The Future of Blockchain

Wendy M. Charles

Abstract Blockchain's current uses demonstrate potential for enhancing efficiencies and patient-centered solutions in life sciences research. For blockchain to continue to present new features and remain relevant in life sciences research, it is critical for blockchain capabilities to evolve and integrate with newer technologies. This chapter introduces the role of blockchain technologies in smart data, quantum computing, digital twins, and the emergence of the metaverse. Additional predictions and recommendations for preparing for future blockchain needs are provided.

Keywords Blockchain · Smart data · Quantum computing · Artificial intelligence · Digital twins · Metaverse

1 Future of Blockchain

To accommodate future research needs, life sciences research organizations are reducing timelines and costs using artificial intelligence (AI) applied to real-world data and previous clinical trials [1]. As this book has demonstrated thus far, life sciences organizations have identified meaningful opportunities to use blockchain in genomics, governance, regulations, security, and legal realms as uses of blockchain are accelerating. Therefore, it is critical for life sciences research organizations to determine the best methods for sustaining this forward momentum. To be successful, organizations should take the lessons learned in this book to create new ways of collaborating and accelerating research advancements. This chapter describes trends within life sciences research and advances in new technologies that are further facilitated by blockchain.

W. M. Charles (✉)
Life Sciences Division, BurstIQ, Denver, CO, USA
e-mail: wendy.charles@cuanschutz.edu

W. Charles (ed.), *Blockchain in Life Sciences*, Blockchain Technologies,
https://doi.org/10.1007/978-981-19-2976-2_14

1.1 Predictions of Future Blockchain Trends

A Gartner report about top trends in 2021 predicts a movement toward “distributed everything” [2]. While the future of technology is unpredictable and subject to variations of technological advances and market forces, this section offers a few trends that will likely affect the direction and adoption of distributed ledger technologies.

1.1.1 Decentralized Clinical Trials

Within life sciences research industries, the uses of blockchain will likely increase to meet the needs of decentralized clinical trials (DCTs). The term “decentralized” is reminiscent of the distribution of nodes. However, within the context of DCT, “decentralized” refers to remote collection [3] and/or the use of remote/virtual technologies [1]. The primary goals of DCTs are to bring clinical studies to the research participants where they live and work [3]. These studies can be designed as pragmatic studies to capture individuals’ real-world experiences or be highly structured as clinical research studies [3]. By allowing remote data capture capabilities using electronic technologies [1], DCTs can enroll and retain more research participants and capture data under real-world circumstances [3]. During the Covid-19 pandemic, there was an extensive movement toward more virtual data collection [1], and there are strong indications that the adoption of virtual trials will increase in the future [4].

Components of blockchain technologies appear necessary for the success of future DCTs. For example, Dr. Khozin [3]—the former Associate Director of the U.S. Food and Drug Administration (FDA) Oncology Center of Excellence—describes successful DCTs as involving “distributed networks of connected technologies” (p. 27), and he has advocated for uses of blockchain to foster innovation (e.g., [5, 6]). In fact, the FDA joined the Decentralized Trials and Research Alliance that includes more than 50 international life sciences organizations [7] and was co-founded by ConsenSys Health, a health-oriented blockchain company [8].

Blockchain capabilities are recognized for offering more security for DCTs than centralized data management and limiting the potential for data loss [7]. There is also potential for enhancing protections of connected devices along distributed channels [3] and the benefit of an inherent audit trail to promote data reliability and integrity [4].

When considering the prospect for blockchain-based DCTs implementations, it is valuable to recall that there are no one-size-fits-all solutions. Each DCT has unique needs, and the selected technologies must be suitable for the population studied [4]. Further, any technology used to process protected health information or data regulated by the FDA must meet applicable Health Insurance Portability and Accountability Act (HIPAA) regulations, FDA regulation 21 CFR § 11 for electronic records and electronic signatures, and/or Good Clinical Practice guidelines [9]. Last, because DCTs could involve telemedicine for health management of research participants, organizations must be vigilant about evolving telemedicine statutes and guidelines

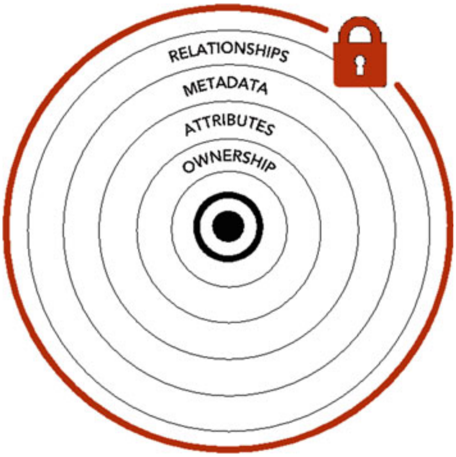

Fig. 1 Components for data objects that create smart data

[4]. Overall, Dr. Gail [7] notes that DCTs have “arrived” (p. 387) and will likely change the nature of clinical trials. With the value added by blockchain technologies, blockchain will likely become an increasingly valuable technology for facilitating future success.

1.1.2 Evolving Data Features

Advances in life sciences research depend on increasing data value and establishing data networks that promote connections between disparate data sets [10]. Because previous book sections described the use of blockchain for connecting and sharing data sets, this section focuses on future predictions of using blockchain and related technologies to create greater value.

Smart Data

Data and analytic models are increasingly used to accelerate business intelligence and insights. While the concept of blockchain-based data integrity has been around for a long time, blockchain data structures are now designed to create deeper insights, sometimes referred to as “smart data” [11]. As shown in Fig. 1, blockchain-based data can be stored with components of data ownership, attributes, metadata, and relationships. Ownership could represent a person, university, company, lab, or anything else. The ownership is linked using blockchain methods to each data object in ways that cannot be modified, increasing the ability to trust data [11]. Life sciences researchers then connect data sources to create more enriched and insightful analytics.

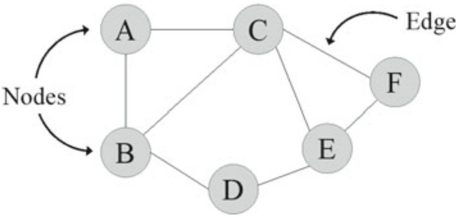

Fig. 2 Roles of edges and nodes in graph diagrams

Blockchain Interoperability

A Gartner report predicts that "by 2023, 35% of enterprise blockchain applications will integrate with decentralized applications and services" ([12], p. 3). While considerable research and progress are required to achieve this level of interoperability, the IBM Blockchain group writes, "83% of organizations today believe assurance of governance and standards that allow interconnectivity and interoperability among permissioned and permissionless blockchain networks to be an important factor to join an industry-wide blockchain network, with more than one-fifth believing it to be essential" ([13], p. 3).

Successful interoperability strategies are needed to promote more intelligent health-oriented ecosystems. Health ecosystems require data management solutions that connect systems more efficiently, involving frameworks of users across healthcare facilities, research facilities, and academic institutions that need to transmit and store large volumes of data [14]. For example, blockchain-based frameworks increasingly connect ehealth technologies [15] and telehealth information systems [16]. These integrations may also require communication of organizations' business processes and models to ensure integrations address the desired value propositions [14]. Last, blockchain programmers are encouraged to learn healthcare and life sciences ontologies to connect to existing healthcare and research systems. Ultimately, progress in blockchain-based health and research ecosystems is predicted to lead to healthcare personalization, data intelligence, and autonomous systems [10].

Graph Technologies

While relational databases are most commonly used for large-scale data systems, they are limited by strict data schema and limitations regarding how data can be displayed and queried [17]. However, graph databases allow data to be represented by nodes, edges, and other properties, creating complex data relationships [18]. As shown in Fig. 2, "nodes" are people, places, or things that have roles in data relationships. "Edges" represent different types of connections between nodes and indicate connection strength [18]. Shifting data analytics to edge relationships allows opportunities for scaling capabilities and analytics where health-related data cannot move outside specific geographic boundaries [2]. Figure 3 shows how data relationships can be presented visually to enable the review of the interrelationships.

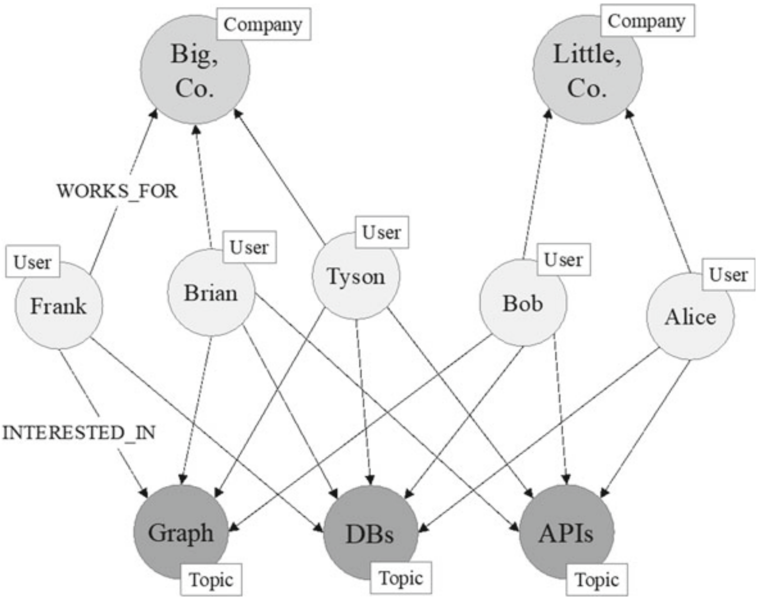

Fig. 3 Visual representation of graph relationships. Diagram inspired by [18]

Gartner predicts that by 2023, graph technologies will facilitate decision-making in 30% of organizations around the world [19]. By 2025, Gartner predicts that graph technologies will enable 80% of analytics innovations, resulting in faster decision-making [20]. Within life sciences research, this growth is driven by researchers' desire to uncover unexpected relationships that would be difficult to identify or analyze with traditional statistical programs [19]. Other scientists seek graph technologies to manage unstructured or semi-structured data more efficiently [20]. Therefore, graph technologies create new underlying data management technologies that can facilitate machine learning models and research collaborations [2].

Blockchain-based technologies store data more effectively for graph analytics. First, blockchain technologies store data on a ledger that manages data provenance, creating longitudinal records of individuals [19]. Blockchain technologies can also interconnect a complex network of collaborators and participants on a granular level [11] while providing a nearly immutable history for data management practices and security [17]. Last, blockchains are used for graphing technologies to track data assets, grant and revoke permissions, and involve strong encryption [21].

The following companies offer graph technologies and related visualization tools for blockchains. For a more comprehensive listing of blockchain visualization technologies with images, examine the systematic review published by [22].

BitExTract was designed by researchers at Hong Kong University of Science and Technology in 2018 [23]. This software provides a multi-view analytics tool that displays and compares bitcoin transaction relationships [23]. The Connection View creates node-edge diagrams that show relationships of transactional exchanges.

Each node is colored to represent the continent in which the exchange originated. The edge thickness shows the frequency or intensity of transactions between nodes [23]. BitExTract designed an "ego-network" graph visualization tool so that individuals can drag nodes of interest to the center of the display to view related transactions. As of November 2021, it does not appear that BitExTract is available as a commercial product.

Bitquery (https://bitquery.io/) offers a set of software products that index and query blockchain data. One of their products, Bitquery Explorer, is a client-side web application that connects an analytics explorer to query across more than 30 different blockchains [24]. Bitquery GraphQL allows for querying blockchains and can create actionable and insightful graphics [25]. Forensic data companies and government agencies use Bitquery's technology to track blockchain transactions and recover stolen funds [26]. Bitquery also advertises that its technology is used for scientific research [24].

Blockchain 3D Explorer (https://blockchain3d.info/) creates visualizations of blockchain transactions as 3D graphs and in virtual reality. The open-source software creates timeline-based 3D graphs that connect input and output addresses over time. The technology currently supports virtual reality systems for Google Cardboard as an immersive experience that allows individuals to view a history of transactions inside the blockchain [22].

BlockchainVis [27] is a blockchain forensic tool developed by the Italian Distributed Ledger Technology Working Group. The tool creates visual displays and queries of a transaction network. A filter panel can restrict specific nodes when examining connections between nodes [22]. As of November 2021, it is unclear whether BlockchainVis is a commercial product.

BurstIQ, Inc. (https://www.burstiq.com/) offers a graph technology called LifeGraph® that combines blockchain with machine learning methods designed for the secure handling of personally identifiable information. The network turns digital health assets into smart data that enforce data ownership, control, and security [11]. The smart data are integrated into a network model that enriches AI algorithms to make solutions more personalized and optimized [11]. For example, this technology was utilized in collaboration with the National Center for Advancing Translational Sciences (NCATS), a division of the National Institutes of Health. The NCATS team sought graph technology to predict the feasibility of creating synthetic molecular reactions [21]. The BurstIQ LifeGraph® network was integrated with the NCATS computational infrastructure so that researchers could collaborate while maintaining traceability and ownership [11]. The solution demonstrated that a collaborative research network could reduce the cost and risks of collaborative research while accelerating the pace of discovery [11].

Databricks is a San Francisco-based company (https://databricks.com) that offers graph analytic platforms and visualization tools for blockchain transaction data. A transaction can be associated with any detail created on the blockchain, including name, ID, or unit [28]. Databricks uses Apache Spark and GraphFrame coupled with graph visualization libraries to identify significant patterns in blockchain transactions [28]. Using Graph APIs, the technology analyzes data for users' incoming and outgoing transactions. The GraphFrames product creates vertices and edges from the transaction data to form directed graphs. The edges are shown with arrows and thickness to represent traffic volume [28].

Dan McGinn and his colleagues from the **Data Science Institute at Imperial College London** designed an unnamed blockchain visualization tool built with the Neo4j graph database [29]. This tool creates blockchain node activity profiles that display connections between nodes in cryptocurrency networks [30]. The goal is to reveal temporal transactions patterns along the entire graph as an edge-weighted adjacency matrix [30]. As of November 2021, it is unclear whether this tool is available as a commercial product.

While the uses of graph technologies in blockchain are still evolving, life sciences research leaders are encouraged to explore opportunities for integrating graph technologies into their analytics solutions. A blockchain may offer advantages for connecting data and AI/ML algorithms to improve these initiatives.

1.2 Quantum Computing

Modern connected networks rely on cryptography to protect our identities, communication, and financial transactions [31]. Blockchain security depends on one-way (asymmetric) cryptography for digital signatures and to validate transactions on the ledger [32]. One-way cryptography can be run on conventional computers. However, efforts to reverse the encryption would require substantial computing resources [33], requiring many years to solve [32]. However, scholars caution that a newer type of technology, quantum computing, will create future risks for blockchain networks that run on traditional computers (e.g., [31, 32]).

Traditional computing uses bits to encode data as 0 or 1. However, quantum computing uses particles of light (photons) to encode quantum bits that similarly have two (basis) states (0 or 1) but could be manipulated in ways that can only be explained by quantum mechanics [33]. Very simply, the particles become “entangled” when the state of one component cannot be described without the others. This composite is a sum, or “superposition,” that can be measured [33]. The system then collapses the superposition to one of the basis states to extract information [34]. Quantum computing can execute calculations much more efficiently because the system can simultaneously perform whole ranges of numbers and return only one result [34]. An image of a quantum computer is shown in Fig. 4.

For life sciences research, quantum technologies enable computing speed and complexity that conventional computing cannot achieve [34]. The improvements also include minimal storage and near-guaranteed security [33]. Quantum computing capabilities can accelerate life sciences research by creating simulations of molecular compounds to discover future medications, performing DNA sequencing, and optimizing personalized medicine [33]. For example, Boehringer Ingelheim partnered with Google to create a Quantum Lab [35]. Ryan Babbush, Google’s head of quantum algorithms, noted that “extremely accurate modeling of molecular systems is widely

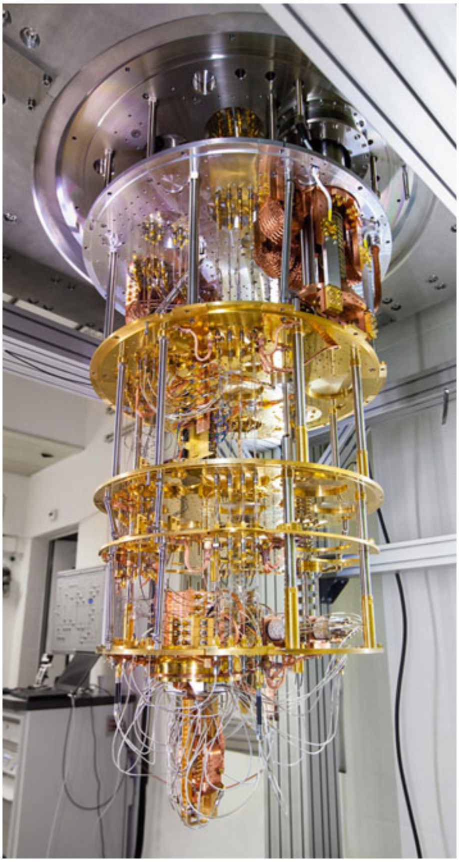

Fig. 4 IBM Zurich Lab quantum computer. "*IBM Zurich Lab Quantum Computer" by IBM Research is licensed under CC-BY-ND 2.0 that allows reusers to distribute in any medium or format, so long as attribution is given to the creator and no derivatives or adaptations are permitted. To view a copy of this license, visit* https://creativecommons.org/licenses/by/2.0/

anticipated as among the most natural and potentially transformative applications of quantum computing" ([35], p. 2).

As a caution noted earlier, blockchain-based networks are designed with the premise that traditional computing would not be able to reverse encryption without extraordinary time and effort [36]. However, quantum computers are projected to calculate the cryptographic codes used by many blockchains within ten years [32]. As the most imminent threat, malicious actors could use quantum computing to deduce private keys from the published public keys with little effort [34]. Cryptocurrency owners are then at high risk of losing control of their cryptocurrency. Further, it is feared that the few cryptocurrency miners who gain access to quantum computing will monopolize future block generation and sabotage transactions, such as engaging in double-spending [32].

The threat of quantum computing, though, appears limited by the cost and complexity of quantum networks [32]. Fedorov et al. [32] state that quantum computers need a “quantum internet” to connect across computers in a communications network. Without an intermediary, each node would require fiber optic channels to connect to other nodes, resulting in a quantum blockchain [32].

Regardless of the time and scope of the emergence of quantum computers, life sciences research organizations should start planning for security threats introduced by quantum computing. Campbell [37] argues that cybersecurity should be a primary concern because organizations cannot afford to lose the protection of their data and intellectual property. This risk assessment should include devices and data storage vulnerabilities for the cyber-attacks that will inevitably arrive [33]. Cybersecurity measures for blockchain should also include extensive planning and testing of post-quantum-resistant cryptography [37]. Post-quantum cryptography involves newer methods of cryptography that utilize suites of algorithms proposed to be more secure than conventional algorithms [34]. Proposals involve quantum key distribution, where the technology creates unconditionally secure message authentication [38]. As alternate approaches, Yaqoob et al. [36] recommend replacing traditional digital signatures, while Fedorov et al. [32] advocate encrypting all peer-to-peer channels in a blockchain network.

It may take years of analysis before industries and individuals trust quantum-resistant security measures [37]. Therefore, longer-term protection measures require investments and guidance from governments. Countries currently leading research developments in quantum technologies include China, the U.S., and several members of the European Union [32]. Legislators should engage in honest discussions and methods to approach cybersecurity regulations in a manner that allows innovation and market forces to drive advancements [37]. Campbell [37] also recommends that countries collaborate toward designing global standards.

Until post-quantum security measures are standardized and established, life sciences organizations are encouraged to consider blockchain platforms that can change cryptographic algorithms or utilize flexible encryption functions [32]. Campbell [37] encourages organizations to ask blockchain vendors about technologies that could adapt to quantum computing to protect regulated data. Implementation plans and updates could be included in contractual obligations. Campbell [37] also reminds organizations to update their policies, procedures, and risk assessments with any modifications to cryptographic methods. Without sufficient planning for quantum computing, the threat to blockchains—and all technologies involving encryption—could be severe [32].

1.3 Digital Twins

Another emerging technology involves “digital twins.” While various definitions of digital twins are available, unifying concepts involve software that takes real-world data to create a digital, cyber, or virtual representation (a “twin”) that generates valuable insights about the real-world object [39]. First used in manufacturing to create digital representations of machinery or sensors [40], digital twins have evolved

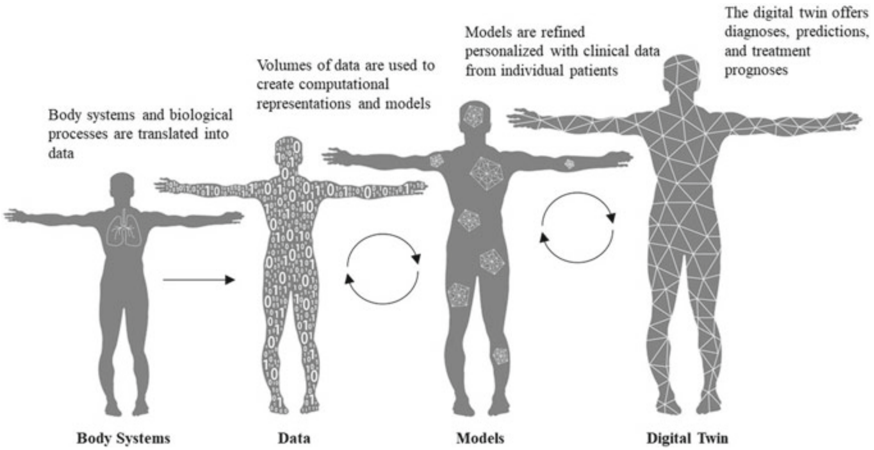

Fig. 5 Representation of methods for creating a digital twin. Substantially adapted from [44]

beyond digital models and now imply that a digital twin is connected in some way to the real-life individual or item (Kritzinger et al. 2018). More than a simulation or 3D model [41], a digital twin model must continually adapt to changing data and information to forecast future conditions [42]. The concept of digital twins has been named one of the top ten emerging strategies, with projected spending of nearly $11 billion in 2022 [42].

In medicine, "digital twins healthcare" (DTH) is an emerging discipline for creating digital twins with health information [43]. As shown in Fig. 5, DTH models involve three components: a physical object (such as a body part), a virtual object (such as a simulation or 3D print design), and healthcare data. Therefore, DTH should not be considered one technology but a cocktail of technologies [42].

In life sciences research, digital twins have been studied to create replicas of human body parts and influence therapy decisions or personalized medicine [40]. For example, Liu et al. [43] designed a digital twin for elder care that provides remote diagnosis health consultations and real-time monitoring. Oklahoma State University researchers created a digital twin of trachea models with individual alveolar sacs to simulate pulmonary oncology drugs delivered with inhalers [45]. Typical aerosol drugs can only reach 25% of the intended cancerous cells; however, Feng et al.'s digital twin model inspired aerosol molecular modifications that could reach 90% of cancerous cells ([45], p. 26). Clinical trials are critical for model modifications and validations, and it is necessary to perform longitudinal studies to characterize long-term DTH responses in various settings [44].

The adaptation of real-life health conditions to digital twins is facilitated by AI, cloud computing, and—in many cases—blockchain [39]. While blockchain is not required to create a digital twin, digital twin projects can innovate faster and more securely with blockchain features [39]. Blockchain-based smart contracts are used to manage the granular consent of multiple collaborators for the collective development of digital twins. At the same time, the audit trail provides accountability for any changes or updates to a model [46]. For example, Leng et al. [47] created a hybrid digital twin/blockchain model called ManuChain that adds a layer of digital twin models on top of a blockchain layer. The blockchain-based smart contracts automate individualized tasks for the twin model and perform a critical role in connecting the cyber and physical components of manufacturing. The blockchain also maintains multiple copies of digital twins on the ledgers for federated learning [47]. In a model designed by [48], the digital twin model is stored on a permissioned blockchain and records all changes and provenance of the model while the IoT data are stored off-chain in separate servers. The smart contracts then update the parameters of the digital twin accordingly [48]. Putz et al. [46] also utilize a hybrid on-chain/off-chain model for their DTH where the healthcare data are supplied by off-chain IoT data. These approaches reduce the computation and storage requirements for the permissioned blockchain [46, 48].

The development of digital twins in life sciences research, however, has been slow, and few models have reached clinical use [49]. First, researchers must model human biology [41]. Laubenbacher et al. [44] note that the ability to replicate the complexity of multi-system interactions, such as an immune response, is currently out of reach because of difficulties with model validation. A human body generates constant molecular changes and adaptations that make it challenging to model physiological processes [40]. Compounding these factors is the need for large volumes of data to perform comparisons of disease states to evolving and heterogenous definitions of “healthy” or “normal” states [40]. Kendzierskyj et al. [40] add that the concepts of “healthy” and “normal” can only be drawn from population statistics but often cannot inform individual digital twin models with sufficient precision. Tao and Qi [41] note it is too early in the development process to create “accepted standards” or “norms.”

Progress with developing digital twins has also been slowed by the difficulty of obtaining and integrating data. Tao and Qi [41] relayed that there may be a need to aggregate data from thousands of sensors, and data providers may maintain data in different formats. If unable to obtain sufficiently representative data, the digital twin results will be distorted [41]. This data limitation is compounded by the need for laboratories worldwide to integrate and validate each other’s work, requiring central coordination [44]. While blockchain could be used for data integration and protection, the more significant issue of sharing DTH knowledge and software involves the desire to maintain commercial secrecy [41]. Additionally, when DTH research is intended to treat, diagnose, or mitigate medical decisions, the software would be regulated as a medical device subject to FDA review and approval [50]. This level of evidence, quality control, and algorithmic performance is believed to hinder current adoption [49].

When designing DTH, life sciences research organizations should be aware of significant privacy risks. As a preliminary factor, data must be obtained from electronic health records and multiple other sources of health information that must be linked to each individual represented in the data set, creating concern about data theft and tampering [40]. As a more extensive consideration, when designing a DTH for an individual, an accurate digital model effectively becomes part of that person's identity [40]. In conclusion, DTH has made significant progress with modeling physiological and behavioral features, but accurate multi-system models still appear far from reality.

1.4 The Metaverse

The term metaverse was coined using the prefix "meta" and "universe" to create a virtual reality environment that can replicate aspects of the physical world [51]. In fact, in October 2021, Facebook changed its name to Meta, stating, "Our company's vision is to help bring the metaverse to life, so we are changing our name to reflect our commitment to this future" ([52], p. 1). Metaverses use high-speed networks and AI to create simulations where avatars represent humans. As shown in Fig. 6, avatars are similar to digital twins in that they can look and behave like humans to create an enhanced user experience [53]. These avatars can engage in various activities in the metaverse, including cultural, economic, and social interactions designed to mimic

Fig. 6 Example of a Second Life Avatar. "*My Second Life Avatar" by Lisa Tripp is licensed under CC-BY-SA 2.0 that allows reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the creator. To view a copy of this license, visit* https://creativecommons.org/licenses/by/2.0/

the real world [51]. The connected ecosystems, including social norms and rules, are often analogous to existing norms and rules in the real world [53]. Lee et al. [53] suggest that the metaverse can support the production of intangible assets in order to become a potentially self-sustaining economic ecosystem.

The earliest metaverse developed was Second Life (https://secondlife.com/), founded in 2003 by Linden Research Inc., based in San Francisco, CA. There are thousands of sites to explore in this virtual environment, including markets that exchange a unique form of payment called a Linden dollar [53]. Other popular metaverses include gaming apps Minecraft (https://www.minecraft.net/) designed by Microsoft, Fortnite (https://www.epicgames.com/fortnite/) built by Epic Games, and Roblox (https://www.roblox.com/) created by Roblox Corporation. All involve avatars and digital economies. To date, the majority of published health-oriented research in metaverses focused on Second Life settings, but later research has studied a wide range of virtual reality environments.

The Covid-19 pandemic has been a significant driver for drawing greater participation in the metaverse. The mass closures and social distancing limitations generated tremendous interest in metaverse environments that offer virtual social interactions [54]. Minecraft was even used to create a virtual graduation for University of California, Berkeley students during the Covid 2020 shutdowns—complete with a speech by Chancellor Carol Christ, Pomp and Circumstance music, and flying mortarboards [55]. These metaverses are also increasingly used in place of videoconferencing and virtual conference attendance [56]. Microsoft announced in November 2021 that Microsoft Teams video conferencing software will offer a mixed-reality platform that combines real-world participation with a metaverse [57]. Microsoft Teams aims to create greater engagement and interaction during remote encounters.

1.4.1 Health Activities in the Metaverse

Metaverses can offer unique support and capabilities for health-oriented education and treatment, including life sciences research. Using avatars, individuals can visit multiple doctors without leaving their (real) homes, and blockchain-based systems have been designed to manage the storage of their health information [53]. To promote interpersonal reactions, avatars can be controlled with body-centric sensors that allow for subtle movements and facial expressions to create a more realistic presence and more profound connection in the virtual environment [53].

The realistic social interactions make the metaverses a viable venue for innovations that have implications in real life. First, metaverses create immersive environments that allow for more effective training simulations. For example, clinical nursing training has been conducted in Second Life to provide examples of simulated patients in high-risk situations [58]. Also, Schaffer et al. [59] found that this virtual reality setting provides an effective learning platform for preparing nursing students to manage clinical situations that rarely occur in real life. Last, Second Life was used to create education sessions to train medical students to review radiology images

[60]. Overall, this immersive training environment has improved decision-making and is believed to translate into more effective clinical practices.

Specialty sites within metaverses have been used to offer one-on-one meetings with physicians, nurses, and other healthcare providers [61]. When coupled with real-world biometric sensors attached to humans who visit a virtual healthcare clinic, the individuals/avatars can receive health monitoring and assessments [53]. In addition, certain health-oriented therapies have proven remarkably successful in the metaverse. Individual consultations are available (for a fee) in an anonymous manner that encourages individuals to ask questions and receive medical or psychological advice that they might not pursue in real life [61, 62]. Gorini et al. [62] describe how individuals have received successful treatment for specific phobias in the metaverse, such as claustrophobia, arachnophobia, and agoraphobia, using desensitizing simulations of fearful environments without the (real) individuals experiencing any physical danger.

Within the metaverse, some sites also facilitate virtual meeting places for patient support groups and community education (Fig. 7). Support groups conducted in virtual reality settings are often more comfortable for individuals seeking support for sexual abuse or other sensitive or stigmatizing conditions [62]. There are also themed lectures and education events for patient communities that discuss diseases, treatment plans [61], and offer a supportive environment for friends and family [62].

Fig. 7 Second Life group meeting place. "*Avatar-Based Marketing: What's the Future for Real-Life Companies Marketing to Second Life Avatars?" by John' Pathfinder' Lester, licensed under CC-BY-SA 2.0 that allows reusers to distribute, remix, adapt, and build upon the material in any medium or format, so long as attribution is given to the creator. To view a copy of this license, visit* https://creativecommons.org/licenses/by/2.0/

For life sciences research, the metaverse offers the opportunity to conduct research directly or indirectly. Within Second Life, there are laboratories and clinics where individuals (as avatars) participate in research and receive tokens for participation [61]. These Second Life research sites also actively recruit for research participation within Second Life and real-world settings.

1.4.2 Blockchain and the Metaverse

Lee et al. [53] assert that blockchain is "expected to connect everything in the world in the metaverse" (p. 16). Therefore, several metaverse applications utilize a blockchain model of distribution where components of virtual spaces are synchronized amid connected users, and users' activities are recorded on the blockchain [56]. The data connectivity features of blockchain can connect computer vision, AI, and IoT into individual patient profiles for more accurate healthcare simulations [53]. Further, emerging blockchain-based graph technologies and edge relationships allow for high-quality queries and make the necessary data selectively available [51]. Blockchain also allows for highly scalable, flexible, and secure data storage [53].

To protect the avatars—and the individuals behind them—it is also necessary to ensure a trusted-based information system can manage identities [53]. van der Merwe [54] recommends implementing a gatekeeping function or levels of access restrictions in the metaverse, depending on the nature of the metaverse site and vulnerabilities. Blockchain technologies are used, then, to enforce specific rules. Ryskeldiev et al. [56] proposed a blockchain-based layer that creates unique identifiers (hashes) for each avatar and created space. For example, when a new space is created, a new block would be formed that contains its geographical coordinates within the metaverse, the URL to a 360° image, and a timestamp [56].

1.4.3 Metaverse Drawbacks

A virtual reality environment introduces unique and complicated ethical considerations. First, an avatar is a digital representation of an individual that creates new questions about what it means to be a person [53]. van der Merwe [54] wonders whether the friendships and romances formed in a metaverse environment are any less real. van der Merwe [54] further speculates about human rights and obligations. Specifically, does an avatar have the same legal rights associated with humans? Is there any recourse available against theft, violence, or harassment within a metaverse? Instead, Jeon et al. [51] argue that virtual people have no legal basis, and it is unlikely that they would have legal rights.

When a person engages in any virtual social interaction, there are questions about the degree to which social behavior in the metaverse reflects individuals' behavior in real life, creating significant cautions where adults could interact with children in the metaverse [53]. Jeon et al. [51] point out that individuals could engage in racial or gender discrimination under the protections of avatar anonymization. Of more significant concern, the avatar-based interactions do not indicate the individual's true identity behind the avatar. Anyone could enter the metaverse to create any avatar, creating possible misrepresentations during social interactions [51]. At the same time, van der Merwe [54] notes that an avatar is not required to portray a real person, so it is unrealistic to expect that the avatar's behavior would correspond with the real person.

When questions about the separations of avatars and humans are applied to healthcare, must a healthcare provider in the metaverse possess a clinical license in real life? Can a metaverse healthcare clinician provide treatment to a person (or specifically, an avatar) who resides in a different state or jurisdiction than permitted by that clinician's state-issued license (in real life)? Gorini et al. [62] advocate for international guidelines to govern the delivery of regulated services in a virtual environment.

Metaverses were not designed for healthcare or research, so virtual environments are not designed to protect individuals' privacy or confidentiality. In the metaverse, it would be necessary for clinicians and researchers to create protected environments where entry requires a secret code [62]. There are also questions about whether HIPAA or other healthcare regulations would apply to health information collected in a metaverse with no geographic boundaries. These environments collect extensive information about avatars, such as their locations and surroundings, which could involve privacy regulations [53]. However, it is unknown how privacy statutes and regulations would apply. Therefore, Lee et al. [53] recommend that these systems collect the minimum amount possible and only for as long as needed. Blockchain technology governance layers could also enforce specific rules [53]. Last, Lee et al. [53] advocate for autonomous agents in the metaverse to observe behaviors and expectations.

Overall, the metaverse is rapidly expanding, and blockchain-based technologies can facilitate some of the required protections and governance. However, there are many questions about the degree to which healthcare or research regulations apply to the virtual world. There are also many questions about managing the privacy of virtual encounters intended to be private. Many of these questions may require the cooperation of international governments to create determinations and guidelines.

1.5 The Carrier Wave Principle

When contemplating the many future directions of technology advancements, it is valuable to reflect on "the carrier wave principle." This principle was coined by Sinnreich and Gilbert [31] to raise concern that "as the cultural infrastructure has become increasingly reliant on computational processing, everyday users have become commensurately less capable of understanding the consequences of their actions and interactions" (p. 5818). Sinnreich and Gilbert [31] use the analogy of radio and television carrier waves to advise that we are constantly creating digital content—that we might not even be aware of—that could remain stored and searchable into perpetuity. Further, when carried forward by digital technologies that expand the scale and speed of knowledge, the cultural and social meaning of that information could be misinterpreted or exploited. Last, Sinnreich and Gilbert [31] explain that information is often taken out of context and then amplified through social platforms, resulting in incorrect AI algorithms that further distort the information's meaning.

In summary, the carrier wave principle raises a caution that "the growing reliance on computational processing as a foundation of knowledge production and social governance makes public oversight and development of best practices for data collection, management, and processing imperative for a functional civil society" ([31], p. 5831). Therefore, the authors advocate for cultural awareness and political reaction to the growing effects of the carrier wave principle as technologies evolve [31].

2 Future Research

Additional research is necessary to understand the best ways to adapt blockchain technologies to meet the future needs of life sciences research. First, it is valuable to consider that health-oriented information is now generated by an increasing number of smart devices [63], clinicians, researchers, and organizations that support life sciences industries [64]. While this book has positioned that this information can be managed successfully by blockchain, the technology must meet applicable regulations [9], and the data should only be used in accordance with individuals' permissions [65, 66]. Additional research is needed to create standards and best practices for evolving representations of individuals, including digital twin and metaverse environments.

Second, future research is needed to advance blockchain interoperability with life sciences applications and services. Organizations will benefit from testing integrations of their blockchains to compatible blockchains or other systems, including healthcare ecosystems [67, 68]. The interoperability should be tested in cross-national and cross-international contexts to create context-based solutions [14]. These solutions should include open standards such as Health Level 7 and Fast Healthcare Interoperability Resources [69].

As blockchain technologies become more diverse, there is an increasing threat of cyber-attacks [37]. Vulnerabilities may exist in underlying algorithms, side-channels, software integrations, and coding errors [37]. Additionally, organizations must prepare for the growing computational threat of quantum computing [33]. To address future technological threats, it is crucial to create long-term security strategies to mitigate emerging risks. Future research should address methods for managing cryptographic keys [14] and protocols for advancing quantum-resistant encryption [38]. Future research is also necessary to create appropriate blockchain cybersecurity standards and design industry-relevant cybersecurity programs for due diligence at protecting networks and organizations [37]. These research efforts should extend to safeguarding increasingly sensitive information with blockchains, such as biometrics and genetic information [14]. Organizations are also encouraged to review and implement appropriate policies and guidelines.

Last, research should determine the factors that may facilitate or hinder the adoption of blockchain technologies in life sciences research. This research should assess how blockchain could create or enhance value within life sciences research organizations [14]. Assessments should focus on the identification and development of strategic issues, such as performance [15], technical requirements [70], and resource limitations [71]. Research on these issues may advance blockchain architectures that offer more utility and efficiencies. For example, there are needs for more cost-effective node management [72], privacy management [73], authentication management [16], and patient-centered access controls [70]. This research will require a multi-disciplinary approach to address the roles of blockchain with evolving technology, regulatory, ethical, and legal considerations [65, 66].

3 Conclusions

As this book has described, blockchain technologies serve as an infrastructure layer of a holistic life sciences research ecosystem. As with any change, blockchain technologies may be perceived to pose threats to current paradigms [74]; however, blockchain technologies need not replace existing life sciences research technologies but can enhance their current capabilities [75]. Ideally, technological advances would allow research professionals to focus more on human interactions and other research tasks requiring human knowledge and facilitation. Therefore, as market forces drive innovation such as quantum computing, digital twins, and the metaverse, blockchain technologies can provide checks and balances on these systems [74]. Sinnreich and Gilbert [31] advise that "we can play a more proactive role in shaping that future by being more deliberate now about what kinds of media we build, what kinds of messages we send, and what kinds of laws and ethics we embrace to guide their development and deployment" (p. 5832).

Acknowledgements The author gratefully acknowledges the review and thoughtful feedback from Brooke Delgado, Leanne Johnson, and Hayley Miller.

References

1. Levy V (2021) 2021 Global life sciences outlook. https://www2.deloitte.com/global/en/pages/life-sciences-and-healthcare/articles/global-life-sciences-sector-outlook.html
2. Panetta K (2021) Gartner top 10 data and analytics trends for 2021. Gartner, Inc. https://www.gartner.com/smarterwithgartner/gartner-top-10-data-and-analytics-trends-for-2021. Accessed 23 Sept 2021
3. Khozin S, Coravos A (2019) Decentralized trials in the age of real-world evidence and inclusivity in clinical investigations. Clin Pharmacol Ther 106(1):25–27. https://doi.org/10.1002/cpt.1441

4. Datacubed Health (2020). Implementing solutions to virtualize and decentralize clinical trials. https://www.datacubed.com/wp-content/uploads/2020/10/Implementing-Solutions-to-Virtual-and-Decentralize-Clinical-Trials-Datacubed-Health.pdf
5. Khozin S, Kim G, Pazdur R (2017) From big data to smart data: FDA's INFORMED initiative. Nat Rev Drug Discovery 16(5):306. https://doi.org/10.1038/nrd.2017.26
6. Khozin S, Pazdur R, Shah A (2018) INFORMED: an incubator at the US FDA for driving innovations in data science and agile technology. Nat Rev Drug Discovery 17(8):529–530. https://doi.org/10.1038/nrd.2018.34
7. Van Norman GA (2021) Decentralized clinical trials. JACC Basic Transl Sci 6(4):384–387. https://doi.org/10.1016/j.jacbts.2021.01.011
8. Dalton B (2021) ConsenSys health joins decentralized trials & research alliance (DTRA) to democratize and accelerate clinical trials. ConsenSys Health. https://consensyshealth.com/news/consensys-health-joins-decentralized-trials-research-alliance-dtra-to-democratize-and-accelerate-clinical-trials/. Accessed 21 Oct 2021
9. Charles WM, Marler N, Long L, Manion ST (2019) Blockchain compliance by design: regulatory considerations for blockchain in clinical research. Front Blockchain 2(18). https://doi.org/10.3389/fbloc.2019.00018
10. BurstIQ (2021) Why smart data is the future of data security. https://www.burstiq.com/smart-data-white-paper/
11. Charles WM (2021) Blockchain innovations in healthcare. PECB Insights (33):6–11. https://insights.pecb.com/pecb-insights-issue-33-july-august-2021/#page6
12. Litan A (2021) Hype cycle for blockchain 2021; More action than hype. Gartner, Inc. https://blogs.gartner.com/avivah-litan/2021/07/14/hype-cycle-for-blockchain-2021-more-action-than-hype/. Accessed 15 Oct 2021
13. Schlapkohl K (2020, April 10) The future of blockchain. IBM. https://www.ibm.com/blogs/blockchain/2020/04/the-future-of-blockchain/. Accessed 28 Aug 2021
14. Tandon A, Dhir A, Islam AKMN, Mäntymäki M (2020) Blockchain in healthcare: a systematic literature review, synthesizing framework and future research agenda. Comput Ind 122:103290. https://doi.org/10.1016/j.compind.2020.103290
15. Hyla T, Pejaś J (2019) eHealth integrity model based on permissioned blockchain. Futur Internet 11(3):76. https://doi.org/10.3390/fi11030076
16. Ji Y, Zhang J, Ma J, Yang C, Yao X (2018) BMPLS: blockchain-based multi-level privacy-preserving location sharing scheme for telecare medical information systems. J Med Syst 42(8):147. https://doi.org/10.1007/s10916-018-0998-2
17. Ermolaev V, Klangberg I, Madhwal Y, Vapper S, Wels S, Yanovich Y (2020) Incorruptible auditing: blockchain-powered graph database management. IEEE. https://doi.org/10.1109/icbc48266.2020.9169431
18. Robinson I, Webber J, Eifrem E (2015) Graph databases, 2nd edn. O'Reilly Media, Inc. http://bit.ly/dl-neo4j
19. Goasduff L (2020, October 19) Gartner top 10 trends in data and analytics for 2020. Gartner, Inc. https://www.gartner.com/smarterwithgartner/gartner-top-10-trends-in-data-and-analytics-for-2020. Accessed 22 Sept 2021
20. Adrian M, Jaffri A, Feinberg D (2021) Market guide for graph database management solutions (G00737853). https://info.cambridgesemantics.com/graph-database-management-solution-market-guide-gartner
21. Warr WA (2021) National Institutes of Health (NIH) workshop on reaction informatics. https://chemrxiv.org/engage/api-gateway/chemrxiv/assets/orp/resource/item/611cf1a6ac8b499b36458d19/original/national-institutes-of-health-nih-workshop-on-reaction-informatics.pdf
22. Tovanich N, Heulot N, Fekete J-D, Isenberg P (2019) Visualization of blockchain data: a systematic review. IEEE Trans Vis Comput Graph 27(7):3135–3152. https://doi.org/10.1109/tvcg.2019.2963018
23. Yue X, Shu X, Zhu X, Du X, Yu Z, Papadopoulos D, Liu S (2019) BitExTract: interactive visualization for extracting bitcoin exchange intelligence. IEEE Trans Vis Comput Graph 25(1):162–171. https://doi.org/10.1109/TVCG.2018.2864814

24. Bitquery (2021) Bitcoin analysis: track bitcoin transactions and address. https://bitquery.io/blog/bitcoin-analysis. Accessed 11 Nov 2021
25. Bitquery (2021) Blockchain GraphQL APIs. https://bitquery.io/labs/graphql. Accessed 14 Nov 2021
26. Brown D (2021, Sep 22) Tracking stolen crypto is a booming business: How blockchain sleuths recover digital loot. The Washington Post. https://www.washingtonpost.com/technology/2021/09/22/stolen-crypto/
27. DLT Group (2020) Italian Distributed Ledger Technology Working Group. http://dltgroup.dmi.unipg.it/tools.php. Accessed 14 Nov 2021
28. Mahapatra A, Gieseke E (2021) Analyzing algorand blockchain data with databricks delta (Part 2). Databricks. https://databricks.com/blog/2021/03/03/analyzing-algorand-blockchain-data-with-databricks-delta-part-2.html. Accessed 11 Nov 2021
29. McGinn D, Birch D, Akroyd D, Molina-Solana M, Guo Y, Knottenbelt WJ (2016) Visualizing dynamic bitcoin transaction patterns. Big Data 4(2):109–119. https://doi.org/10.1089/big.2015.0056
30. McGinn D, McIlwraith D, Guo Y (2018) Towards open data blockchain analytics: A Bitcoin perspective. R Soc Open Sci 5(8):180298. https://doi.org/10.1098/rsos.180298
31. Sinnreich A, Gilbert J (2019) The carrier wave principle. Int J Commun 13:5816–5840. 1932-8036/20190005
32. Fedorov AK, Kiktenko EO, Lvovsky AI (2018) Quantum computers put blockchain security at risk. Nature 563(7732):465–467. https://doi.org/10.1038/d41586-018-07449-z
33. Farouk A, Alahmadi A, Ghose S, Mashatan A (2020) Blockchain platform for industrial healthcare: vision and future opportunities. Comput Commun 154:223–235. https://doi.org/10.1016/j.comcom.2020.02.058
34. Stewart I, Ilie DI, Zamyatin A, Werner S, Torshizi MF, Knottenbelt WJ (2018) Committing to quantum resistance: a slow defence for bitcoin against a fast quantum computing attack. R Soc Open Sci 5(6):180410. https://doi.org/10.1098/rsos.180410
35. Hale C (2021) JPM: boehringer partners with Google to bring quantum computing to biopharma R&D. Fierce Biotech. https://www.fiercebiotech.com/medtech/boehringer-partners-google-to-bring-quantum-computing-to-biopharma-r-d. Accessed 11 Nov 2021
36. Yaqoob I, Salah K, Jayaraman R, Al-Hammadi Y (2021) Blockchain for healthcare data management: opportunities, challenges, and future recommendations. Neural Comput Appl. https://doi.org/10.1007/s00521-020-05519-w
37. Campbell RE (2019) Transitioning to a hyperledger fabric quantum-resistant classical hybrid public key infrastructure. J Br Blockchain Assoc 2(2):4. https://doi.org/10.31585/jbba-2-2-(4)2019
38. Sun X, Kulicki P, Sopek M (2020) Lottery and auction on quantum blockchain. Entropy (Basel) 22(12):E1377. https://doi.org/10.3390/e22121377
39. Raj P (2021) Empowering digital twins with blockchain. Adv Comput 121:267–283. https://doi.org/10.1016/bs.adcom.2020.08.013
40. Kendzierskyj S, Jahankhani H, Jamal A, Ibarra Jimenez J (2019) The transparency of big data, data harvesting and digital twins. In: Jahankhani H, Kendzierskyj S, Jamal A, Epiphaniou G, Al-Khateeb HM (eds) Blockchain and clinical trial: securing patient data. Springer Nature Switzerland AG, pp 139–148). https://doi.org/10.1007/978-3-030-11289-9_6
41. Tao F, Qi Q (2019) Make more digital twins. Nature 573:490–491. https://doi.org/10.1038/d41586-019-02849-1
42. Popa EO, Van Hilten M, Oosterkamp E, Bogaardt M-J (2021) The use of digital twins in healthcare: socio-ethical benefits and socio-ethical risks. Life Sci Soc Policy 17(1). https://doi.org/10.1186/s40504-021-00113-x
43. Liu Y, Zhang L, Yang Y, Zhou L, Ren L, Wang F, Liu R, Pang Z, Deen MJ (2019) A novel cloud-based framework for the elderly healthcare services using digital twin. IEEE Access 7:49088–49101. https://doi.org/10.1109/access.2019.2909828
44. Laubenbacher R, Sluka James P, Glazier James A (2021) Using digital twins in viral infection. Science 371(6534):1105–1106. https://doi.org/10.1126/science.abf3370

45. Feng Y, Chen X, Zhao J (2018) Create the individualized digital twin for noninvasive precise pulmonary healthcare. Significances Bioeng Biosci 1(2):26–30. https://doi.org/10.31031/SBB.2018.01.000507
46. Putz B, Dietz M, Empl P, Pernul G (2021) EtherTwin: blockchain-based secure digital twin information management. Inf Process Manag 58(1):102425. https://doi.org/10.1016/j.ipm.2020.102425
47. Leng J, Yan D, Liu Q, Xu K, Zhao JL, Shi R, Wei L, Zhang D, Chen X (2019) ManuChain: combining permissioned blockchain with a holistic optimization model as bi-level intelligence for smart manufacturing. IEEE Trans Syst Man Cybern Syst 50(1):182–192. https://doi.org/10.1109/tsmc.2019.2930418
48. Lu Y, Huang X, Zhang K, Maharjan S, Zhang Y (2021) Communication-efficient federated learning and permissioned blockchain for digital twin edge networks. IEEE Internet Things J 8(4):2276–2288. https://doi.org/10.1109/jiot.2020.3015772
49. Corral-Acero J, Margara F, Marciniak M, Rodero C, Loncaric F, Feng Y, Gilbert A, Fernandes JF, Bukhari HA, Wajdan A, Martinez MV, Santos MS, Shamohammdi M, Luo H, Westphal P, Leeson P, Diachille P, Gurev V, Mayr M et al (2020) The 'digital twin' to enable the vision of precision cardiology. Eur Heart J 41(48):4556–4564. https://doi.org/10.1093/eurheartj/ehaa159
50. Charles WM (2021). Accelerating life sciences research with blockchain. In: Namasudra S, Deka GC (eds) Applications of blockchain in healthcare, vol 83. Springer Nature, Berlin, pp 221–252. https://doi.org/10.1007/978-981-15-9547-9_9
51. Jeon H-J, Youn H-C, Ko S-M, Kim T-H (2021) Blockchain and AI meet in the metaverse. In: Fernández-Caramés TM, Fraga-Lamas P (eds) Blockchain potential in AI [Working Title]. IntechOpen. https://doi.org/10.5772/intechopen.99114
52. Meta (2021, October 28) Connection is evolving and so are we. https://about.facebook.com/meta. Accessed 13 Nov 2021
53. Lee L-H, Braud T, Zhou P, Wang L, Xu D, Lin Z, Kumar A, Bermejo C, Hui P (2021) All one needs to know about metaverse: a complete survey on technological singularity, virtual ecosystem, and research agenda. University of Helsinki. https://doi.org/10.13140/RG.2.2.11200.05124/7
54. van der Merwe D (2021) The metaverse as virtual heterotopia. Diamond Scientific Publishing. https://www.dpublication.com/abstract-of-3rd-socialsciencesconf/41-20250/
55. Kell G (2020) Unforgotten: COVID-19 era grads to be celebrated virtually this Saturday. University of California, Berkeley. https://news.berkeley.edu/2020/05/14/unforgotten-covid-19-era-grads-to-be-celebrated-virtually-this-saturday/. Accessed 13 Nov 2021
56. Ryskeldiev B, Ochiai Y, Cohen M, Herder J (2018) Distributed metaverse: creating decentralized blockchain-based model for peer-to-peer sharing of virtual spaces for mixed reality applications. Association for Computing Machinery. https://doi.org/10.1145/3174910.3174952
57. Roach J (2021, November 2) Mesh for Microsoft Teams aims to make collaboration in the 'metaverse' personal and fun. Microsoft. https://news.microsoft.com/innovation-stories/mesh-for-microsoft-teams/. Accessed 13 Nov 2021
58. Hudson K, Taylor LA, Kozachik SL, Shaefer SJ, Wilson ML (2015) Second life simulation as a strategy to enhance decision-making in diabetes care: a case study. J Clin Nurs 24(5–6):797–804. https://doi.org/10.1111/jocn.12709
59. Schaffer MA, Tiffany JM, Kantack K, Anderson LJW (2016) Second Life® virtual learning in public health nursing. J Nurs Educ 55(9):536–540. https://doi.org/10.3928/01484834-20160816-09
60. Rudolphi-Solero T, Jimenez-Zayas A, Lorenzo-Alvarez R, Domínguez-Pinos D, Ruiz-Gomez MJ, Sendra-Portero F (2021) A team-based competition for undergraduate medical students to learn radiology within the virtual world Second Life. Insights Imaging 12(1). https://doi.org/10.1186/s13244-021-01032-3
61. Beard L, Wilson K, Morra D, Keelan J (2009) A survey of health-related activities on second life. J Med Internet Res 11(2):e17. https://doi.org/10.2196/jmir.1192

62. Gorini A, Gaggioli A, Vigna C, Riva G (2008) A second life for eHealth: prospects for the use of 3-D virtual worlds in clinical psychology. J Med Internet Res 10(3):e21. https://doi.org/10.2196/jmir.1029
63. Casado-Vara R, Corchado JM (2019) Distributed e-health wide-world accounting ledger via blockchain. J Intell Fuzzy Syst 36:2381–2386. https://doi.org/10.3233/JIFS-169949
64. Tian H, He J, Ding Y (2019) Medical data management on blockchain with privacy. J Med Syst 43(2):6. https://doi.org/10.1007/s10916-018-1144-x
65. Kuo T-T, Gabriel RA, Ohno-Machado L (2019) Fair compute loads enabled by blockchain: sharing models by alternating client and server roles. J Am Med Inform Assoc 26(5):392–403. https://doi.org/10.1093/jamia/ocy180
66. Kuo T-T, Ohno-Machado L, Zavaleta Rojas H (2019) Comparison of blockchain platforms: a systematic review and healthcare examples. J Am Med Inform Assoc 26(5):462–478. https://doi.org/10.1093/jamia/ocy185
67. Firdaus A, Anuar NB, Razak MFA, Hashem IAT, Bachok S, Sangaiah AK (2018) Root exploit detection and features optimization: mobile device and blockchain based medical data management. J Med Syst 42(6):112. https://doi.org/10.1007/s10916-018-0966-x
68. Mamoshina P, Ojomoko L, Yanovich Y, Ostrovski A, Botezatu A, Prikhodko P, Izumchenko E, Aliper A, Romantsov K, Zhebrak A, Ogu IO, Zhavoronkov A (2018) Converging blockchain and next-generation artificial intelligence technologies to decentralize and accelerate biomedical research and healthcare. Oncotarget 9(5):5665–5690. https://doi.org/10.18632/oncotarget.22345
69. Durneva P, Cousins K, Chen M (2020) The current state of research, challenges, and future research directions of blockchain technology in patient care: systematic review. J Med Internet Res 22(7):e18619. https://doi.org/10.2196/18619
70. Quaini T, Roehrs A, Da Costa CA, Da Rosa Righi R (2018) A model for blockchain-based distributed electronic health records. IADIS Int J WWW/Internet 16(2):66–79. https://doi.org/10.33965/ijwi_2018161205
71. Dwivedi AD, Srivastava G, Dhar S, Singh R (2019) A decentralized privacy-preserving healthcare blockchain for IoT. Sensors (Basel) 19(2):326. https://doi.org/10.3390/s19020326
72. Yang J, Onik MMH, Kim C-S (2020) Blockchain technology for protecting personal information privacy. In: Ahmed M (ed) Blockchain in data analytics. Cambridge Scholars Publisher, pp 122–144. https://books.google.com/books?id=z_zLDwAAQBAJ&dq
73. Al Omar A, Bhuiyan MZA, Basu A, Kiyomoto S, Rahman MS (2019) Privacy-friendly platform for healthcare data in cloud based on blockchain environment. Futur Gener Comput Syst 95:511–521. https://doi.org/10.1016/j.future.2018.12.044
74. Meyyan P (2018, January 16) Decrypting the utility of blockchain in clinical data management. VertMarkets. https://www.clinicalleader.com/doc/decrypting-the-utility-of-blockchain-in-clinical-data-management-0001. Accessed 23 Oct 2018
75. Goossens M (2018, June 6) Blockchain and how it can impact clinical trials. ICON. http://www2.iconplc.com/blog/blockchain. Accessed 18 Dec 2018

Dr. Wendy Charles has been involved in clinical trials from every perspective for 30 years, with a strong background in operations and regulatory compliance. She currently serves as Chief Scientific Officer for BurstIQ, a healthcare information technology company specializing in blockchain and AI, where she leads the Life Sciences division. Dr. Charles augments her blockchain healthcare experience by serving on the EU Blockchain Observatory and Forum Expert Panel, HIMSS Blockchain Task Force, Government Blockchain Association healthcare group, and IEEE Blockchain working groups. She is also involved as an assistant editor and reviewer for academic journals. Dr. Charles obtained her PhD in Clinical Science with a specialty in Health Information Technology from the University of Colorado, Anschutz Medical Campus. She is certified as an IRB Professional, Clinical Research Professional, and Blockchain Professional.