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Blockchain Technology in Health Care — Lessons and Implications from the COVID-19 Pandemic

Abstract. The aim of this article is to investigate possible applications of blockchain technology in the fight against the pandemic, which, among other negative consequences, has disrupted global supply chains. Bottlenecks in the supply of raw materials and intermediary products for drug production had cascading effects in other areas, causing shortages in the supply of finished products. The author shows how blockchain-based smart contracts can help improve the functioning of the health service in general, how they can be used to optimize treatment methods and make social insurance more efficient. After reviewing the key features of blockchain technology and tracking the stages of its development, from the creation of the Bitcoin virtual currency to its use in smart contracts and other applications in combination with artificial intelligence in many spheres of the economy and social life, the presentation focuses on the use of blockchain in the management of medical records and its role in securing the stability of supplies of medicines and medical equipment.

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1. Introduction

A blockchain is an advanced, new generation information technology in the form of a public distributed ledger, which can efficiently record encrypted transactions between two parties in a direct, verifiable and permanent manner (Iansiti, Lakhani, 2017; Ganne, 2018; Dash, Gantayat, & Das, 2021). Blockchain owes its existence to decades of research in the field of digital technology but it was not until 2008 that it actually became available, only to be used as the main component in the Bitcoin cryptocurrency a year later.

The second milestone in the history of blockchain took place in 2015, with the launch of Ethereum, a digital platform enabling the use of many decentralised applications in different areas, thanks to smart contract functionality.

Another important stage in the development of blockchain was the support given to Ethereum in 2016 by a decentralized autonomous organization (DAO), whose members could create smart contracts based on the Ethereum blockchain. DAO was designed as a venture capital fund in the crypto space (Das, 2019).

New distributed ledger technologies are being developed with an aim of improving the efficiency of Bitcoin and Ethereum networks and enabling new applications, meeting specific needs of particular areas of economic and non-economic activity, including health care, medicine, the pharmaceutical industry, culture, education, science and administration (Ganne, 2018).

The unexpected outbreak of the COVID-19 pandemic revealed the limited capacity of national health care systems to cope with emergency situations and showed their weaknesses. Traditional systems of registering infection cases, identifying high-risk patients, tracking the spread of the pandemic in real time proved ineffective. Various means of collecting and transmitting data turned out to be unreliable and incompatible, creating the risk of data loss or falsification as well as disinformation. Because most health care units resemble silos as regards patient data, the degree of interoperability between them is low, which impedes or delays the transfer of information, with an adverse effect on treatment effectiveness. Given imperfect methods of tracking the supply chain of medicines and medical equipment, counterfeit, low quality or overpriced products started to appear, as was often the case with COVID vaccines, ventilators, face masks and other medical supplies. As a result of the complex, time-consuming and quite expensive record keeping and transaction processing, doctors and nurses had less time and resources to look after their patients. The above-mentioned problems, as well as other issues faced by health care services, especially during the pandemic, can be largely solved by applying blockchain technology, as shown in this article.

2. Literature review

The COVID-19 pandemic has triggered a lively discussion about the causes of its global spread, preventive measures, its multifaceted effects and strategies of mitigating them. In a relatively short time, a large number of publications on these topics has appeared , mainly in international and national journals. A detailed overview of this discussion can be found in abstract and citation databases, such as Scopus, Google Scholar, Research Gate and Pub Media. Many authors concentrate on the possibility of exploiting inventions of the Fourth Industrial Revolution, also known as Industry 4.0, to combat the pandemic and possible future pandemics, since traditional methods and procedures used in health care systems proved to be unreliable. The key role among these new technologies is attributed to artificial intelligence (AI), the Internet of things (IoT) and next-generation mobile networks (e.g. 5G), big data analytics, automation and robotisation, augmented reality (AR), 3D printing and blockchain. These technologies are believed to improve the effectiveness of research on new generations of drugs (vaccines), ensure faster, cheaper, safer and qualitatively better production, transport, storage and distribution (Javaid et al., 2020; Vaishya et al., 2020;

Ting et al., 2020; Davenport, Kalakota, 2019; Coveri et al., 2020; Magableh, 2021; Rong et al., 2020; Gereffi, 2020; Shamman et al., 2021; Malik et al., 2021; Iiang et al., 2017).

The production of medicines, hygiene products and medical equipment will increasingly rely on AI-based cyber-physical machines tools, which will considerably limit human participation. As processes in the area of management, administration, office work, teaching and training become increasingly digitalised, more people can work remotely, which reduces the risk of the spread of a pandemic. The Internet of things, with access to large datasets and the use of AI can make facilitate the detection, monitoring and diagnosis of future pandemics. These inventions can be used to create virtual clinics offering remote medical consultations or medical chatbots capable of providing patients with constant medical care without them having to stay in hospital and freeing medical staff to look after more serious cases.

Global supply chains turned out to be a highly critical element in the fight against COVID-19. By offshoring the production of many intermediate goods necessary for the manufacture of medicines and medical equipment to countries with low labour costs, highly developed countries and emerging markets became dependent on goods supplied by these countries. The collapse in the production of these semi-finished goods in East Asia, mainly in China and India, created bottlenecks with cascading impacts across supply chains, ultimately causing declines in the supply of finished medical products all over the world. To prevent another crisis on such a scale should COVID-19 strike back again or in the case of any future pandemics, four main strategies are considered (Shao et al. 2021; Flach, Aichele, & Braml, 2020; Bunde, 2021; Schnelle, Schöpper, & Kersten, 2021; Lang, 2021):

a. reshoring or backshoring[1] or nearshoring[2] the production of products that are crucial for national security, including medical products;
b. diversifying (finding alternative) suppliers;
c. giving up on the use of just-in-time deliveries and increasing companies' storage capacities;
d. improving the process of managing supply chains by a greater reliance on digital technology.

It is in the implementation of the fourth strategy that blockchain can play a major role by making sure that the transfer of information is direct, transparent, efficient, safe, unchanged and verifiable and enabling smart medical and insurance contracts. These features of blockchain can help to make progress in detecting, diagnosing and preventing

[1] bringing domestic manufacturing back to a given country
[2] moving manufacturing to a neighbouring country

pandemics (Opportunites, 2020; Sharma et al. 2020; Marbouh et al. 2020; Nguyen et al., 2020; Degnarain, 2020; Du et al. 2021; Schnitzbauer, 2021; Bansal, 2021).

3. Research method

The theoretical article is based on results of desk research and the author's own predictions. A wide body of literature was reviewed as well as Internet sources about the impact of Industry 4.0 on the progress in medicine in the context of COVID-19, and, more specifically, about medical applications of blockchain technology. The author argues that this technology can bring potential benefits in the field of medicine and health insurance, particularly with regard to combating future pandemics COVID-19.

The main body of the article consists of five sections. In section 4, the author presents the key features and types of blockchain. It is followed by an overview of the main stages of its development (section 5), from the creation of the virtual Bitcoin cryptocurrency, through the launch of the Ethereum platform, which enabled users to create decentralized applications and register, confirm and transfer encrypted, peer-to-peer (P2P) transactions and ownerships, including those in the field of medicine and health insurance, in the form of smart contracts, to the present stage, known as Blockchain 3.0, where digital applications are combined with AI, IoT and other Industry 4.0 inventions. Section 6 contains examples of the exceptional usefulness of blockchain for registering, storing, sharing, analysing and evaluating information about the course of COVID-19 and possible future pandemics. Section 7 shows how this technology can be used to manage medical supply chains by providing tools that increase their transparency, security, velocity and reliability. The eighth section is devoted to the importance of smart contracts in medicine and health insurance. The author argues that they will prove useful in optimising treatments based on telemedicine and personalised therapies as well as insurance procedures.

4. Features and principles of blockchain

There are five basic principles governing blockchain, which distinguish it from other information systems and make it superior to them (Dhillon, Metcalf, & Hooper, 2018; Szpringer, 2019):

- **Reliance on a distributed database** means that resources are not located in one place but each node (computer) has full access to it, which is independent of others, i.e. it has a complete replica of the database. This blockchain ledger is not controlled by anyone and each participant can verify the record of transactions;

- **Information is transferred from peer to peer**, without passing through a central node. Each node stores and transfers data to all other nodes;
- **Transparency is combined with encryption (pseudonymisation).** All transactions are visible to any participant. Each participant has a unique address, usually consisting of 26–35 alphanumeric characters. Transactions take place between these addresses;
- **The record of transactions is immutable.** Once a transaction is recorded in the ledger and user accounts have been updated, the information cannot be altered. It becomes another block of the chain, which is linked with the preceding ones and contains its unique hash together with the hash of the block before it. Different algorithms are used to protect the integrity of transactions, their chronology and availability to all network participants;
- **Computational logic.** Since the ledger is digital, blockchain transactions can be tied to computational logic and programmed using algorithms and rules to automate the transaction process.

There are many types of blockchain, which differ in terms of their degree of decentralisation, the level of accessibility, the kind of consensus between blockchain parties, scalability, transaction speed, transaction fees, energy use, etc. (Ganne, 2018; Piech, 2016).

5. Stages in the development of blockchain

The first stage in the development of blockchain, described as Blockchain 1.0, was connected with the creation of a virtual currency called Bitcoin in the form of a special code consisting of several dozens of characters. The code is created in the process called mining, during which the miner's computer has to solve a complicated cryptographic task, known as the proof of work. After special software has been installed on the miner's computer, the task involves solving a certain inequality using a Secure Hash Algorithm, known as SHA-256. The solution is found by the trial-and-error method (Piotrowska, 2018; Ross, 2017; Dhillon, Metcalf, & Hooper, 2018), and is equivalent to the creation of a new block.

The next stage in the development of the digital ledger technology, known as Blockchain 2.0, was characterised by the possibility of registering, confirming and forwarding encrypted, P2P transactions and ownerships (Swan, 2015; Appendix B, 2014). The technology could be applied in finance, health care, insurance, administration, science, politics, etc. All these possibilities were made possible by the creation of Ethereum, a decentralized blockchain platform conceived by programmer Vitalik Buterin and launched in 2015 (Szpringer, 2019; Czajkowski, 2021; Czym jest Ethereum, 2018). The platform has its own cryptocurrency, called Ether, which is mined, as in the case of Bitcoin, by solving cryptographic problems through a proof-of-work system. While Bitcoin is used for payments, applications of Ethereum are much wider, enabling users, as already mentioned, to create and run decentralised applications and smart contracts.

Smart contracts can be defined as "programmes stored on a blockchain that run when predetermined conditions are met" (IBM, n.d.). Thanks to the development of blockchain, smart contracts are becoming increasingly complex, autonomous, and widely used. Smart contracts enable the creation of decentralized applications (DApp), decentralized autonomous organisations (DAO), also known as decentralized autonomous corporations (DAC) and decentralized autonomous societies (DAS) (Decentralized, 2019; Swan, 2015; Bashir, 2018; Kosior, 2019; Kropopek, 2019; Wiktor, 2020; Czym są, 2020).

A decentralized application is a type of distributed software application that operates on a peer-to-peer blockchain network and relies on smart contracts. A decentralized autonomous organization can be regarded as a more advanced form of decentralized applications. By purchasing tokens issued by a DAO, a party becomes one of its investors. The organisation is controlled by a computer programme, which stores encoded rules of how it should be managed and its business logic. After launching the programme, a DAO operates autonomously, making independent business decisions and taking appropriate actions by exploiting its AI functionality.

Sets of smart contracts or entire autonomous ecosystems can be used to perform many functions that are normally carried out by health care institutions, e.g. to issue, sign and transfer prescriptions or documentation regarding treatments, insurance, records of patients and payments for health services, to enable autonomous management of health care centres. When the range of services provided by means of smart contracts constitutes a considerable percentage of all services, one can talk about a decentralized autonomous society, which is still a long way off.

While Blockchain 2.0 is already being implemented to various degrees depending on company, industry and country, Blockchain 3.0 is a nascent technology, enabling digital applications combined with artificial intelligence, which go far beyond the economic sphere. They can be used in health care and medicine, the pharmaceutical industry, the insurance sector, government and administration, science, education, culture and art. It can be described as an improved version of Blockchain 2.0, without the following shortcomings (Swan, 2015; Ackermann, 2016; Colomo-Palacios, Sanchez-Gordon, & Arias-Aranda, 2020; Terzi et al. 2019):

1. poor scalability. Blockchain 1.0 was capable of processing 7 TPS[3]; with Ethereum, this figure increased to 15 TPS, which is still incomparably less than the average transaction speed of Visa, which is 2000 TPS (What is, 2019);

[3] transactions per second

2. limited interoperability between different blockchain systems and other cloud resources for data storage and analysis;
3. huge energy consumption required by computationally intensive algorithms used as proof of work or complex privacy protection schemes;
4. the difficulty of increasing the level of privacy and intellectual property protection without limiting accessibility the complication of the blockchain system;
5. not enough protection against cyberattacks;
6. the need to decrease the costs of participating in the system and improve transaction efficiency

Many attempts are made to solve these problems. One of the most promising solutions is the use of directed acyclic graphs (DAG) in the underlying structure of distributed ledger technology (DLT), (Consensus, 2021; Joshi, 2019; Beebeejaun, 2019; Czym jest skierowany, 2020; Lee, 2018). In DAG-based blockchain architectures, individual transactions are not added to the network in a chain but as multiple paths forming a tree-like structure. Consequently, a DAG-based blockchain is faster and more efficient compared with conventional blockchain technology. There are no miners or blocks in this framework and new transactions added to the network are based on previous ones, which are used to verify them. Thanks to this approach, the infrastructure required to verify transactions can be considerably scaled down, which results in shorter transaction approval times and reduces transaction fees to almost zero. Transactions are made nearly in real time, which solves the problem of scalability. A DAG-based DLT is capable of handling 10.000 TPS and it is believed that this speed can even be exceeded with a much lower energy consumption.

6. Using blockchain for medical record management

The main application of blockchain during COVID-19, and more generally, in health care consists in improving medical record management (Kuo, Kim, & Ohno-Machado, 2017; Kumar et al., 2018; Vazirani et al. 2019; Pakdemirli et al., 2021; Attaran, 2020; Marbouh et al., 2020; Azim et al., 2020; Bhat, 2020; Haleem et al., 2021). Currently, medical record systems, largely based on manual record keeping, are very labour-intensive and inefficient. Studies indicate that despite high costs they generate, most doctors do not receive enough data or receive them with delays. It is estimated that every year over 300,000 patients die globally as a result of errors in medical records. The wide scale of data collection and transmission between different health care units involved in the treatment of patients has also been one of the key challenges in the fight against COVID-19. An effective response to any pandemic requires reliable information about its symptoms, scale and development in different countries, treatment methods and preventive measures used and their effectiveness. Blockchain technology can serve as a useful tool for registering, storing, sharing, exchanging, analysing and evaluating information about the course of the pandemic at the global, national, regional and individual level. Until now, patients' medical records are kept in different places of the health care system: by doctors in private practice and general practitioners, by hospitals, health care centres, laboratories, insurance companies, in different locations and sometimes even different countries. Different kinds of software are used to collect and manage medical data, which in addition to compatibility issues may make it difficult to establish the order in which records were created. Since patients' medical records are scattered in different places, information is often transferred with delays and its authenticity cannot be easily verified. As a result, a doctor seeing a patient in a hospital may not have a complete and reliable record of his or her disease. In serious cases, when urgent intervention is required, time is a key factor in the patient's recovery.

In the case of a pandemic, blockchain technology can be used to collect general and individual information in one place in the form of blocks, which can be quickly and easily forwarded between parties involved in treating a given patient. This saves time and costs normally incurred to transfer data between different locations, obviates the need to repeat medical tests and provides better security compared to e-mail. Thanks to a high degree of interoperability, treatments can be highly personalised, because there is just one point of access to all patient's data in real time. The system ensures a high level of data accuracy and transparency, making it impossible for a doctor or a patient to remove or alter them. Data are authorised by their source of origin, so that their legality and quality can be verified. The security of data transmission and their confidentiality is better protected because data are recorded by encryption algorithms and registered by distributed networks, without the mediation of a central institution, which could be hacked much more easily than a large number of nodes in a given private blockchain network. The patient and authorised entities can easily access the medical record system, which is much cheaper to maintain in comparison with those based on conventional methods. Being able to access secure, reliable and comprehensive database containing health records, doctors run a much smaller risk of misdiagnosing their patients, can offer more effective treatments, and consequently, decrease the number of deaths, especially during a pandemic.

7. Using blockchain to manage medical supply chains

Blockchain can and is already beginning to play an important role in managing the medical supply chain (Opportunities, 2020; Sharma et al., 2020; Marbouh et al., 2020; Nguyen et al., 2020; Betti, Hong, 2020; Degnarain, 2020). Its advantages are particularly evident in the context of the difficulties experienced by global supply chains during COVID-19.

As a result of movement restrictions, social distance requirements and limits for indoor gatherings, many companies had to close their operations or limit production. At the same time, there was a sudden rise in the demand for medical supplies, such as face masks, gloves, ventilators, hygiene products and disinfectants, and, later on, COVID-19 vaccines. Faced with the prospect of possible shortages, consumers started stocking up on medical products and food, which made it difficult to maintain continuous and sufficient supply of goods. It became much more likely that urgently needed medicines would not be delivered on time or at all, or that the amount actually delivered would be of poor quality or counterfeit. Pharmaceutical companies lose an estimated $200 billion in revenue as a result of counterfeit prescription medications (Arsene, 2020). Forced to rely on new, unverified suppliers of medical equipment or medications and having to deal with cases of contract terms being broken, business owners were more likely to charge higher prices and demand advance payments. One such case made headlines in Poland, after the government had ordered ventilators from an arms dealer, had paid for them in advance but did not receive either the equipment or the money.

It is precisely these kinds of problems that blockchain technology is capable of preventing. By improving communication and eliminating intermediaries, a blockchain system makes it possible to match supply to demand in terms of quantity, quality and time of delivery. Because a blockchain-based supply chain is transparent, the flow of medications from the producer to the consumer can be easily tracked. This is particularly important in the case of long, cross-border supply chains, where the large number of stakeholders makes verification difficult and increases the risk of a failed delivery. Using blockchain, recipients can make good choices by checking if products are good quality, whether suppliers are reliable and what procedures they use. They can verify the origin and authenticity of medications, thus avoiding the risk of purchasing a counterfeit, low quality or potentially harmful product.

An effective response to any future pandemic requires a global consensus on how the supply chain of vaccines should be managed. Any such system should be transparent, verifiable, secure, timely, inexpensive and easy to implement. It should enable real time tracking of the flow of vaccines from the producer to end consumers and should provide effective means of communication and feedback between them. All these requirements are met by blockchain technology, although its effective and wide-scale implementation requires education, IT expertise, appropriate national regulations and uniform international norms and standards.

8. The role of smart contracts in medicine and health insurance

In the health care sector a number of contracts are concluded between different stakeholders, such as patients, hospitals, suppliers of medical services, pharmaceutical companies, medical laboratories, medical and insurance organisations as well as universities and clinics. Traditional contract procedures are labour-intensive and time-consuming, not very secure and expensive. Various health care institutions rely on different software to collect information, manage medical records and conclude contracts. These inconveniences can be overcome by employing smart contracts on blockchain, which are automatically executed when conditions predetermined in an algorithm are met, thus enabling access to health care and improving its effectiveness (Du et al., 2021; Thompson, 2019; Schnitzbauer, 2021). Smart contracts are used to store agreements in a digital ledger. If a patient moves from one medical unit to another or receives treatments at various units, doctors working in these different units can, with the patient's consent, immediately access their complete medical records and administer treatments according to conditions set out in smart contracts. Changes in agreements in the form of entries approved by all parties concerned are added to consecutive blocks of data in a chain. The system guarantees that data sources are authentic and identities of patients and medical staff can be verified. Records of the latest diagnosis and their previous corrections stored in the contract block enable the hospital to choose the most qualified staff and treatment method for a given patient.

Smart contracts are used to optimise treatments in telemedicine and personalised therapies. Sensors connected to patients communicate with smart wearables and use the Internet to send information about their health, which is recorded in the form of smart contracts on blockchain. Smart contracts can notify doctors about their patients' health status, enabling them, if necessary, to make a medical intervention in real time. Based on these data, the doctor sends a diagnosis to the patient, administers a particular course of treatment and decides if the patient needs to be hospitalised. All these data are recorded in the system of smart contracts, which can also be used to conduct community health programmes based on health data of a given population, such as preventive measures against an epidemic, or mass vaccination programmes. The system reduces costs of communication between doctors and patients and other medical specialists, facilitates diagnosis and the choice of medications and accelerates the decision making process, all of which improve treatment effectiveness. With this system, each patient is really treated individually and there are no cases of misplaced or duplicated records, which are not so infrequent in traditional health care systems.

Health insurance is another area where smart contracts can eliminate existing inefficiencies. For one thing, all details of an insurance policy are automatically recorded and securely stored in a distributed ledger, which is much less prone to cyberattacks than a traditional database. There is no need for patients to fill in long and complicated claim forms before undergoing a treatment, because a smart contract will automatically file a claim if certain conditions are met. A decision to transfer money from the insurer's bank account to the hospital's account will also be triggered automatically. This guarantees that payments are made correctly and minimises the likelihood of insurance fraud and legal disputes. By reducing bureaucracy, an insurance transaction is simplified and takes less time.

9. Conclusions and recommendations

There is no doubt that blockchain is a breakthrough digital technology, which is very likely to gain importance, not only in financial applications but also in other domains, such as health care and health insurance. Its main feature and benefit for society is the elimination of intermediaries by enabling P2P transactions, which are recorded, combined, encrypted, validated and updated in a distributed database in a secure manner that does not depend on the amount of trust between transaction parties. Blockchain enables automatic transactions executed by means of smart contracts. Thanks to these features, the technology can be used to considerably decrease costs and the amount of administrative in health care. This is particularly relevant when health care systems in many countries suffer from underinvestment or bad debts due to uncompensated care, and from a shortage of doctors and nurses. These and other problems, which became particularly evident during the COVID-19 pandemic, can be resolved or mitigated by applying blockchain technology. Although it was invented barely several years ago, it is already undergoing a third stage of development (Blockchain 3.0) in an effort to eliminate the shortcomings of the previous system connected with scalability, speed, complexity, high energy use and transaction fees. Moreover, Blockchain 3.0 is paving the way for the implementation of AI, which is already utilised in smart contracts on Ethereum.

New technologies, especially those associated with breakthrough innovations, are not embraced without a certain amount of resistance resulting from a number of technical, economic, social, psychological and educational hurdles that stand in the way. History shows that all these hurdles are eventually overcome because innovators and their sponsors think in terms of profit and loss. They are confident that after resolving objective and subjective problems standing in the way of a new technology, profits will outweigh losses. Ultimately, it is a matter of how to be more competitive. This is what motivates companies to spend millions in R&D, as this is a *sine qua non* of survival and growth, enabling them to retain or increase their market share and improve profitability. Competition also takes place between countries, with governments pursuing different policies to support innovation. This phenomenon is best exemplified by developed countries such as the USA, Japan, UK, Germany, France, South Korea and China, which is becoming the second biggest player in the field of applications involving new digital technologies and AI, after the USA. In the years to come one can expect not only new digital, AI-based businesses but also entire ecosystems of such companies, perhaps on a global scale. All these issues should become the subject of future research, with emphasis on various applications of Industry 4.0 solutions in medicine and health insurance. More research is required on ways of combining blockchain with AI, IoT and other innovative technologies, which will possibly lead to revolutionary changes in how they are used. Results of this research should be of interest not only to health care institutions and companies in this sector but also to governments and international organisations and centres of IT education. However, the processes described in this article cannot be implemented without a supportive regulatory framework, financial backing and appropriate education.

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