Broadening of horizons: a review of blockchains' influence on EHRs development trend

G. Kalivaraprasanna Babu

Department of Computer Science,
Central University of Tamil Nadu,
Neelakudi, Tamil Nadu, India
Email: gkbabu20@gmail.com

P. Thiyagarajan*

Department of Computer Science (Cyber Security),
Rajiv Gandhi National Institute of Youth Development,
Sriperumbudur, Tamil Nadu, India
Email: thiyagu.phd@gmail.com
*Corresponding author

Abstract: Electronic health records (EHR) improves the quality and effectiveness of healthcare. The introduction of blockchain opens up new paths in the development trend of EHR. This review aims to find the developmental trends of the EHR, blockchain-based EHR and its impact on EHR evolution. A total of 85 articles published in 2015 to 2021 were selected, addressing the general development of EHR. Development aspects of EHR addressed by each were analysed, hence tracing the path taken by each. Researchers for the betterment of traditional EHR sought to address usability, adaptability, needs of specialised areas, and patient inclusivity in the workflow, while stressing the application of EHR for predictive analysis, preventive healthcare, population health, etc. The literature on blockchain-based EHR contributed to mitigating the interoperability, promoting data sharing and patient-centric records. While traditional EHR deepens their reach into healthcare, blockchain-based EHR broadens the reach of healthcare itself.

Keywords: electronic health records; EHR; healthcare; health information management; review; blockchain; decentralisation; health informatics; smart contract.

Reference to this paper should be made as follows: Babu, G.K. and Thiyagarajan, P. (2023) 'Broadening of horizons: a review of blockchains' influence on EHRs development trend', *Int. J. Electronic Healthcare*, Vol. 13, No. 2, pp.134–157.

Biographical notes: G. Kalivaraprasanna Babu is a full-time PhD scholar in the Department of Computer Science, Central University of Tamil Nadu, India from 2018. He completed his Masters degree from the Osmania University, Hyderabad. His areas of interest are blockchain and information security.

P. Thiyagarajan is an Associate Professor at the Department of Computer Science (Cyber Security) of the Rajiv Gandhi National Institute of Youth Development, Sriperumbudur, Tamil Nadu, India. He completed his Integrated MS from the Anna University and PhD from the Pondicherry Central

University, followed by a Post-doctorate at the Department of Atomic Energy, Indira Gandhi Centre for Atomic Research. He has published 44 research papers in reputed international journals, conferences and workshops as well as delivered 75+ invited talks in various universities and institutions across India. His research interest covers information security, image processing, machine learning, steganography, threshold cryptography, security aspects in smart city and health analytics.

1 Introduction

Health records are crucial in the management of patient's health data. They ease the storage of information in a formatted manner, aid in the progress of health practices and the development of medicine. Electronic medical records (EMR), electronic health records (EHR) and personal health records (PHR) are various Health records classified based on the scope of access. EMR is confined to and maintained by the clinic while EHR is meant for inter-organisation portability and maintenance. Along with EHR data, PHR consists of much detailed health information of an individual and maintained by them. From paper-based records to computer-based records, health data has evolved and has adopted technological advancements for the better.

Further sections detail the evolution of EHR; introduce blockchain and present recent development trends of EHR against blockchain-based EHR. Figure 1 depicts the basic organisation of the papers selected for this review.

2 A brief history of EHR

EHR is defined as "any information relating to the past, present or future physical/mental health, or condition of an individual which resides in electronic system(s) used to capture, transmit, receive, store, retrieve, link and manipulate multimedia data for the primary purpose of providing healthcare and health-related services" (Gartee, 2012). Efforts to digitise health records started around the 1960s. Since then, EHR systems have progressed, with cautious adoption of technology, in response to the needs of physicians, political and social influences.

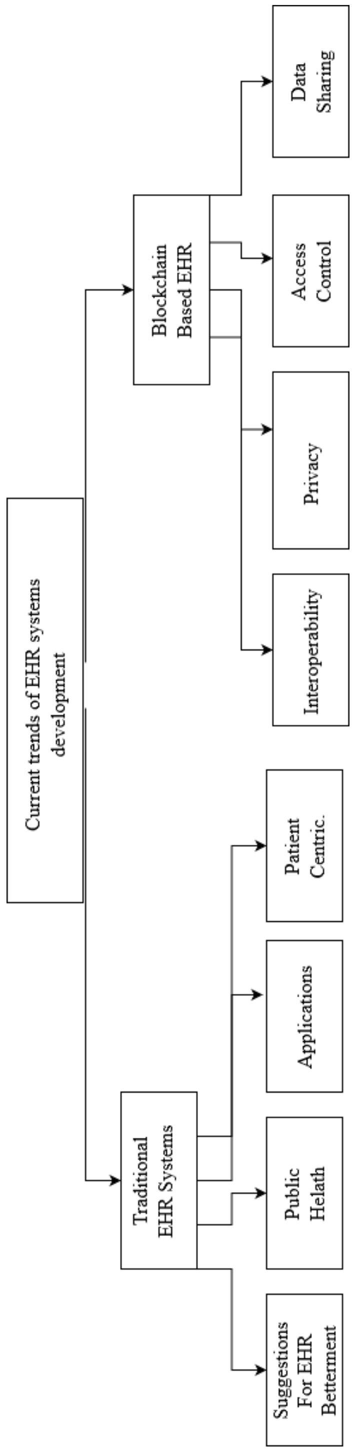
The development of EHR systems can be traced in given periods:

- 1960s – problem-oriented medical records
- 1970s – the dawn of the EHR systems
- 1990s – the internet's effects on EHR
- 2000s – EHR standardisation and adaptation.

2.1 1960s – problem-oriented medical records

To ease physicians' efforts in recording and managing patients' health data newly developing computer systems were utilised in the 1960s laying the foundation for EHR systems (Atherton, 2011), referred to as clinical information systems.

Figure 1 Different classification of papers selected



2.2 1970s – the dawn of the EHR systems

The US Government adopted EHR in the 1970s for veteran health services that aided EHR systems to become fully integrated systems (ICANotes, no date; Atherton, 2011). This resulted in bulk of sensitive data with no means of secure, affordable and rapid transmission (ICANotes, no date).

The Institute of Medicine (IOM) in the 1980s identified analysing paper-based records cumbersome, resulting in the development of Health Level Seven (HL7) to develop electronic standards aiding different EHR modules to interact with each other (Atherton, 2011).

2.3 1990s – the internet's effects on EHR

Advancement and availability of the internet by the 1990s facilitated shareability of EHR. New capabilities and expansion of EHR led to their commercialisation resulting in Health Insurance Portability and Accountability Act (HIPPA) to protect patients' records and development of EHRs (Atherton, 2011).

2.4 2000s – EHR standardisation and adaptation

Arising security issues with the rapid advancement of the internet required new EHR systems to be built around safeguards such as physical, technical and administrative safeguards (ICANotes, no date). Organisations in need of standardisation adopted HL7 International for EHRs development. To facilitate access to patient data through a single system EHRs were integrated and centralised (Atherton, 2011).

Adoption of EHR leads to greater continuity of care, improved efficiency, better emergency preparedness and response (Atherton, 2011). Despite the benefits, EHR systems have multitudes of issues. The adoption rate of EHRs in developed countries is very higher than in developing countries. Practice of partial usage of EHR and fragmented patient records across different clinics are prevalent.

3 Brief introduction to blockchain

Blockchain was introduced by Nakamoto (2019) in 'Bitcoin: a peer-to-peer (P2P) electronic cash system'. Blockchain is an open, decentralised and distributed ledger that is P2P based, cryptographically secure, append-only and immutable, i.e., extremely hard to alter. Blockchain could be defined as an immutable chain of blocks, where block stores transaction records, secured in an indestructible manner.

3.1 Structure of blockchain

Blockchain is a linear structure of blocks where each block is linked to the previous block. Blockchain consists of a distributed ledger, P2P network, blocks, consensus mechanism. Also, new blockchains have smart contracts as well.

3.1.1 Distributed ledger

The distributed ledger is shared among peers on the blockchain. It is an open ledger, in the sense that participants can view all the transactions on it and maintain this ledger. The ledger is made by the blocks linked together like a chain.

3.1.2 Block

The blockchain is made up of blocks; each block has verified transactions, timestamp and a cryptographic hash of the transactions. Each block is immutably linked to the previous block using the previous block's hash. Hash could be understood as a unique digital fingerprint of the blocks' data, and even a minute alteration in block data would result in a very different hash. This property of hash secures the blockchain as any tampering is easily detected and rectified by peers.

3.1.3 Consensus

Consensus means agreement between peers. This is used for appending a new block to the chain. There are several consensus protocols of which the popular one is proof-of-work (PoW), which is the original consensus mechanism used for Bitcoin. Proof-of-stake (PoS), raft, practical Byzantine fault tolerance (PBFT) are a few well-known consensus protocols.

3.1.4 P2P network

P2P network is a distributed network, it decentralises the blockchain. Each peer node simultaneously acts as a server and client.

3.1.5 Smart contracts

Blockchains like Ethereum and Hyperledger have smart contracts which are self-executing codes. They ensure the enforcement of pre-agreed terms of a transaction. On the accomplishment of set conditions, a contract will self-execute.

3.2 Key characteristics of blockchain

3.2.1 Decentralisation

P2P network renders decentralisation. A user does not have to rely on any central authority. All transactions occur directly between the acting parties; these transactions are recorded in the ledger.

3.2.2 Persistency

Persistency is ensured by the immutability of the ledger and consensus protocol. To make any changes one needs to go through the entire consensus process for every change.

3.2.3 Pseudonymity

Pseudonymity is achieved by using public key infrastructure, the user is provided with a pair of private and public key. The public key is used as the user ID of an individual. This ID is used for transactions; a unique address is generated for each transaction.

3.2.4 Auditability

Auditability is ensured as all the transactions are logged on a shared ledger. Users on the blockchain can view all the transactions from this ledger and verify them with others.

4 Current status of EHRs

The term traditional EHR will be used to refer to the corresponding literature which do not use blockchain. Articles published in Springer, IEEE and Elsevier are given preference. Literature that addresses and depicts the current work on EHR is screened by the title, abstract and conclusion presented. Works that contributed towards development of EHR in general were chosen in screening. A total of 41 articles are selected for traditional EHR, of which three are conference papers and 38 are journal articles.

4.1 Suggestions for EHR betterment

Implementing an EHR is often greeted by resistance as any change gets when replacing an existing system promoting successful implementation.

Table 1 Factors effecting EHR implementation

Reference	*Factors*
Sidek and Martins (2017)	Identified six factors: usability of the system, emergent behaviours, requirements analysis, training, change management, and project organisation.
McCrorie et al. (2019)	Preparedness for EHR use mitigates perceived threats to quality and safety of care
Khajouei et al. (2017)	Found that heuristic evaluation and cognitive walkthrough are similarly efficient in finding usability issues but differ in severity of those issues.
McDowell et al. (2017)	Temporary increase in efficiency on deploying new HER.
Matthews (2017)	Identified barriers to EHR integration into behavioural health.

Table 1 presents factors that affect implementation and usage EHR to their full extent. Suggesting towards changes or issues to be considered for better or successful EHR usage. Concerns of the disruption caused by the new EHR system (Jacobs et al., 2019) are for a short span while the benefits are long-term. Preparing staff in-advance in using EHRs mitigates quality and safety concerns of patient care (McCrorie et al., 2019), promoting successful implementation.

Table 2 Suggestions from research articles for improving EHR

Reference	*Suggestions from research articles*
Agboola et al. (2017)	Suggests combining EMR and PERS for improving health outcomes.
De Hoon et al. (2017)	Recording of adverse events of medication for enhanced patient safety.
Adenuga et al. (2015)	Identified integration and interoperability issues; architecture for eHealth in developing countries to enhance healthcare delivery.
Namulanda et al. (2018)	Better surveillance of rare diseases, prevalent health conditions or risk factors for health outcomes at a finer geographic level.
Van Hoeven et al. (2017)	Identified and developed approach assures data quality and enhancement of multi-sourced data with increased transparency and reliability.
Bollaerts et al. (2019)	Demonstrated practical feasibility of near real-time monitoring of vaccination coverage; test the feasibility of near real-time monitoring of vaccination coverage, benefits and risks based on multiple EHR databases.
Savoy et al. (2019)	Patient-centred UI supporting referral process
Plastiras and O'Sullivan (2018)	Proposed middleware solution with number of advantages; Developing information model extension to facilitate exchange of patient generated health data (PGHD) and observations of daily living (ODL) between PHR and HER.
Day et al. (2019)	Feasible to implement a decision aid directly into users' standard EHR; tested feasibility and benefits of integrating mobile apps into EHR workflow.
Liang et al. (2020)	Proposed a multi-source order-preserving encryption (MSOPE) scheme for cloud-based eHealth systems which enables doctors to perform privacy-preserving range queries over encrypted EHRs from multiple patients.
Goldstein et al. (2020)	Identified need for protecting adolescent data, room for innovation and improvement of confidentiality.
Blijleven et al. (2019)	Aids in identifying, analysing and resolving EHR workarounds; Develop a conceptual framework, SEWA, addressing challenges of studying workarounds emerging from EHR system usage.
Kasthurirathne et al. (2015)	Design and develop a FHIR API for OpenMRS for improving interoperability.
Karapiperis et al. (2019)	A novel framework for privacy-preserving large-scale linkage of EHRs; privacy preserving.
Zive et al. (2016)	Address completion errors and streamline documentation and availability of physician orders for life sustaining treatment (POLST) forms in EHR ePOLST; improved workflow efficiency, effective completion of error free forms.

Usability of an EHR is the evaluation of ease, effectiveness and satisfaction on using such systems. In evaluation of usability of healthcare information systems (HIS), cognitive walkthrough (CW) is preferable for identifying learnability of system for novice users while heuristic evaluation (HE) is better at detecting dissatisfaction for experienced users (Khajouei et al., 2017). Diagnostic outcomes are affected by barriers to EHR usability and communication gap between clinicians and diagnostic services (Murphy et al., 2019). Kaipio et al. (2020) studied end-user EHR usability experiences finding that EHRs could be bettered by considering the perspective of end-users, i.e., nurses and physicians to improve patient safety and quality of care.

For improving patient care in EHR, uniform recording of adverse events and creation of a learning health system could prevent potential damage to patients' health (De Hoon et al., 2017). Whereas, integrating mobile app into EHR workflow could aid in patient engagement and improve shared decision making (Day et al., 2019).

Table 3 Different issues addressed by the selected literature on traditional EHR

Solutions provided	*References*	*Total number of references*
Interoperability	Adenuga et al. (2015), Kasthurirathne et al. (2015) and Plastiras and O'Sullivan (2018)	3
Quality (accuracy, efficiency)	Raval et al. (2015), Zive et al. (2016), Van Hoeven et al. (2017), Ben Hassen et al. (2019), McCrorie et al. (2019), Suresh and Florence (2019) and Liang et al. (2020)	7
Security	Eom et al. (2016) and Liang et al. (2020)	2
Privacy	Karapiperis et al. (2019), Li et al. (2019), Suresh and Florence (2019) and Liang et al. (2020)	4
Improvement factors/ suggestions	Adenuga et al. (2015), Kasthurirathne et al. (2015), Mishuris et al. (2016), Agboola et al. (2017), Matthews (2017), De Hoon et al. (2017), Khajouei et al. (2017), Namulanda et al. (2018), Plastiras and O'Sullivan (2018), McCrorie et al. (2019), Murphy et al. (2019), Savoy et al. (2019), Blijleven et al. (2019), Bollaerts et al. (2019), Day et al. (2019), Karapiperis et al. (2019) and Kaipio et al. (2020)	17
Application of EHR in/with new areas	Raval et al. (2015), Wang et al. (2015, 2020), Militello et al. (2016), Zive et al. (2016), Butt and Shan (2016), Amoah et al. (2017), McDowell et al. (2017), Van Hoeven et al. (2017), Bruland et al. (2018), Chatzakis et al. (2018), Ben Hassen et al. (2019), Nguyen et al. (2019), Zhao et al. (2019), Day et al. (2019), Hong et al. (2019), Jacobs et al. (2019), Li et al. (2019), Yoo et al. (2020) and Ingram et al. (2020)	20
Transparency	Van Hoeven et al. (2017)	1
Access control	Eom et al. (2016) and Suresh and Florence (2019)	2

EHR development and effectiveness could be improved by Educating emerging health professionals regarding EHR development and design (Matthews, 2017), as well as addressing mismatch between end user and vendor perspective (Sidek and Martins, 2017). Table 2 presents suggestions for improving EHR from relevant articles included in the review.

Care of vulnerable groups such as adolescents, older and near end of life patients require special attention. Confidentiality of adolescents' data be ensured by standardised and comprehensive framework regarding electronic access of data (Goldstein et al., 2020). Using fall alert system for older patients in combination of EMR data (Agboola et al., 2017), electronic physician orders for life-sustaining treatment (ePOLST) Form completion system for near end of life patients could be effective for efficient care (Zive et al., 2016). Table 3 presents the issues that are addressed by selected literature.

Despite EHRs being around for a long time and progressing, they are not adopted by all instead, workarounds are employed. Blijleven et al. (2019) developed sociotechnical EHR workaround analysis (SEWA), a conceptual framework to study EHR workarounds to improve patient safety, effectiveness of care, and efficiency by identifying, analysing, and resolving workarounds.

4.2 Public health

EHR systems, when used broadly, benefit and contribute to public health. EHRs aid monitoring public health such as vaccination coverage Bollaerts et al. (2019) tested the feasibility of near real-time monitoring of vaccination coverage, benefits and risks focussing on timeliness, i.e., data latency of data capture. Affirming the use of EHR as a tool for measuring population health outcomes Amoah et al. (2017) used EHR data to assess seasonality-based trends of blood pressure over patient population highlighting a more significant association with the increased proportion of diabetic patients. Whereas Namulanda et al. (2018) tested the use of EHR in surveillance of public health using pilot projects focusing on non-communicable rare diseases.

4.3 Application

Combining EHR with other technologies provide insights to patients' health. In Table 5 papers that incorporate such technologies with EHRs are presented. Multi-sourced data provide much better information due to variations in form and kind. Addressing potential data inconsistency, Van Hoeven et al. (2017) identified existing frameworks for EHR data and selected concepts for validating collected data. Whereas, Li et al. (2019) implemented distributed noise contrastive estimation (distributed NCE) to access multiple EHR data while maintaining the privacy make predictions on underlying conditions of patients health and potential threats.

On a large scale, EHRs could be levied to benefit the patient population. Ingram et al. (2020), Wang et al. (2020) and Hong et al. (2019) applied various algorithms for classifying patient EHR data into similar health conditions. Facilitating easy identification of practices that promote health and patterns that could lead to or further the condition.

Early detection of chronic diseases provides scope to control or limit its' severity. To predict the onset of type 2 diabetes Nguyen et al. (2019) implemented a novel wide and deep feed-forward neural network. While Mishuris et al. (2016) proposed integration of external health data generated by patients through their devices like Fitbit, capture their daily activity into EHR. Chatzakis et al. (2018) developed CDSS integrated EHR for early-stage pediatric cardio vascular (CV) disease screening. Monitoring and logging of personal activity consistently will provide a better picture of an individual's health. This in-turn enhances the effectiveness and quality of healthcare. Table 4 presents articles that are applying EHR in new ways or utilising new methods on EHR. Providing an insight to the general areas where EHR have focused on recent times.

Promoting usability, Butt and Shan (2016) developed CyberCare user-friendly health information management system with support for voice navigation, medical image processing and analysing ability. Ben Hassen et al. (2019) developed an eHealth system based on IoT and fog computing for monitoring elderly health. Table 5 presents technologies used with EHR systems aiding in creation, monitoring, learning and storage.

Table 4 Tabulating papers on application of EHR

References	*Applications and relevant areas*
Chatzakis et al. (2018)	Integrated CDSS supporting cardio vascular disease screening.
Namulanda et al. (2018)	Bettering rare disease surveillance, prevalent health condition or risk factors for health outcomes at a finer geographic level.
Ben Hassen et al. (2019)	Efficient low cost e-health system using IoT and android app for monitoring elderly health.
Bruland et al. (2018)	Feasible support to multicentre studies and workflow optimisation.
Murphy et al. (2019)	Identified total testing process (TTP) reliability issues, barriers and facilitators in EHR-enabled care.
McDowell et al. (2017)	Identified temporary increase in work efficiency on new EHR introduction.
Van Hoeven et al. (2017),	Identified that developed approach assures data quality and enhancement of multi-sourced data with increased transparency and reliability.
Zhao et al. (2019)	Improved performance compared to state-of-art, associative attention networks to identify relevant contextual information for a specific entity pair from EHRs using NLP.
Amoah et al. (2017)	Identified cyclic trends in BP control, potential of EHR as a measuring tool of population health outcomes.
Yoo et al. (2020)	User-friendly mobile app with overall epilepsy management.
Hong et al. (2019)	Improved portability of phenotyping, enhanced reproducibility and interpretability of ML based phenotyping algorithms.
Ingram et al. (2020)	Found that a simple algorithm could be used for stratifying entire patient population.
Li et al. (2019)	Implemented distributed predictive model with privacy protection, stand-alone python library.
Jacobs et al. (2019)	Measured long-term effects of EHR on patient processes in radiotherapy.
Day et al. (2019)	Feasible to implement a decision aid directly into users' standard EHR, tested feasibility and benefits of integrating mobile apps into EHR workflow.
Nguyen et al. (2019)	State of art ML algorithm, optimised diabetes prediction.
Wang et al. (2020)	Effectively identifies disease clusters based on latent patterns in HER.
Militello et al. (2016)	Comprehensive and unified view of patients' health, improved service, VHR and better support.
Wang et al. (2015)	Self-learning system, intelligent EMR
Butt and Shan (2016)	Voice navigation system, medical image processing and analysing ability, and interactive calendar.
Raval et al. (2015)	Quality improvement (improved accuracy, increased efficiency) and safety.

Table 4 Tabulating papers on application of EHR (continued)

References	*Applications and relevant areas*
Zive et al. (2016)	Improved workflow efficiency, effective completion of error free forms.
Eom et al. (2016)	Secure patient-controlled health data scheme with provision for emergency data access by staff.
Mishuris et al. (2016)	Provided an efficient and effective way to integrate external data to HER.
Suresh and Florence (2019)	Proposed a novel diversified access control framework composed of user usage based encryption (UUBE) which is normally based on the searchable encryption scheme resulting reduced key management, better privacy, scalability and efficiency.

Table 5 Other technologies used with EHRs

Technology used	*Reference*	*Total number of references*
Mobile	Raval et al. (2015), Eom et al. (2016), Mishuris et al. (2016), Zive et al. (2016), Plastiras and O'Sullivan (2018), Ben Hassen et al. (2019), Day et al. (2019) and Yoo et al. (2020)	8
IoT	Ben Hassen et al. (2019)	1
Cloud	Eom et al. (2016), Mishuris et al. (2016), Ben Hassen et al. (2019), Suresh and Florence (2019), Liang et al. (2020) and Yoo et al. (2020)	6
ML/deep learning	Wang et al. (2015, 2020), Hong et al. (2019), Li et al. (2019), Nguyen et al. (2019) and Zhao et al. (2019)	6
NLP	Hong et al. (2019)	1

Table 6 Healthcare fields where these papers have contributed

Type of application	*Reference*	*Total number of references*
Clinical care	Wang et al. (2015), Mishuris et al. (2016), Agboola et al. (2017), Amoah et al. (2017), Matthews (2017), Chatzakis et al. (2018), Ben Hassen et al. (2019), Hong et al. (2019), Zhao et al. (2019) and Yoo et al. (2020)	10
Public health	Amoah et al. (2017), Namulanda et al. (2018) and Bollaerts et al. (2019)	3
Clinical research	Bruland et al. (2018) and Li et al. (2019)	2
Epidemiology research	Bollaerts et al. (2019) and Wang et al. (2020)	2
Management	Raval et al. (2015), Butt and Shan (2016), Eom et al. (2016), Sidek and Martins (2017), Khajouei et al. (2017), Plastiras and O'Sullivan (2018), Ben Hassen et al. (2019), Bollaerts et al. (2019), Jacobs et al. (2019), McCrorie et al. (2019) and Savoy et al. (2019)	11
Clinical informatics	Day et al. (2019), Karapiperis et al. (2019), Ingram et al. (2020) and Yoo et al. (2020)	4

4.4 Patient-centric/controlled

Patient is the central entity around whom healthcare functions. With this respect few articles provide patient centric solutions. Such as Savoy et al. (2019) designed a cognitive framework that identifies the needs of information for referring primary care providers (PCPs) based on patient-centred displays. Eom et al. (2016) proposed a patient-controlled attribute-based encryption (PC-ABE) providing patient control over their health data with time-sensitive access grant. Similarly, Suresh and Florence (2019) implemented a novel access control framework based on user usage-based encryption (UUBE). In Table 6 presents various fields of healthcare selected literature has contributed.

5 Blockchain-based EHRs

Research articles focussing on utilising blockchain solutions for EHR systems were screened preferable from Springer, Elsevier and IEEE. A total of 44 articles are chosen of which 13 are conference papers while 31 articles are from journals. The selected literature on blockchain based EHR do not focus on replacing legacy EHR. Most of the publications propose to use blockchain over or along with legacy EHR for health record sharing, logging of access or other operations over data, decentralised data management, patient-controlled records, secure integration of patients' data via body sensors or IoTs, integration of existing with other systems. Table 7 presents an overview of the proposed architectures in selected articles for this study.

Table 7 Overview of the issues addressed by blockchain based EHR solutions in selected literature

Reference	*Application*	*Data sharing*	*Storage*	*Access control*	*Privacy*
Tripathi et al. (2020)	S2HS	-	Cloud	-	Yes
Roehrs et al. (2017)	OmniPHR	Yes	EHR database	-	-
Azaria et al. (2016)	MedRec	Yes	Off-chain	Yes	-
Fan et al. (2018)	MedBlock	Yes	Database	Yes	Yes
Zhang et al. (2018)	FHIRChain	Yes	Database	-	-
Xia et al. (2017)	MedShare	Yes	Cloud	Yes	-
Dagher et al. (2018)	Ancile	-	EHR database	Yes	Yes

A significant part of literature utilises smart contracts exclusively for specialised purposes in addition to basic blockchain architecture. Such papers are separately presented to highlight smart contracts also enhance the functionality of blockchain.

6 Blockchain-based contribution to EHR

Here published articles utilising blockchain architecture with EHR are discussed as noted in Table 8. Blockchain is used in EHR to achieve what traditional EHR systems lacked or were not effective in decentralised architecture. Those fields were excluded which depended inherently on blockchain's integral properties.

Table 8 Reason for use of blockchain

Blockchain used for	*References*	*Total number of references*
Data sharing	Azaria et al. (2016), Yue et al. (2016), Zhang et al. (2016, 2018), Xia et al. (2017), Roehrs et al. (2017), Chen et al. (2018, 2019), Fan et al. (2018), Griggs et al. (2018), Liang et al. (2018), Wang et al. (2018, 2019), Wu et al. (2019) and Tanwar et al. (2020)	15
Access control	Azaria et al. (2016), Yue et al. (2016), Brogan et al. (2018), Zhang and Poslad (2018), Dagher et al. (2018), Fan et al. (2018), Guo et al. (2019), Nortey et al. (2019), Radhakrishnan et al. (2019), Shahnaz et al. (2019), Tanwar et al. (2020), Li et al. (2021) and Saberi et al. (2022)	13
Integrity	Kleinaki et al. (2018), Liang et al. (2018), Choudhury et al. (2019), Nortey et al. (2019), Shahnaz et al. (2019), Tian et al. (2019), Tripathi et al. (2020) and Chelladurai et al. (2021)	8
Privacy	Yue et al. (2016), Liu et al. (2017), Badr et al. (2018), Fan et al. (2018), Hussein et al. (2018), Liang et al. (2018), Sun et al. (2018), Choudhury et al. (2019), Wang et al.,(2019), Nortey et al. (2019), Tian et al. (2019) and Tripathi et al. (2020)	12
Confidentiality	Wang and Song (2018), Zhang and Poslad (2018), Cao et al. (2019) and Chen et al. (2019)	4
Security	Yue et al. (2016), Xia et al. (2017), Liu et al. (2017), Badr et al. (2018), Brogan et al. (2018), Wang and Song (2018), Zhang and Poslad (2018), Dagher et al. (2018), Griggs et al. (2018), Hussein et al. (2018), Sun et al. (2018), Wang et al. (2019), Guo et al. (2019), Radhakrishnan et al. (2019), Shahnaz et al. (2019), Tanwar et al. (2020) and Tripathi et al. (2020)	17
Interoperability	Azaria et al. (2016), Roehrs et al. (2017), Brogan et al. (2018), Dagher et al. (2018), Talukder et al. (2018), Zhang et al. (2018), Nortey et al. (2019), Wu et al. (2019) and Reegu et al. (2021)	9
Transparency	Nortey et al. (2019) and Tripathi et al. (2020)	2

6.1 Interoperability

Heterogeneous systems in healthcare generate various forms and formats of data for a patient. The ability of different devices to exchange, understand and utilise data among them is interoperability. To promote interoperability Kaur et al. (2018) proposed moving all healthcare data from healthcare stakeholders to blockchain cloud warehouse while maintaining the record hash and location pointers on a blockchain.

While others focused using blockchain over legacy systems and applying existing standards for interoperability. Roehrs et al. (2017) proposed OmniPHR using openEHR standard for converting data from different sources to connect different health data standards. Integrating with existing systems (Azaria et al., 2016) MedRec supports open standards for health data exchange like FHIR and flavours of HL7. Zhang et al. (2018) implemented FHIRCHain based on HL7 FHIR norms while Wu et al. (2019) developed patient-centric EHR using a novel framework based on blockchain. Established standards for interoperability ensure proper exchange and interpretation of data, Table 9 enlists the standards used by researchers in the literature selected.

Table 9 Standards applied for interoperability

Reference	*Standards used in the selected literature*
Brogan et al. (2018)	FHIR, LOINC
Azaria et al. (2016)	HL7 FHIR, HIPAA
Roehrs et al. (2017)	OpenEHR, HL7 FHIR, HIPAA, SNOMED
Zhang et al. (2018)	HL7 FHIR
Talukder et al. (2018)	CD and SNOMED
Dagher et al. (2018)	HIPAA
Wu et al. (2019)	HL7 FHIR

Wearable technology and smart devices emerged as efficient personal activity monitoring devices. Identifying their effective usage, Brogan et al. (2018) utilised this health data, converted to standard format by coupled fast healthcare interoperability resources (FHIR) and logical observation identifiers names and codes (LOINC). Such activity data provides a much dense estimation of individuals' health level. Interoperability is affected by advances in technology; Table 10 lists the identified technologies that were used in the selected literature:

Table 10 Involving other technologies

Technologies	*References*	*Total number of references*
Mobile	Zhang et al. (2016), Roehrs et al. (2017), Brogan et al. (2018) and Liang et al. (2018)	4
IoT	Badr et al. (2018), Brogan et al. (2018), Griggs et al. (2018), Talukder et al. (2018), Islam and Young Shin (2020) and Tripathi et al. (2020)	6
Cloud	Yue et al. (2016), Xia et al. (2017), Liu et al. (2017), Badr et al. (2018), Chen et al. (2018), Kaur et al. (2018), Talukder et al. (2018), Wang and Song (2018), Cao et al. (2019), Wu et al. (2019), Rahman et al. (2019), Wang et al. (2019) and Islam and Young Shin (2020)	13
ML/deep learning	Liu et al. (2017), Choudhury et al. (2019) and Yong et al. (2020)	3
NLP	Roehrs et al. (2017), Talukder et al. (2018) and Choudhury et al. (2019)	3

6.2 Privacy

Health data is sensitive, maintaining its security and privacy is crucial. Deviation from established security standards could lead to data leak. Liang et al. (2018) and Choudhury et al. (2019) use Hyperledger fabrics' private channels to provide privacy. Apart from this researchers have explored other methods such as Badr et al. (2018) proposed a novel protocol pseudonym based encryption with different authorities (PBE-DA) for a multi-tiered blockchain, to preserve the privacy of patient in such environment. Hussein et al. (2018) utilised a discrete wavelet transform to generate a new key format to better data privacy in data sharing. To maintain privacy and the availability of data (Tian et al., 2019), shared key was used based on sibling intractable function families (SIFF) between patient and doctor after diagnosis.

Yue et al. (2016) proposed an app healthcare data gateway (HDG), allowing patient-owned data to be controlled and shared based on the purpose of the data request by the requestor. This facilitates access to data while preserving privacy for purposes such as research or references.

6.3 Access control

Access control ensures authorised access to data; the data owner provides such authorisation. Liang et al. (2018) proposed user-centric mobile healthcare application with Hyperledger fabric logging data requests and a user-defined access control list (ACL) for approving data requests. Yue et al. (2016) proposed a system of sharing records securely while maintaining privacy based on purpose-centric, time-limited access-control by the patient. Similarly, to cater requests Zhang and Poslad (2018) proposed granular access control with varied levels of access for different levels of users.

Table 11 Access control solutions provided by the articles in selected literature

Reference	*How achieved*
Brogan et al. (2018)	Public, private and restricted modes for access control using multi authenticated messaging (MAM) channels.
Azaria et al. (2016)	Smart contract holding record ownership and permissions data under patient control.
Shahnaz et al. (2019)	Contracts defining roles and corresponding permitted operations on the records.
Yue et al. (2016)	Proposed a indicator centric schema (ICS) model based purpose-centric access control
Fan et al. (2018)	A simple access control scheme utilising signatures and search-compare method facilitating access.
Dagher et al. (2018)	Record specific permissions contract holding interacting node addresses and respective level of access.
Zhang and Poslad (2018)	Proposed a flexible granular access authorisation supporting flexible queries without requiring public key infrastructure.
Guo et al. (2019)	Applied attribute based access control (ABAC) on EHR data with patient defined ACL to validate access requests.
Tanwar et al. (2020)	Smart contracts empowered patient access control scheme with all access granting and revoking rights.
Nortey et al. (2019)	Access control policies defined smart contracts for patient authorised party access records.
Radhakrishnan et al. (2019)	Applied a access management layer for ensuring access control.

For events concerning emergencies, Brogan et al. (2018) used masked authenticated messaging (MAM) module for access control to keep transaction data private, with emergency event access provisions. Table 11 present the articles focussing on access control solution and the way it is achieved.

6.4 Data sharing

Blockchain's use for data sharing is preferred by researchers as shown in Table 12, given its inherent security features. Most of the researchers have preferred blockchain layer over legacy EHRs or cloud storage for sharing while Tanwar et al. (2020) employs Hyperledger-based EHR ledger. Xia et al. (2017), Chen et al. (2018, 2019), Liang et al. (2018), Wang et al. (2019) and Wu et al. (2019) utilise cloud for EHR storage, Table 12 identifies such usage, while blockchain is used for data sharing. Similarly, Roehrs et al. (2017), Griggs et al., 2018 and Zhang et al. (2018) use EHR database storage, data sharing across such databases powered by blockchain. Further blockchain is used for logging the requests for EHR access, location-pointer of EHR and hash of such records ensuring integrity. Compared to traditional EHR, preference is given to patient authorised data sharing similar to access control (Yue et al., 2016; Fan et al., 2018; Quaini et al., 2018; Wang et al., 2019).

Table 12 Tabulating articles on data sharing

References	*Summarised description*
Azaria et al. (2016)	Access of offchain local database data via usage of smart contracts with access control.
Chen et al. (2018)	Patient defined access control over data sharing for records stored in cloud under the chain.
Liang et al. (2018)	User-centric personal health data sharing scheme with user-defined access control.
Zhang et al. (2018)	Applied HL7-FHIR standard for sharing clinical data.
Xia et al. (2017)	Medical data sharing between cloud service providers with access control and action logging.
Yue et al. (2016)	Patient own, control and share their data easily and securely without violating privacy.
Fan et al. (2018)	Record sharing scheme between authorised users with access control and encryption strategy ensuring security and privacy.
Wu et al. (2019)	Applied a scheme of cross-enterprise document sharing (XDS).
Chen et al. (2019)	EHR sharing scheme with searchable encryption.
Tanwar et al. (2020)	Chain code based sharing scheme with access control policy.
Wang et al. (2019)	Data sharing between medical institutes with keyword searchable encryption and conditional proxy re-encryption.

7 Smart contracts

Smart contracts are a great addition to blockchain, simplifying contracts for usage within the blockchain. Automation achieved by their usage makes speedier execution, effectively eliminating the need for intermediaries. Exploitation of smart contracts in blockchain-based EHRs is presented in further sections. Table 13 presents the identified usage of smart contracts in selected literature.

Table 13 Use of smart contracts

How used	*References*	*Total number of references*
Automated data evaluation and standardisation	Griggs et al. (2018), Zhang et al. (2018), Choudhury et al. (2019), Rahman et al. (2019) and Yong et al. (2020)	5
Access control	Azaria et al. (2016), Xia et al. (2017), Yang and Li (2018), Zhang et al. (2018), Dagher et al. (2018), Talukder et al. (2018), Choudhury et al. (2019), Guo et al. (2019), Nortey et al. (2019), Shahnaz et al. (2019), Wu et al. (2019), Tanwar et al. (2020), Li et al. (2021), Saberi et al. (2022) and Kaur et al. (2021)	15
Data masking	Dagher et al. (2018)	1
Security	Dagher et al. (2018), Choudhury et al. (2019) and Islam and Young Shin (2020)	3
Data sharing	Chen et al. (2019)	1
Data integrity	Kleinaki et al. (2018) and Choudhury et al. (2019)	2

7.1 Automated data evaluation and standardisation

Researchers have applied smart contracts for evaluating and recording collected data (Griggs et al., 2018), monitoring vaccination process and supply management (Yong et al., 2020). For assured availability and secured data while system upgradation processes (Zhang et al., 2018), automated standards based validation of transactions (Rahman et al., 2019) and to enforce adherence to the clinical trial protocol (Choudhury et al., 2019).

7.2 Access control

Access control is the most worked on aspect of health records based on blockchain. Dagher et al. (2018) uses multiple contracts for entire possible scenarios from ID management, relationship, ownership, permission management ensuring authorised access to records. Similarly Guo et al. (2019) uses smart contracts with ACL, while Nortey et al. (2019) used predefined rules for authorised access of data via channels. Azaria et al. (2016), Yang and Li (2018), Zhang et al. (2018) and Tanwar et al. (2020) used smart contract for recording ownership and relevant permissions. Blockchain logging actions performed on data with the user controlling the access rights.

Limiting unauthorised third party access, Shahnaz et al. (2019) used a role-based assignment of access to data to known entities with defined access rights. Apart from the access list, Xia et al. (2017) used contracts to monitor actions performed on requested data, similarly, Wu et al. (2019) implemented patient-controlled access rights. Whereas, Talukder et al. (2018) used shared keys for access to data coupled with time-bound access enforced by contracts and Choudhury et al. (2019) used smart contracts along with channels for consent management.

7.3 Data sharing

Smart Contracts are employed in data sharing as they aid secure transfer of record between concerned parties. In this regard smart contacts are used to facilitate sharing of records while maintaining the search query of authorised access publicly available (Chen et al., 2019), as well as monitor the legal usage of data shared over cloud service (Xia et al., 2017).

8 Discussion

This review explored contemporary literature on traditional EHR and blockchain-based EHR, tracing the course taken by each. On observing the areas stressed in the literature, it is evident that traditional EHR extends the depths of healthcare, whereas blockchain-based EHR broadens the reach of healthcare.

Traditional EHR stresses feasibility, refinement and application of EHR in different aspects of healthcare. Researchers attempted to address the needs of healthcare, refine EHR to cater to the specialised needs, improve the usability and promote adoptability. Application of EHR to improve decision support and preventive healthcare is given equal value. Various popular technologies are integrated into EHR to facilitate the exploitation of those for the betterment of EHRs.

Blockchain-based EHR levied the capabilities of the uprising technology to broaden the horizons of EHRs. Blockchains' properties used for opening barriers of traditional EHR such as secure sharing of health records confined to silos. Patient inclusion in health-record management is promoted vastly, stressing on patient-owned and controlled records. Access-control and interoperability are stressed on. Like traditional EHR literature here, other technologies such as IoT, mobile, and cloud have also been used equally.

From the review, an understanding of the current trends of EHR development is achieved. This directs to the future possibilities of integrating blockchain to enhance EHR systems reach and functionality. In this context, future directions could be enlisted as:

- *Utilising blockchain for fully decentralised EHR systems*: a blockchain based fully decentralised EHR would have greater functionality and benefit over a centralised EHR. That is a desirable and eventual developmental phase for EHR. Blockchain based EHR might further be applied to achieve universal linking of healthcare systems for better response and exchange of data. Such a system would be effective in a situation like the current pandemic.

- *Development of patient centric and patient inclusive healthcare solutions:* compared to traditional EHR, blockchain based EHR solutions are patient centric and include them in healthcare processes. Personalised patient education for better personal health practices, management as well as understanding and logging of the adverse events could be achieved in future blockchain based EHR.
- *Greater interoperability and secure data sharing:* for traditional EHR interoperability and data sharing is a significant issue. Blockchains' usage to address these issues is seen in this review. On a wider scale further works for universal secure access of EHR coupled with greater interoperability, capable of linking with upcoming and widespread smart devices is a need.
- *Cost effective healthcare solution:* healthcare is essential for the populace and it often tends to be costly. Effective health solutions are limited to the locality of the patient. Blockchains based EHR has the potential to eliminate that constraint. It is a challenging task to avail globally existing best practices to a patient in a cost effective manner irrespective of geographic locality.

References

Adenuga, O.A., Kekwaletswe, R.M. and Coleman, A. (2015) 'eHealth integration and interoperability issues: towards a solution through enterprise architecture', *Health Information Science and Systems*, Vol. 3, No. 1, pp.1–8, BioMed Central, DOI: 10.1186/s13755-015-0009-7.

Agboola, S. et al. (2017) 'Healthcare utilization in older patients using personal emergency response systems: an analysis of electronic health records and medical alert data: brief description: a longitudinal retrospective analyses of healthcare utilization rates in older patients', *BMC Health Services Research*, Vol. 17, No. 1, pp.1–10, DOI: 10.1186/s12913-017-2196-1.

Amoah, A.O. et al. (2017) 'Bridging the gap between clinical practice and public health: using EHR data to assess trends in the seasonality of blood-pressure control', *Preventive Medicine Reports*, Vol. 6, pp.369–375, Elsevier Inc., DOI: 10.1016/j.pmedr.2017.04.007.

Atherton, J. (2011) 'History of medicine: development of the electronic health record', *Virtual Mentor*, Vol. 13, No. 3, pp.186–189, DOI: 10.1001/virtualmentor.2010.12.8.medu1-1008.

Azaria, A. et al. (2016) 'MedRec: using blockchain for medical data access and permission management', *Proceedings – 2016 2nd International Conference on Open and Big Data, OBD 2016*, pp.25–30, DOI: 10.1109/OBD.2016.11.

Badr, S., Gomaa, I. and Abd-Elrahman, E. (2018) 'Multi-tier blockchain framework for IoT-EHRs systems', *Procedia Computer Science*, Elsevier B.V., Vol. 141, pp.159–166, DOI: 10.1016/j.procs.2018.10.162.

Ben Hassen, H., Dghais, W. and Hamdi, B. (2019) 'An e-health system for monitoring elderly health based on internet of things and fog computing', *Health Information Science and Systems*, Vol. 7, No. 1, Springer International Publishing, DOI: 10.1007/s13755-019-0087-z.

Blijleven, V., Koelemeijer, K. and Jaspers, M. (2019) 'SEWA: a framework for sociotechnical analysis of electronic health record system workarounds', *International Journal of Medical Informatics*, May 2018, Vol. 125, pp.71–78, Elsevier, DOI: 10.1016/j.ijmedinf.2019.02.012.

Bollaerts, K. et al. (2019) 'ADVANCE: towards near real-time monitoring of vaccination coverage, benefits and risks using European electronic health record databases', *Vaccine*, The Author(s), DOI: 10.1016/j.vaccine.2019.08.012.

Brogan, J., Baskaran, I. and Ramachandran, N. (2018) 'Authenticating health activity data using distributed ledger technologies', *Computational and Structural Biotechnology Journal*, Vol. 16, pp.257–266, The Authors, DOI: 10.1016/j.csbj.2018.06.004.

Bruland, P. et al. (2018) 'Connecting healthcare and clinical research: workflow optimizations through seamless integration of EHR, pseudonymization services and EDC systems', *International Journal of Medical Informatics*, July, Vol. 119, pp.103–108, Elsevier, DOI: 10.1016/j.ijmedinf.2018.09.007.

Butt, N. and Shan, J. (2016) 'CyberCare: a novel electronic health record management system', *Proceedings – 2016 IEEE 1st International Conference on Connected Health: Applications, Systems and Engineering Technologies, CHASE 2016*, pp.326–327, DOI: 10.1109/CHASE.2016.52.

Cao, S. et al. (2019) 'Cloud-assisted secure eHealth systems for tamper-proofing EHR via blockchain', *Information Sciences*, Vol. 485, pp.427–440, Elsevier Inc., DOI: 10.1016/j.ins.2019.02.038.

Chatzakis, I. et al. (2018) 'Electronic health record with computerized decision support tools for the purposes of a pediatric cardiovascular heart disease screening program in Crete', *Computer Methods and Programs in Biomedicine*, Vol. 159, pp.159–166, Elsevier B.V., DOI: 10.1016/j.cmpb.2018.03.009.

Chelladurai, M.U., Pandian, D.S. and Ramasamy, D.K. (2021) 'A blockchain based patient centric electronic health record storage and integrity management for e-Health systems', *Health Policy and Technology*, Vol. 10, No. 4, p.100513, Elsevier Ltd, DOI: 10.1016/j.hlpt.2021.100513.

Chen, L. et al. (2019) 'Blockchain based searchable encryption for electronic health record sharing', *Future Generation Computer Systems*, Vol. 95, pp.420–429, Elsevier B.V., DOI: 10.1016/j.future.2019.01.018.

Chen, Y. et al. (2018) 'Blockchain-based medical records secure storage and medical service framework', *Journal of Medical Systems*, Vol. 43, No. 1, DOI: 10.1007/s10916-018-1121-4.

Choudhury, O. et al. (2019) *A Blockchain Framework for Managing and Monitoring Data in Multi-Site Clinical Trials*, pp.1–13 [online] http://arxiv.org/abs/1902.03975 (accessed 23 January 2022).

Dagher, G.G. et al. (2018) 'Ancile: privacy-preserving framework for access control and interoperability of electronic health records using blockchain technology', *Sustainable Cities and Society*, August 2017, Vol. 39, pp. 283–297, Elsevier, DOI: 10.1016/j.scs.2018.02.014.

Day, F.C. et al. (2019) 'Feasibility study of an EHR-integrated mobile shared decision making application', *International Journal of Medical Informatics*, December 2018, Vol. 124, pp.24–30, DOI: 10.1016/j.ijmedinf.2019.01.008.

De Hoon, S.E.M. et al. (2017) 'Adverse events recording in electronic health record systems in primary care', *BMC Medical Informatics and Decision Making*, Vol. 17, No. 1, p.163, DOI: 10.1186/s12911-017-0565-7.

Eom, J., Lee, D.H. and Lee, K. (2016) 'Patient-controlled attribute-based encryption for secure electronic health records system', *Journal of Medical Systems*, Vol. 40, No. 12, pp.1–16, DOI: 10.1007/s10916-016-0621-3.

Fan, K. et al. (2018) 'MedBlock: efficient and secure medical data sharing via blockchain', *Journal of Medical Systems*, Vol. 42, No. 8, pp.1–11, DOI: 10.1007/s10916-018-0993-7.

Gartee, R. (2012) 'History of electronic health records', *Electronic Health Records*, p.576 [online] http://blog.softwareadvice.com/articles/medical/ehr-timeline-113/ (accessed 20 January 2022).

Goldstein, R.L. et al. (2020) 'Providers' perspectives on adolescent confidentiality and the electronic health record: a state of transition', *Journal of Adolescent Health*, Vol. 66, No. 3, pp.296–300, Elsevier Inc., DOI: 10.1016/j.jadohealth.2019.09.020.

Griggs, K.N. et al. (2018) 'Healthcare blockchain system using smart contracts for secure automated remote patient monitoring', *Journal of Medical Systems*, Vol. 42, No. 7, pp.1–7, DOI: 10.1007/s10916-018-0982-x.

Guo, H. et al. (2019) 'Access control for electronic health records with hybrid blockchain-edge architecture', *Proceedings – 2019 2nd IEEE International Conference on Blockchain, Blockchain 2019*, IEEE, pp.44–51, DOI: 10.1109/Blockchain.2019.00015.

Hong, N. et al. (2019) 'Developing a FHIR-based EHR phenotyping framework: a case study for identification of patients with obesity and multiple comorbidities from discharge summaries', *Journal of Biomedical Informatics*, October, Vol. 99, p.103310, Elsevier, DOI: 10.1016/j.jbi.2019.103310.

Hussein, A.F. et al. (2018) 'A medical records managing and securing blockchain based system supported by a genetic algorithm and discrete wavelet transform', *Cognitive Systems Research*, Vol. 52, pp.1–11, DOI: 10.1016/j.cogsys.2018.05.004.

ICANotes (no date) *History of Electronic Health Records |EHR|* [online] https://www.icanotes.com/2019/04/16/a-history-of-ehr-through-the-years/ (accessed 24 June 2020).

Ingram, W.M. et al. (2020) 'Defining major depressive disorder cohorts using the EHR: multiple phenotypes based on ICD-9 codes and medication orders', *Neurology Psychiatry and Brain Research*, February, Vol. 36, pp.18–26, Elsevier, DOI: 10.1016/j.npbr.2020.02.002.

Islam, A. and Young Shin, S. (2020) 'A blockchain-based secure healthcare scheme with the assistance of unmanned aerial vehicle in internet of things', *Computers and Electrical Engineering*, Vol. 84, p.106627, Elsevier Ltd, DOI: 10.1016/j.compeleceng.2020.106627.

Jacobs, M. et al. (2019) 'Electronic health record implementation in a large academic radiotherapy department: temporarily disruptions but long-term benefits', *International Journal of Medical Informatics*, March, Vol. 129, pp.342–348, Elsevier, DOI: 10.1016/j.ijmedinf.2019.07.008.

Kaipio, J. et al. (2020) 'Physicians' and nurses' experiences on EHR usability: comparison between the professional groups by employment sector and system brand', *International Journal of Medical Informatics*, October 2019, Vol. 134, p.104018, Elsevier, DOI: 10.1016/j.ijmedinf.2019.104018.

Karapiperis, D., Gkoulalas-Divanis, A. and Verykios, V.S. (2019) 'FEMRL: a framework for large-scale privacy-preserving linkage of patients' electronic health records', *2018 IEEE International Smart Cities Conference, ISC2 2018*, IEEE, pp.1–8, DOI: 10.1109/ISC2.2018.8656943.

Kasthurirathne, S.N. et al. (2015) 'Enabling better interoperability for healthcare: lessons in developing a standards based application programing interface for electronic medical record systems', *Journal of Medical Systems*, Vol. 39, No. 11, DOI: 10.1007/s10916-015-0356-6.

Kaur, H. et al. (2018) 'A proposed solution and future direction for blockchain-based heterogeneous medicare data in cloud environment', *Journal of Medical Systems*, Vol. 42, No. 8, DOI: 10.1007/s10916-018-1007-5.

Kaur, J., Rani, R. and Kalra, N. (2021) 'Blockchain-based framework for secured storage, sharing, and querying of electronic healthcare records', *Concurrency and Computation: Practice and Experience*, Vol. 33, No. 20, pp.1–24, DOI: 10.1002/cpe.6369.

Khajouei, R., Zahiri Esfahani, M. and Jahani, Y. (2017) 'Comparison of heuristic and cognitive walkthrough usability evaluation methods for evaluating health information systems', *Journal of the American Medical Informatics Association*, Vol. 24, No. e1, pp.e55–e60, DOI: 10.1093/jamia/ocw100.

Kleinaki, A.S. et al. (2018) 'A blockchain-based notarization service for biomedical knowledge retrieval', *Computational and Structural Biotechnology Journal*, Vol. 16, pp.288–297, The Authors, DOI: 10.1016/j.csbj.2018.08.002.

Li, F. et al. (2021) 'EHRChain: a blockchain-based EHR system using attribute-based and homomorphic cryptosystem', *IEEE Transactions on Services Computing*, pp.1–13, DOI: 10.1109/TSC.2021.3078119.

Li, Z. et al. (2019) 'Distributed learning from multiple EHR databases: contextual embedding models for medical events', *Journal of Biomedical Informatics*, February, Vol. 92, p.103138, Elsevier, DOI: 10.1016/j.jbi.2019.103138.

Liang, J. et al. (2020) 'Privacy-preserving range query over multi-source electronic health records in public clouds', *Journal of Parallel and Distributed Computing*, Vol. 135, pp.127–139, Elsevier Inc., DOI: 10.1016/j.jpdc.2019.08.011.

Liang, X. et al. (2018) 'Integrating blockchain for data sharing and collaboration in mobile healthcare applications', *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications, PIMRC*, October 2017, pp.1–5, DOI: 10.1109/PIMRC.2017.8292361.

Liu, W., Zhu, S.S., Mundie, T. et al. (2017) 'Advanced block-chain architecture for e-health systems', *2017 IEEE 19th International Conference on e-Health Networking, Applications and Services, Healthcom 2017*, Institute of Electrical and Electronics Engineers Inc., December, pp.37–42, DOI: 10.1109/HEALTHCOM.2017.8210847.

Matthews, E.B. (2017) 'Integrating the electronic health record into behavioral health encounters: strategies, barriers, and implications for practice', *Administration and Policy in Mental Health and Mental Health Services Research*, Vol. 44, No. 4, pp.512–523, Springer, USA, DOI: 10.1007/s10488-015-0676-3.

McCrorie, C. et al. (2019) 'Staff expectations for the implementation of an electronic health record system: a qualitative study using normalisation process theory', *BMC Medical Informatics and Decision Making*, Vol. 19, No. 1, pp.1–14, DOI: 10.1186/s12911-019-0952-3.

McDowell, J. et al. (2017) 'Effect of the implementation of a new electronic health record system on surgical case turnover time', *Journal of Medical Systems*, Vol. 41, No. 3, DOI: 10.1007/s10916-017-0690-y.

Militello, C. et al. (2016) 'A virtual health record-based EHR system', *2015 E-Health and Bioengineering Conference, EHB 2015*, DOI: 10.1109/EHB.2015.7391425.

Mishuris, R.G. et al. (2016) 'Integrating data from an online diabetes prevention program into an electronic health record and clinical workflow, a design phase usability study', *BMC Medical Informatics and Decision Making*, Vol. 16, No. 1, pp.1–13, DOI: 10.1186/s12911-016-0328-x.

Murphy, D.R. et al. (2019) 'Barriers and facilitators impacting reliability of the electronic health record-facilitated total testing process', *International Journal of Medical Informatics*, February, Vol. 127, pp.102–108, Elsevier, DOI: 10.1016/j.ijmedinf.2019.04.004.

Nakamoto, S. (2019) *Bitcoin: A Peer-To-Peer Electronic Cash System* [online] https://git.dhimmel.com/bitcoin-whitepaper/ (accessed 16 December 2020).

Namulanda, G. et al. (2018) 'Electronic health record case studies to advance environmental public health tracking', *Journal of Biomedical Informatics*, September 2017, Vol. 79, pp.98–104, Elsevier, DOI: 10.1016/j.jbi.2018.02.012.

Nguyen, B.P. et al. (2019) 'Predicting the onset of type 2 diabetes using wide and deep learning with electronic health records', *Computer Methods and Programs in Biomedicine*, Vol. 182, p.105055, Elsevier B.V., DOI: 10.1016/j.cmpb.2019.105055.

Nortey, R.N. et al. (2019) 'Privacy module for distributed electronic health records (EHRs) using the blockchain', *2019 4th IEEE International Conference on Big Data Analytics, ICBDA 2019*, IEEE, pp.369–374, DOI: 10.1109/ICBDA.2019.8713188.

Plastiras, P. and O'Sullivan, D. (2018) 'Exchanging personal health data with electronic health records: a standardized information model for patient generated health data and observations of daily living', *International Journal of Medical Informatics*, Vol. 120, pp.116–125, Elsevier Ireland Ltd., DOI: 10.1016/j.ijmedinf.2018.10.006.

Quaini, T. et al. (2018) 'A model for blockchain-based distributed electronic health records', *IADIS International Journal on WWW/Internet*, Vol. 16, No. 2, pp.66–79, DOI: 10.33965/ijwi_2018161205.

Radhakrishnan, B.L., Sam Joseph, A. and Sudhakar, S. (2019) 'Securing blockchain based electronic health record using multilevel authentication', *2019 5th International Conference on Advanced Computing and Communication Systems, ICACCS 2019*, IEEE, pp.699–703, DOI: 10.1109/ICACCS.2019.8728483.

Rahman, M.S. et al. (2019) 'A novel architecture for tamper proof electronic health record management system using blockchain wrapper', *BSCI 2019 – Proceedings of the 2019 ACM International Symposium on Blockchain and Secure Critical Infrastructure, Co-Located with AsiaCCS 2019*, pp.97–105, DOI: 10.1145/3327960.3332392.

Raval, M.V. et al. (2015) 'Development and implementation of an electronic health record generated surgical handoff and rounding tool', *Journal of Medical Systems*, Vol. 39, No. 2, DOI: 10.1007/s10916-015-0202-x.

Reegu, F.A. et al. (2021) 'Blockchain-based framework for interoperable electronic health record', *Annals of the Romanian Society for Cell Biology*, Vol. 25, No. 3, pp.6486–6495 [online] http://annalsofrscb.ro6486 (accessed 24 February 2022).

Roehrs, A., da Costa, C.A. and da Rosa Righi, R. (2017) 'OmniPHR: a distributed architecture model to integrate personal health records', *Journal of Biomedical Informatics*, Vol. 71, pp.70–81, Elsevier Inc., DOI: 10.1016/j.jbi.2017.05.012.

Saberi, M.A., Adda, M. and Mcheick, H. (2022) 'Break-glass conceptual model for distributed EHR management system based on blockchain, IPFS and ABAC', *Procedia Computer Science*, Elsevier B.V., Vol. 198, No. 2021, pp.185–192, DOI: 10.1016/j.procs.2021.12.227.

Savoy, A. et al. (2019) 'Cognitive requirements for primary care providers during the referral process: information needed from and interactions with an electronic health record system', *International Journal of Medical Informatics*, May, Vol. 129, pp.88–94, Elsevier, DOI: 10.1016/j.ijmedinf.2019.05.027.

Shahnaz, A., Qamar, U. and Khalid, A. (2019) 'Using blockchain for electronic health records', *IEEE Access*, Vol. 7, pp.147782–147795, DOI: 10.1109/ACCESS.2019.2946373.

Sidek, Y.H. and Martins, J.T. (2017) 'Perceived critical success factors of electronic health record system implementation in a dental clinic context: an organisational management perspective', *International Journal of Medical Informatics*, August, Vol. 107, pp.88–100, Elsevier, DOI: 10.1016/j.ijmedinf.2017.08.007.

Sun, Y. et al. (2018) 'A decentralizing attribute-based signature for healthcare blockchain', *Proceedings – International Conference on Computer Communications and Networks, ICCCN*, IEEE, July, pp.1–9, DOI: 10.1109/ICCCN.2018.8487349.

Suresh, D. and Florence, M.L. (2019) 'Securing personal health record system in cloud using user usage based encryption', *Journal of Medical Systems*, Vol. 43, No. 6, DOI: 10.1007/s10916-019-1301-x.

Talukder, A.K. et al. (2018) 'Proof of disease: a blockchain consensus protocol for accurate medical decisions and reducing the disease burden', *Proceedings – 2018 IEEE SmartWorld, Ubiquitous Intelligence and Computing, Advanced and Trusted Computing, Scalable Computing and Communications, Cloud and Big Data Computing, Internet of People and Smart City Innovations, SmartWorld/UIC/ATC/ScalCom/CBDCo*, IEEE, pp.257–262, DOI: 10.1109/SmartWorld.2018.00079.

Tanwar, S., Parekh, K. and Evans, R. (2020) 'Blockchain-based electronic healthcare record system for healthcare 4.0 applications', *Journal of Information Security and Applications*, Vol. 50, p.102407, Elsevier Ltd., DOI: 10.1016/j.jisa.2019.102407.

Tian, H., He, J. and Ding, Y. (2019) 'Medical data management on blockchain with privacy', *Journal of Medical Systems*, Vol. 43, No. 2, pp.1–6, DOI: 10.1007/s10916-018-1144-x.

Tripathi, G., Ahad, M.A. and Paiva, S. (2020) 'S2HS – a blockchain based approach for smart healthcare system', *Healthcare*, Vol. 8, No. 1, p.100391, Elsevier Inc., DOI: 10.1016/j.hjdsi.2019.100391.

Van Hoeven, L.R. et al. (2017) 'Validation of multisource electronic health record data: an application to blood transfusion data', *BMC Medical Informatics and Decision Making*, Vol. 17, No. 1, pp.1–10, DOI: 10.1186/s12911-017-0504-7.

Wang, H. and Song, Y. (2018) 'Secure cloud-based EHR system using attribute-based cryptosystem and blockchain', *Journal of Medical Systems*, Vol. 42, No. 8, DOI: 10.1007/s10916-018-0994-6.

Wang, S. et al. (2018) 'Blockchain-powered parallel healthcare systems based on the ACP approach', *IEEE Transactions on Computational Social Systems*, Vol. 5, No. 4, pp.942–950, IEEE, DOI: 10.1109/TCSS.2018.2865526.

Wang, Y. et al. (2015) 'An electronic medical record system with treatment recommendations based on patient similarity', *Journal of Medical Systems*, Vol. 39, No. 5, DOI: 10.1007/s10916-015-0237-z.

Wang, Y. et al. (2019) 'Cloud-assisted EHR sharing with security and privacy preservation via consortium blockchain', *IEEE Access*, Vol. 7, pp.136704–136719, IEEE, DOI: 10.1109/ACCESS.2019.2943153.

Wang, Y. et al. (2020) 'Unsupervised machine learning for the discovery of latent disease clusters and patient subgroups using electronic health records', *Journal of Biomedical Informatics*, Elsevier Inc., Vol. 102, p.103364, DOI: 10.1016/j.jbi.2019.103364.

Wu, H. et al. (2019) 'A patient-centric interoperable framework for health information exchange via blockchain', *ACM International Conference Proceeding Series*, pp.76–80, DOI: 10.1145/3376044.3376055.

Xia, Q. et al. (2017) 'MeDShare: trust-less medical data sharing among cloud service providers via blockchain', *IEEE Access*, Vol. 5, pp.14757–14767, DOI: 10.1109/ACCESS.2017.2730843.

Yang, G. and Li, C. (2018) 'A design of blockchain-based architecture for the security of electronic health record (EHR) systems', *Proceedings of the International Conference on Cloud Computing Technology and Science, CloudCom*, IEEE, December, pp.261–265, DOI: 10.1109/CloudCom2018.2018.00058.

Yong, B. et al. (2020) 'An intelligent blockchain-based system for safe vaccine supply and supervision', *International Journal of Information Management*, October, Vol. 52, p.1, Elsevier, DOI: 10.1016/j.ijinfomgt.2019.10.009.

Yoo, S. et al. (2020) 'Developing a mobile epilepsy management application integrated with an electronic health record for effective seizure management', *International Journal of Medical Informatics*, Vol. 134, p.104051, Elsevier Ireland Ltd., DOI: 10.1016/j.ijmedinf.2019.104051.

Yue, X. et al. (2016) 'Healthcare data gateways: found healthcare intelligence on blockchain with novel privacy risk control', *Journal of Medical Systems*, Vol. 40, No. 10, DOI: 10.1007/s10916-016-0574-6.

Zhang, J., Xue, N. and Huang, X. (2016) 'A secure system for pervasive social network-based healthcare', *IEEE Access*, Vol. 4, pp.9239–9250, DOI: 10.1109/ACCESS.2016.2645904.

Zhang, P. et al. (2018) 'FHIRChain: applying blockchain to securely and scalably share clinical data', *Computational and Structural Biotechnology Journal*, Vol. 16, pp.267–278, The Authors, DOI: 10.1016/j.csbj.2018.07.004.

Zhang, X. and Poslad, S. (2018) 'Blockchain support for flexible queries with granular access control to electronic medical records (EMR)', *IEEE International Conference on Communications*, IEEE, May, pp.1–6, DOI: 10.1109/ICC.2018.8422883.

Zhao, S. et al. (2019) 'Associative attention networks for temporal relation extraction from electronic health records', *Journal of Biomedical Informatics*, May, Vol. 99, p.103309, Elsevier, DOI: 10.1016/j.jbi.2019.103309.

Zive, D.M. et al. (2016) 'Implementation of a novel electronic health record-embedded physician orders for life-sustaining treatment system', *Journal of Medical Systems*, Vol. 40, No. 11, pp.5–8, DOI: 10.1007/s10916-016-0605-3.