Front. Eng. Manag. 2020, 7(4): 605–614
https://doi.org/10.1007/s42524-020-0138-9

RESEARCH ARTICLE

Jianxia GONG, Lindu ZHAO

Blockchain application in healthcare service mode based on Health Data Bank

Abstract Blockchain is commonly considered a potential disruptive technology. Moreover, the healthcare industry has experienced rapid growth in the adoption of health information technology, such as electronic health records and electronic medical records. To guarantee data privacy and data security as well as to harness the value of health data, the concept of Health Data Bank (HDB) is proposed. In this study, HDB is defined as an integrated health data service institution, which bears no "ownership" of health data and operates health data under the principal–agent model. This study first comprehensively reviews the main characters of blockchain and identifies the blockchain-based healthcare industry projects and startups in the areas of health insurance, pharmacy, and medical treatment. Then, we analyze the fundamental principles of HDB and point out four challenges faced by HDB's sustainable development: (1) privacy protection and interoperability of health data; (2) data rights; (3) health data supervision; (4) and willingness to share health data. We also analyze the important benefits of blockchain adoption in HDB. Furthermore, three application scenarios including distributed storage of health data, smart-contract-based healthcare service mode, and consensus-algorithm-based incentive policy are proposed to shed light on HDB-based healthcare service mode. In the end, this study offers insights into potential research directions and challenges.

Keywords Health Data Bank, blockchain, data assets, smart contract, incentive mechanism

Received November 28, 2019; accepted August 25, 2020

Jianxia GONG, Lindu ZHAO (✉)
School of Economics & Management, Southeast University, Nanjing 210096, China
E-mail: ldzhao@seu.edu.cn

This work was supported by the National Natural Science Foundation of China (Grant No. 71671039).

1 Introduction

Blockchain is commonly considered a potential disruptive technology (Felin and Lakhani, 2018), which is a distributed ledger technology in the form of a distributed transactional database secured by cryptography and governed by a consensus mechanism (Constantinides et al., 2018) to verify transactions and to ensure the legitimacy of a transaction. These measures prevent double-spending, censorship, or fraud. Such conditions can create a trustworthy environment for high-value transactions in a distributed infrastructure without an intermediary (e.g., a bank, a service platform) (Risius and Spohrer, 2017). The price of Bitcoin, a cryptocurrency based on blockchain technology, increased dramatically to $900 in January 2017 since its launch in 2009, and it peaked to more than $19500 in December 2017 (Cheng et al., 2019). The rise in Bitcoin price came with growing interest in how blockchain technology could improve and perhaps revolutionize many industries, such as finance, energy, government, and healthcare (Ziolkowski et al., 2020). A number of countries are ramping up their efforts to accelerate blockchain development. For example, applications of blockchain-based industrial Internet of Things (IoT) systems have immensely increased. A key feature of blockchain is the enhancement of security and incorporation of a large number of devices in IoT ecosystems (Moin et al., 2019). With the transformation of energy systems from fossil fuel to distributed energy resources, blockchain technology can improve current practices significantly, ranging from energy trading, electric vehicle charging, as well as e-mobility (Andoni et al., 2019). In addition, critical assessments for the application of blockchain in governmental organizations and smart cities have been discussed (Chen, 2019; Ziolkowski et al., 2020). Given its inherent nature, blockchain can provide a satisfactory solution to privacy and security problems, providing a promising paradigm for domains with high demand for privacy and security.

With the growing number of electronic health records

(EHRs), electronic medical records (EMRs), wearable devices, sensors, and Internet of Medical Things (IoMT), we are facing the explosion of health big data. Although the issues of security and circulation of health data play a vital role, these concerns have not been effectively solved. In 2018, authorities in Singapore announced that Singapore's largest healthcare group SingHealth was targeted by a major cyber-attack, resulting in an unprecedented breach that affected approximately 1.5 million patients' records (Tan et al., 2019). These concerns show an urgent demand to develop a paradigm to effectively and efficiently record, track, and manage massive health data. The unique features of blockchain have the potential to overcome challenges related to health data. At present, blockchain in healthcare is progressing from constructing the underlying structure at the industrial ecology level to tackling technological difficulties in realizing advanced application in business. For example, Alibaba and Tencent have been pioneers in healthcare blockchain. Early in 2017, Alibaba, collaborated with the government of Changzhou city, connected the city's existing infrastructure of medical treatment systems by blockchain (Zhou et al., 2019). Tencent launched blockchain-based digital prescriptions in medical treatment, which are tamper-resistant (Jia et al., 2018).

In response to challenges in health data sharing, such as delineation and implementation of accepted standards for health data, accurate patient identification and record matching, Gold and Ball (2007) presented an alternative option to health information system, which is the Health Record Banking (HRB) system. This system emulates commercial banking and provides a means for financial independence and a mechanism for fostering medical and health research. The concept of the Health Data Bank (HDB) was first proposed in 1997 (Dodd, 1997) and was regarded as a promising third-party for mining the value behind the huge amounts of health data and providing valuable service to the individuals, medical institutions, and public governments (Gong and Zhao, 2019). A uniform definition of HDB has not been reached yet. In this study, we consider the HDB as a form of health data service institution, which bears no "ownership" of health data and operates health data under the principal–agent model. HDB users include individuals (healthy people, patients, and rehabilitation crowd), organizations (pharmaceuticals, insurance companies, and hospitals), and government departments. The value creation of health data lies not only in data processing but also in the collaborative process of data bodies. Hence, how to optimize business processes, enhance health data management service mode, and improve collaboration among different agents in the HDB requires further investigation. Our motivation lies in the feasibility of integrating blockchain with the HDB. The contributions of this study are as follows: (1) reviewing the current application of blockchain technology in typical healthcare scenarios; (2) discussing the key challenges in blockchain application in the HDB; and (3) exploring three scenarios of blockchain application in HDB-based service mode.

The remainder of this study is organized as follows. Section 2 describes the unique features of blockchain that are particularly suitable for the healthcare industry. Section 3 reviews the typical applications of blockchain in the healthcare area. Section 4 discusses the challenges in the HDB's development and the potential opportunities of blockchain application in the HDB. Finally, Section 5 presents the conclusions and future research directions.

2 Advantages of blockchain in healthcare

In essence, blockchain is composed of distributed ledgers with timestamps. The unique feature of blockchain provides an effective solution to trust issues in the digital world. In healthcare, trust is the priority concern, because health data are commonly obtained from different organizations and individuals. Such data include patients' records, mutual information of medical equipment, circulation information of medicine, and insurance contracts. In this section, we analyze the advantages of blockchain in healthcare.

(1) Distributed storage ensures the consistency of health data

In the traditional centralized storage pattern, all health and medical data are kept in the central server computer. The computers in each hospital department can store, collect, and query health data. In this case, health data are compromised when the central server is attacked by hackers. In fact, the healthcare sector saw nearly millions of patient records compromised in hundreds of breaches in 2010–2017 (Chernyshev et al., 2019). Statistics remain on the rise. On the contrary, in the distributed storage pattern of blockchain, each member of the network stores a copy of the health data ledger. In addition, the stored data in the ledger are difficult to tamper with due to the validation mechanism of blockchain. Hence, the blockchain of health data can be secure and tamper-resistant.

(2) Asymmetric cryptographic algorithms achieve authentication

The asymmetric cryptographic algorithm can help solve the trust problem in health data management (Babich and Hilary, 2020). Trust is the foundation of healthcare service. "Trust" means that patients are convinced that the healthcare service provider could give them high-quality medical treatment; whereas, the medical and nursing staff are confident that patients would follow the doctors' advice. The blockchain-based healthcare system is effective to solve the authentication problem via the asymmetric cryptographic algorithm. Each node holds two cryptographic keys, a public key and a private key. The public key can be distributed to anyone who wants to send encrypted data to the holder of the private key. Asymmetric encryption algorithms use the public–private key pair for encryption and decryption (Babich and Hilary, 2020). Health data are encrypted by the sender, who obtains the receiver's public key and is verified by the network. This message can only be decrypted by the receiver's private key. With such one-way nature of the encryption function, access permission and privilege control can be predefined for different users to ensure privacy and transparency.

(3) Self-enforceable smart contracts reduce transaction cost

Smart contract, or self-executing contract, is the computer code stored and replicated on the system and supervised by the blockchain, resulting in ledger feedback, such as transferring money and receiving a product or service (Dolgui et al., 2020). Smart contracts can process credible transactions without third parties, because these transactions are trackable and irreversible in blockchain. Smart contracts can reduce transaction cost and strengthen interoperability between transaction systems by removing intermediaries. For example, the company MedRec applies smart contracts on an Ethereum to associate patients' medical records with access permission and data retrieval instructions (Ekblaw et al., 2016). Other applications of blockchain in healthcare include medical claim reimbursements among patients, hospitals, and insurance service providers. The application of blockchain makes the claim process integrated, traceable, and transparent. If a patient uses smart contracts to buy healthcare insurance, then all details of the reimbursement policy will be automatically recorded in the patient's profile. When the patient receives the medical treatment procedure that meets the insurance policy, the smart contract would be triggered. The hospital would transfer the medical digest rather than the entire medical record to the insurance company, then the insurance company would pay the patient directly. The patient does not need to wait for a long time as in a traditional claim reimbursement.

(4) Consensus algorithms encourage collaboration and sharing behavior

The consensus algorithm makes sure that each new block added to the blockchain is the only version of the truth that is agreed on by all nodes in the network. The consensus algorithm consists of several objectives, such as reaching an agreement, equal rights to every node, collaboration, and mandatory participation of each node in the consensus process. Consensus algorithms have several types, for example, Proof of Stake (PoS), Proof of Work (PoW), and Practical Byzantine Fault Tolerance (PBFT) (Gerry and Brett, 2020). Among them, PoW was first created and employed by Bitcoin, in the protocol of which, validators (or called miners) compete to solve a cryptographical puzzle. This mathematical puzzle requires massive computational power. A miner who solves the puzzle first takes a financial reward by adding the validated block to the blockchain. The company Nebula Genomics, which focused on genomic data analysis, proposed Proof of Devotion (PoD) consensus algorithm on the basis of the devotion of accounts to reward the validator Nebulas token, which functions as the original money in the Nebulas network (Shabani, 2019).

3 Notable use cases of blockchain in healthcare applications

The Gartner issued a report about the blockchain business in 2019, which presented that blockchain in healthcare is at the beginning phase of the peak of inflated expectations, implying that the blockchain business would take more than 10 years to have an impact on the healthcare industry (Gartner, 2019). In this section, we study the typical and current business cases of blockchain in healthcare, including health insurance, pharmacy, and medical treatment. Blockchain technology can provide an effective paradigm to solve issues such as health data management and privacy protection. Table 1 lists the typical blockchain businesses in healthcare applications in the recent five years.

3.1 Health insurance

Blockchain can help automate claim processes, save billions of hours of paperwork, and reduce human error because all data are safely stored in ledgers. Smart contracts enable blockchain users to transfer valuable data in a transparent manner without the interference of intermediaries. Insurance companies can immediately accept or refute any insurance claim according to the principles of the smart contract.

Table 1 lists some blockchain-based health insurance company cases. Among them, Zhongtuobang is a health insurance platform, and its blockchain network is based on WeChat's mechanism for mutual funds (Mao, 2019). Zhongtuobang provides critical illness policies and makes use of smart contracts to authenticate policyholders' identities. Users can join this new mutual assistance plan with an advanced deposit of only \$1.5 and gain repayment up to approximately \$42800. If there are 1 million users and when one user applies for \$42800 as mutual aid money, then each user only needs to share \$0.05.

3.2 Pharmacy

The authenticity and quality of medicine are essential for patients. The traditional pharmaceutical industry uses central databases, which are costly and are not possible to be used for large-scale interoperability. This storage pattern exposes the risk of diversion and counterfeit, and causes a trust gap between inventory systems. However, a blockchain-based network can meet the track-and-trace demands of drug quality regulation, in which a product identifier can be tracked at any point in the drug supply

Table 1 Typical blockchain businesses in healthcare applications

Area	Company	Year launched	Description
Health insurance	Qingsongchou	2014	Insurance
	InsurChain	2015	Insurance
	Zhongtuobang	2016	Insurance
	Anlink	2017	Insurance
	ShineChain	2017	Insurance
Pharmacy	BlockVerify	2015	Blockchain technology
	Hashed Health	2016	Healthcare products
	Florence	2016	Pharmaceutical
Medical treatment	Gem Health	2013	Genomic data
	AliHealth	2015	Medical informatization
	NestVision	2015	Medical informatization
	IBM Watson Health	2015	Healthcare blockchain
	Philips Healthcare	2016	Medical informatization
	Hashed Health	2016	Healthcare blockchain
	Akiri	2017	Healthcare blockchain
	AIDOC	2017	Medical informatization

Source: Crunchbase Company. Available at: crunchbase.com.

chain, from the manufacturer to the distributors. For example, if a product is presented with the incorrect hash at any point in the supply chain, then the distributor network can identify immediately and reject the product as counterfeit.

Although the adoption of blockchain in the health sector is rarer than that in other sectors, some companies have had great achievements. For example, BlockVerify and Hashed Health use the blockchain to ensure the authenticity of their pharmaceuticals. Good Shepherd Pharmacy and Remedi-Chain use blockchain technology to track medicine logistics in the drug supply chain by recreating missing information, such as where the drug was manufactured and the expiration dates, to validate the legitimacy of medication (Benniche, 2019).

3.3 Medical treatment

Many blockchain companies have entered the area of medical treatment. Although EHRs are important for patients and doctors, no efficient system can keep all records in one place. Moreover, different organizations have different systems that severely lack interoperability. A blockchain for health data management can align the data mess in the healthcare industry. In addition, medical staff credentialing is a time-consuming effort, but it is a necessary process to ensure the quality of care in organizations. The objective of credentialing is to ensure that only qualified doctors are employed as medical staff and that they practice within their scope of experience. Given that blockchain can be verified and updated incrementally, the technology may be well suited for the credentialing process in medical treatment.

Gem Health, launched in 2016, intends to leverage blockchain technology to address the trade-off between patient-centric care and operational efficiency by creating a healthcare ecosystem connected to universal data infrastructure (Engelhardt, 2017). The Gem Health blockchain network includes identity schemes, data storage, and smart contract applications. To date, Gem has raised \$20.5 million in Series A funding round by the end of 2019.

4 Blockchain in HDB-based service mode

Blockchain technology has been a promising disruption for the healthcare domain, and various business companies have explored the operation modes in this area. In this section, a novel healthcare ecosystem incorporated with HDB based on blockchain is investigated, that is, blockchain-based HDB. We take into consideration not only the security, transparency, and interoperability of health data but also the data assets value.

4.1 Challenges of HDB development

The aim of HDB is to provide precision medicine service and personal healthcare management service (including preventive intervention and clinical intervention), as shown in Fig. 1. In general, HDB should operate similarly to commercial banking. HDB includes small account holders (individuals with personal health record), medium-sized clients (physicians or pharmacies), and large

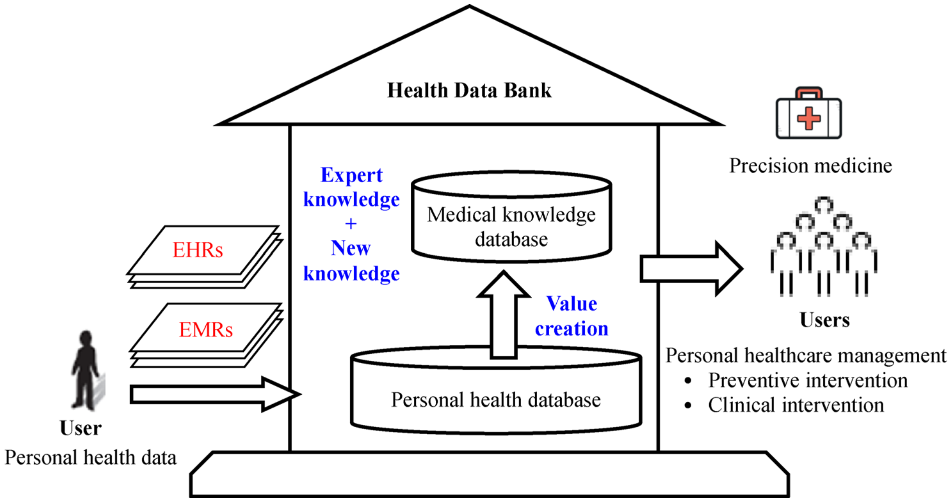

Fig. 1 Conceptual model of Health Data Bank.

enterprise customers (hospitals and health maintenance organizations (HMOs)). Different accounts would be used for storing different classes of health data, such as EMRs and EHRs including health index, illness history, disease classification, hereditary disease history, and gene sequence. Moreover, HDB should guarantee data privacy, data security, and intellectual property. HDB works as a bank that can absorb public deposits and grant loans so as to operate the health data assets and provide digital service for patients, medical institutions, and governments.

What needs to be emphasized is that HDB bears no "ownership" of health data and operates health data under the principal–agent model. Hence, HDB can utilize health data that are only authorized by owners (e.g., individuals, medical institutions) to generate the value for healthcare management. As shown in Fig. 1, HDB can gather huge amounts of personal health data and generate standard medical knowledge data through the modules of data integration, knowledge discovery, and expert knowledge. Specifically, the medical knowledge database consists of new knowledge and expert knowledge. New knowledge refers to scientific knowledge, such as the characteristics of gastric cancer or the cause of diabetes. Such knowledge is generated from personal health data by applying big data analysis techniques in data mining, knowledge discovery, and knowledge refining. Expert knowledge refers to the clinical experience of medical experts, such as complete records of patients' treatment process and effective clinical guidelines. HDB can retrieve medical knowledge data packages and provide valuable information for individuals and institutions according to their needs.

HDB acts as a courier in the network of value transmission, which is composed of individuals, medical institutions, pharmaceutical companies, insurance companies, and supervision institutions. HDB can push customized information to an individual and offer the individual's data to different institutions, with simultaneously guaranteed security and privacy. In addition, professional medical knowledge can be shared between medical institutions so that they can increase the ability to provide precision healthcare services, such as accurate risk prediction, precise diagnosis of disease, accurate classification of diseases, precise application of drugs, and accurate assessment of efficacy.

Similar to commercial banking, HDB would give "interests" in return to individuals and medical institutions. For individuals, they could earn interests that would enable them to "buy" different types of personal health care management services. HDB could analyze and update the basic information, health index, health diary, and hereditary disease history in HDB. Once early warnings are given regarding health status, HDB would send the information to the patient. Medical institutions can also benefit from HDB. Hospitals can share medical knowledge data about rare diseases to achieve precision medical service. Medical research topics can be discovered from massive health data. Insurance companies can seek main factors for claimants and control the insurance risk. Furthermore, governments can optimize public healthcare resource allocation on the basis of public health data with consideration to equality and efficiency.

To achieve the sustainable development of HDB, several critical issues need to be solved.

(1) Privacy protection and interoperability of health data

The evolution of HDB shows that the security of health data are the first and foremost issue, and the conflict between data privacy and openness makes data sharing a challenging task. Numerous health data scandals were reported on the traditional centralized storage pattern. The threat to data security has a profound impact on individuals' trust in HDB. Effective data encryption method is essential, but the interoperability problem should also be taken into consideration. Thus, only authorized users can decrypt health data, and users with different security levels have different permissions.

(2) Property rights

In the sharing and circulation process of personal health data and medical knowledge data, the data are easy to be copied. If the individual property rights of the data producer, user, manager, and beneficiary cannot be determined, then the long-term operation of HDB will be obstructed. Another issue lies in the operation structure if the data-sharing system is constructed by multiple parties: Any party in this system would have the ambition to lead the operation, eventually resulting in competition for rights.

(3) Health data supervision

To win the trust of users, the transactions of personal health data and medical knowledge data within the HDB should be supervised by the functional departments or non-profit organizations. Increasing the transparency of health data and transactions and protecting data privacy at the same time are great challenges.

(4) Willingness to share health data

The value-added services of HDB are provided to users on the basis of huge amounts of health data contributed by individuals and medical institutions. The incentive policy for users to increase their willingness to share health data is extremely important. If users receive the same income or return regardless of the quantity and quality of the shared health data, then they would be dissatisfied with HDB in the long run.

The development of blockchain technology brings opportunities to solve critical issues facing HDB.

4.2 Blockchain-based Health Data Bank

The remarkable features of blockchain, such as distributed ledger technology, cryptographic algorithm, smart contracts, and consensus mechanism, can be integrated with HDB. The architectural form of a public chain, a private chain, and an alliance chain makes the operation of HDB flexible.

4.2.1 Distributed storage of health data

Unlike the centralized storage system, the data in HDB can be kept in the distributed storage system based on blockchain (Fig. 2), thus ensuring a high degree of security and privacy protection.

Each ledger in the blockchain stores its own health data. Each member of the network receives a full copy of the blockchain, which can later be used to validate the entire blockchain. The health data cannot be tampered with if they are not authorized by the owner. Given that all transactions are easy to track and trace accurately, the ownership of the health data can be verified. The transparency and privacy levels of a network can be strengthened by using asymmetric cryptographic authentication. With a public key and a private key, the identities of different users can be determined during the circulation of health data. Thus, users can take full control of their health data with access permission.

In addition, different blockchain architectures, including public, private, and alliance chains, can be constructed for different service modes of HDB for individuals and medical institutions, yielding different levels of privacy. The main difference between the three blockchain architectures is the access mechanism, which determines the degree of publicity of the blockchain.

In a public chain, anyone can query transactions, and a transaction can be validly confirmed. Most blockchain projects are public chains, such as Bitcoin and Ethereum. Given that everyone in this network is in a competitive environment, the public chain needs a consensus mechanism to select the accounting nodes, which is called mining. Owing to the characteristics of the public chain, the

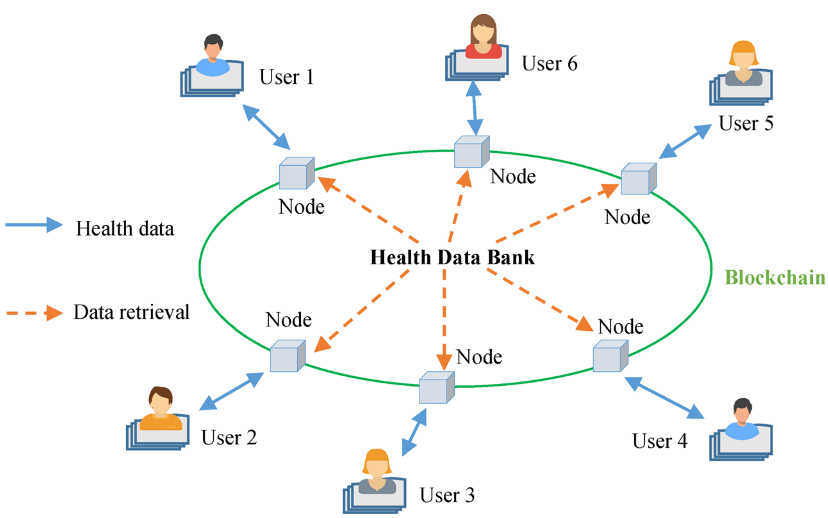

Fig. 2 Distributed health data storage platforms in HDB.

personal health data services provided by HDB can be designed integrated with it, just as shown in Fig. 2. An individual's reward for sharing health data can be used to pay for the corresponding service. We should further determine the consensus mechanism to offer the incentive for individuals.

In a private chain, only the person or the organization with write permission has the authority to the account, and participation is recorded. Read access can be open to another party and can be restricted to any degree. Usually, a private chain is applied to companies or organizations. Given that the accounting environment is credible, a private chain has the advantages of fast accounting and high privacy. As shown in Fig. 3, in the operation of HDB, a private chain can be utilized for authorized medical institutions and scientific research institutions, which will help accumulate medical knowledge, tackle rare diseases, facilitate precision medicine, and reduce operational costs.

An alliance chain refers to a blockchain that is managed and maintained by multiple organizations. The nodes participating in an alliance chain are selected in advance; hence, similar to a private chain, the number of nodes in an alliance chain is small. The degree of openness and decentralization of an alliance chain is limited. An alliance chain is not limited to transactions, but may also include industry information sharing. Hence, alliance chains are applicable to connect the HDBs in different areas, promoting resource integration, as shown in Fig. 4. It would be especially useful to curb the wide spread of infectious diseases.

4.2.2 Smart-contract-based healthcare service mode

With the development of IoMT, rich data can be obtained, such as heart rate and fitness records from wearable devices, gene information, historical medical records, and medical examinations involving diagnosis from doctors. As described in the public-chain-based HDB for personal healthcare management service, personal health data can

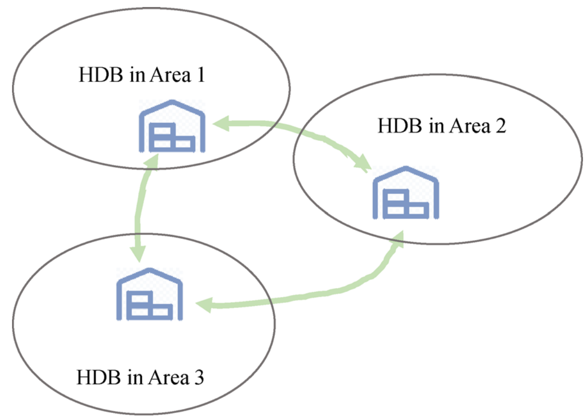

Fig. 4 Alliance-chain-based Health Data Bank for multi-area resource integration.

be put on the chain and will be under the control of individuals. With the help of smart contracts and artificial intelligence technologies, personal health management and preventive intervention can be achieved.

Smart contracts can monitor an individual's health status, and once the specific conditions are triggered, HDB can guide the behavior of this individual for a healthier lifestyle or to control chronic diseases. In some emergency situations, information can be directly transferred to the hospital and family members, which can guarantee the safety of the elderly, as shown by the dotted line in Fig. 5.

As shown in Fig. 5, health status notifications from HDB can help healthcare providers easily intervene with patients in a timely manner. Smart contracts would evaluate uploaded health data and release corresponding warnings to users and healthcare providers of HDB. In this scenario, only authorized healthcare providers can access and inspect patients' EHRs or full health data. Smart-contract-based healthcare service can provide an interactive communication interface for individuals and healthcare providers while protecting the integrity and privacy of patients' health care process.

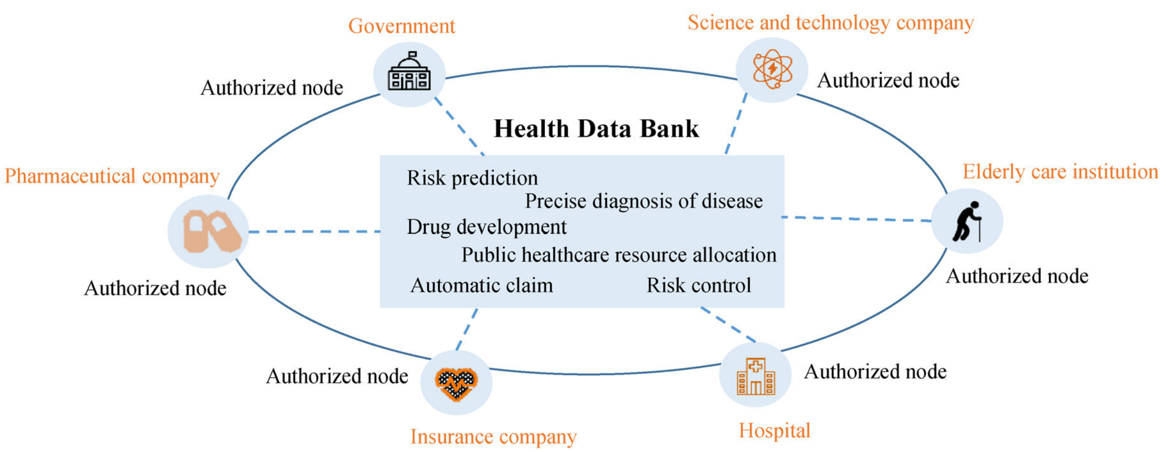

Fig. 3 Private-chain-based Health Data Bank for medical knowledge service.

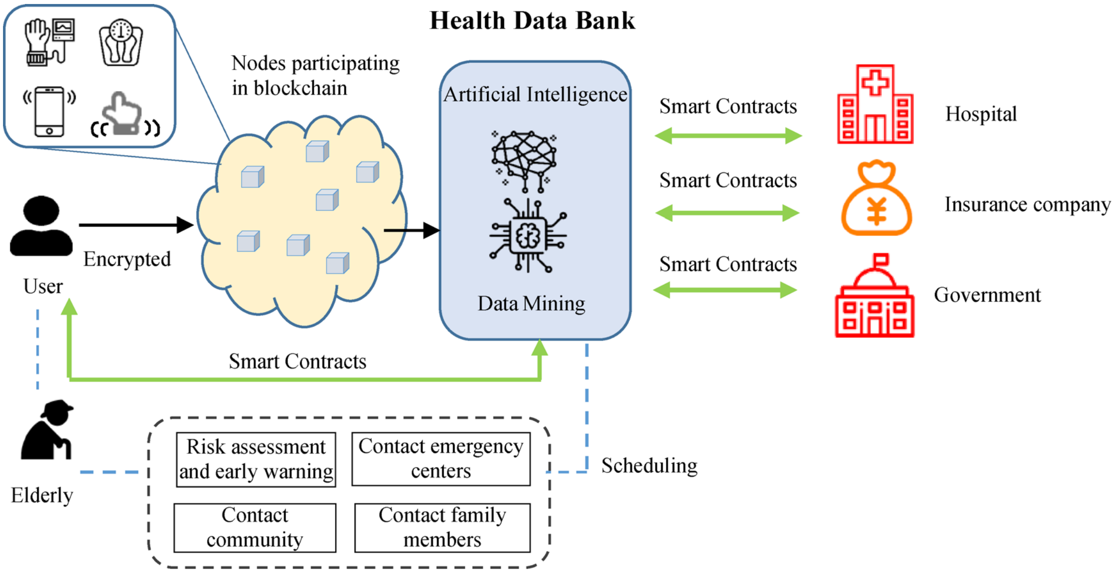

Fig. 5 Smart-contract-based healthcare service mode.

Apart from health care management, HDB could provide precision epidemic management service for the public. To prevent the outbreak of an epidemic, relevant governments or disease control departments could monitor and access individuals' health data on the basis of specific smart contracts through HDB. In this way, HDB can carry out real-time monitoring of key populations and gauge the health status of the population.

4.2.3 Consensus-algorithm-based incentive policy

Similar to commercial banking, the main revenue of HDB will be achieved by offering various health data services to individuals and medical institutions. The value generation of HDB is dependent not only on the huge amounts of health data shared by users but also on the collaborative process of data providers. Hence, HDB should design reasonable and applicable mechanisms to motivate users to share their health data and participate in the synergies of HDB in the long run. Given this background, we consider that the PoW and the PoD consensus algorithm could be taken into consideration.

To drive users to upload supplementing and comprehensive health data as required, we propose the flat pricing mode for HDB, wherein the data provider would be offered two forms of income: One is the fixed price in the form of interest, and the other is the incentive price (i.e., data utilization). On the basis of flat pricing mode, we design the consensus algorithm as an incentive policy as shown in Fig. 6. Users receive the token, the virtual currency in the blockchain, as the economic reward for their sharing behavior, similar to what miners do. Users can gain more tokens when the uploaded health data are large and consecutive. If the health data shared by a user are utilized by a data consumer, then their tokens will be increased. A token can be used to pay for the treatment cost or redeem special health-related services.

5 Conclusions and future work

By utilizing decentralized ledgers, asymmetric cryptographic algorithms, smart contracts, and consensus algorithms, blockchain is a promising technology that brings in transparency, traceability, and interoperability. In healthcare management, blockchain has been applied to different projects, including insurance, pharmacy, and treatment. HDB is a novel integrated healthcare management business mode, in which personal health data and medical knowledge data are regarded as data assets. Most importantly, HDB bears no "ownership" of health data, and it is designed to generate value from health data as an entrusted agent for individuals and medical institutions. However, some essential issues need to be answered for HDB's sustainable development. On the basis of the unique features of blockchain, we proposed several feasible resolutions.

We conclude this work with open questions that require further discussions. (1) First, the development of HDB and blockchain is in the early stage, and the standardization of the industry is based on national macro policies. Sound policy and legal systems should be established to ensure blockchain application in the healthcare area. (2) In the domain of healthcare, "data island" effect is pervasive in most hospitals. The reform of the information system of medical institutions is necessary to increase openness. Another important issue is the improvement of the legal system of health data areas so as to strengthen the

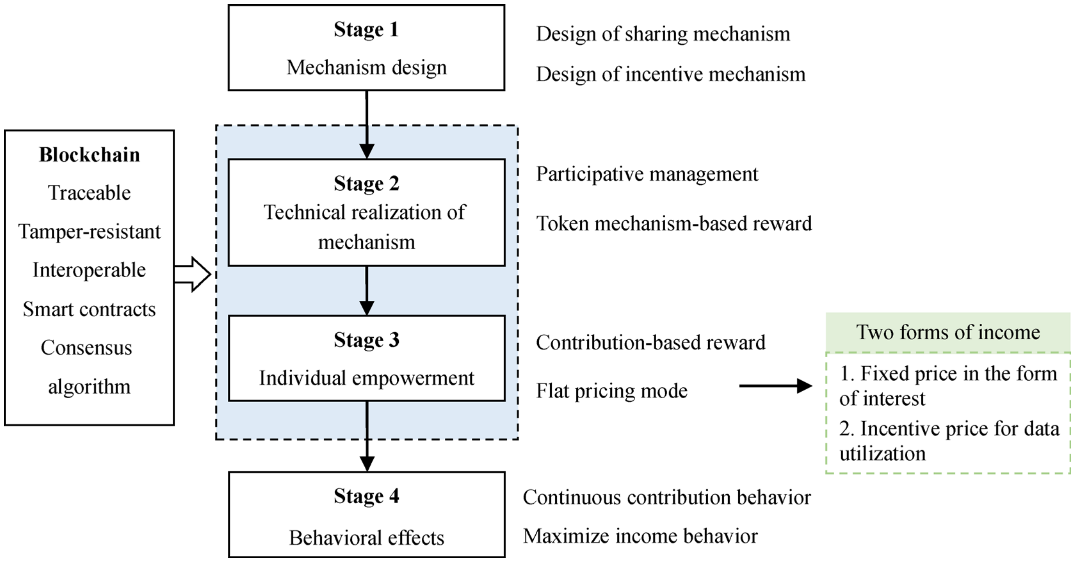

Fig. 6 Consensus-algorithm-based incentive policy.

supervision and management of the corresponding industry. (3) The role of blockchain lies not only in privacy protection but also in the protection of data assets value. We need to explore the value-creating interactions in the healthcare ecosystem and blockchain-based HDB healthcare service mode in breadth and depth. (4) Finally, from the technical view, extant blockchain is incapable of holding a large amount of health data in one block. One Bitcoin block is said to be capable of holding approximately 1 MB of data and takes approximately 10 min to process one transaction. However, an individual's health data expand over time, especially when diagnosis images are added. In addition, remote monitoring and diagnosis need less time delay. We must continue to increase research and development (R&D) investment on blockchain and strive for important breakthroughs in the innovation of its core technology. Despite increasing developments in blockchain technology, academic research is lacking on the economic, organizational, and managerial impacts of blockchain in healthcare. Further research into blockchain-based HDB will need to consider underlying technological and managerial challenges of the application of blockchain.

References

Andoni M, Robu V, Flynn D, Abram S, Geach D, Jenkins D, McCallum P, Peacock A (2019). Blockchain technology in the energy sector: A systematic review of challenges and opportunities. Renewable & Sustainable Energy Reviews, 100: 143–174

Babich V, Hilary G (2020). Distributed ledgers and operations: What operations management researchers should know about blockchain technology. Manufacturing and Service Operations Management, 22 (2): 223–240

Benniche S (2019). Using blockchain technology to recycle cancer drugs. The Lancet Oncology, 20(6): e300

Chen X (2019). The development trend and practical innovation of smart cities under the integration of new technologies. Frontiers of Engineering Management, 6(4): 485–502

Cheng S F, de Franco G, Jiang H, Lin P (2019). Riding the blockchain mania: Public firms' speculative 8-K disclosures. Management Science, 65(12): 5901–5913

Chernyshev M, Zeadally S, Baig Z (2019). Healthcare data breaches: Implications for digital forensic readiness. Journal of Medical Systems, 43(1): 7

Constantinides P, Henfridsson O, Parker G G (2018). Introduction—Platforms and infrastructures in the digital age. Information Systems Research, 29(2): 381–400

Dodd B (1997). An independent "Health Information Bank" could solve data security issues. British Journal of Healthcare Computing & Information Management, 14(8): 2

Dolgui A, Ivanov D, Potryasaev S, Sokolov B, Ivanova M, Werner F (2020). Blockchain-oriented dynamic modelling of smart contract design and execution in the supply chain. International Journal of Production Research, 58(7): 2184–2199

Ekblaw A, Azaria A, Halamka J D, Lippman A (2016). A case study for blockchain in healthcare: "MedRec" prototype for electronic health records and medical research data. In: Proceedings of the 2nd International Conference on Open & Big Data. Vienna: IEEE, 1–13

Engelhardt M A (2017). Hitching healthcare to the chain: An introduction to blockchain technology in the healthcare sector. Technology Innovation Management Review, 7(10): 22–34

Felin T, Lakhani K (2018). What problems will you solve with blockchain? MIT Sloan Management Review, 60: 32–38

Gartner (2019). Gartner 2019 Hype Cycle for blockchain business shows blockchain will have a transformational impact across industries in five to 10 years. Available at: gartner.com/en/newsroom/press-releases/2019-09-12

Gerry T, Brett H F (2020). Token-weighted crowdsourcing.

Management Science, in press, doi: 10.1287/mnsc.2019.3515
Gold J D, Ball M J (2007). The health record banking imperative: A conceptual model. IBM Systems Journal, 46(1): 43–55
Gong J, Zhao L (2019). Creditworthiness-based service differentiation strategy for health data bank. Procedia Computer Science, 159: 1833–1842
Jia K, Kenney M, Mattila J, Seppala T (2018). The application of artificial intelligence at Chinese digital platform giants: Baidu, Alibaba and Tencent. ETLA Reports, 81
Mao Q (2019). Developing status and system construction of crowd funding insurance system based on blockchain technology. Journal of Xihua University (Philosophy & Social Sciences), 38(2): 67–81 (in Chinese)
Moin S, Karim A, Safdar Z, Safdar K, Ahmed E, Imran M (2019). Securing IoTs in distributed blockchain: Analysis, requirements and open issues. Future Generation Computer Systems, 100: 325–343
Risius M, Spohrer K (2017). A blockchain research framework. Business & Information Systems Engineering, 59(6): 385–409
Shabani M (2019). Blockchain-based platforms for genomic data sharing: A de-centralized approach in response to the governance problems? Journal of the American Medical Informatics Association, 26(1): 76–80
Tan K H, Pang N L, Siau C, Foo Z, Fong K Y (2019). Building an organizational culture of patient safety. Journal of Patient Safety and Risk Management, 24(6): 253–261
Zhou T, Li X, Zhao H (2019). Med-PPPHIS: Blockchain-based personal healthcare information system for national physique monitoring and scientific exercise guiding. Journal of Medical Systems, 43(9): 305
Ziolkowski R, Miscione G, Schwabe G (2020). Decision problems in blockchain governance: Old wine in new bottles or walking in someone else's shoes? Journal of Management Information Systems, 37(2): 316–348