Mapping Distributed Ledger Technology Characteristics to Use Cases in Healthcare: A Structured Literature Review

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Following the success of the Bitcoin blockchain, distributed ledger technology (DLT) has received extensive attention in health informatics research. Yet, the healthcare industry is highly complex with many different stakeholders, information systems, regulations, and challenges. Thus, DLT may be used in various settings and for different purposes. First surveys have started to synthesize our knowledge of the different use cases, in which healthcare may benefit from DLT implementations. However, an in-depth understanding of whether and how these use cases differ concerning their requirements of DLT characteristics (i.e., technical or administrative design features) is still lacking. In this work, we conducted a structured review of 185 studies on DLT-based applications in healthcare. The results reveal six pertinent use cases, each with its own combination of different purposes that DLT is used for. Furthermore, our study shows that each of these use cases has a unique set of requirements with regard to the most important DLT characteristics. In doing so, we seek to guide practitioners in the development of highly effective DLT-based applications in various healthcare settings and pave the way for future research to investigate the understudied areas of DLT-based applications in healthcare.

CCS Concepts: • **Applied computing** → Life and medical sciences; Health care information systems; • **Software and its engineering** → Designing software; Software creation and management;

Additional Key Words and Phrases: Distributed ledger technology, DLT-based applications, DLT characteristics

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1 Introduction

Following the success of the Bitcoin blockchain, **distributed ledger technology (DLT)** has received extensive attention from various domains, including, amongst others, finance, energy, and real estate. Especially in the healthcare domain, a considerable number of applications that utilize DLT (i.e., DLT-based applications) have been proposed, centered around diverse application scenarios. Such application scenarios can be grouped into

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cohesive use cases (i.e., abstract classes of application scenarios), for example, sharing patient health data across involved parties (e.g., providers and patients), automating business or administration processes (e.g., verifying insurance requests), or fostering medical research initiatives [1].

Initial research endeavors on DLT-based applications in healthcare aim to investigate whether DLT can contribute to addressing challenges in the health sector, such as issues surrounding the sensibility and critical value of health data as well as the complexity of collaboration between stakeholders [2]. Although many scholars assert that research on the use of DLT in healthcare is still in its infancy (e.g., [1, 3]), the number of DLT-based applications proposed in the literature continues to increase [2]. To move DLT forward in healthcare, scholars are becoming growingly concerned about the actual suitability of DLT-based applications proposed for healthcare, which can be assessed by whether this disruptive technology fulfills actual needs in healthcare [4].

First studies exist that seek to provide a comprehensive overview of the benefits that different DLT-based applications in healthcare may yield [3, 5]. While we acknowledge these studies' value in synthesizing existing knowledge on the suitability of DLT for healthcare, they usually focus on the utilization of DLT in healthcare from a holistic perspective and do not consider the peculiarities of each use case. However, extant research highlighted that the suitability of DLT-based applications for the health sector depends on the specific context because each use case in healthcare has unique requirements, which need to be fulfilled by utilizing DLT [6]. By way of illustration, supplying pharmaceutical drugs is more focused on process compliance and accuracy of drugs, while **remote patient monitoring (RPM)** takes more of the timeliness of data transmission into account.

Besides diverse requirements in different use cases, DLT-based applications also vary in their own DLT characteristics, which present the technical (e.g., block creation interval) or administrative (e.g., degree of decentralization) nature of DLT designs (e.g., Ethereum, IOTA). A DLT design specifies an abstract DLT concept (e.g., blockchain) with its unique DLT characteristics [7]. As different DLT characteristics have different effects on fulfilling certain requirements, understanding the possible contribution of a characteristic for a given requirement helps to select the desirable characteristics and, consequently, a suitable DLT design for a specific DLT-based application utilized in a unique use case. The study conducted by Mackey et al. [4] has attempted to reveal the benefits of DLT for each specific use case in healthcare. Nevertheless, the study only touches on the general technical perspective without discussing distinct DLT characteristics in detail. As a result, a comprehensive analysis of the relationship between DLT characteristics and requirements in each unique healthcare use case (i.e., case-specific purposes of utilizing DLT in healthcare) is still missing and sorely required to better understand the suitability of DLT for healthcare and to move the field forward. Moreover, investigating how the configuration of DLT characteristics contributes to achieving the purposes of the different use cases can provide insights into the effective use of DLT in healthcare. Therefore, we aim to answer the following **research questions (RQs)** in this study:

RQ1: What are pertinent use cases of DLT in healthcare and the associated purposes of utilizing DLT?
RQ2: What are (the most) relevant DLT characteristics for each use case and how do they facilitate achieving the associated purposes?

To answer our RQs, we conducted a structured literature review of 185 articles that unfolded in three steps. First, we synthesized pertinent use cases of DLT in healthcare and the associated purposes within the reviewed literature. Second, we identified the DLT characteristics of DLT-based applications proposed in the extant literature. Finally, we consolidated the identified characteristics with the targeted use cases and analyzed the rationale of each characteristic for the associated purposes.

In doing so, the contribution of our work is three-fold. For one, we provide an overview of contemporary DLT use cases in healthcare by validating six established and identifying two nascent use cases in the health domain. This results in an up-to-date understanding of meaningful DLT-based applications in healthcare. For another, by revealing the purposes of utilizing DLT in healthcare, we advance the scientific knowledge base about which challenges in healthcare can be addressed by DLT-based applications. Finally, our study sheds light on the variety of reasons for choosing specific DLT characteristics for use case-specific requirements by analyzing the rationales for the selection of DLT characteristics discussed in the literature. Thus, we provide initial insights into assessing DLT characteristics' suitability for the associated use cases in healthcare. Overall, our findings may serve as a starting point for researchers and practitioners alike, who aim to develop suitable and effective DLT-based applications to address challenges in healthcare.

This article proceeds as follows: First, we introduce the basic concept of DLT and the current state of research on DLT in healthcare. Following the description of our research approach, we present the identified use cases in healthcare for DLT with associated purposes of utilizing DLT as well as the desired DLT characteristics in each use case. We then discuss our principal findings, summarize the implications, and elaborate on the potential limitations of our study. Finally, we conclude our study.

2 Background and Related Work

2.1 DLT

The emergence of DLT marks a shift in data management from centralized systems to decentralized solutions. At its core, DLT serves as an innovative approach to recording and sharing data across a peer-to-peer network comprising multiple computing devices [8, 9]. In this network, each device functions as a node and can be controlled by individuals or organizations (referred to as node controllers) [7]. Relying on a pre-defined algorithmic validation method, known as the consensus mechanism, nodes can verify the accuracy of information exchanged within the network and securely store identical copies of the related data [9]. By relinquishing control from a singular entity, DLT exhibits potential in fortifying security and mitigating the risk of data tampering in untrustworthy environments [7, 9].

Within distributed ledgers, the actions of transferring, updating, or modifying data within the ledger manifest as transactions [7]. Depending on how the distributed ledger organizes these transactions, various DLT concepts emerge, which abstractly define the structure and functionality of the ledger [10]. The most prevalent DLT concept is Blockchain, which organizes transactions added by nodes in interconnected blocks forming a linked list. Each DLT concept can be implemented in diverse ways, with the specific implementation termed as a DLT design [7]. Representative examples of DLT designs for the Blockchain concept include Bitcoin and Ethereum.

A DLT design is represented by its inherent characteristics (i.e., DLT characteristics). These include technical aspects like scalability or throughput, alongside administrative features, such as incentive mechanism [7]. DLT characteristics can be categorized under DLT properties (e.g., performance, security). Each DLT design incorporates all DLT properties, though not every DLT design encompasses all DLT characteristics [7]. For instance, **transaction-based directed acyclic graphs (TDAGs)** deviate from the conventional use of blocks, lacking any DLT characteristics typically linked to them, such as block size or block creation interval [7]. The diversity of DLT characteristics indicates the complexity of choosing suitable DLT designs.

Extent research also highlights the tradeoffs between DLT characteristics that resulted in the dependencies between them [7]. As the improvement of one DLT characteristic can interfere with another DLT characteristic, the combination of DLT characteristics for developing an effective DLT-based application is challenging. Despite challenges caused by its inherent characteristics, DLT has extended far beyond the realm of digital currencies since the introduction of Bitcoin. A growing multitude of DLT-based applications have been developed across diverse domains, including energy [11], public sector [12], and healthcare [1].

2.2 Related Work

In recent years, a multitude of studies has been conducted to review existing DLT-based applications for healthcare. Table 1 provides an overview of seminal literature reviews on DLT-based applications in healthcare with a comparison of their key findings. Generally, extant research has attempted to identify the predominant use cases of blockchain, instead of all DLT concepts. Most reviews (e.g., [1, 2, 13, 14]) provide an overview of blockchain use

Table 1. Overview of Key Literature Reviews Analyzing DLT-Based Applications in Healthcare

Review	**Number of reviewed studies**	**Key findings**	**DLT use cases in health-care**	**DLT characteristics**	
				Technical characteristics	**Administrative characteristics**
Abu-Elezz et al. [15]	37	–Patient-related and healthcare organizational-related use cases –Organizational, social, or technical threats of blockchain	●	◒	◒
De Aguiar et al. [14]	unknown	–Pertinent use cases of blockchain in healthcare –Purposes of utilizing blockchain in each use case –Limitations and advantages of commonly known blockchain-based applications in healthcare	●	◒	◒
Durneva et al. [17]	70	–Pertinent use cases of blockchain in healthcare –Health information technology challenges that blockchain addressed –Barriers and challenges of utilizing blockchain in healthcare	●	◒	○
Hasselgren et al. [1]	39	–Pertinent use cases of blockchain in healthcare –Purposes and challenges of utilizing blockchain –Prevalent types of DLT designs, consensus algorithms, and the support of smart contracts	●	◒	○
Hölbl et al. [18]	33	–Pertinent use cases of blockchain in healthcare –Prevalent types of DLT designs, consensus algorithms, and the support of smart contracts	●	◒	◒
Hussien et al. [2]	58	–Pertinent use cases of blockchain in healthcare –Purposes and (technical) challenges of utilizing blockchain	●	◒	○
Kuo et al. [16]	10	–Prevalent types of DLT designs, consensus algorithms, and support of smart contracts	○	●	◒
Tandon et al. [13]	42	–Pertinent use cases of blockchain in healthcare –Purposes and challenges of utilizing blockchain –Prevalent types of blockchain designs and consensus algorithms	●	◒	◒
This study	185	–Pertinent use cases of DLT in healthcare –Purposes of utilizing DLT –Rationales of desired DLT characteristics for the identified use cases	●	●	●

● = complete analysis conducted; ◒ = partial analysis conducted; ○ = no analysis conducted

cases in healthcare and focused on the purposes of introducing blockchain (e.g., access control, interoperability, data integrity [1]). However, they have mainly synthesized the purposes of utilizing blockchain from a holistic perspective without considering the peculiarities of each use case. While some studies have additionally provided some details about issues of each use case (e.g., [14]), they do not systematically synthesize the purposes of utilizing DLT in each use case.

Meanwhile, some studies have highlighted potential technical and administrative challenges when adopting DLT in the health domain (e.g., [14, 15]). However, much of the research up to now is limited to discussion about the desired technical and administrative features of DLT and the use cases of DLT in healthcare in isolation. Especially, the impacts of DLT's technical and administrative features on the realization of the purposes have not been treated in much detail. Although the review conducted by Kuo et al. [16] touches on the general technical and administrative perspective, distinct DLT characteristics have not been discussed in detail. As different DLT characteristics have different effects on fulfilling certain requirements of each use case, it is necessary to integrate the technical perspective (i.e., DLT characteristics) with domain-specific aspects (i.e., DLT use case in healthcare).

3 Methods

To answer the two outlined RQs, we followed a descriptive literature review approach. Our review process was informed by extant recommendations for conducting literature reviews [19, 20].

3.1 Data Collection

To begin, we conducted an online database search in the six scientific databases ACM Digital Library, EBSCOHost, IEEE Xplore, PubMed, ScienceDirect, and Scopus. We chose such a diverse set of databases due to the interdisciplinary nature of our research focus (i.e., DLT in healthcare), which covers multiple disciplines, such as computer science, information systems, and medical informatics. All databases were searched on March 23rd, 2021, by using the following search string in the title, abstract, and keywords:

> *TITLE-ABSTR-KEY (distributed ledger technology OR DLT OR blockchain) AND TITLE-ABSTR-KEY (health* OR medical) AND TITLE-ABSTR-KEY (application OR scenario OR use case)*

This database search yielded a total of 1,048 publications. We evaluated the relevance of each publication based on predefined exclusion criteria. First, we excluded publications that were duplicated in our dataset ($n = 265$), not peer-reviewed ($n = 158$), or not written in English ($n = 25$). After this step, 600 publications remained for further analysis. Subsequently, we excluded 301 publications that were not directly related to a healthcare context (e.g., studies in veterinary contexts) or did not focus on the use of DLT (e.g., simply mentioning the concept of DLT without detailed information). Finally, we assessed whether publications fulfilled at least one of the following criteria: They either provided descriptions of potential use cases of DLT in healthcare or any information regarding the technical or administrative features of specific DLT-based applications in healthcare settings. Each publication was thereby assessed by two authors independently and results were subsequently compared. Differences in assessments were resolved through mutual discussions and the involvement of a third author. The described search and filter approach led to a final sample of 185 articles for further analysis. Figure 1 shows an overview of the approach following the PRISMA 2020 flow diagram template [21].

3.2 Data Analysis

To synthesize the relevant literature, we conducted a manual concept-centric data analysis approach that was informed by Webster and Watson [2002]. Considering the two RQs, we divided the sample into two sets: (a) *set* 1 consisting of 61 articles that provide overviews of use cases, such as relevant summary reviews, and (2) *set* 2 consisting of 124 articles that specifically discuss the targeted use case and considered DLT characteristics of a specific DLT-based application. Based on these two sets, we first reviewed the 61 articles from *set* 1 to develop an inventory of extant use cases proposed in the extant literature. Following the identification of use cases, we analyzed the 124 articles from *set* 2 by using a coding schema comprising (a) the use case in healthcare in which DLT applied ("where"), (b) the purposes of application ("what"), (c) the DLT characteristics proposed to achieve the purposes ("how"), and (4) rationale for selecting these characteristics ("why"). To analyze the DLT characteristics, we decided to base our coding on the list proposed by Kannengießer et al. [7]. This list has been developed more recently than other lists (e.g., [22, 23]) and is thus more applicable to the modern landscape of DLT-based applications in healthcare. It consists of 40 distinct DLT characteristics which are categorized along six

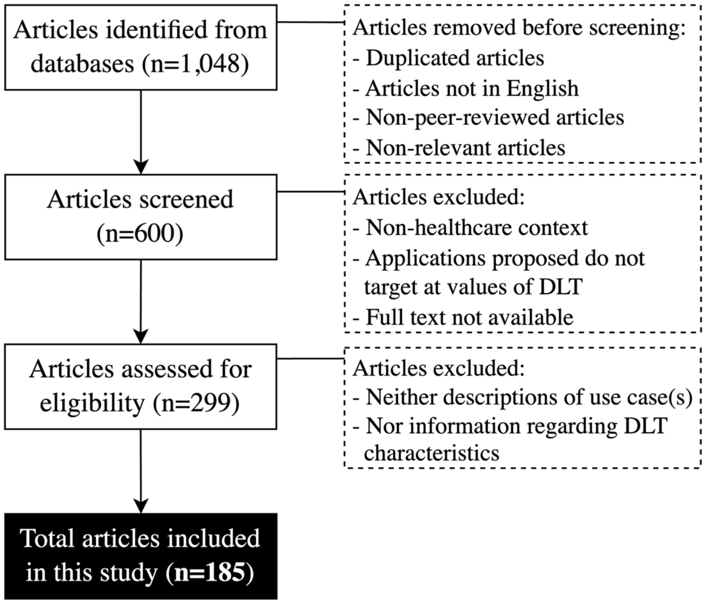


Fig. 1. Literature review procedure.

DLT properties (see Table A.1 in Appendix A.1). These 40 characteristics derive from a comprehensive literature review and a survey with DLT experts which makes it suitable for assessing DLT-based applications, including those in the health domain.

During the coding process, each article was broken down into discrete passages, closely examined, reorganized after comparing similarities as well as differences, and interpreted with regard to the phenomena reflected in the data. Meanwhile, we verified the categorization of use cases and the purposes of utilizing DLT in these use cases. For two use cases discussed in the related articles, we only found one article that proposed a DLT-based application and provided descriptions of DLT characteristics. Given the limited representation of one article, we excluded these two use cases in the analysis of the corresponding DLT characteristics. The final stage of the study consisted of the mapping of DLT characteristics to the use cases and purposes based on the consolidation of rationales found in the 124 articles. We iteratively discussed our findings within the author team, diverged and converged them as appropriate, until we were able to settle on a sufficiently comprehensive understanding of the rationales for selecting a specific DLT characteristic.

4 Results

Our literature review alluded to six use cases in healthcare for which DLT is applied and four purposes, which motivate the utilization of DLT. For each purpose, we identified different DLT characteristics that were discussed in the reviewed studies to contribute to realizing the purpose. Before delving into the topic of DLT characteristics and the rationales for their selection, we first present some characteristics of our reviewed literature. Figure 2(a) shows the use cases targeted by the 124 studies analyzed in our study. Patient-centric health data management was by far the most often investigated use case ($n = 49$). The proposed DLT-based applications also varied in their development phases (Figure 2(b)). While the majority of studies has not progressed their applications beyond proofs-of-concept (conception or lab prototyping), two studies were able to launch their solutions. As can be observed from Figure 2(c) and (d), blockchain is the dominant DLT concept, with the two DLT designs Ethereum and Hyperledger Fabric being the most widely utilized ones.

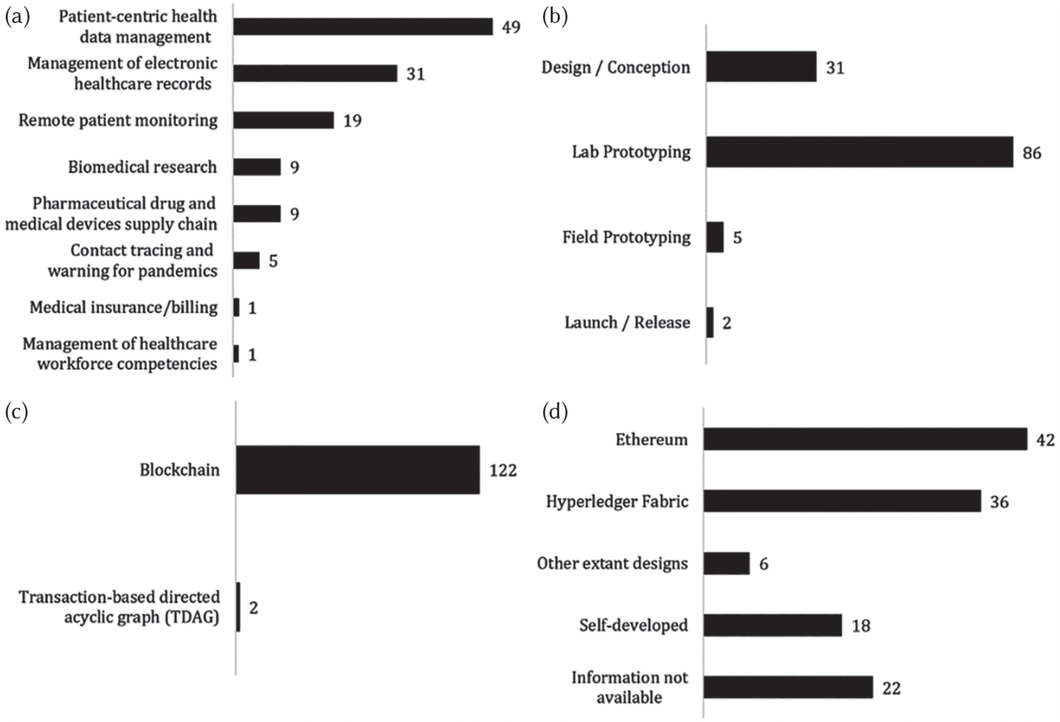


Fig. 2. Descriptive data of included studies.

In the following, we describe each use case briefly and explain the purposes of utilizing DLT in this use case. Due to the repeatedly discussed DLT characteristics, for each purpose in each use case, we explain the rationale for selected DLT characteristics exemplarily to avoid unnecessary repetition and improve the readability of the article. A comprehensive overview of all characteristics discussed in the 124 studies can be found in Table A.2 (Appendix A.2).

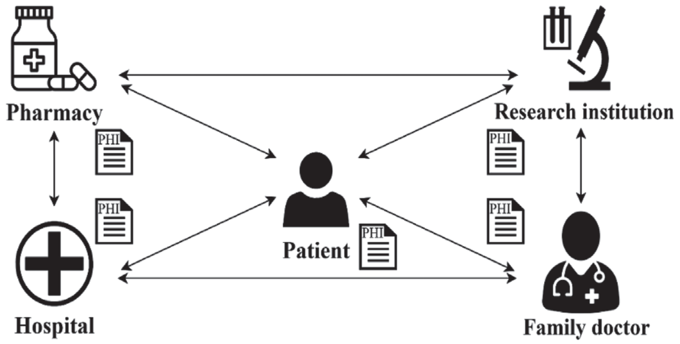
4.1 Patient-Centric Health Data Management

4.1.1 Use Case Description. Among the articles we reviewed, the use case that received the most attention was patient-centric health data management. The general idea behind this use case is enabling patients to autonomously manage their own health data. Especially, patients can access their health data at any time and independently decide whom to authorize for which data during which time frame. This is particularly beneficial in collaborative medical decision-making, where patients participate in their care decisions by controlling their data distribution (e.g., [24, 25]). A prime example of this use case is the blockchain-based mobile application *Patientory*, launched in 2015, which enables patients to access and manage their health information across multiple care facilities [26].

The success of patient-centric health data management depends on several factors. An individual's health data is generated and maintained by different parties, including health professionals, insurance companies, researchers, smart device providers, and many others. Thus, a lack of interoperability between different systems owned by these different parties poses difficult barriers to providing a patient-centric, unified view of health data [27]. Furthermore, patients may hesitate to share their health data if they doubt the confidentiality of any separate data management or the complete data exchange process. Due to their distributed structure and

Table 2. Purposes and Relevant Characteristics of Patient-Centric Health Data Management

Use case: patient-centric health data management



PHI: patient health information

Purpose	**Description of purpose**	**Key DLT characteristics**
Access management	Enabling patients to authorize and revoke access to specific health information	*Flexibility*: Interoperability [33]; Use of smart contracts [34]; Token support [35] *Opaqueness*: Transaction content visibility [36]; User unidentifiability [35]; Node controller verification [37]; *Policy*: Compliance [37] *Performance*: Scalability [38]; Resource consumption [39]; Transaction validation latency [40] *Practicality*: Ease of node setup [39]; Ease of use [39] *Security*: Authenticity [31]; Availability [32]; Confidentiality [30]; Consistency [30]; Fault tolerance [40]; Integrity [31]; Isolation [41]; Strength of cryptography [32]
Secure record-keeping	Maintaining log files of activities within DLT-based applications for patient-centric health data management to prevent tampering	*Flexibility*: Interoperability [29]; Use of smart contracts [38]; Token support [42] *Opaqueness*: Transaction content visibility [36]; User unidentifiability [35]; Node controller verification [25] *Policy*: Compliance [25] *Performance*: Scalability [38]; Resource consumption [24] *Practicality*: Ease of use [29] *Security*: Confidentiality [42]; Integrity [25]; Isolation [35]; Strength of cryptography [38];
Data sharing incentivization	Establishing a trustworthy and transparent environment to encourage patients to share their health data	*Flexibility*: Interoperability [43]; Use of smart contracts [36] *Opaqueness*: Transaction content visibility [36]; Node controller verification [36] *Policy*: Degree of decentralization [43]; Incentive mechanism [36] *Security*: Availability [44]; Confidentiality [44]; Integrity [44]

disintermediation of trust, distributed systems have emerged as a potential solution to these issues and to facilitate the data exchange between heterogeneous databases in an untrusted environment. Our review yielded 49 studies equipping patient-centric health data management with DLT to overcome such challenges mentioned above (e.g., [15, 17]), especially in terms of (1) access management, (2) secure record-keeping, and (3) data sharing incentivization. Table 2 exemplifies the use case and summarizes the purposes and relevant DLT characteristics of this use case.

4.1.2 Access Management. Access management for patient-centric health data management generally consists of the rule-setting to authorize and revoke access to specific patient health information [28]. Typical activities of access management are identifying and verifying access requests, declining requests, or granting access permissions. For this purpose, DLT is used to enable patients to exercise control over who can access their personal health information. This is evident in the case of allowing a hospital to view patients' health information collected by a wearable device owned by another independent provider [29] or permitting their relatives to edit their health information so that relatives can help update patients' health status when necessary [30]. We found 20 DLT characteristics worth considering in 40 articles that intend to use DLT to facilitate access management for patient health data management.

Given the high sensitivity of health data and the severe consequences of illegitimate disclosures, patient health information necessitates effective protection from unauthorized access. In general, a party is authorized to access if its access is accurate and consistent with patients' wishes and defined access rules. From this point of view, ensuring the correctness of access authorization (i.e., that a patient has truly allowed a stakeholder to access their personal health information) and preventing access authorization (i.e., transactions) from unintended modification or deletion [29] contributes to detecting and avoiding manipulated authorization [31, 32]. Accordingly, previous studies suggested that a high level of *authenticity* and *integrity* of a DLT design lay the foundation for protecting personal health data from unintended disclosures in applications that use DLT for access management in patient-centric health data management.

Meanwhile, stakeholders involved in this use case (e.g., hospitals, caregivers, research institutions, and family members) can demand access to patients' health information by participating as node controllers on the DLT design. Node controllers can create new transactions (e.g., request access to a dataset), verify transactions (i.e., access request and authorization), or perform necessary actions (e.g., provide requested information) to complete transactions. If anyone can freely register on the ledger without verification of their identity, patients may not be able to authenticate them before authorizing them to access highly sensitive health information [45]. Thus, to avoid any illegitimate misuse of personal health information, our reviewed literature has also emphasized the pivotal role of *node controller verification* in access management for patient-centric health data management (e.g., [32, 46]).

4.1.3 Secure Record-Keeping. The second purpose of using DLT in this use case stems from this technology's tamper resistance [14]. All activities within DLT-based applications for patient-centric health data management, such as sharing user data, or requesting and approving access can be recorded to prevent tampering [32]. These log files allow patients to track the authorization given by themselves in alignment with defined rules. Our review revealed 14 characteristics in terms of featuring DLT for secure record-keeping in patient-centric health data management. Obviously, DLT designs used here should also focus on their *authenticity* and *integrity*, since the accuracy and comprehensibility of the data are directly influenced by the initial input as well as each modification or deletion [47].

Besides, after the DLT-based application is put into use, the number of records stored on the ledger has the possibility of gradually increasing. In order to guarantee the effectiveness of the system by keeping records secure, the related DLT design must have certain *scalability*, particularly to be able to properly address the requirements imposed by data expansion [35]. Another characteristic discussed in previous studies is *transaction content visibility* (e.g., [42]). The content of a transaction in this use case implies the information stored as records, which will be required to be disclosed to certain parties (e.g., patients). Without the ability to view the content of a transaction in a DLT design, even if the system keeps the records, it cannot prove the transparency and authenticity of the records' content, thus inhibiting the full realization of the purpose of secure record-keeping.

4.1.4 Data Sharing Incentivization. Given the value of health information, sharing personal health data can contribute to several fields, especially health and medical research. Several studies reviewed in this work indicated that a lack of trust in the data-sharing environment can hinder patients' willingness to share their health data [28, 45]. By providing an immutable and transparent view of all activities that have operated on the available patients' health data, DLT contributes to establishing trust, accountability, and transparency in sharing health data [29], thereby encouraging patients to share their data with authorized parties. For implementing DLT to incentivize data sharing in patient-centric health data management, nine DLT characteristics have been suggested in five reviewed studies. Incentives are the most intuitive way to motivate nodes to actively participate in maintaining the secure operation of DLT-based applications. Accordingly, three articles in our review suggested that *incentive mechanism* (e.g., tokens) enables patients to be rewarded for voluntarily sharing their information, which will directly entice them to share again [34, 42, 43]. Moreover, people will be more eager to provide their health data if they do not have to be concerned about the consequences of disclosure, missing or fabricated health information, such as being discriminated or misdiagnosed. Thus, increasing patients' trust in DLT-based applications by enhancing the *confidentiality* and *integrity* of the DLT designs is a prerequisite for persuading patients to use this system to share data [44, 48].

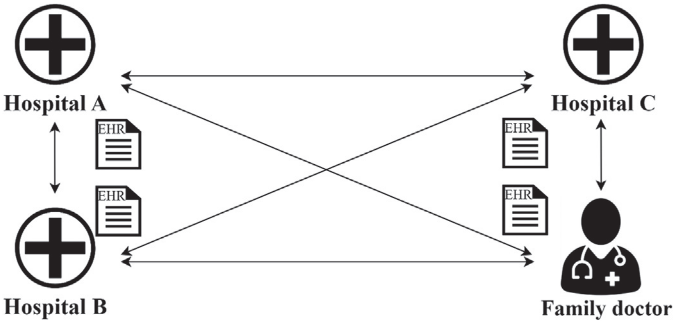
4.2 Management of **Electronic Healthcare Records (EHRs)**

4.2.1 Use Case Description. Another use case leveraging DLT in health information systems was first conceptualized in research by Azaria et al. [49] with their novel decentralized EHRs management system MedRec. EHRs generally refer to an electronic version of a patient's medical history which includes all major administrative clinical data relevant to that person's care, such as laboratory data, radiology reports, and medications [50]. The management of EHRs is concerned with the creation, storage, change as well as sharing of these medical records [4, 52]. Compared to the first use case, only patients' health data obtained by healthcare providers following professional diagnoses are considered in this use case. Moreover, these data are exclusively exchanged between healthcare providers and relevant laboratories without patients' participation in order to eliminate duplicate diagnoses and facilitate collaboration among healthcare providers. Especially, a patient's medical history located at other institutions can be requested in emergency treatment by a new clinician, to where the patient is spontaneously transferred due to the resource availability and shortest distance [15].

As EHRs assist with patient care, ensuring the correctness and availability of these records can improve the efficiency of healthcare services [50] and accordingly mitigate the risk of medico-legal repercussions [53]. Extensive research has shown that the management of EHRs can benefit from leveraging DLT [14, 54]. Especially, its decentralized nature enhances the resilience of patients' data against unintended manipulation and reduces the risk of unauthorized access to this sensitive information. Estonia's electronic health record illustrates this use case. The blockchain-based nationwide system created a unified patient record by integrating data from various healthcare providers across the country. This allows health practitioners to access comprehensive patient records from a single electronic file, streamlining the process and ensuring consistency in the medical information available to them [54]. In our review, 31 studies have engaged with this use case. These studies were built on DLT primarily for two reasons: (1) access management and (2) secure record-keeping. The two purposes with associated characteristics are listed in Table 3, which also illustrates the use case.

4.2.2 Access Management. Similar to the first use case, utilizing DLT for the management of EHRs is often driven by the need for access management. 24 of the 31 articles in this use case intended to apply DLT for access management and suggested 15 DLT characteristics for consideration. Among them, frequently mentioned are *smart contracts* and *node controller verification.* In half of the articles, *smart contracts* are mainly used to automate the execution of access rules which can be computationally represented, thereby improving the effectiveness of access management [49, 55, 56]. Accordingly, unauthorized access can be detected in time, and gained access to EHRs can be continuously monitored. Employing DLT for access management, all activities of access management will be verified by node controllers and stored as transactions in the ledger. As the identity of node controllers guarantees the trustworthiness of their verification of transactions, 11 of the 24 studies suggested the registration of healthcare institutions with their identity information to ensure their legitimation (e.g., [56–58]). In addition,

Table 3. Purposes and Relevant DLT Characteristics of Management of EHRs

Use case: management of EHRs		
		
Purpose	**Description of purpose**	**Key DLT characteristics**
Access management	Controlling access permissions for EHRs	*Flexibility*: Interoperability [57]; Use of smart contracts [55]; Token support [66] *Opaqueness*: User unidentifiability [58]; Node controller verification [60] *Policy*: Compliance [59] *Performance*: Resource consumption [67]; Transaction validation latency [55] *Practicality*: Ease of use [63] *Security*: Authenticity [68]; Availability [69]; Confidentiality [55]; Consistency [59]; Integrity [56]; Non-repudiation [56]
Secure record-keeping	Recording log files of operations on EHRs in a secure and transparent manner	*Flexibility*: Interoperability [70]; Use of smart contracts [71] *Opaqueness*: User unidentifiability [71]; Node controller verification [72] *Performance*: Scalability [70]; Resource consumption [67] *Practicality*: Ease of use [71] *Security*: Authenticity [73]; Availability [69]; Confidentiality [73]; Integrity [72]; Non-repudiation [69]; Strength of cryptography [73]

many countries of the world have strict data privacy regulations regarding access to health data, especially the need-to-know principle when authorizing access [59]. This enforces applications for access management of EHRs via DLT in *compliance* with the regulations, for example, by specifying fine-grained access rules implemented in the DLT design [59] or parting records of patients from their anonymized meta information [60].

Given the fundamental role of time and speed in preserving life, EHRs can be requested spontaneously, for example in emergencies [61]. Therefore, four studies suggested that the *availability* of DLT-based applications for access management should be improved to ensure their flawless operation in all circumstances [55, 62]. In addition, *ease of use* has been discussed regarding its contribution to the timely and effective provision of EHRs [63, 64]. One study explicitly explained that they selected Hyperledger Fabric due to the numerous available resources for its implementation, its wide range of applications, and a big community of developers [63]. Interestingly, one study focused on integrating an innovative *incentive mechanism* with the Proof of Authority consensus algorithm to measure the efforts of EHRs' providers regarding maintaining EHRs and creating new blocks [65]. The authors claim that this *incentive mechanism* can contribute to improving the legibility, completeness, consistency, correctness, and non-redundancy of EHRs.

4.2.3 Secure Record-Keeping.

Owing to its tamper resistance characteristic, DLT can record data generated during the management of EHRs with timestamps securely and transparently [14]. However, storing EHRs directly in a ledger is a challenge, as EHRs typically document patients' health information for many years, leading to a theoretically massive amount of data needed to be added to the ledger. Thus, in this use case, utilizing DLT for secure record-keeping commonly relates to the log files of operations on EHRs. We found 13 characteristics that may contribute to secure record-keeping in this use case. Given strict regulatory requirements for editing EHRs, the log files stored in the ledger may serve as audit trails to improve the conformity of all involved stakeholders and their systems. Therefore, for the secure keeping of log files in the ledger, studies (e.g., [69]) emphasized the need to protect these log files from unintended modification or deletion (i.e., *integrity*). Meanwhile, two studies touched on *resource consumption* due to the number of log files which will possibly be processed in a ledger [67, 74]. While three studies recognized the importance of *availability* for secure record-keeping in EHRs [62, 69, 73], one of these studies specifically intended to prohibit the merging of different ledgers in order to enable users to prove the continuity of the log files as well as EHRs implicitly [73].

4.3 RPM

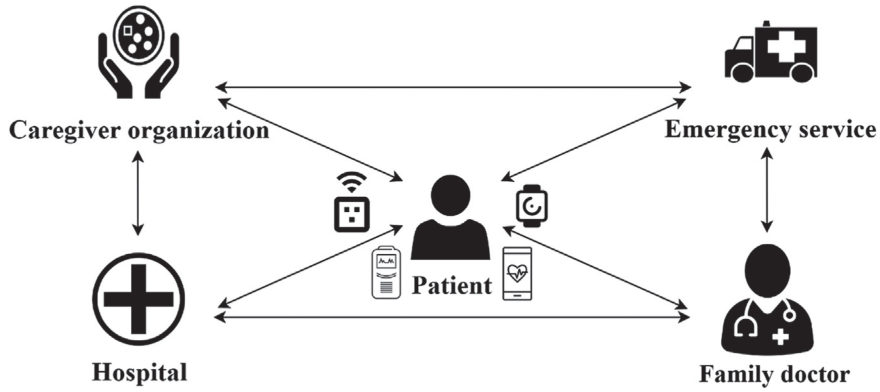
4.3.1 Use Case Description. RPM covers a variety of health services outside the conventional clinical setting, for instance, continuous vital signs monitoring, fall detection, or glucose monitoring [75]. An RPM system basically consists of data measurement and processing components, the end-terminal at the hospital, and the communication network. The monitoring is performed by measuring the health data of patients, such as pulse or blood pressure, and temperature, with wearable or implantable devices and evaluating these data under certain permissions. If the measured data exceeds the predetermined thresholds, both patient and doctor will be notified as soon as possible [76, 77]. The data measurement components vary from wearable devices with sensors to contactless methods like sensors attached to the environment [78]. The heterogeneity of these components can limit the interoperability between them. Additionally, sharing personal health information poses concerns for the privacy and security of the communication network. Previous research has established that DLT paves the way for overcoming these challenges in RPM (e.g., [14, 17]). 19 articles in our review explored the benefits of DLT for RPM, especially aiming to enable (1) access management, (2) secure record-keeping, and (3) process automation (see Table 4). However, despite academic research recognizing the extensive potential of DLT in this use case and demonstrating its feasibility in proof-of-concept studies [e.g., [76]], the market has not yet witnessed the advent of fully matured related products. Applications like BurstIQ's Lifegraph Experience [79] touch upon the concept of monitoring user health conditions, but overall, DLT-based applications for RPM are still at a nascent stage.

4.3.2 Access Management. Within RPM, DLT can provide patients access control over health data gathered by various remote devices (e.g., wearable sensor devices, environmental sensors), allowing for the value of this information to be synthesized and optimized for patient monitoring. Depending on individual needs, hospitals, family doctors, caregivers, or family members may have access to data collected on mobile devices with different permissions, such as view-only, view and insertion, or modification and deletion. According to previous research, DLT-based fine-grained access control can contribute to dealing with the complexity and security issues associated with access to health data in RPM. Our review uncovered 19 pertinent DLT characteristics that were discussed in earlier studies to use DLT for access management in RPM.

One of the most prominent specificities of RPM is the connection of various systems. These systems vary in system architecture and data format [76]. To connect and communicate with these heterogeneous external systems, DLT designs for access management in RPM have to first achieve a certain degree of *interoperability*. Moreover, the diversity of systems increases the probability that access authorizations stored and transmitted as data in DLT-based applications may be misused by unauthorized modification or deletion owing to the various principles of data security mechanisms in different devices [76]. Therefore, it is necessary to strengthen the *integrity* of DLT-based access management in RPM.

In addition, the permissions available to the participants in RPM are different depending on the purpose for which they access the data. Defining detailed and comprehensive access policies and automating their management can greatly improve the efficiency of access management and reduce possible errors in the authorization process.

Table 4. Purposes and Relevant DLT Characteristics of RPM

<table>
<tr><th colspan="3">Use case: RPM</th></tr>
<tr><td colspan="3">
</td></tr>
<tr><th>Purpose</th><th>Description of purpose</th><th>Key DLT characteristics</th></tr>
<tr><td>Access management</td><td>Controlling fine-grained access permissions over health data gathered by various remote devices</td><td><i>Flexibility</i>: Interoperability [75]; Use of smart contracts [81]
<i>Opaqueness</i>: Transaction content visibility [77]; User unidentifiability [83]; Node controller verification [81]
<i>Policy</i>: Compliance [84]; Degree of decentralization [76]
<i>Performance</i>: Scalability [85]; Resource consumption [84]; Throughput [81]; Transaction validation latency [81]
<i>Practicality</i>: Transaction fee [84]
<i>Security</i>: Availability [86]; Censorship resistance [83]; Confidentiality [75]; Fault tolerance [75]; Integrity [87]; Non-repudiation [76]; Reliability [75]</td></tr>
<tr><td>Secure record-keeping</td><td>Timestamping and logging data transmissions with RPM accurately and securely</td><td><i>Opaqueness</i>: Node controller verification [88]
<i>Policy</i>: Compliance [84]; Degree of decentralization [76]
<i>Performance</i>: Scalability [89]; Resource consumption [84]; Throughput [84]; Transaction validation latency [90]
<i>Practicality</i>: Transaction fee [84]
<i>Security</i>: Authenticity [88]; Availability [90]; Confidentiality [87]; Integrity [87]; Non-repudiation [76]</td></tr>
<tr><td>Process automation</td><td>Notifying of abnormal situations automatically for the timely detection of possible medical conditions</td><td><i>Flexibility</i>: Use of smart contracts [77]
<i>Opaqueness</i>: User unidentifiability [77]; Node controller verification [91]
<i>Policy</i>: Compliance [91] <i>Security</i>: Scalability [77]; Transaction validation latency [88]; Authenticity [77]; Strength of cryptography [77]</td></tr>
</table>

In this study, we found 10 articles proposing the implementation of *smart contracts* to facilitate access management in RPMs, for example, by automatically verifying user identities [80] or approving access requests based on predefined rules [81, 82].

4.3.3 Secure Record-Keeping. The health information acquired within RPM is subject to health regulations as fundamental evidence for diagnosis and treatment. As a result, for the RPM to better comply with associated requirements, all data transmissions within RPM have to be timestamped and logged securely. Owing to its tamper resistance, DLT can contribute to enhancing the accuracy and security of stored log files in RPM [77], as suggested in eight studies found in this review (e.g., [89, 90]). These studies highlighted 13 DLT characteristics, which should be considered when featuring DLT in applications for secure record-keeping in RPM. A remarkable characteristic is *scalability*. With each new user (e.g., patient) added to the DLT-based application for RPM, the corresponding frequency of information exchange will rise substantially. Conversely, when disconnecting a user or a device, the frequency of log files to be recorded will drop dramatically [91]. Therefore, when DLT design is used to securely keep RPM-related records, maintaining appropriate scalability helps stabilize the effectiveness of the DLT-based application itself [89]. Beyond performance-related characteristics like scalability, the correctness and comprehensibility of the data generated within the RPM are the backbones of their use as audit trails. Thus, deployed DLT designs for secure record-keeping in RPM should pursue *integrity* in order to detect all unintended modifications or deletions as soon as possible and eliminate their side effects on the stored records [88].

4.3.4 Process Automation. RPM essentially assists in the timely detection of illnesses and the prevention of worsening health. The earlier the abnormal situation can be identified, the more efficiently the RPM is performed. Existing surveys suggested the potential of DLT for simplifying the data analysis in RPM, relieving both healthcare professionals and patients from unnecessary appointments and time-consuming diagnoses, thereby improving the efficiency of healthcare services [2, 17]. In our review, five studies highlighted the advantages of DLT for secure real-time notifications [77, 88, 89, 91, 92]. These studies suggested eight characteristics that have been proposed for a DLT design enabling process automation in RPM. At the heart of DTL-based process automation for RPM are *smart contracts*. In those DLT-based applications described in the literature, smart contracts were responsible for customizing the conditions for automatic notification, namely when and how to compare data measured in RPM with predefined conditions. [91]. Once the smart contract receives a value from a connected device on-site that is below or above the patient-specific indicated range of values, it may send an alert message to an authorized person or healthcare provider [77]. In some systems, the smart contract may also enable to store the abnormal data off-chain so that healthcare providers can recall the information if needed [77].

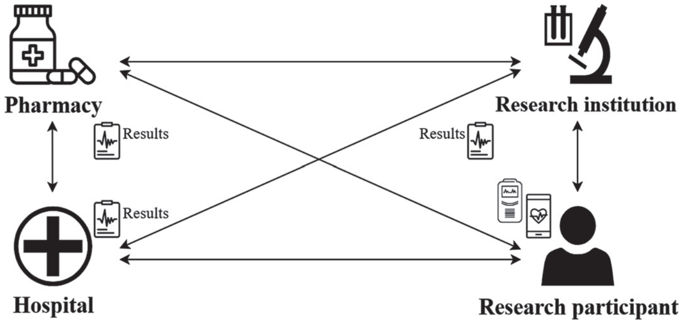
Generally, automated processes in RPM must operate quickly and smoothly to ensure that patients can be provided with the help they need in a timely manner, especially in the case of an emergency. Thus, two studies in our review discussed the role of *transaction validation latency* in DLT-based process automation for RPM. While one study came to the conclusion that the delay in their Ethereum-based system was negligible [88], another discussed the possibility of reducing delay by clustering nodes within the network [91].

4.4 Biomedical Research

4.4.1 Use Case Description. Biomedical research mostly involves research studies, such as clinical trials which generate confidential information from research participants to test new treatments or pharmaceuticals [93]. Such studies often consist of multiple stages, from the definition of the protocol and execution to data collection, analysis, and auditing, thereby requiring complex data recording and involving numerous parties, including research participants, healthcare providers, pharma companies, regulators, and academic researchers [94]. Typical data gathered in this use case are patient consent, treatment data with electronic case report forms, and adverse event tracking [94]. Any error in these data (e.g., omission, forgery, or falsification) may lead to erroneous prescription or treatment, thereby producing serious consequences which affect the safety of patients or the interpretation of study results [95]. Therefore, one of the main challenges in biomedical research is ensuring the provision and interpretation of high-quality data while minimizing the error rate. Previous research recognized that DLT can monitor data integrity within biomedical research to meet research standards and regulatory requirements [4, 96]. A notable real-world example is Triall's Verial, a blockchain-based solution for managing electronic trial master files in clinical research [97]. In 2022, the Mayo Clinic, a globally recognized medical center, adopted this solution with the objectives of securing data capture and document management including the integration of electronic consent processes [98]. Our review identified nine studies that engage with leveraging DLT in biomedical research. Table 5 presents the four purposes found in these studies to be motivating the utilization of DLT: (1) access control, (2) secure record-keeping (3) data sharing incentivization, and (4) process automation.

Table 5. Purposes and Relevant DLT Characteristics of Biomedical Research

Use case: biomedical research



Purpose	Description of purpose	Key DLT characteristics
Access management	Defining and operating rules for access to research data and preventing study results from arbitrary manipulation	*Flexibility*: Interoperability [105]; smart contracts [102] *Opaqueness*: Traceability [102]; Transaction validation latency [95]; User unidentifiability [100]; Node controller verification [100] *Security*: Integrity [102]
Secure record-keeping	Recording data gathered through research studies according to documentation requirements for biomedical research	*Opaqueness*: Traceability [102]; Transaction validation latency [95]; Node controller verification [94] *Security*: Confidentiality [94]; Integrity [102]
Data sharing incentivization	Incentivizing individuals to participate in research studies	*Opaqueness*: User unidentifiability [100]; Node controller verification [100] *Security*: Confidentiality [103]; Integrity [100]
Process automation	Monitoring specific values (e.g., effects of a drug on participants) generated in biomedical research without manual checks	*Flexibility*: Interoperability [99]; Use of smart contracts [99] *Opaqueness*: Node controller verification [101] *Performance*: Block creation interval [99]; Throughput [99]

4.4.2 Access Management. As argued before, effective access management is the first step toward ensuring data integrity. Five studies in our reviews equipped access management in biomedical research with DLT, especially for verifying the identity of the involved stakeholders [99]. In this way, DLT contributed to identifying unauthorized access to research data and preventing the study results from arbitrary manipulation. For this purpose, in this use case, seven characteristics are proposed in five studies. Similar to previous use cases, *smart contracts* have been suggested by scholars to improve access management. In biomedical research, stakeholders beyond patients (e.g., healthcare providers and academic researchers) are generally publicly registered entities, such as hospitals, research institutions, or pharmaceutical companies. The identity of these stakeholders can usually be simply verified with some normalized information and publicly available databases [100]. Therefore, it is possible to standardize the rules for access to health information in biomedical research and implement these in smart contract codes. Four studies in our review suggested the use of *smart contracts* for access management in this use case. While one study specified the data collected and verified by its smart contract [101], other studies only mentioned the benefit of smart contracts, (e.g., removing the possibility of human manipulation of access authorization) [100].

4.4.3 Secure Record-keeping. Biomedical research must adhere to strict documentation requirements, including recording participants' consent to their participation, anonymous health data gathered throughout the research, as well as log files presenting the access activities. Our review found seven studies that valued five characteristics of DLT designs to provide reliable audit trails according to complex obligations in biomedical research [94, 95, 102–104]. Here, large amounts of research data can be generated, especially when there are numerous participants. Whether this data is directly recorded on the ledger or only log files of access to this data are stored, there will likely be a high demand for transactions in a short period. Improving the efficiency of transaction validation helps guarantee that the system remains effective and reliable amid a rise in transactions. Accordingly, two studies advocated the need for low levels of *transaction validation latency* in DLT-based applications for secure record-keeping in biomedical research [95, 103], while one study advised increasing the maximum number of transactions that can be added to a distributed ledger in a given period (i.e., high *throughput*) [99]. Moreover, research experiments often emphasize examining participants' subsequent gradual reactions as experimental settings change, such as before and after taking medications. Thus, DLT-based applications for the secure recording of research-related data should be able to trace the relevant experimental data chronologically (i.e., *traceability*), according to two studies we reviewed [102, 104].

4.4.4 Data Sharing Incentivization. Two studies in our review sample mentioned that privacy and security guarantees through DLT-based applications can incentivize patients to participate in research experiments [100, 103]. These studies have not only mentioned several common characteristics (e.g., *node controller verification*, *integrity*, and *confidentiality*) that improve the privacy and security of DLT designs but have also emphasized *the high level of user unidentifiability* to prevent participants' identification, thereby allaying participants' privacy concerns in biomedical research [100]. One study suggested pseudonymizing participant identification by data consumers [103], while the other article directly recommended integrating zero-knowledge technology with DLT to achieve anonymous identity verification [100].

4.4.5 Process Automation. In some phases of biomedical research, persistent monitoring (e.g., detection of anomalies) is necessary but may be constrained by the heterogeneous sources and forms of data collected in experiments [99]. Replacing frequent manual checks with predefined automatic detection can improve the timely decision for potential recalls. In this regard, Zhuang et al. [99] proposed the possibility of DLT for automated notification of adverse events and real-time analysis of log files. According to the authors, the latter will enable regulators to check the quality and legitimacy of data continuously. This study not only considered *smart contracts* to automate the monitoring but also mentioned the relevance of performance-related characteristics like *throughout* and *block creation interval*, because of the potential size of data gathered in biomedical research. Besides, one study intended to use *smart contracts* to automatically control whether a third party can access participants' geolocations [101], emphasizing the value of smart contracts for process automation in biomedical research.

4.5 **Supply Chain Management (SCM)** for Pharmaceutical Drugs or Medical Devices

4.5.1 Use Case Description. Beyond medical treatments delivered by health professionals, the supply of pharmaceutical drugs and medical devices also plays a fundamental role in healthcare. As a collection of complex processes from production to distribution of pharmaceutical drugs or medical devices, SCM for these specific products involves various stakeholders, such as suppliers, manufacturers, distributors, pharmacies, hospitals, and patients. On the one hand, such supply chains can suffer from a lack of transparency due to highly fragmented structures, obsolete systems, and disconnectedness in information sharing among stakeholders [106]. On the other hand, the visibility of each stage within the supply chain lays the foundation for the monitoring of counterfeit drugs or the efficient supply of critical devices. To solve this complex dilemma, DTL-based applications have been proposed in previous studies (e.g., [107, 108]) or implemented in the practice (e.g., MediLedger by Chronicled [109]), as DLT can help to record all transaction details in an immutable way while the generated data can be distributed. In this way, DLT ensures that each transaction of pharmaceutical drugs or medical devices cannot be changed and provides a transparent trail from production to end use. Moreover, DLT's decentralized nature allows real-time tracking and verification of products among stakeholders. Nine articles investigated in our review exploit DLT mainly for two reasons: (1) secure record-keeping and (2) process automation. Table 6 depicts the use case and highlights these purposes with associated key characteristics.

4.5.2 Secure Record-Keeping. Given the core of DLT as a ledger, this technology enables the recording of data generated among a supply chain, from procurement to production, to delivery, and even ongoing usage or maintenance. Its reliable workflow and the distributed data structure make it more difficult to smuggle counterfeit products (i.e., drugs or medical devices) into the supply chain and support stakeholders with complete traceability to disclose the contaminated products before they reach end-users [110]. This can furthermore simplify the turnover control for authorized state bodies [111]. Eight of the nine articles we found were dedicated to the use of DLT for secure record keeping in SCM, for which 14 DLT characteristics are proposed. Notable among them are the *ease of node setup* and *ease of use*. Stakeholders in the supply chain can participate in the ledger as nodes, with varying information technology capabilities and infrastructure conditions [112]. As a result, lowering the threshold for employing DLT can help all stakeholders in the supply chain to adopt DLT-based applications. Accordingly, two studies suggested developing generic guidance like configuration files to simplify the node setup as well as accessing and working with a ledger, thereby ensuring DLT implementation for secure record-keeping in this use case [108, 113]. Meanwhile, similar to the use case of biomedical research, SCM can generate a massive amount of data that needs to be recorded and transmitted in a ledger. Due to the above, while implementing a DLT design for secure record-keeping in this use case, two studies recommended paying attention to performance-related characteristics, such as *transaction validation latency* and throughput [114], as well as *scalability* and *block size limit [113]*.

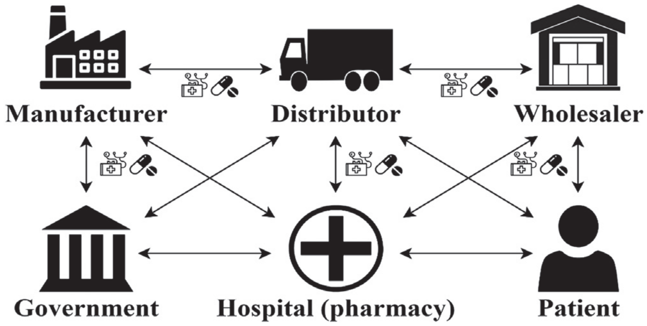
4.5.3 Process Automation. As many stakeholders are involved in the supply chain for pharmaceutical drugs or medical devices, automating processes within the SCM may contribute to ultimately saving costs and enhancing effectiveness [110]. We found three studies focusing on the use of DLT to automate pharmaceutical and medical device supply chain processes. Seven characteristics mentioned in their DLT-based applications are listed in Table 6. Unsurprisingly, *smart contracts* are the backbone, as they are programmed to execute functions automatically without interference from third parties [106]. While two studies intended to standardize negotiation terms or pricing rules and automate the payment process by smart contracts [106, 114], another study has emphasized this characteristic to monitor the temperature of medical products and notify the involved stakeholders in accordance with regulatory requirements [107]. Besides, due to the contractual agreements between stakeholders, all transactions (e.g., payment or order delivery) are legally binding and should not be denied by any program in the DLT-based application, when they are carried out. Accordingly, Omar et al. [106] emphasized that *non-reputation* has to be taken into consideration to ensure that participants in the supply chain cannot dispute that a payment or rebate was not received, or that an order was not delivered.

4.6 Contact Tracing and Warning for Pandemics

4.6.1 Use Case Description. The outbreak of the COVID-19 pandemic in late 2019 has caused the world to face an existential health crisis and exposed the limitations of many modern healthcare systems [117, 118]. A major issue was the rapid and uncontrolled transmission of the virus, especially in the early phase of the pandemic, which led to a large number of infections and deaths. To combat the spread of COVID-19, many governments adopted comprehensive measures, including lockdowns and social distancing regulations. In many countries,

Table 6. Purposes and Relevant DLT Characteristics of SCM for Pharmaceutical Drugs or Medical Devices

Use case: SCM for pharmaceutical drugs or medical devices



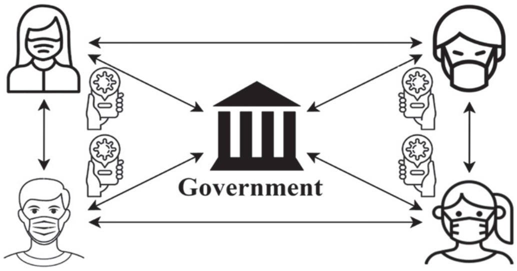
Purpose	**Description of purpose**	**Key DLT characteristics**
Secure record-keeping	Recording data generated during procurement, production, and delivery of pharmaceutical drugs or medical devices according to related regulations in an accurate manner	*Flexibility*: Use of smart contracts [115] *Opaqueness*: Transaction content visibility [112]; Node controller verification [115] *Policy*: Compliance [115] *Performance*: Block size limit [113]; Scalability [113]; Throughput [114]; Transaction validation latency [114] *Practicality*: Ease of node setup [108]; Ease of use [113] *Security*: Authenticity [116]; Availability [114]; Integrity [107]
Process automation	(Partly) Automating negotiation and payment processes within the supply of pharmaceutical drugs or medical devices	*Flexibility*: Use of smart contracts [106] *Opaqueness*: Transaction content visibility [106] *Security*: Availability [114]; Confidentiality [106]; Consistency [114]; Integrity [106]; Non-repudiation [106]

one building block for effectively fighting the pandemic was systems for digital contact tracing [119]. Contact tracing aims to support early diagnosis and interrupt onward transmission of the virus by rapidly identifying and managing potential infection cases even before the respective individuals suffer from disease symptoms. Many contract tracing applications were developed, utilizing the sensors in individuals' mobile devices (e.g., RFID or Bluetooth) or other technologies, like QR codes that had to be scanned before entering certain places [119]. MiPasa, a notable system in this context, is built on the Hyperledger Fabric blockchain in collaboration with the World Health Organization and tech companies like IBM [120]. This platform allows public health officials and individuals to upload data about the time and exact location of different infections, to assist in effectively managing the coronavirus pandemic with reliable information [121]. However, for many researchers and privacy groups, these technologies also posed serious privacy risks and security concerns with regard to data transmission and storage [118]. In our review, five articles explore the role that DLT may play in overcoming these challenges. We identified two different purposes of DLT in contact tracing systems: (1) secure record-keeping, and (2) process automation. Table 7 describes each purpose with relevant DLT characteristics.

4.6.2 Secure Record-Keeping. Contact tracing systems constantly produce data about individuals' spatial movements, their encounters with other users, and potentially their infection status. Similarly, as in the use case of RPM, this data constitutes potentially sensitive personal information. To overcome privacy concerns and enable the storage and retrieval of data in accordance with strict privacy regulations, DLT may play an important role. In fact, all five articles within our review that dealt with DLT for contact tracing mentioned secure record

Table 7. Purposes and Relevant DLT Characteristics of Contact Tracing and Warning for Pandemics

Use case: contact tracing and warning for pandemics



Purpose	Description of purpose	Key DLT characteristics
Secure record-keeping	Storing individuals' spatial movements, their infection status, and other related information for tracing their encounters with others	*Flexibility*: Use of smart contracts [122]; *Opaqueness*: Traceability [117]; User unidentifiability [122]; Node controller verification [124] *Policy*: Compliance [124]; Degree of decentralization [123] *Security*: Scalability [122]; Transaction validation latency [122]; Authenticity [117]; Availability [122]; Consistency [123]; Integrity [117]
Process automation	Evaluating individuals' movements and notifying them of potential infection risks based on their encounters	*Flexibility*: Use of smart contracts [117]; *Opaqueness*: Node controller verification [117]; *Security*: Scalability [118]; Transaction validation latency [117]

keeping as the main purpose of utilizing DLT in contract tracing systems. Thereby, some articles argued that it was feasible and useful to store data on the ledger since the data produced by RFID tags or similar technologies were sufficiently small in size (e.g., [122]). Others argue, similarly as in the RPM use case, that sensitive information should be stored in external systems (e.g., [123]). Regardless of where data is stored, health data (e.g., symptoms, test results) collected in this use case should be stored anonymously (e.g., [123]), which leads to considerable difficulty in identifying the sender—who reports their symptoms—and recipients—other people connected with the tracing system—or even impossibility (i.e., *user unidentifiability*).

Meanwhile, when many individuals use the system, this poses serious requirements concerning *scalability* as the DLT has to efficiently handle increasing amounts of transactions [122] Another important requirement for DLT-based record-keeping in contact tracing is *availability* [123, 124]. Only if the contact tracing system is operating correctly at any point in time, can it be ensured that all relevant movements and encounters between potentially infectious individuals are captured.

4.6.3 Process Automation. For contact tracing to be effective it needs to be prompt. Thus, incoming information about individuals' movements, potential encounters, and infection status needs to be efficiently and automatically processed. Similar to the RPM use case, for this purpose DLT-based applications for contact tracing, rely on *smart contracts* [117]. The smart contracts are responsible for analyzing the reported data and notifying affected users or even authorities in some cases, e.g., if the value exceeds the specified threshold due to frequent entry and exits or prolonged time spent outside [118]. Similar to secure record-keeping, a large number of potential users of contact tracing systems require a sufficient level of *scalability* of the DLT-based application [118].

5 Discussion

5.1 Principal Findings

Overall, the results of our study paint a heterogeneous landscape of possibilities of how DLT may play a role in digitizing the healthcare industry. In particular, our analysis of 185 studies revealed interesting findings on the most pertinent use cases of DLT in healthcare settings, the different purposes of including DLT in said use cases, as well as their respective requirements with regard to the different characteristics of DLT. We discuss the key findings of our study in the following.

First, our results reveal six pertinent use cases of applying DLT in healthcare. The most prevalent use cases in our review are patient-centric health data management and management of EHRs, while other use cases, such as biomedical research and SCM for pharmaceutical drugs or medical devices have received substantially less attention in extant research. These results broadly corroborate those of previous related literature reviews on DLT in healthcare (e.g., [1, 17]). However, it is interesting to note the literature on patient-centric health data management outnumbered the literature on EHR in our review, which differs from the findings provided in other recent literature reviews [1]. We believe that this difference can be explained by the ongoing shifts to the patient-centered care model as a healthcare delivery paradigm due to its positive influence on patient experiences as well as care and treatment efficiency [125]. This trend leads to calls for research on the implementation of many emerging technologies, such as DLT in this use case. Besides, we identified two incipient use cases: (1) medical insurance including claims and fraud detection, and (2) management of healthcare workforce competencies, for which only one article introduced specific DLT characteristics. Although we did not discuss these two articles in depth to avoid inappropriate generalizations, they, along with six other use cases, highlight the richness of opportunities that DLT may provide when it comes to augmenting the healthcare industry.

Additionally, we identified four general purposes for utilizing DLT in healthcare (i.e., access management, secure record-keeping, data sharing incentivization, and process automation). These purposes indicate the potential issues or desired benefits in healthcare which can be addressed by DLT-based applications. All general purposes are reported in multiple use cases. Interestingly, while the basic idea of a purpose is consistent across use cases, there are use-case-specific peculiarities. For example, in terms of process automation, studies regarding SCM for pharmaceutical drugs or medical devices mainly focus on the standardization of contractual agreements and automate the negotiation and payment process (e.g., [106, 114]), while DLT-based applications in RPM aimed at pursuing automatic notification of abnormal values based on predefined conditions [91].

What stands out in our results is that each of the six use cases has taken the purpose of secure record-keeping into account. This result seems to be consistent with other research on the main challenges in healthcare that can be addressed by DLT (e.g., [1, 96]) or the motivations behind the use of DLT in healthcare (e.g., [2]). However, in terms of scope and definition, the purpose we found is slightly different from the relevant findings in extant literature. This discrepancy could be attributed to that while previous studies intended to highlight the practical issues (e.g., data privacy, interoperability) that motivate the use of DLT in healthcare, all four purposes in our study demonstrate the concrete functions in applications that DLT can contribute (e.g., secure record-keeping, access management). Surprisingly, no article mentioned the purpose of data sharing incentivization in the use case of contract tracing and warning for pandemics. A possible explanation for these results may be the infancy stage of related research. At the time we collected the data for our review, research on pandemic-related applications was still in its infancy. Therefore, it is reasonable to prioritize purposes related to more urgent issues, such as secure record-keeping (relates to security with data storage and exchange), and process automation (relates to the effectiveness of timely notifications). Overall, our results highlighted that DLT can be driven by different purposes in different health-related use cases and applied for specific functions in the targeted applications.

With respect to the second RQ, 30 DLT characteristics are proposed for the DLT-based applications in the six pertinent use cases. It is interesting to note that the proposed characteristics are strongly associated with the purposes of utilizing DLT in targeted use cases. This can be seen in the case of secure record-keeping for RPM and SCM for pharmaceutical drugs and medical devices or of access management in patient-centric health data management and RPM. This especially accords with earlier findings investigated by Mackey et al. [4], which highlighted the relevance of "fit-for-purpose" in deploying DLT in healthcare. However, the identified characteristics overall still look different in the intended purposes and targeted use cases. Especially, some characteristics are only reported in specific use cases for specific purposes. For instance, incentive mechanism has only been considered in studies that intended to utilize DLT for data-sharing incentivization in patient-centric data management. Another example is that only DLT-based applications in RPM discussed the *transaction fee* characteristic. On the one hand, this result further strengthens the assumption that there will be no one-size-fits-all DLT-based applications for the health sector [7], as the suitable DLT characteristics depend on the specific context. On the other hand, due to the different number of available studies in each use case, some use cases include a more comprehensive sample of data from the literature which can be used to identify relevant DLT characteristics. This may lead to different numbers of characteristics found in different use cases in our survey.

Another obvious finding to emerge from the analysis is that extant research has focused on particular DLT concepts, DLT designs, and DLT characteristics. Unsurprisingly, only two of the 124 studies used DLT concepts other than Blockchain [84, 123] and both have chosen TDAG. In terms of DLT designs, while only six articles considered other extant DLT designs, such as IOTA [84, 123] or Ripple Blockchain [126], Ethereum (33,87%), and Hyperledger Fabric (29,03%) have received the most attention from scholars. These results broadly support the work of previous studies (e.g., [1, 127]). The prevalence of these DLT designs is potentially due to the number of developers available with sufficient knowledge as well as the strong overall market position of both designs [1].

Regarding the characteristics, almost all use cases considered DLT characteristics, such as *node control authentication*, *smart contracts*, *integrity*, and *availability*. The focus of attention may stem from the adaptability of these designs themselves and the importance of the characteristics themselves for the desired purposes in the targeted use cases [96], but also indicates the possibility and necessity of expanding the relevant research objects to unexplored designs and characteristics.

5.2 Implications

From a research perspective, our study yields three important theoretical contributions (see Table 8). First, our results reinforce the need for contextual designs of DLT-based applications in healthcare by revealing that the interplay of both use cases and purposes of utilizing DLT influences the requirements of DLT-based applications. We identified six pertinent and two nascent DLT use cases in the health domain with their associated purposes of utilizing DLT, thereby extending research efforts to understand the meaningful use of DLT in healthcare (e.g., [1, 13]). Moreover, our findings indicate that when proposing DLT-based applications for healthcare, researchers should not only consider the use case, that they target, but also assert the concrete purpose transparently, for which the DLT-based application intends to achieve. The clarification of these two points is beneficial to lay a stable and reasonable foundation for the system design on the one hand, and to facilitate the later evaluation and the communication and discussion with related researchers on the other hand.

Second, we disentangle the concrete contribution of DLT to healthcare by synthesizing possible rationales for choosing specific characteristics under specific conditions (i.e., purposes and use cases) based on 124 DLT-based applications proposed in research articles. Earlier research on DLT in healthcare is limited to analyzing the benefits of DLT in an isolated way from the needs of healthcare (e.g., [16]) or discussing its suitability for healthcare from a holistic perspective (e.g., [4]). Our study synthesized both perspectives and provides a useful basis for

Table 8. Research Implications

RQ	**Key findings**	**Implications for research**
RQ1	—Six pertinent and two nascent DLT use cases in the health domain —Four general purposes of utilizing DLT in healthcare —While the basic idea of a purpose is consistent across use cases, there are use case-specific peculiarities	Our results reinforce the need for more contextualized research on and designs of DLT-based applications in healthcare. Especially researchers should consider and transparently report the domain-specific use case and the purpose for which they use DLT, when proposing, discussing, or evaluating DLT-based applications for healthcare.
RQ2	—30 DLT characteristics were proposed for DLT-based applications in the six pertinent use cases —Both use cases and purposes of utilizing DLT as well as their interplay can influence the requirements of DLT-based applications —The identified rationales provide a useful basis for explaining the suitability of specific DLT characteristics for a DLT-based application —Some DLT characteristics (e.g., auditability) are currently understudied	The identified rationales help to disentangle the concrete contributions of DLT to various use case-specific challenges in healthcare. Besides, the saturation of existing studies on DLT in healthcare in terms of some DLT characteristics is insufficient. Research on DLT in healthcare has a long way to go for a holistic picture of DLT-based applications.

explaining the suitability of specific characteristics for a DLT-based application, thereby serving as a reference direction for the future design of DLT-based applications in healthcare.

Lastly, by revealing less considered DLT concepts, designs, and DLT characteristics, our work challenges the saturation of existing studies on specific aspects, especially DLT concepts other than Blockchain (e.g., TDAG) as well as DLT designs other than Ethereum and Hyperledger Fabric (e.g., IOTA). Accordingly, more research on DLT concepts other than Blockchain and related designs would be worthwhile, since they have been neglected in academia so far, despite their development on the market.

Our study also provides several practical implications for healthcare institutions, related companies, and developers of health information systems, who want to utilize DLT in order to address issues in healthcare. The presented characteristics provide these stakeholders with blueprints of potential aspects that have been considered when they design a DLT-based application in a specific healthcare-related use case. In addition, the rationales we analyzed can provide a reasonable reference for developers to prioritize specific characteristics, especially when the inherent tradeoffs between DLT characteristics are considered [7]. Overall, our work contributes to a better understanding of how DLT can be implemented to facilitate healthcare information systems.

5.3 Limitations and Future Research

The findings of this study should be interpreted in consideration of some key limitations. First, within our survey of the literature, we only analyzed explicit statements that researchers made about the requirements of their systems. However, many researchers likely made additional considerations about DLT characteristics without explicitly stating them in their articles. Future research could address this issue by conducting interviews with researchers and designers of DLT-based applications in the different use cases to strengthen our knowledge about the relevance of such DLT characteristics that were rarely discussed in the literature so far (e.g., auditability, ease of node setup). Second, the majority of articles included in our survey describe prototypes. Only very few of them were evaluated outside of laboratory settings. This may have limited the external validity of our results. We aimed to account for this issue by also considering whether requirements for DLT characteristics were stated by multiple researchers across different studies for the same use case. By doing so, we intended to avoid unreasonable generalizations. Future research will be able to overcome this limitation when more DLT-based applications in healthcare move to the field. Beyond the technical and administrative characteristics, the success of these applications in real-world settings will also hinge on factors like the accessibility of DLT technology and overall user acceptance. Studies that delve into these aspects will significantly enhance our understanding of the practicality and effectiveness of DLT-based applications in everyday healthcare scenarios. Third, we identified two use contexts (i.e., management of healthcare workforce competencies and medical insurance including claims as well as fraud detection) that were only mentioned in one article each. While these use cases promise to yield interesting unique requirements with regard to DLT characteristics that may open up new discussions in the health informatics community, we were not able to deduce meaningful, generalizable results. We propose that future research should keep an eye on these use cases in order to investigate the insights that researchers will make about their specificities in the future. Finally, a central finding of the work by Kannengießer et al. [7] is that there exist tradeoffs between the different characteristics of DLT. For example, the use of smart contracts may threaten the confidentiality of a DLT-based application, when the compiled smart contract code is visible to the public [7]. In this work, we focused on the identification of DLT characteristics that researchers deemed most relevant for each use case without accounting for these tradeoffs. Future research could further build on our findings and develop archetypes of DLT-based applications for each combination of use case and purpose that address this issue and consider tradeoffs between DLT characteristics.

6 Conclusion

Although DLT-based applications in healthcare are a relatively young and dynamic field of research, they nowadays show signs of maturing with the first systems being in productive use. In this study, we reviewed the current state of literature and identified the six most pertinent use cases of DLT in healthcare, each with its own combination of different purposes that DLT is able to fulfill. Our results reveal a heterogeneous landscape of different DLT requirements for each combination of use cases and purposes. Our work contributes to a better understanding of the versatile applications, but also the current limitations of DLT-based applications in the healthcare sector. For future research, our study may serve as a foundation for research inquiries that deal with those application areas of DLT in healthcare that have been underrepresented in literature so far (e.g., medical insurance and management of healthcare workforce competencies) or those DLT characteristics that researchers have so far mostly neglected in their considerations (e.g., auditability). For practitioners our study provides a synthesis of the current knowledge base on use case-specific DLT requirements and, thus, may be a convenient starting point when designing and implementing highly effective DLT-based applications in various healthcare settings.

A Appendix

A.1 DLT Characteristics

Table A.1. DLT Properties and Characteristics (Adopted from Kannengießer et al. [7])

DLT Property	DLT Characteristics
Flexibility	—Interoperability —Maintainability —Use of Smart Contracts —Token Support —Transaction Payload
Opaqueness	—Traceability —Transaction Content Visibility —User Unidentifiability —Node Controller Verification
Policy	—Auditability —Compliance —Degree of Decentralization —Incentive Mechanism —Liability
Performance	—Block Creation Interval —Block Size Limit —Confirmation Latency —Resource Consumption —Propagation Delay —Scalability —Stale Block Rate —Throughput —Transaction Validation Latency
Practicality	—Transaction Fee —Ease of Node Setup —Ease of Use —Support for Constrained Devices
Security	—Atomicity —Authenticity —Availability —Censorship Resistance —Confidentiality —Consistency —Durability —Fault Tolerance —Integrity —Isolation —Non-Repudiation —Reliability —Strength of Cryptography

A.2 Rationale for Characteristics

Table A.2. Explanation of Rationales for DLT Characteristics Found in Our Review

Use Case	Patient-centric health data management			Management of electronic healthcare records		Remote patient monitoring			Biomedical research				SCM for pharmaceutical drugs and medical devices		Contact tracing and warning for pandemics	
Purpose	AM	SRK	DSI	AM	SRK	AM	SRK	PA	AM	SRK	DSI	PA	SRK	PA	SRK	PA
Interoperability	●	●	●	●	●	●	-	-	●	-	-	●	-	-	-	-
Smart contracts	●	●	●	●	●	●	-	●	●	-	-	●	○	●	●	●
Token support	●	●	-	●	-	-	-	-	-	-	-	-	-	-	-	-
Traceability	-	-	-	-	-	-	-	-	●	●	-	-	-	-	●	-
Node controller verification	●	●	●	●	●	●	●	●	●	●	●	●	●	-	●	●
Transaction content visibility	●	●	●	-	-	●	-	-	-	-	-	-	●	●	-	-
User unidentifiability	●	●	-	○	○	○	-	○	○	-	●	-	-	-	●	-
Compliance	●	●	-	●	-	●	●	●	-	-	-	-	●	-	●	-
Degree of decentralization	-	-	○	-	-	●	●	-	-	-	-	-	-	-	●	-
Incentive mechanism	-	-	●	-	-	-	-	-	-	-	-	-	-	-	-	-
Block creation interval	-	-	-	-	-	-	-	-	-	-	-	○	-	-	-	-
Block size limit	-	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-
Scalability	●	●	-	-	-	●	●	●	-	-	-	-	●	-	●	●
Resource consumption	○	○	-	●	●	○	○	-	-	-	-	-	-	-	-	-
Throughput	-	-	-	-	-	●	●	-	-	-	-	●	●	-	-	-

AM: Access management; SRK: Secure record-keeping; DSI: Data sharing incentivization; PA: Process automation; SCM: Supply chain management

●: rationale explained; ○: information about rationale not available; -: characteristic not mentioned

(Continued)

Table A.2. Continued

Use Case	Patient-centric health data management			Management of electronic health-care records		Remote patient monitoring			Biomedical research				SCM for pharma-ceutical drugs and medical devices		Contact tracing and warning for pandemics	
Purpose	AM	SRK	DSI	AM	SRK	AM	SRK	PA	AM	SRK	DSI	PA	SRK	PA	SRK	PA
Transaction validation latency	○	-	-	●	●	●	●	●	●	●	-	-	●	-	●	●
Transaction fee	-	-	-	-	-	○	○	-	-	-	-	-	-	-	-	-
Ease of node setup	●	-	-	-	-	-	-	-	-	-	-	-	●	-	-	-
Ease of use	●	●	-	●	●	-	-	-	-	-	-	-	●	-	-	-
Authenticity	●	-	-	○	○	-	○	●	-	-	-	-	●	-	●	-
Availability	○	-	●	●	●	●	●	-	-	-	-	-	●	●	●	-
Censorship resistance	-	-	-	-	-	○	-	-	-	-	-	-	-	-	-	-
Confidentiality	●	●	●	●	●	●	●	-	-	●	●	-	-	●	-	-
Consistency	○	-	-	●	-	-	-	-	-	-	-	-	-	●	●	-
Fault tolerance	●	-	-	-	-	●	-	-	-	-	-	-	-	-	-	-
Integrity	●	●	●	●	●	●	●	-	●	●	●	-	●	●	●	-
Isolation	○	○	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Non-repudiation	-	-	-	●	●	○	○	-	-	-	-	-	-	●	-	-
Reliability	-	-	-	-	-	○	-	-	-	-	-	-	-	-	-	-
Strength of cryptography	●	●	-	-	●	-	-	●	-	-	-	-	-	-	-	-
Nr. of identified characteristics	20	14	9	15	13	19	13	8	7	5	4	5	13	7	12	4

AM: Access management; SRK: Secure record-keeping; DSI: Data sharing incentivization; PA: Process automation; SCM: Supply chain management

●: rationale explained; ○: information about rationale not available; -: characteristic not mentioned

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