secure encryption of patient data and the management of epidemics. A new type of blockchain trust model,

a consortium trust, is also gaining traction. Microsoft has released the Coco framework, which enables the creation of blockchain-agnostic consortiums. A predefined group of trusted parties is used in these consortium structures. Multiple hospitals, medical device makers, and third parties are examples of this in healthcare. Smart contracts are executed on a trusted partner's hardware to generate consensus without the use of miners. This has resulted in far better performance, with a Coco-optimized blockchain capable of processing 1600 transactions per second, bringing blockchain much closer to the big payment processors. Blockchain can assist the pharmaceutical business in overcoming the rising risks of counterfeit and unapproved pharmaceuticals. With integrated GPS and chain-of-custody logging, it is possible to build smart contracts for pharmaceuticals and then identify pill containers, just as it is for devices. Blockchain can be used in clinical trials to solve concerns such as false results and data deletions that go against the researcher's bias or the funding source's goal. As a result, clinical investigations will be more reliable. It also allows for the creation of an irreversible log of trial subject consent. The pharmaceutical industry may save $200 billion by identifying a chain of custody in the supply chain. Many sectors of health insurance could benefit from a reliable record of events surrounding the patient pathway, such as improved incident reporting and automated underwriting operations. Contracts, such as automated payments for segments of the patient journey, could also be precisely stated and then implemented. The following are some of the current blockchain application cases, primarily in healthcare [6]:

1. **Clinical trials:** Clinical trials are one area where blockchain has the potential to improve medical practitioner and researcher transparency, auditability, and accountability. Regulators may readily monitor clinical trial standards by keeping an immutable ledger of patient consent, ensuring that the experiment complies with informed consent rules. This is especially important because faked informed consent forms, along with tampering with data and faking patient agreements, are among the most common types of clinical fraud. A high level of trial subject authentication would be required to prevent this scam. This system could be enhanced even further by developing a smart contract system that blocks clinicians from accessing patient data until a key is released at the end of an auditable smart contract procedure that requires agreement from the patient at each stage of the trial. Clinical trial subjects gain ownership of their data by using a blockchain clinical trial consent ledger, which also provides an audit trail for clinical staff, researchers, and regulators.
2. **Patient records:** Blockchain has the potential to revolutionize healthcare by putting data in the hands of people. MedRec keeps a permanent record of healthcare data for patients and providers. Its strategy is to reward miners by giving them access to unidentified healthcare data in exchange for helping to keep the network running [7]. MedRec maps patient-provider relationships (PPR) using smart contracts, in which the contract displays a list of references that details the relationships between nodes on the blockchain. It also gives patients control over PPRs, allowing them to accept, reject, or change partnerships with healthcare providers such as hospitals, insurers, and clinics.
3. **Drug tracking:** Drug monitoring on the blockchain is another possibility, as it improves the blockchain's immutability and allows for the development of tracking and chain of custody from the manufacturer to POW patient. An example is a technology start-up producing a solution that generates a chain that shows where a drug was created, where it is now, and when it was distributed to patients, eliminating pharmaceutical fraud and theft. This enables

healthcare providers to comply with current healthcare requirements in terms of pharmaceutical supply security, with an emphasis on interoperability between providers. The Counterfeit Medicines Project was recently started by Hyperledger, the open-source blockchain working group, to address the problem of counterfeit drugs. The sources of counterfeit drugs may be traced and discarded from the supply chain using blockchain. The advantage of blockchain in drug monitoring over traditional methods is the inherent decentralization of confidence and authority in the technology's principles. While central authorities can be bribed or falsified, bribing a consensus of those on the blockchain is considerably more difficult. Counterfeit drugs can be totally eradicated from participating supply chains if they can be updated and tracked utilizing blockchain's intrinsic tamper-proofing capabilities at the moment of manufacture.

4. **Device tracking:** Medical device tracking is another opportunity for blockchain in disrupting healthcare from the manufacturer to decommissioning. The use of blockchain in conjunction with this technology allows for an immutable log that shows not only where the device is, but also where it has been in its lifecycle as well as which manufacturer, reseller, and serial number are associated with it, assisting in regulatory compliance. Deloitte identified this feature as one of the potential game-changers for blockchain in the healthcare sector in a white paper. According to an IBM survey, 60% of government stakeholders in healthcare say medical device integration and asset management are the most disruptive areas in the industry. In comparison to traditional location tracking technologies, a blockchain method has various advantages. The immutability and tamper-proof properties of blockchain are the most obvious. This prohibits a malicious user from altering a device's location history or erasing it from the database. This is especially relevant given that medical equipment theft has become a huge problem in the United States and the United Kingdom. This immutability also prevents gadgets from being misplaced and reordered, which costs a lot of money in terms of both care and equipment expenditures. This method should not add significantly to nurse, porter, or support worker burden because it simply requires a tap on the device with a mobile phone or scanner, followed by the entry of the device's present location.

2.1 Electronic health records systems

Technology's recent advancements are touching many aspects of our lives and altering how we use and view things. Technology is finding new methods to improve the healthcare sector, just as it has in other areas of life. The key advantages of technological innovation include improved security, user experience, and other aspects of the healthcare business. EHR and electronic medical record (EMR) systems provide these advantages [8]. EHR is the collection of the patient's electronic health information serving as a data source fetched from and to healthcare providers for medical purposes. It follows a centralized architecture that has a central authority responsible for managing, coordinating, and controlling activities on the network. On the contrary, in a decentralized architecture such as blockchain, all nodes are managed without any dependence on a central authority, as described previously. Ideally, EHR systems should ensure the confidentiality, integrity, and availability of the data, which should be shared with authorized users only to carry on with diagnosis and other medical help when needed. With the right implementation, this system can reduce the replication of data and the risk of losing the data. However, the challenge of data security in such

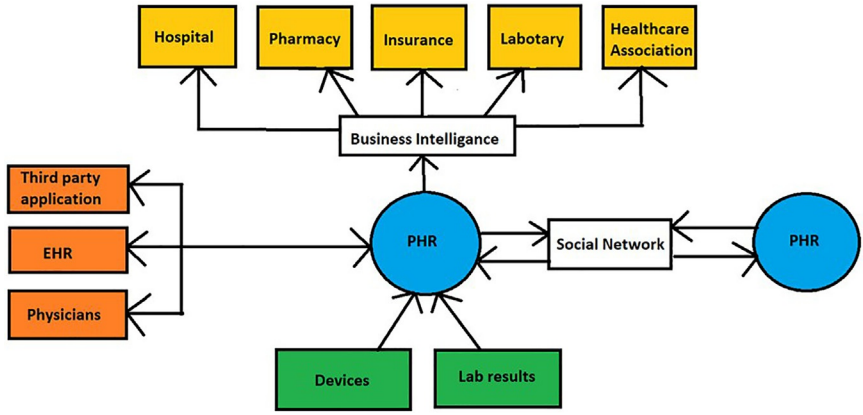

Fig. 3 Personal health record.

systems is threatened by the increasing connections to these systems. They are vulnerable to attack vectors while mobile devices issued by hospitals can be exploited with malware software installed to gain access to sensitive data. EHR systems provide us with enormous data in terms of volume, which can be used to carry out data analysis and machine learning. For example, it can be beneficial to inform others about disease forecasting such as in the case of the 2019 coronavirus. Also, wearable IoT devices can provide relevant information that can help facilitate healthcare monitoring and personalized medical services. But that can be difficult to manage as one healthcare provider's EHR for a patient may differ from the same patient's other information provider. Blockchain offers the ability to create a single system for securely storing and retrieving health records by authorized users in a timely and safe manner. Innumerable mistakes can be avoided by minimizing communication gaps between different healthcare personnel and the patient. Faster diagnosis and interventions are possible, and care can be individualized to each patient, even remotely. The personal health record (PHR) is the personal healthcare information obtained from wearable devices such as smart watches that are owned and controlled by patients themselves, as shown in Fig. 3. This information collected by PHRs can be made available to healthcare providers by patients.

2.2 The essence of mobile health and remote monitoring

Mobile health or mHealth technologies have the potential to significantly impact health research, healthcare, and health outcomes. A **mHealth App** is offered by a healthcare organization to their patients. Patients use these apps to access self-service tools to pay their medical bills, schedule an appointment with the doctor, access lab results, find a suitable physician, and view medical records. The most common applications for mHealth include spreading awareness, diagnostic and treatment support, tracking disease and epidemic outbreaks, healthcare supply chain management, remote data collection, remote monitoring, and healthcare worker telecommunication.

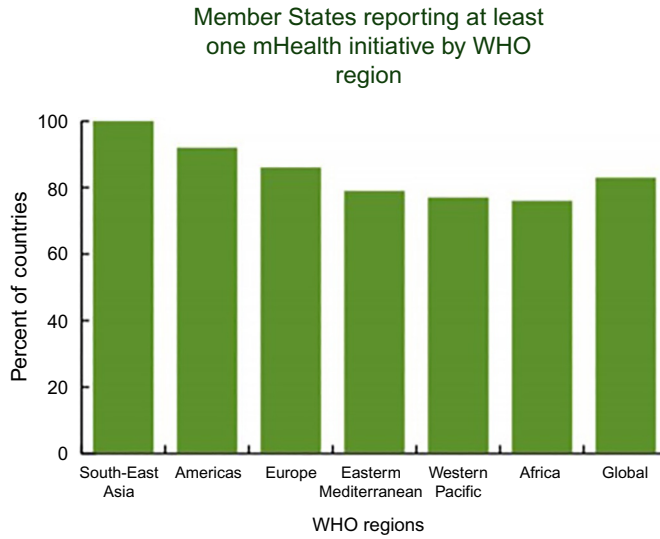

Fig. 4 Member states reporting at least one mHealth app [9].

Top mHealth apps on the market are Fitbit, Apple Heart Study, GoogleFit, Samsung Health, Practo, Medlife, etc. Fig. 4 shows the outcome of a recent study by the World Health Organization of regions where at least one mhealth application is in use [9].

The global mobile health industry is predicted to reach $311.98 billion by 2027, according to a new report from Reports and Data. With the expanding use of smart phones and the advent of innovative technologies in the healthcare sector, the industry has experienced an increase in demand in recent years. Not only for stakeholders in the healthcare industry but also for various companies outside of healthcare, digital health is proving to be a profitable venture. Advanced technologies have revolutionized the healthcare industry. The rate of increase in investment in health startups has accelerated, increasing the market's need. Newcomers are creating innovative ways to make these apps more user-friendly while also attempting to expand the app's potential. To digitalize the US healthcare system, a total of $7.5 billion has been invested in several start-ups. Babylon Health, based in the United Kingdom, received almost $500 million in private funding in 2019, followed by Ginkgo Bio Works, a bioengineering firm that designs microorganisms, which received $300 million. Currently, the COVID-19 pandemic has triggered a wave of fear, prompting lockdowns virtually everywhere to maintain social distancing. As a result, the market has shrunk in the short term, but producers believe that demand for these products will increase in the long run, especially as a result of the pandemic. The use of mobile health will grow, especially in rural areas. Fitness-tracking devices are projected to be in high demand, and home workout sessions are becoming increasingly popular. Fig. 5 represents the percentage of revenue of publishers of mHealth applications.

Blockchain has shown considerable adaptability in recent years, as almost every sector finds a way to incorporate its abilities into its domain. The financial industry

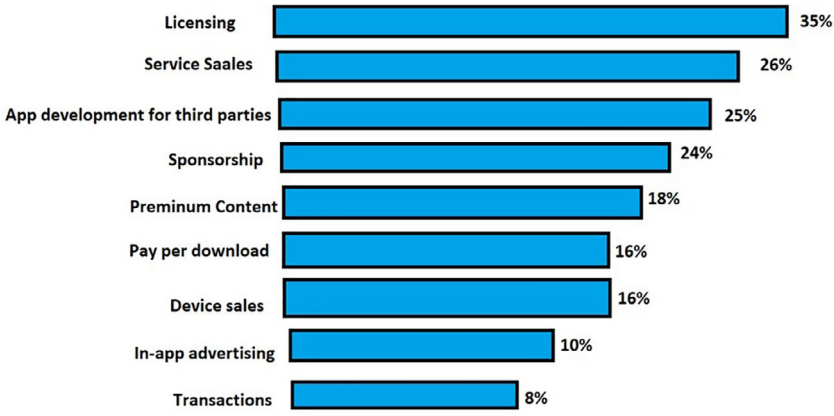

Fig. 5 The percentage of revenue of publishers of mHealth applications.

has received most of the attention thus far, but numerous projects in other sectors, such as healthcare, are beginning to show signs of change in areas such as public healthcare administration, user-oriented medical research, and medication counterfeiting in the pharmaceutical sector [10]. Patient data management is one of the most popular blockchain applications in healthcare. MedBlock is a blockchain-based information management system that enables electronic information access and retrieval through distributed blockchain parameters. The improved consensus mechanism ensures that the network is not overly burdened by activities. It is highly secured due to the features of access control and cryptography. Similarly, a data preservation system (DPS) is also blockchain based for medical data [11]. DPS uses similar cryptographic algorithms to ensure security. One more system called omniPHR places all the PHRs in one accessible place. OmniPHR combines attribute-based encryption (ABE), identity-based encryption, and identity-based signatures to create a new type of cryptographic framework called combined attribute or identity-based encryption and signature. This cryptographic framework maximizes security, as sharing healthcare data in a secure way is also an integral part of healthcare. Diseases in general are becoming more widespread. To treat and monitor these diseases ideally requires going to hospitals, increasing the burden of both hospitals and patients. This process can take a significant amount of time and may often result in mistakes due to human error. Presently, enhancements in wearable devices, sensors, and communication through these devices contribute to modifying the healthcare system in a way that will reshape medical management in no time. Remote patient monitoring (RPM) is the foremost of these advancements visible to us. RPM systems are based on the collection of patient vital signs extracted using presumptuous as well as chronic techniques and then sending them in real time to physicians. These data enable physicians to take the timely, right decision. Developed on the Ethereum blockchain, **MedRec** is a system that prioritizes patient agency and hence gives a transparent and accessible view of medical history. It stores all the patient's information in one place, making it simple for both patients and doctors to view when required. Providers maintain the blockchain

through the proof of authority (POA) mechanism to safeguard authenticity and security. **SimplyVital** Health also has two projects running on blockchain technology. **ConnectingCare** uses care coordination and financial forecasting to help providers in bundled payments get insight into what happens to patients when they leave the hospital. It is currently on the market, helping healthcare providers determine how much a patient's care will cost. **Health Nexus** stores a patient's information on a blockchain for all parties to view. It will also allow patients to sell their data to researchers for profit. The Taipei Medical University Hospital and Digital Treasury Corporation (DTCO) have recently released **phrOS**. It seeks to improve medical institution transparency by storing all the patient's medical records on a blockchain, which contains photographs and other information about the patient's condition. This information can be accessed by doctors and patients through a mobile app. This in turn increases the security of medical information through the decentralized ledger technology (DLT). A blockchain-based system would allow for data to be added and tracked through a ledger, therefore providing a live feed of multiple agencies' relief efforts. It has the potential to save lives and money. Hashed Health, a health-focused blockchain development company, intends to make credentials in the health sector more transparent and easily accessible. With professional credentials exchange, members of the chain can verify the credentials and track records of various health professionals. This streamlines the hiring process while also providing an unalterable history of a professional's healthcare career history. Change Healthcare develops a wide variety of products focused on payments and data management in the healthcare sector. According to their website, 92% of top US health plans use their services. One of their most recent developments simplifies claims management and revenue cycle management. It helps hospitals and health systems manage and improve the collection of patient payments, minimize denials and underpayments, and manage daily revenue cycles and business operations more effectively. **MedicalChain** helps in ensuring full access and control over our own personal health data. Users can easily grant doctors immediate access to their health records via their mobile devices while keeping the data secure on the blockchain. Patients can also wear wristbands, which medical professionals can scan to access a person's medical history if they are unconscious in case of emergencies. It also offers telemedicine communication, enabling online video consultations with doctors. Healthcare Data Gateway (HGD) is another such application presented for organizing patient data. The application uses a simple unified indicator-centric schema to organize this data and a secure multiparty computing system. This prevents privacy violations without any ownership over the information. Smart contracts based on blockchain could aid in ensuring that devices are operated safely. To improve remote monitoring, a private blockchain based on Ethereum was developed. Before participating in this blockchain, participants must first be invited. Here, the transactions are visible only to persons who are part of the blockchain ecosystem. Private blockchain usually has a network administrator who can take care of user permissions in case any particular user requires additional authority. These are typically used in private organizations to store sensitive information. Smart devices interact with sensors that record events in this private blockchain. The smart contracts enable patient monitoring in real time. This is possible because notifications are sent

to patients and healthcare providers securely. This is essential for care at home for patients while a healthcare provider is always accessible remotely. We can upload our health data easily from various devices such as smart gadgets, mobiles phones, etc., and store them on the cloud platform using blockchain. This makes it easier for people trying to access our data from a distance. **Guardtime** provides a specialized cybersecurity module called **Guardtime Cybersecurity** for several industries, including healthcare. Guardtime Health is a platform for patients, providers, regulators, and others that provides all with a single, immutable copy of health data shared across all the involved parties. This system signs every data asset in the network with a cryptographic stamp, which allows tracing the originality of each piece. Thus, any attempt at corruption is immediately spotted in real time. The start-up creates blockchain networks for chain of custody in drug supplies. Because of this, pharmacies can trace the origins of supplies, detect suspicious activities such as drug trafficking, and forge drugs during the process. In 2017, Chronicled created **MediLedger**, which is a blockchain-based project that allows checking the pharma supply chains with local regulations. The solution keeps a forgery-proof record of transactions on a blockchain, thus helping to authenticate raw materials that drugs are made of and detect counterfeits promptly. Currently, the US Centers for Disease Control explores blockchain-related use cases for disease control. In particular, it's mapping out blockchain usage for time-stamping of records to detect and report disease outbreaks in real time in a quick manner. For the same purpose, CDC teamed up with IBM to create a surveillance system for public agencies that will gather and accumulate data about patients and prescriptions effectively. **Dentacoin** is an ecosystem of applications focused entirely on the dental industry. Those include loyalty programs and dental insurance powered by smart contracts; own-issued tokens for payments among patients, dentists, suppliers, manufacturers, and other involved parties; and a platform for affordable care services that is currently under development. The new project will be a wholly new ecosystem that will reportedly encompass:

1. **Dentacare**—It is an app for oral hygiene notifications and reminders for the same.
2. **DentaVox** surveys—It is an online platform for surveying patients.
3. **Trusted reviews**—It is a platform for collecting patient reviews about dentists.
4. **Dentacoin assurance**—Preventive dental care with lower costs based on patient income.

Blockchain use cases in healthcare are plentiful and have the ability to transform the entire sector. The only issue now is getting healthcare providers to adopt blockchain systems on a wider scale. Once mass adoption occurs, it will foster the improvement of the entire healthcare system. More than ever, we are in charge of our own health and well-being. Many of us have devices that count our steps or tell us how we slept. All this information tells a complete story about what we're going through and who we are. This is a unique opportunity to bring all that together technologically to enable us to take charge of our own health. There are high chances of EGRs being adopted. There is an opportunity now to weave all that information meaningfully. The best health systems are those that provide the patient with the most visibility and access as well as those that enable the most inputs to be added to that core set of data. One of the biggest trends we are seeing in digital health is remote monitoring. Say

you are treated for a particular condition at a hospital and then you go home. It has the capacity to deliver continuous monitoring of your vitals. In terms of providers, they are absolutely looking at technologies such as blockchain. Mobile health applications are becoming more important nowadays with the advancements in technology. In this context, EMRs were found to be kept secure in a blockchain network. The data can be sent to medical practitioners rapidly as well as being available for self-monitoring and home care as well. This area is particularly sensitive to malware; however, particularly a root exploit can give the hacker access to the patient's private key. Mobile applications and remote monitoring machines are an integral part of this technological era and blockchain can further enhance this. Blockchain has also been applied to clinical trials and very recently to medical insurance storage as well. A recent study outlines that **MIStore** is a blockchain-based medical insurance storage system that utilizes different servers of hospitals, patients, and insurance companies to verify each other's activity and security concerns. Such systems can encourage a more productive relationship between patients' hospitals and insurance companies.

3 Motivations for using the blockchain-based EHR system

Patients are increasingly empowered to access medical information and services digitally and securely on blockchain by a growing number of organizations. "Blockchain is exploding in clinical trials right now," says Maria Palombini, the IEEE Standards Association's director of emerging communities and projects development. Despite all this promise, just 5% of healthcare chief information officers (CIOs) and 12% of payer CIOs have blockchain in their written business strategies. According to a poll of 3700 physicians, nearly half of them (47%) are unaware of BT. There are a variety of scientific and operational hurdles, as with any maturing consumer technology. Hence, security and privacy become necessary for such data. Some of the challenges include a single point of failure of centralized servers and malicious attacks. Patients' whose data are saved in EHR systems lose control over who has access to it and for what purposes it could be utilized, which is a breach of personal privacy. This information may also be passed from malicious users to another organization such as an insurance company that may deny insurance to a patient based on a leaked medical history. The coronavirus pandemic, in which remote patient monitoring and other healthcare deliveries are being used to limit the situation, demonstrates the potential of EHRs. The following requirements should be met when implementing secure EHR systems:

1. Any unauthorized modification to data is not allowed and can be detected.
2. Security and privacy of data.
3. An efficient data-sharing mechanism.
4. It returns the control of EHRs back to patients so that patients can see their records and be notified of loss or malicious acquisition.

Jarzbek started **TrustedHealth**, a virtual platform that connects patients with life-threatening or rare illnesses with the best physicians for their needs. It's like

telemedicine on steroids because it allows for virtual interactions and knowledge sharing while also collecting data for future research. Blockchain is used by Trusted Health to accomplish all of this. By making EHRs more efficient and secure, this technology could create a new model for health information exchange (HIE). It becomes an easier and more efficient information exchange. More security is achieved in terms of confidentiality, meaning only rightful users can access the data. Integrity implies that data must be accurate and should not be altered by any users and availability means that legitimate users' access to data and resources is accepted. The audit logs inside the blockchain have information about who accesses which EHR or PHR. It has information about the aim of accessing this information and also the time stamp of any operation in the entire life cycle. A person or an entire organization will be accountable and responsible for misconduct with any type of information. The above properties can be achieved using blockchain as explained below [12]:

Decentralization: Blockchain-based networks provide fault-tolerance architecture as end-to-end replications remove the reliance on a single point of failure. A significant amount of time has been saved after applying the decentralization in the process, which manage security and privacy.

Consensus mechanism: The winner from the miners releases this block to all other nodes in the network, which confirm and validate this block and add it to their chain; the winner gets a financial incentive for doing the work [13]. There are many consensus algorithms used to ensure data integrity and to validate blocks such as proof of stake, proof of burn, etc.

Immutability: Blockchain is immutable and tamper-free, hence it ultimately provides security. The hash function makes it tamper-resistant to any sort of change. A hash value is calculated by applying some hashing algorithms such as SHA-256, RSA, and RIPEMD-16, to name a few [1].

Traceability: Blockchain is a ledger that keeps on growing as the number of blocks grows. A block is comprised of a list of all done transactions. In this chain of blocks, every block has a parent block. The first block in the chain is the genesis block or the 0th block. The hash code of the 0th block is added to the header of the next block, then the hash code for the second block is computed. The hash of the second block becomes the parent of the third block and so on. This feature of blockchain provides data provenance to keep chronological track of activities and track the chain backward for investigations. The blocks are hence linked with each other, having a time stamp as well. This link can be chased back to the origin, the 0th block.

Smart contract: A smart contract is a computerized logic or terms of a contract written in a programming language, mostly Solidity. It implements transactions between two or more parties only after fulfilling the coded logic or when certain conditions are met. This implementation makes the blockchain flexible as well as programmable [14]. Smart contracts can enforce traceability and transparency.

Open source: Blockchain projects are mostly open source. Developers or any person can make contributions to it freely. Blockchain technology can accommodate evolution in the future. Various transformations from financial blockchains to nonprofit blockchains have been announced, as there is big interest of the community. Ethereum and Counterparty have paramount interest in building more value-added services for the future of blockchain.

4 Proposed patient-centered blockchain model

Fig. 6 is an overview of the model based on this very concept. It is secure and allows patients to claim ownership over their own records while allowing hospitals to have easy access to these records too [12]. This is based on Ethereum, which is a decentralized platform that allows developers to run various applications on a custom blockchain. Because blockchain may not offer sufficient storage many times, the actual medical records are on decentralized cloud storage such as Ethereum Swarm, which is a native base layer service of the Ethereum acting as a distributed storage platform. Each medical record has a unique swarm hash that is then combined with the decryption key. Only those that know the reference to this root can access the content within it. These root chunks are stored in smart contracts securely and are released only under certain conditions when required. Smart contracts are lines of code that are stored on a blockchain and automatically execute when predetermined terms and conditions are met. They are programs that run and have been set up to run by developers. Smart contracts are most useful in cases of business. They are used to implement some agreement so that all participants can be aware and certain of the outcome without any involvement of a third party. Say you have bought a car at a dealership and there are several steps, hence it can be frustrating. If cannot pay for the car, you will have to obtain financing. This will require a credit check and you will have to fill several forms with personal information to verify your identity. We will also have to interact with several different people such as the salesperson, finance broker, lender, and so on. To compensate for their work, various commissions and fees are added to the basic cost of the car. Smart contracts can streamline this complex process involving several intermediaries as there can be a lack of trust among various participants in the entire transaction. With our identity stored on a blockchain, lenders can quickly make a decision about credit, etc. A smart contract will be created among our bank, the dealer, and the lender so that once the funds have been released, the lender will hold the car's title and repayment will be initiated based on the agreed terms. The transfer of ownership would be automatic as the transaction gets recorded to a blockchain, is shared among the participants globally, and can be cross-checked at any time. The problem of data ownership and control can be solved by the concept of multisignature contracts. Multisignature requires multiple users to use their private keys to sign a transaction for

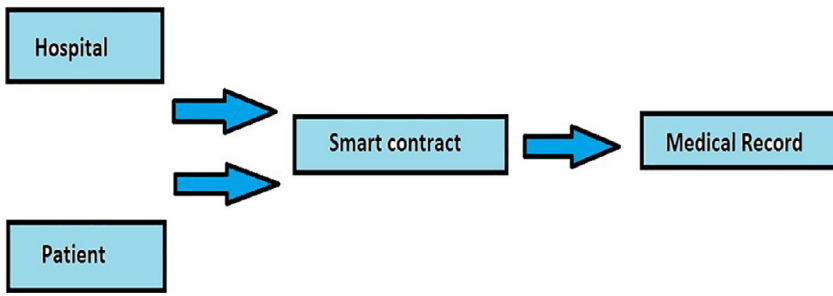

Fig. 6 Patient-centered blockchain model.

authentication. So the patient cannot tamper with the record without the permission of the hospital. But the patient still has control over who can access their record. A new swarm hash must be generated every time the data was accessed so a "last accessed" time stamp was added. Changes in data will automatically change the swarm hash, which is secured again until the required permissions for access are received. This paradigm improves blockchain's security and immutability while also providing a multisignature solution for data ownership and accessibility. Interoperability, secure storage, and dependable access to patient data are also included in this proposed paradigm.

5 Applications of blockchain technology to combat COVID-19

The different areas in which blockchain can play a key role in tackling the COVID-19 pandemic include outbreak tracking, user privacy protection, medical supply chain management, and donation tracking. The key purpose of blockchain is to aid in the control of the pandemic's propagation. Improved solutions, outbreak tracking, user privacy protection, the performance of the medical supply chain, donor tracking, and secure day-to-day operations are all things that technology can aid with during this pandemic crisis. Blockchain should be used in a way that reduces network latency while still providing a secure environment for storing and transmitting essential data. The ultimate combination of blockchain technology and other developing technologies such as artificial intelligence, big data, and cloud computing can effectively handle fatal pandemics such as the coronavirus. The primary areas where blockchain is helping in combating coronavirus are listed below [15]:

1. The first area is controlling the disease [16]. Effective and reliable disease surveillance is required for infectious disease control and pandemic prevention. Diseases that can be tracked and controlled with blockchain include the Ebola virus, yellow fever, cholera in Africa, Nipah in Asia, coronavirus, and others. This is accomplished by putting the blockchain network in people's electronic devices so they can be used globally to track the development of COVID-19 and other diseases among humans. In COVID-19, blockchain technology is critical for assisting virus sufferers by immutably recording patient symptoms of infection. BurstIQ's platform enables healthcare organizations to manage huge amounts of patient data in a safe and secure manner. Its blockchain allows for the secure storage, sale, sharing, and licensing of data while adhering to HIPAA regulations. BurstIQ's platform, which has complete and up-to-date information about an individual's health and healthcare activity, could aid in the detection of opioid and other prescription drug abuse. Factom develops tools to assist the healthcare business in securely storing digital information on the company's blockchain network, which is exclusively accessible to hospitals and healthcare managers. Physical papers can be embedded with Factom security chips that save patient information as private data that are only accessible by authorized individuals. The US Department of Homeland Security awarded Factom a roughly $200,000 grant in June 2018 to beta test a platform aimed at combining secure data from Border Patrol cameras and sensors to better evaluate the benefits of blockchain in "a realistic field scenario."

2. The second area is related to traceability. The term "traceability" refers to the ability to track infected patients. Controlling the spread of coronavirus is critical. With blockchain, infected patient travels can be tracked, real-time data about impacted areas can be provided, and direct fighting actions may be reported. BT can also be used to track people's movements in virus-free zones. The chain blocks are used to record information on safe zones, such as population, location, and the current condition of the coronavirus outbreak. To ensure transparency in the medical supply chain, goods and medical supplies must be tracked constantly. This tracking is possible thanks to the blockchain network's transaction logging and monitoring capabilities. The Centers for Disease Control and Prevention are investigating blockchain as a means of tracking infections in a supply chain-like fashion. The time stamps, peer-to-peer health reporting, and data-processing capabilities of blockchain, according to the US government agency, can assist in recording disease outbreaks in real time. Scientists can discover the origin of a disease and trends that aid in disease suppression by investigating the trail of reported outbreaks. The CDC may use blockchain to track the opioid epidemic. IBM is collaborating with the CDC to create a blockchain-based monitoring system that will allow public health organizations to collect data on patients and prescriptions more efficiently.
3. Maintaining a steady supply of medicines and nutrients has become a significant concern for the healthcare industry during this pandemic crisis. So the third area revolves around the use of blockchain in the commodities supply chain, and the trade supply chain has proven to be extremely beneficial. It can ensure the medical chain's stability by securely linking blocks and transactions. As a result, blockchain encryption is utilized to protect supply chain data privacy. During COVID-19, IBM announced the launch of a blockchain network to support the medical supply chain, named Rapid Supplier Connect. Chronicled creates blockchain networks that show proof of ownership. The networks assist pharmaceutical businesses in ensuring that their drugs arrive on time, and also allow law enforcement to investigate any suspect activities such as drug trafficking. In 2017, Chronicled launched the Mediledger Project, a blockchain-based ledger focused on medical supply chain security, privacy, and efficiency. Results from this project, according to the business, show that their blockchain-based system "is capable of operating as an interoperable system for the pharmaceutical supply chain" and "can meet the data privacy standards of the pharmaceutical industry."
4. One of the most important characteristics of blockchain is its transparency. It is critical to protect the personal data and information of patients undergoing treatment. Due to unconfirmed data, the spread of fake news on social media causes anxiety and panic. Because of its ability to check information and deliver real-time data updates, blockchain could be a promising solution to ensure data accuracy. It can help with the move from interoperability driven by institutions to interoperability driven by patients. Robomed blends AI and blockchain to provide a single point of care for patients. To collect patient data and share it with the patient's medical team, the company uses chatbots, wearable diagnostic gadgets, and telemedicine sessions. The Panacea platform from Robomeds involves patients in smart contracts that encourage and guide them toward improved health. Robomed collects patient data securely and shares it with the patient's healthcare providers using blockchain. To more securely store and distribute medical records, the Taipei Medical University Hospital recently integrated blockchain, including Robomed's network.
5. During the COVID-19 epidemic, BT could be critical in tracking healthcare tools, medications, and other items. It guarantees that healthcare instruments are transported safely and securely from one location to another. Alipay, in collaboration with the Zhejiang Provincial Health Commission and the Chinese Ministry of Economy and Information Technology, recently established a blockchain-based platform. Blockpharma provides an

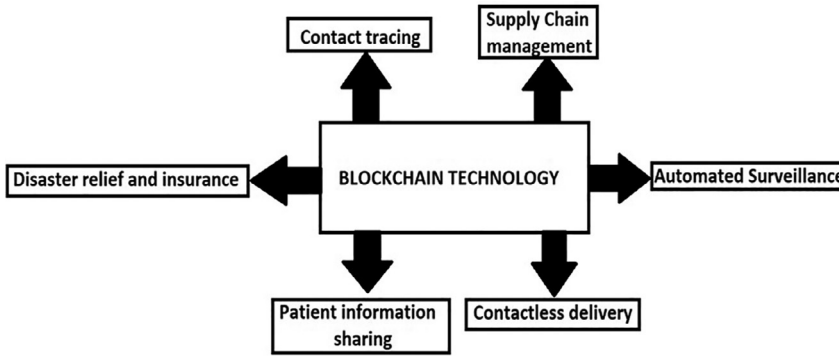

Fig. 7 Various domains in healthcare leveraging blockchain technology.

anticounterfeiting and medicine tracking solution. The company's software scans the supply chain and verifies all points of shipment, alerting patients if they are receiving counterfeit medications. Blockpharma picks out the bogus 15% of all pharmaceuticals in the world with the use of a blockchain-based SCM system. The company's blockchain-based solution can help people avoid counterfeit drugs through its app. Fig. 7 showcases various domains in the healthcare sector leveraging blockchain globally.

6 Conclusion

Blockchain is the buzzword of the year, and as this new technology evolves, it appears that it is ready to disrupt everything from banking to supply chain operations. Particularly in healthcare, there is a massive opportunity for a blockchain revolution to disrupt and lead a digital transformation. From medical records to pharmaceutical supply chains to smart contracts for payment distribution, there are plenty of opportunities to leverage this technology. Every modern healthcare system is built on the foundation of EHR. Each visit to our doctor tends to get longer and more complicated. Every hospital as well as every doctor's office has a different way of keeping these records. As a result, obtaining them is not always simple for healthcare providers. Some companies such as Patientory, Medibloc, or Medicalchain aim to solve this very problem. The goal is to give patients authority over their entire medical history and one-stop access to it for patients and physicians as well. Blockchain would not only simplify and make access more efficient but inherently bring data security to the field as well. The pharmaceutical industry has one of the highest standards for product safety, security, and stability; it is ripe for disruption. For example, supply chain management with blockchain can be monitored securely and transparently. This can greatly reduce time delays and human mistakes. It may also be used to track coats, labor, and even waste emissions throughout the supply chain. It may be used to check the validity of items by following them back to their source, battling the counterfeit medication business, which loses $200 billion each year. Companies such as Chronicled, Blockpharma, and Modum are already working toward more efficient blockchain logistic solutions. Modumin particular works in compliance with EU laws that require proof that medicinal products have not been exposed to particular conditions, especially certain

temperatures that may compromise their quality. Companies such as EncrypGen and Nebula Genomics are building blockchain platforms to enable people to share genomic data safely and securely on a new emerging market. They bet in the future that opportunities around personnel genome sequencing will create a data market worth billions of dollars, and what is the best technology to solve data security issues and to ensure that data gets from the source to its end users without any middleman? It is the blockchain. Along with the pros, there are definite cons to this technology. Because each transaction necessitates the utilization of strong hardware resources, it consumes a lot of energy. The technology's main drawback is its scalability. Because the majority of nodes must approve transactions before they can be validated, this takes time. Another disadvantage of blockchain is its complexity, which necessitates the creation of a large user network. Another significant problem that this technology faces is maintaining privacy.

References

[1] B.A. Tama, B. Kweka, Y. Park, K.H. Rhee, A critical review of blockchain and its current applicat ions, 2017, pp. 109–113, https://doi.org/10.1109/ICECOS.2017.8167115.
[2] S. Nakamoto, Bitcoin: A peer-to-peer electronic cash system, 2008, p. 9. www.bitcoin.org.
[3] https://www.investopedia.com/terms/b/blockchain.asp.
[4] K. Rabah, Challenges & opportunities for blockchain powered healthcare systems: a review, in: ISSN 2523-5680, no-1, 2017, pp. 45–52.
[5] T.-T. Kuo, H.Z. Rojas, L. Ohno-Machado, Comparison of blockchain platforms: a systematic review and healthcare examples, J. Am. Med. Inform. Assoc. 26 (5) (2019) 462–478, https://doi.org/10.1093/jamia/ocy185.
[6] L. Bell, W.J. Buchanan, J. Cameron, O. Lo, Applications of blockchain within healthcare, in: 2020 Blockchain in Healthcare Today™, 2020, https://doi.org/10.30953/bhty.v1.8. ISSN 2573-8240 online.
[7] A. Azaria, A. Ekblaw, T. Vieira, A. Lippman, MedRec: Using Blockchain for Medical Data Access and Permission Management, in: 2nd International Conference on Open and Big Data, 2016, pp. 25–30.
[8] A. Shahnaz, U. Qamar, A. Khalid, Using Blockchain for electronic health records, IEEE Access 7 (2019) 147782–147795, https://doi.org/10.1109/ACCESS.2019.2946373.
[9] S. Salam, B. Faith, P.P. Martín, B. Ramalingam, The contribution of digital technologies to service delivery: an evidence review, 2017, https://doi.org/10.13140/RG.2.2.28618.16329.
[10] M. Mettler, Blockchain technology in healthcare: The revolution starts here, in: 2016 IEEE 18th International Conference on e-Health Networking, Applications and Services (Healthcom), 2016, pp. 1–3, https://doi.org/10.1109/HealthCom.2016.7749510.
[11] H.S. Chen, J.T. Jarrell, K.A. Carpenter, D.S. Cohen, X. Huang, Blockchain in healthcare: a patient-centered model, Biomed. J. Scient. Tech. Res. 20 (3) (2019) 15017–15022.
[12] T. Ahram, A. Sargolzaei, S. Sargolzaei, J. Daniels, B.A. Amaba, Blockchain technology innovations, in: 2017 IEEE Technology & Engineering Management Conference (TEMSCON), 2017, pp. 137–141.
[13] T. Nugent, D. Upton, M. Cimpoesu, Improving data transparency in clinical trials using blockchain smart contracts, F1000 Research 5 (2016) 2541, https://doi.org/10.12688/f1000research.9756.1.

[14] P. Mamoshina, L. Ojomoko, Y. Yanovich, A. Ostrovski, A. Botezatu, P. Prikhodko, E. Izumchenko, A. Aliper, K. Romantsov, A. Zhebrak, I. Ogu, A. Zhavoronkov, Converging blockchain and next-generation artificial intelligence technologies to decentralize and accelerate biomedical research and healthcare, Oncotarget 9 (2018) 5665–5690, https://doi.org/10.18632/oncotarget.22345.

[15] A. Sharma, S. Bahl, A.K. Bagha, M. Javaid, D.K. Shukla, A. Haleem, Blockchain technology and its applications to combat COVID-19 pandemic (published online ahead of print 2020 Oct 22), Res. Biomed. Eng. (2020) 1–8, https://doi.org/10.1007/s42600-020-00106-3.

[16] ZIGURAT, Innovation and technology business school. Blockchain in healthcare: the case of coronavirus, 2020, Available from: https://www.e-zigurat.com/innovation-school/blog/blockchain-in-healthcare/.