

REVIEW

Blockchain Technologies: Opportunities for Solving Real-World Problems in Healthcare and Biomedical Sciences

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ABSTRACT

Introduction: Blockchain technology is associated with the financial industry, but it can be applied to other industries. The supporting architecture of blockchain has the immense potential to transform the delivery of healthcare, medical, clinical, and life sciences, due to the extended functionality and distinct features of its distributed ledger. The potential scale of impact is comparable to that seen with the introduction of TCP/IP. Blockchain technology has captured the interest of healthcare providers and biomedical scientists within various healthcare domains such as longitudinal healthcare records, automated claims, drug development, interoperability in population health, consumer health, patient portals, medical research, data security, and reducing costs with supply chain management. It is not yet clear if blockchain is going to disrupt healthcare, but healthcare organizations are monitoring its potential closely for prospective concepts like secure patient IDs. Realistically, the adoption and implementation of blockchains will be a gradual evolution over time, but now is the time to take a fresh look at its possibilities in healthcare and biomedical sciences. Blockchain technology revolutionary solutions are bringing us closer to the possibility of every patient record being able to send updates to an open-source, community-wide trusted ledger that is accessible and understood across organizations with guaranteed integrity. **Aim and Methods:** This paper discusses as a review some potential areas of opportunity for blockchain in the health and biomedical sciences fields. **Results and Conclusions:** This paper describes and synthesizes 20 examples of real-world use-case scenarios for blockchains in healthcare and biomedical practice.

Keywords: Blockchain; Distributed ledger; Biomedicine, Cryptocurrencies, Healthcare.

1. AN INTRODUCTION TO BLOCKCHAIN

The Future Potential of Blockchain

Blockchain means a digital system for executing and recording transactions can be visualized as a building block constructed from intelligent algorithms and collected data, and secured by cryptography. Whether in financial markets, healthcare, or the military; industries and governments are using blockchain technologies to redesign hi-tech paradigms (1). According to Gartner, blockchain is among the top 10 strategic technology trends for the years 2018 (2) and 2019 (3). Cearley, Burke (2) explain that using a public blockchain can remove the need for trusted central authorities in record transactions and dispute arbitrations.

This is because *trust* is built into the model through *immutable* records on a *distributed ledger*. Blockchain technology is considered by some as the most significant invention after the Internet, and is widely anticipated to resolve trust issues through *peer-to-peer networking* and *public-key cryptography* solutions (4). It is commonly agreed that the technology still needs time to mature (4-8), but we need to be ready for adoption of this unprecedented archetype. The potential of blockchain technology to radically transform interactions should raise critical questions for governments and society.

Predictions for Blockchain

In a forecast by Gartner, Kandaswamy and Furlonger (9), they predict that by 2022 innovative new companies will start exploiting

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blockchain technologies, and at least one innovative business built on blockchain technology will be worth \$10 billion. They also project that by 2026, the business value added by blockchain will grow to slightly over \$360 billion, then surge to more than \$3.1 trillion by 2030. The anticipated exponential growth of blockchain is an appealing prospect for those interested in radically altering their business paradigms towards a more secure and distributed model of transaction. IBM Institute for Business Value (6) maintain that blockchain adoption is accelerating faster than originally anticipated. Their research found that nine in ten government organizations intend to invest in blockchain for use in financial transaction management, asset management, contract management and regulatory compliance. While, seven in ten government executives predict blockchain will significantly disrupt the area of contract management.

Although the potential is immense, so is the uncertainty. Blockchain is not the application of a technology to existing business models, but rather, it is a technology that can reform the business model itself (10). Distributed ledger technologies are so new, complex, and prone to progressive development, that it is difficult to predict what form they will ultimately take on. The Gartner Group declared in an August 2015 report that crypto-currency was traveling in a “hype cycle”. It had passed the ‘Peak of Inflated Expectations’ and was headed for the ‘Trough of Disillusionment’. In another report, the research firm, Forrester, titled its 2015 blockchain report “Don’t Believe in Miracles,” advising enterprises to wait five to ten years before introducing blockchain, in part because of legal constraints (11). Ultimately, there are real business cases for improvement based on the lessons learned from cryptocurrencies, but the potential is shrouded in a great deal of hype. Research on the potential is still being carried out. We need to learn to decipher the hype and look diligently forward to real-world applications of blockchain (10, 12). This paper introduces blockchain technologies and its relevance to healthcare and biomedical sciences, and synthesizes examples of real-world blockchain applications in these fields.

Blockchains and Distributed Ledger Technologies

A blockchain is a distributed system of record that is shared between participants, records all transactions carried out by any member, and all participants have their own copy of the ledger through *replication*. Technically speaking, each transaction is enclosed in a block. A block may contain multiple transactions and is a basic unit to be *verified* by the members. Each block also contains a *hash* value of the previous block’s header, and thus forms a hash-chain or blockchain (Figure 1). As all blocks are chained, the order of the blocks is deterministic; therefore, each block can serve as a timestamp of the enclosed transactions to solve the double-spending problem (13). Each member maintains a copy of the whole blockchain, thus every member can verify every transaction (14, 15).

Based on how the identity of a member is defined

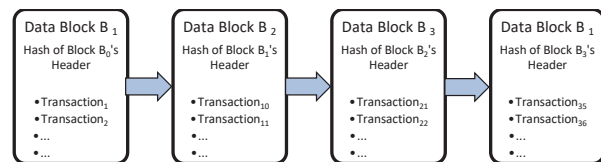


Figure 1. How Data Blocks Form a Blockchain

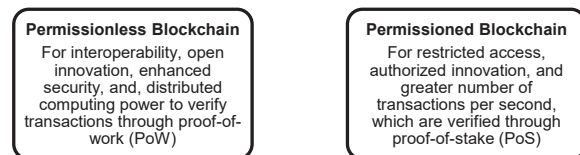


Figure 2. Permissioned and Permissionless Blockchain Uses

within a network, one could distinguish between *permissioned* and *permissionless* blockchain systems. In a permissionless blockchain, members remain anonymous or use pseudonyms and each member is able to append new blocks to the chain. While in a *permissioned* blockchain, the identity of each member is controlled as well as their right to validate a new block (16, 17). In the first, transactions are verified through proof-of-work (PoW), while in the latter, transactions are verified through proof-of-stake (PoS) (Figure 2).

In an article by the Harvard Business Review (7), Iansiti and Lakhani explain how blockchain technology works in practical terms; underscoring five basic principles (Table 1).

2. BLOCKCHAIN-BASED TRANSFORMATION

Potential Radical Change to Business and Technology Paradigms

Similar to how the Internet changed the world by providing greater access to information, blockchain is poised to change how people do business. Anything recorded on a blockchain is immutable and cannot be altered, and there are records of where each asset has been. So, while participants in a business network might not be able to trust each other, they can trust the blockchain. The benefits of blockchain for business are numerous, including reduced time (for finding information, settling disputes and verifying transactions), decreased costs (for overhead and intermediaries) and alleviated risk (of collusion, tampering and fraud) (18). Price Waterhouse Cooper (PwC), infer that blockchain could become a force anywhere trading occurs, trust is at a premium, and people need protection from identity theft (11).

Disruptive or Foundational Technology

Industrial revolutions are momentous events. Most will concede that there have been only three. The first occurred in the 1700s by the commercial steam engine and the mechanical approach. The harnessing of electricity and mass production sparked the second, around the start of the 20th century. The computer was the third after World War II (19). It is now perhaps time for the “next big thing”. In the technology world, block-

chain is in position to become the fifth disruptive computing paradigm after mainframes, PCs, the Internet, and mobile/social networking (20). It is considered by many as a revolutionary technology (21). It could potentially become the system of record for trade. Despite the hype and claims that blockchain will revolutionize business and economies, it is still not viewed by some as a “disruptive technology”, but rather as a “foundational technology” that has the potential to create new constructs for economic and social systems (7).

Iansiti and Lakhani (7) explain that blockchain has the potential to do for business what Transmission Control Protocol/Internet Protocol (TCP/IP) did for the Internet. TCP/IP created an open, shared public network without any central authority or party responsible for its maintenance. The complete adoption of foundational technologies typically happens in four phases (7). It took more than 30 years for TCP/IP to move through its four phases of single-use, localised use, substitution and transformation before it could reshape business and economies. By comparison, blockchain technologies are still in their early days. Some of the revolutionary blockchain frameworks are (1) Enterprise Ethereum Alliance, (2) Microsoft Coco Framework, and (3) IBM/ Linux Hyperledger Fabric (22-24).

3. CRYPTOCURRENCIES VERSUS BLOCKCHAIN FOR BUSINESS

Cryptocurrencies

Cryptocurrency is a term used to describe an encrypted, decentralized digital currency transferred between peers and confirmed in a permissionless public ledger through the labour intensive process of PoW or ‘mining’(16). Encryption techniques are used to generate units of currency and verify the transfer of funds. These transactions operate independently of a central bank, and participants on the network remain anonymous. Cryptocurrencies have known weaknesses, such as digital security, market regulation and speculative attacks (11). Most of the cryptocurrency market is shared between Bitcoin and Ethereum. Bitcoin (13) is accepted as the most widely used cryptocurrency (20, 22, 25) and was the first application that used blockchain as a technology. While Ethereum has quickly become the second largest digital currency in just over two years. Microsoft adopted Ethereum as the core of its new Blockchain-as-a-Service on the Azure cloud computing environment (14). Other leading cryptocurrencies are Litecoin, Dogecoin and Altcoin.

Smart Contracts are computer programs capable of facilitating, executing, and enforcing the negotiation or performance of an agreement. Ethereum is the most-known blockchain with smart contracts (12). Once set, a smart contract is immutable and can be trusted to operate the same way, indefinitely (26).

Blockchain for Business Requirements

As Lucas (18) explains, the blockchain that supports Bitcoin was developed specifically for the cryptocurrency and had to be modified to meet the rigorous standards of businesses. There are three main char-

SN	Blockchain Principle	Details
1)	Distributed Database	Each member on the blockchain has access to the entire ledger and its complete history. No single member has control over the data, while each has the ability to verify the transactions directly, without an intermediary.
2)	Peer-to-Peer Transmission	Communication occurs directly between members without the need for a central authority (no intermediaries).
3)	Transparency with Pseudonymity	Every transaction is visible to anyone with access to the blockchain. Each user, on a blockchain has a unique 30-plus-character alphanumeric address that identifies them. Users can choose to remain anonymous or provide proof of their identity to others.
4)	Irreversibility of Records	Once a transaction is entered, the records cannot be altered. Each block contains the hash value of the previous block’s header (hence the term “chain”).
5)	Computational Logic	Blockchain transactions can be tied to computational logic and in essence be programmed.

Table 1. How Blockchain Works (Adopted from the HBR Article “The Truth About blockchain” [7])

Blockchain Feature	Advantage for Healthcare
Peer-to-peer networks	Network infrastructure security
Smart Contracts	Permissioned access to patient data
Permissioned closed network	Data integrity
Distributed Ledger	Interoperability
Shared real-time updates to all members	Collaboration
Distributed, secure access	Patient longitudinal health record
Cryptography	Protecting patient identity
Disintermediation of trust	Secure health data
Distributed framework	Health information exchange
Disintermediation of transactions	Reduced transaction costs

Table 2. Blockchain Advantages for Healthcare

acteristics that separate the Bitcoin blockchain from a blockchain designed for business. (1) *Assets over cryptocurrency*: Blockchain can be used for a broad range of assets like cars and estates, as well as intangible assets such as bonds and securities. (2) *Identity over anonymity*: Bitcoin thrives on anonymity, while in blockchain for businesses it is required to know exactly who each participant is dealing with. (3) *Selective endorsement over PoW*: Consensus in a blockchain for business is not achieved through mining, but rather through a process called “selective endorsement.” This allows the control of exactly who verifies transactions.

4. REAL-WORLD BLOCKCHAIN APPLICATIONS IN HEALTHCARE AND BIOMEDICAL SCIENCES

The Future of Blockchain in Healthcare

Blockchain has applications that began in finance, but have expanded to government, healthcare, manufacturing, supply chain and others (3). The future outlook is that blockchain could lead to radical changes in many industries, with a probable impact on whole economies (20), including healthcare. There is real interest in its potential to enable secure lifetime patient record sharing among dispersed healthcare pro-

Issue to Address	SN	Blockchain Supported Use Case
Counter Prescription Drug Fraud	1)	Nuco, HealthChain RX Scalamed [26]
	2)	
	3)	
Supply Chain Intervention	4)	Pharmacosurveillance Blockchain System[40]
Biomedical Knowledge Retrieval	5)	A Blockchain-Based Notarization Service [44]
Connect Dental Providers	6)	Dentacoin [26]
Collect Patient Forms	7)	Time-stamping Patients' Consent [38]
Health Information Interoperability	8)	FHIRChain[31]
Patient-Centric Data	9)	Medicalchain [26] Healthcare Data Gateway [35] Deloitte's Prescript [17]
	10)	
	11)	
Patient wearable medical devices	12) 13)	Wearable Embedded Devices [36]
Access Shared Genomics Data	14)	Cancer Gene Trust CryptDist Project [45]
	15)	
Commercial Genomic Data Distribution	16) 17)	Gene-chain Zenome [45]
Integrate Genomic Data Analysis	18) 19)	Nebula Genomics[45]
Decentralize the Web	20)	InterPlanetary File System [45]

Table 3. Real-World Use Cases in Healthcare and Biomedical Sciences

viders (27). A blockchain for healthcare would need to include technological solutions for three key elements: scalability, access security and data privacy (28). Other key potential benefits are immutable audit trails, data provenance, availability and security as well as privacy (14) (Table 2).

According to IBM Institute for Business Value (24), the disruptive effect that blockchain is anticipated to have on healthcare will arise from the creation of a common database that caregivers can access from any electronic medical system, while eliminating the undesired a central intermediary and single point of failure (14). Engelhardt (26) describes four existing issues in healthcare that blockchains can address; (1) putting the patient at the center, (2), privacy and access, (3) completeness of information, and (4) Costs. While, a study by McKinsey & Company (1) estimated that more than \$300 billion could be recovered per year by using health data effectively and creatively. Stagnaro (29) describes five innovative blockchain uses in healthcare that could resolve the aforementioned issues; longitudinal healthcare records, automated health claims adjudication, interoperability, online patient access and supply chain management.

Blockchain Applications in Healthcare

Currently, development of blockchain solutions in healthcare are dominated by prototypes, proof-of-concept efforts and initial phases of project investments (26). These prototypes aim to solve existing problems, with a focus on public health, advanced research modalities, prescriptions monitoring, lowering administrative overheads, and organizing patient data (5, 17, 26, 30). Engelhardt (26) describes actual use cases in three important healthcare applications built on blockchain that address *Prescription Drug Fraud*, *Patient-Centred Medical Records* and solutions for *Con-*

necting the Dental Industry.

Health Information Exchange and Interoperability

In the US, the Office of the National Coordinator for Health Information Technology (ONC HIT) issued a Shared Nationwide Interoperability Roadmap (17, 31). This roadmap includes necessitates secure network infrastructure, authentication of all participants, authorization to access electronic health information. Building upon these requirements by using a blockchain structure, the information stored on the blockchain could be universally available to a specific individual through the private network, enabling patients to share their information with healthcare organizations much more seamlessly. Blockchain technology can help accomplish ONC HIT's interoperability goals while creating a trust-less, and collaborative ecosystem of information-sharing (17).

Interoperability in healthcare has traditionally been focused around data exchange between different hospital systems (32). Fast Healthcare Interoperability Resources (FHIR) (15, 31, 33) is an emerging standard that depicts data formats, while providing publicly accessible Application Programming Interfaces (APIs) for the purpose of exchanging Electronic Health Records (EHR)s. FHIR is designed to meet the requirements of the ONC HIT (34). Many pilot projects are currently underway with a focus on using blockchains to aid exchange of patient data and interoperability (14), since the technology offers a promising distributed framework to support integration of healthcare information across a range of uses (17). *FHIRChain* (31) is one such project. It is a smart-contract based system for exchanging health data based on the standard FHIR, where clinical data is stored off chain, and the blockchain itself stores encrypted meta-data which serve as pointers to the primary data source as in an EHR (32).

Patient-Centric Data Sharing

Prescript is a proof-of-concept developed by Deloitte Netherlands, in collaboration with SNS Bank and Radboud3. It gives patients complete ownership of their medical records, allowing them to grant and revoke provider access to their data. Providers, in turn, can issue prescriptions directly on the blockchain (17). Yue, Wang (35) proposed Healthcare Data Gateway (HGD) App with an architecture based on blockchain to enable patients to own, control and share their data securely without violating privacy, offering a new way to improve healthcare systems while keeping patient data private. Gordon and Catalini (32) describe how blockchain technology might facilitate the transition from institution-centric to patient-centric to data exchange interoperability, through five mechanisms: (1) digital access rules, (2) data aggregation, (3) data liquidity, (4) patient identity, and (5) data immutability. Brogan, Baskaran (36) demonstrated that it was possible to build upon these mechanisms by using a distributed ledger to broadcast and receive authenticated, encrypted activity data from patient wearable devices. The source and integrity of the data were authenticated through a Masked Authenticated Messaging (MAM) module. The

data was systematized using FHIR enabling structural interoperability across a diverse digital healthcare ecosystem. They also exhibited the possibility of allowing patient-defined access controls by changing authentication keys that would allow a patient to revoke access to their future data. Blockchain technology could then be integrated with Internet-of-Things (IoT) solutions, to overcome the security, privacy and reliability concerns of IoT (8, 37).

Secure and Trustable Clinical Data

The existing technical infrastructure today inhibits secure and scalable data sharing across healthcare providers, thereby limiting support for much needed collaborative clinical decision making (31). As a solution to this Zhang, White (31) describe a blockchain based decentralized application that uses digital health identities (to authenticate network participants and to manage data access) in their case study on clinical data sharing in remote cancer care. The resulting application enables users to share specific and structured pieces of information, thereby providing flexible clinical data sharing options for the healthcare providers. Similarly, Benchoufi, Porcher (38) designed a proof-of-concept protocol consisting of time-stamping each step of the patient's informed consent form collection in clinical trials using blockchain, thus archiving and keeping an audit trail for the consent process through cryptographic validation.

Supply Chain and Pharmaceutical Delivery

Supply chain is a vital area for companies which is concerned with transporting products between parties. However, the problem of this sector is that its scale may lead to delays and defaults in the delivery of goods as well as other logistical and data theft issues (39). Casado-Vara, Prieto (39) propose a model that leverages blockchain's smart contracts with multi agent systems aimed at increasing efficiency in the logistics system management; which can be applied in pharmaceutical supply chain.

Drug counterfeiting is a global problem that poses a public health hazard, wastes consumer income, and reduces the incentive to engage in research and development and innovation, while posing a high burden on the population drug expenditures and on governments (40, 41), costing pharmaceutical companies an estimated \$200 billion annual losses (26). For example, the *Pharmacosurveillance* blockchain system proposed by Sylim, Liu (40) is a disruptive intervention in the context of drug supply chains that aims to counter these risks.

Blockchain in Healthcare Insurance

Blockchain technology also offers potential use cases for insurers that include innovating insurance products and services for growth, increasing effectiveness in fraud detection and pricing, and reducing administrative cost (42). The technology can also be used to remove intermediaries and clearing houses by going directly to the providers. This can serve as the foundation for more sophisticated applications of blockchain, including prior-authorisations and automatic claims

processing (17). Furthermore, blockchain can potentially reduce operations costs through automated verification of policyholder identity and contract validity, auditable registration of claims and data from third parties (42).

Blockchain Technology in Healthcare and Biomedical Research

Reproducibility, data sharing, personal data privacy concerns and the difficulties associated with patient enrolment in clinical trials are significant medical challenges (43). Blockchain principles can provide better sharing of medical research, which can prompt new avenues for biomedical research, and drug and treatment therapies to cure disease (43). Blockchains, for example can be leveraged to reward computation and storage resource-sharing, facilitate decentralized data distribution, promote collaborative work, and provide genome privacy. Given the dynamic nature of biomedical evidence data, it is important to ensure the proper retrieval and integrity of collected data (44).

Smart Digital Contract for Biomedical Research

Kleinaki, Mytis-Gkometh (44) propose a blockchain-based notarization service that uses smart digital contracts to seal the query and the respective results of that query each time a third-party requests knowledge from a biomedical database. Biomedical evidence data versioning can also be supported by this solution. While Mamoshina, Ojomoko (30) introduce a new approach to appraise and evaluate personal records, including the combination-value, time-value and relationship-value of the patient data that the patients themselves do not control. They also show a roadmap for a blockchain-enabled decentralized personal health data ecosystem to enable new approaches for drug discovery, biomarker development, and preventative healthcare.

Genomics and Big Data Research

In genomics and Big Data research, the data sets involved are generated by high-throughput sequencing processes that require immense amounts of computational power, and there is a need for secure and decentralized platforms for data distribution, with user-level data governance (45). Genomics and Big Data research can benefit from blockchain distributed ledger and trust features to address these issues. Ozercan, Ileri (45) describe several blockchain-based proposals and use cases that were designed to support genomics and Big Data research. The first one is the *Cancer Gene Trust (CGT)* being developed by the Global Alliance for Genomics and Health (GA4GH) Consortium, and the second is the *CrypDist Project*. Similar to these two approaches, they also discuss the recently announced projects, *Gene-chain* and *Zenome*. Additionally, they describe *Nebula Genomics*, which integrates all aspects of genomic data analysis. Last, there is the *InterPlanetary File System*, which is a distributed file system that aims to bring the web to its decentralized roots.

Blockchain Technology Implementation Challenges Size and Volume of Clinical Information

Most of the efforts spent by the academic world in the

last five years have been devoted to resolving the challenges that are slowing down the potential disruption led by blockchain (12). High-volume, high-frequency transactions are a cornerstone of clinical data, while its size is increasing exponentially (32). For healthcare information stored on the blockchain, the most immediate concern is the sheer size and volume of clinical information. To standardize data stored on the blockchain and to manage performance, organizations should align on a framework for defining what data type, size, and format could be submitted (17). This alignment, however is in itself a challenge.

Standards and Interoperability

Lack of interoperable data standards enforcement is a concern when dealing with health information. Without the means to enforce existing interoperable data standards such as Health Level 7 (HL7), it becomes more challenging to integrate clinical information etched in blockchain infrastructures (31). The collaborative nature of blockchains makes interoperability and enforcement of standards a genuine challenge. Ultimately, standards will be vital in guaranteeing interoperability between blockchains, and to establish rules for the safe storage and transfer of health information (26).

Information Privacy

When it comes to security of data, the norm is that top management support is a significant predictor of an organization's security culture, and level of policy enforcement (46). When relying on blockchain technology, the accepted norms of data security and its enforcement are upended. Instead of internal reliance on security administration, the blockchain itself becomes the security enforcer. Cases of falsifying the ledger and double transactions of blockchain pose the biggest problem (47). With that, blockchain technology gives rise to concerns over the security of transactions and wallet. When dealing with healthcare data, privacy and security are non-negotiable, and unintended privacy breaches are a real risk. For example, some implementations of blockchain technology are pseudonymous with the identity of users obscured, but at times attributable information like demographical data could lead to a breach where patient identities can be deduced from the publicly shared information on a blockchain. This would mean that an individual's public key is matched to their identity, and their health data is subsequently revealed (17, 26, 32, 48).

Incentives and Regulation

Six in ten governments recognize regulatory constraints as the greatest barrier to the adoption of blockchains, followed closely by what they perceive as immature technology and lack of executive buy-in (6). While blockchain technology enables faster, near-real time transactions, the cost of operating such a system are not yet known (17). Further to that, incentivising institutions to build patient-facing data connections without financial motivation to do so will be challenging (32). Large health systems have already invested into new vendor-led commercial health re-

cord systems; many with government incentives (49), so they are not incentivised to move to technologies deemed experimental in nature (like blockchain), and that are not supported with funding.

Securing the Blockchain

Security incidents and their impact on the economic losses like those reported by Bitcoin users have increased (25). Kuo, Kim (14) summarizes the key challenges for blockchain adoption as transparency and confidentiality, speed and scalability, and the threat of a 51% attack. The last is perhaps the most serious concern. A 51% attack occurs when there are fewer "honest" participants on the network than "malicious" ones, who can take over the blockchain by majority (4). In a security sensitive field like healthcare, such risks must be mitigated solicitously.

Another risk to blockchain security is quantum computing, because one-way functions and cryptographic algorithms are its sole line of defense, and a user's only protection is their digital signature (50). Fedorov, Kiktenko (50) suggests that within a decade, quantum computers will be able to break a blockchain's cryptographic codes, that are used to secure the Internet and financial transactions. Conversely, quantum cryptography could also be used to replace classical digital signatures, and to encrypt all peer-to-peer communications in the blockchain network, using quantum-safe encryption (50).

5. CONCLUSIONS

Blockchain has the potential to offer long-term benefits despite its challenges; such as improved cash flow, lower transaction costs, reduced settlement times, asset provenance, native asset creation and creating new models of trust (2). Using a blockchain can remove the need for central authorities when making transactions. This is because trust is built into the model through immutable records on a distributed ledger, and all members contribute to the integrity of the database (36). The potential of this technology to radically transform economic interactions has gripped the interest of many; including economists, strategists and healthcare providers (2). The more promising applications within healthcare include health information exchange, combating prescription drug fraud, sharing patient data, supply chain applications and health insurance. In research there is strong potential for blockchain in genomics and Big Data research.

Despite the potential benefits, there still remain many challenges, such as the size and volume of clinical data, standards and interoperability problems, information privacy concerns, lack of incentives or clear regulation, and security concerns. To date, it is largely in the banking arena where blockchain use cases have been successful. However, there are many use cases, pilot projects and proof-of-concept ventures currently utilizing blockchain principles to improve the provision of healthcare. Twenty real-world use case scenarios for healthcare and biomedical sciences solutions were reviewed and discussed throughout this paper,

and are summarized in Table 3. These demonstrate the true potential for blockchain to influence a pragmatic paradigm shift in the delivery of healthcare, and in biomedical science. Governments, policy-makers, and healthcare organizations should be prepared for these anticipated blockchain technologies.

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