A Narrative Review on Emerging Technologies in Medicine: Opportunities & Challenges in Modern Healthcare

ABSTRACT

Recent years have seen an unparalleled exploration of novel technological developments for the betterment of the healthcare industry and have profoundly changed how medical professionals approach the diagnosis, treatment, and management of a wide range of health disorders. Technologies ranging from nanotechnology to self-healing materials, from quantum mechanics to the semantic web, have surfaced. Integration of these innovative technologies holds great promise and potential for improving healthcare delivery, patient outcomes, cost-effectiveness, control of logistic burden, and effortless management of huge healthcare data. However, in addition to their possible advantages, these inventions often bring special difficulties that need to be overcome in order to reach their full potential. Regulatory compliance, interoperability, ethical considerations, and healthcare disparities must be effectively managed in order to ensure meaningful access to these breakthroughs and safeguard patient well-being while considering data privacy and security. This review article explores the state of latest technologies that can be used in the medical domains at the moment.

Keywords: Blockchain technology; Nanotechnology; Self-healing materials; Quantum Mechanics; Semantic Web; Artificial Intelligence

1. INTRODUCTION

Medicine is never static and has continuously evolved across all domains of healthcare which includes, but is not limited to diagnostic protocols, management practices, technologies, procedures, and data storage. That evolution is anticipated to happen at an unprecedented rate with the gleaming progress achieved in available technologies and the polished development of new technologies in recent years. This article currently focuses on blockchain technology, quantum mechanics, artificial intelligence (AI), extended reality (XR), semantic web (SW), nanotechnology, and self-healing materials – all of which have formidable scope in healthcare, some are currently in use while others show great promise for future. Integrating these technologies offers significant potential to enhance healthcare delivery, improve patient outcomes, increase cost-effectiveness, streamline logistics, and manage vast healthcare data. However, these advancements also present unique challenges that must be addressed to realize their full benefits. We started by giving an introduction of each technology, detailing how it is currently applied in the healthcare industry, and highlighting noteworthy developments and anticipated breakthroughs, if any. In the conversation that follows, we examine each technology's shortcomings.

2.1 Blockchain Technology

Blockchain technology was first developed as a cryptocurrency platform but has since expanded to become a powerful force in a wide range of businesses including applications in the medical field. Immutable data can be safely transmitted using this technology without the involvement of third parties by functioning as a customized database run by a network of certified people (referred to as nodes) (Saeed H, 2022). Due to this fundamental feature, Blockchain integration in medicine has the potential to improve security, transparency, and overall efficiency. In traditional healthcare systems, problems like data leaks and unauthorized access put patient confidentiality at risk (Price WN, 2019). By restricting access to only those who are permitted and lowering the possibility of data breaches, blockchain's decentralized and cryptographic characteristics safeguard electronic medical records (EMRs) (Kuo TT, 2017). Blockchain technology can also be used to promote interoperability among diverse healthcare systems while safeguarding patient data. Facilitating this seamless interchange of patient data using the decentralized ledger structure eliminates the need for convoluted and usually ineffective data-sharing techniques (Dubovitskaya A, 2020).

Improving drug tracking and supply chain management is a crucial component in the medical field where blockchain technology implementation would be critical. Blockchain technology's transparent and unchangeable ledger can be used to track the whole pharmaceutical supply chain, from manufacturing to delivery, avoiding counterfeit items, increasing overall efficacy, and reducing administrative costs (Uddin M, 2021; Gomasta SS, 2023).

One aspect of blockchain technology that helps with automation and streamlined procedures is smart contracts. Self-executing contracts can be used to save paperwork and administrative burden by turning on automatic triggering if the preset requirements are met (Cong LW, 2019). The faster processing of insurance claims by smart contracts, for example, leads to faster financial reimbursements to organizations and healthcare providers and creates a more efficient system overall. Another advantage of blockchain technology has been demonstrated to be efficient prescription management. Research that used the blockchain electronic prescription tool in three family medical clinics found that it significantly reduced time (Seaberg RW, 2021). The program's accurate medication reconciliation and thorough PDMP (Physician Drug Monitoring Program) checks allowed the provider to inexorably alter the patient's prescription, improving safety and saving money (Seaberg RW, 2021).

2.1.1 Limitations

Although blockchain technology is commended for being decentralized and unchangeable, it has certain disadvantages. Understanding these limits is essential, especially in the medical industry. Its lack of scalability is the primary barrier. As the number of actions on a blockchain increases, so do the time and resources required to record and validate each transaction (Hughes L, 2019). Another significant limitation is energy consumption. Many blockchains use a proof-of-work consensus mechanism, which demands a significant amount of processing power to process data. This results in the consumption of a significant quantity of electricity and environmental issues are also thrown up (Sapra N, 2023). Moreover, the limited research conducted in the medical field and the immaturity in understanding this technology present obstacles to the broader implementation of the blockchain (Gulia P, 2024).

2.2 Quantum Mechanics

Understanding atomic structures like protons and electrons depends heavily on quantum mechanics, which has its roots in physics and has now spread to chemistry and biology. This integration into biology is known as quantum biology, and it looks into processes that are outside the purview of traditional physics. Like all matter, living things are governed by physical rules, and biological activities in the cellular organelles include constant exchanges of protons and electrons. Such a system is called an open quantum system (Marias A, 2018), and understanding quantum principles is essential which is the goal of quantum biology. In a nutshell, quantum biology is the understanding of biological processes at the quantum level, challenging traditional interpretations.

Along with quantum biology, understanding quantum chemistry is also essential to get an overall understanding of these open quantum systems. Quantum chemistry adds to the conceptual framework of quantum physics by shedding light on molecular bonding, which are essential to quantum life. Quantum approaches have been used in recent years to analyze biological phenomena, including photosynthesis and bird navigation, both theoretically and experimentally (Tuszynski JA, 2020). Furthermore, quantum principles are used to forecast evolutionary biology (Torday JS, 2018) and introduce quantum metabolism theory (Tuszynski JA, 2020), which clarifies the allometric scaling laws of physiology. Another area of study in quantum biology is consciousness, which some see as the final frontier of contemporary research (Tuszynski JA, 2020).

Research on cancer and quantum biology may have consequences for cellular functions such as DNA replication, mutation, and signaling. Tunneling effects and quantum coherence may affect DNA repair systems, causing genomic instability and the emergence of cancer (Bordonaro M, 2019). Targeting quantum processes inside cancer cells is one theory that aims to break coherence, cause cell death, or prevent metastasis. Subtle DNA alterations and telomere shortening in cancer patients have logical explanations in quantum theory, which advances our knowledge of disease and its management in a variety of medical fields. Integrating quantum mechanics into medicine presents possibilities for early diagnosis of the illness and cutting-edge therapeutic approaches. Also, understanding neurological disorders can be improved by theory-based mathematical constructs that describe neuron transmission at the quantum scale (Bisiani J, 2023). Even the knowledge of quantum physics and chemistry can be directly applied to areas of patient care, such as the identification of potential sentinel events and drug administration.

Furthermore, computer-aided drug design appears to benefit from the deployment of quantum mechanics-based electronic structure techniques. When quantum-based methods are compared to empirically generated functions, the former increases prediction accuracy by forecasting binding affinities and protein-ligand geometries. Advanced algorithms, machine learning methods, and large-scale molecular databases work together to drive quantum mechanics' role in the future of structure-based drug discovery. With these initiatives, the application of quantum mechanics to medicine is becoming more and more promising, providing answers and new perspectives on a wide range of medical problems (Bryce RA, 2020).

2.2.1 Limitations

It is true that applying quantum knowledge has its limits. The first is the extent of unexplored land in the quantum domain because we haven't fully investigated and grasped the realm of quantum mechanics. The second is that external elements like electromagnetic fields, pressure, and temperature can affect quantum systems. Changes in these variables may impact the stability and efficacy of healthcare technologies that are developed on quantum principles, which may restrict their use in a range of clinical contexts (Yu CJ, 2021). Although quantum mechanics has made great theoretical progress, there is still a lack of extensive experimental confirmation in healthcare applications (Ur Rasool R, 2023).

2.3 Artificial Intelligence (AI)

Recently, artificial intelligence (AI) has revolutionized a number of areas, including the medical field. AI has the potential to completely transform the healthcare sector because of its ability to read vast amounts of data, spot trends, and forecast results (Mintz y, 2019).

One area where AI has had the largest impact in medicine is diagnosis. Machine learning algorithms can analyze medical imaging data, such as MRIs and CT scans, with remarkable accuracy, which can aid in the early detection of conditions like cancer and stroke (Katta MR, 2023). Additionally, AI-powered predictive models may assess a patient's risk of developing particular diseases based on lifestyle, genetic, and environmental factors. As a result, conditions like diabetes and hypertension can be proactively managed or prevented (Rajkomar A, 2018). By integrating patient data, including genetic profiles, medical histories, and therapeutic responses, AI systems can develop individualized treatment plans that are best for each individual patient (Topol EJ, 2019). Furthermore, AI is used in the drug discovery process to analyze massive datasets in order to identify qualified candidates and predict their safety and efficacy characteristics. Using techniques like deep learning, AI models may mimic chemical interactions, significantly reducing the time and cost associated with traditional drug development pipelines. In addition to expediting the search for novel medicines, this approach facilitates the repurposing of existing drugs for other uses (Bender A, 2021).

Natural language processing algorithms can extract relevant information from scientific journals and EMRs, giving doctors timely, evidence-based recommendations. Additionally, AI-powered chatbots and virtual assistants can provide patients with personalized recommendations, symptom evaluations, and medication reminders, which enhances patient involvement and treatment plan adherence (Alowais SA, 2023).

2.3.1 Limitations

Unlike other technologies, AI is fully input-based and only as good as the data we provide it. The effectiveness of AI medical models is significantly impacted by the volume and caliber of input data. Depending on the circumstances, overfitting and measurement errors in small datasets may result in inconsistent outcomes. Quality issues could lead to incorrect diagnoses and lower model accuracy (Katta MR, 2023). Additionally, medical practitioners are unable to embrace and trust AI-driven diagnosis and treatment recommendations because of ongoing problems with interpretability (Arnold MH, 2021). Another significant drawback of adopting AI is the ethical and legal ramifications. When an AI machine makes a mistake despite its training, the question of accountability comes up. Ascertaining who bears the responsibility for such mistakes is a challenging undertaking that requires considerable thought and definition within the ethical and legal frameworks governing the use of AI (Morley J, 2020).

2.4 Extended Reality (XR)

Virtual reality (VR), augmented reality (AR), and mixed reality (MR) are all included in XR, which has become a game-changing tool for a number of industries, including medicine. The integration of XR with other technologies has provided new applications in patient care, surgical training, and medical education, even though it is not as recent as other technologies highlighted.

XR technologies have revolutionized medical education by providing accurate preoperative planning, intraoperative navigation, and immersive and interactive learning experiences for students and professionals (Laspro M, 2023; Prunjou Vm, 2022). Through the use of VR simulators, which offer realistic training scenarios, surgeons can conduct surgeries in a risk-free setting, enhancing their skills and reducing medical errors. For instance, ‘Osso VR’ provides surgical simulation platforms that replicate complex procedures (Laspro M, 2023). By allowing students to examine anatomical components in real-time, AR applications—like Microsoft HoloLens' 3D anatomy visualization tools—help them comprehend and remember difficult subjects (Prunoju VM, 2022). Surgeons can plan complicated surgeries and foresee possible difficulties by using XR and can examine patient-specific anatomy using medical imaging data. Additionally, XR projects real-time patient data onto the operating field, offering crucial operational guidance. For example, venipuncture treatments are made easier for clinicians by the use of XR technologies such as AccuVein, which is projected onto patients' skin for guidance (Aulagnier 2014).

Recent years have seen the emergence of new applications for XR in the medical field, which improve patient care by facilitating remote consultations, lowering patient anxiety, and increasing treatment results. Distraction therapy based on VR has shown promise in reducing anxiety and pain during medical operations. For instance, burn patients are relieved from the agonizing wound care treatments by submerging themselves in a snowy virtual world with Hunter Hoffman and his team's VR game, SnowWorld (Hoffman HG, 2000; Dinh A, 20230. Additionally, new methods of therapy and rehabilitation for a range of medical disorders are provided by XR technology. In order to promote neuroplasticity and functional recovery, VR-based rehabilitation programs offer interactive exercises to patients recuperating from musculoskeletal problems, spinal cord injuries, and strokes (Laver KE, 2017). AR applications also improve prosthetic fitting procedures by overlaying digital models onto patients' residual limbs, which allows for more exact customization and increases mobility and comfort (Górski F, 2023)

Participating in computational technology—which encompasses XR, AI, and computational simulations—allows for improved decision-making in real-time, shorter procedure durations and costs, and a decline in the rate of complications. It also facilitates real-time communication amongst multidisciplinary physicians who are geographically dispersed, offering an authentic experience (Samant S, 2023).

2.4.1 Limitations

Despite encouraging outcomes, barriers exist that prevent XR from being widely used in medicine. Many institutions, especially smaller clinics, are unable to adopt XR systems because of the high initial costs that are associated with setup, software acquisition, and hardware upkeep (Logeswaran A, 2021). Reliability problems are brought on by technical complexity, including compatibility problems, system breakdowns, and hardware and software errors (Baniasdai T, 2020). It is imperative to design XR interfaces that are intuitive and easy to use while taking into account, concerns such as motion sickness and sensory overload. In order to maximize the usability and adoption of XR in clinical settings, makers should place a high priority on including human factors and developing user-centered design (Liang S, 2023).

2.5 Semantic Web (SW)

The World Wide Web's extension, the Semantic Web (SW), was initially conceived in 1989. This development involves making data on websites machine-readable by structuring and tagging. Extending from this, SW provides an organized and methodical approach to data structure and interconnection, making it possible for machines to understand and analyze data available on the internet in a comprehensible manner (Karami M, 2018; Machado CM, 2015).

SW technologies that have emerged from this paradigm have the potential to support knowledge management, sharing, and promoting interoperability amongst healthcare information systems (Haque AB, 2015). The development of semantic models and ontologies (an ontology is a formal representation of knowledge or conceptualization of a domain), that define data representation is made possible by SW technologies like the Resource Description Framework (RDF) and Web Ontology Language (OWL) (Cardoso J, 2006). This encourages smooth interchange and integration across many data sources. Additionally, SW can be used to develop a range of e-healthcare systems that help doctors make decisions, give patients automated hospital services, and deliver vital health information (Haque AB, 2022).

Furthermore, SW technology is an effective tool for training AI models that utilize big datasets with little assistance from humans since it can immediately comprehend data (Pinto-Coelho L, 2023). However, a significant doubt concerning the accuracy of the available facts arises. Inconsistent study findings, outdated data (such as outdated guidelines), or inadequately sponsored research can all jeopardize reliability. To address this issue, smart contracts and blockchain technology might be required (Baqa H, 2019). By establishing predetermined criteria for data inclusion and only ingesting data when the smart contract is executed, SW technologies guarantee that AI models are trained with the highest quality data accessible.

The SW's ability to extract and process data from the internet makes it a valuable tool that can help physicians with diagnosis and treatment plans. Using its capabilities, SW can assist physicians in developing comprehensive and accurate lists of potential diagnoses through the use of differential diagnosis algorithms. Additionally, SW can promptly give doctors up-to-date information on potential medicines, ensuring that treatment plans reflect the latest advancements in medicine. Better patient outcomes may result from the integration of SW into clinical workflows, which may increase therapeutic efficacy and diagnostic accuracy (Mohammed O, 2014).

2.5.1 Limitations

The difficulty of creating and maintaining ontologies and semantic models, which calls for substantial resources and specialized knowledge, is one major disadvantage of SW (de Mello BH, 2022). Moreover, there are numerous challenges to integrating SW with cutting-edge technologies like blockchain and AI. Considering how quickly these technologies are developing and how little is researched in relation to healthcare, achieving seamless integration with SW may be difficult. Further constraints include the requirement for thorough training of healthcare personnel and prompt adaptation to ever-upgrading models (Pinto-Coelho L, 2023; Baqa H, 2019).

2.6 Nanotechnology

Nanotechnology—Expertise to manipulate matter at the atomic and molecular level—has become a vital component in medicine. This section of the article examines the many uses of nanotechnology in the medical field, including imaging, medication delivery, diagnostics, and regenerative medicine.

Drug delivery has been completely transformed by nanotechnology, which has made it possible to create highly advanced nanoparticle carriers that can release therapeutic chemicals in a targeted and regulated manner (Patra JK, 2018). These nanoparticles, which include dendrimers, polymeric micelles, and liposomes, have benefits, such as increased bioavailability and improved drug solubility. Additionally, site-specific drug delivery is made possible by surface functionalization of nanoparticles, which reduces off-target effects and increases therapeutic efficacy (Begines B, 2020).

Medical imaging methods are also improved as a result of advances in nanotechnology, making it smoother to identify diseases timely and accurately locate the lesions. Magnetic resonance imaging (MRI), computed tomography (CT), and fluorescence imaging are among the high-resolution imaging modalities that benefit from the distinctive optical and magnetic properties of nanoparticles, such as iron oxide and quantum dots (the word "quantum" in this context is not related to quantum mechanics discussed earlier in the article). Furthermore, as compared to traditional imaging agents, nanoparticle-based contrast agents have higher sensitivity and specificity, which enhances diagnostic precision and patient outcomes (Han X, 2019).

In the domain of tissue engineering and regenerative medicine, where exact control over cellular behavior and tissue regeneration is critical, nanotechnology has enormous promise. Hydrogels, nanofibers, and scaffolds are examples of nanomaterials that imitate the natural extracellular matrix and offer a favorable milieu for tissue regeneration, cell proliferation, and differentiation (Chaudhury K, 2014). Furthermore, the introduction of growth factors and bioactive compounds via nanoparticles promotes tissue regeneration and quickens the healing of wounds.

Very recently nanotechnology has been combined with other developments to increase efficiency and unlock novel capabilities. One prominent instance is the combination of nanotechnology with self-healing polymers and nanocomposites, which results in an extraordinary class of materials possessing an amazing healing capacity (Kausar A, 2023). This particular characteristic is promising for the creation of bioengineered models that mimic the dynamic and sensitive characteristics of live tissues, allowing for the successful healing of severe wounds and the facilitation of adaptability to changes in the wound environment (D'elia E, 2016). Another use is the development of portable diagnostic devices through nanotechnology and loading them with AI models for prompt diagnostic results, saving time and increasing productivity (Thwala LN, 2023).

2.6.1 Limitations

Although nanotechnology has great scope, the potential toxicity and biological reactions of nanomaterials can jeopardize their safety in clinical applications. One significant toxicity is the enhanced generation of reactive oxygen species caused due to the higher reactivity of nanomaterials. This can lead to oxidative stress, production of inflammatory cytokines, damage to proteins, membranes, DNA, and also cell death (Najahi-Missaoui W, 2020). Furthermore, predicting the long-term impacts of nanoparticles and guaranteeing regulatory compliance is difficult due to the intricate interconnections between them and biological systems (Desai N, 2012). To address these obstacles and realize the broad application of nanomedicine technologies for bettering healthcare outcomes, a thorough risk assessment, strict safety regulations, and coordinated efforts are needed.

2.7 Self-Healing Materials

(Note: Although not strictly a technology but rather a structural material, the authors discussed here to highlight its relevance and application within healthcare.)

Materials with self-healing properties have the extraordinary capacity to heal, emulating the tenacity of live tissues. This feature creates opportunities for improved drug delivery systems, tissue engineering scaffolds, and medical devices. One application of these materials was already covered in the discussion above and other uses in medicine are discussed below.

Biomedical implants are one prominent application where self-healing materials are having a significant impact. Over time, these implants are vulnerable to wear and tear, which calls for expensive and intrusive replacement procedures. Nonetheless, scientists hope to extend the life of implants and lessen the frequency of replacements by including self-healing ceramics or polymers in their designs. For example, by mending cracks and fractures that may occur during use, self-healing hydrogels have shown promise in extending the lifespan of implantable devices, such as pacemakers and prosthetic joints (Devi VK A, 2021; Brochu AB, 2011).

In addition, self-healing materials have great promise for use in drug delivery systems, where exact control over the kinetics of drug release is essential. Researchers can create drug carriers that can mend structural damage and deliver therapeutic chemicals in a regulated and sustained manner by combining self-healing polymers into the vehicle. This method reduces the possibility of burst release side effects while simultaneously improving the effectiveness of drug administration (Sanyal S, 2024).

2.7.1 Limitations

The biocompatibility of the materials may be harmed by the addition of stimuli-responsive or host immunological agents, which would reduce their potential for biomedical applications (Wu J, 2024). Also, as the synthesis of self-healing materials frequently calls for complex techniques and specialized tools, scalability and cost-effectiveness continue to be major obstacles (Speck O, 2019).

3. CONCLUSION

By combining cutting-edge technologies, the healthcare sector has the potential to drastically change patient care, diagnosis, and treatment. These developments promise to increase security, transparency, and general efficiency while tackling significant problems including medicine delivery, data interoperability, and efficient bio-models. Combining these technologies could lead to even more superior outcomes. However, we must also recognize and get over obstacles like moral conundrums, problems with scalability, and legal restrictions. Together, scientists, physicians, policymakers, and technologists can make the most of these discoveries to improve global health outcomes and expand medical knowledge.

AUTHORS' CONTRIBUTIONS

P.K, A.C, H.K contributed to the conception of the narrative review and structure of the article. P.K, A.C, V.B, S.S, S.G conducted the literature review, gathered data and performed the initial analysis. P.K, A.C, V.B, S.S, S.G, S.G contributed to the writing and editing of the manuscript. S.G, H.K provided critical revisions to the manuscript, supervised the overall project, provided significant intellectual input and reviewed the final manuscript. All authors approved the final version of the manuscript for submission.

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DISCLAIMER (ARTIFICIAL INTELLIGENCE)

Author(s) hereby declares that no generative ai technologies such as large language models (chatgpt, copilot, etc.) And text-to-image generators have been used during the writing or editing of this manuscript.

REFERENCES

1. Saeed H, Malik H, Bashir U, et al. Blockchain technology in healthcare: A systematic review. Plos one. 2022 Apr 11;17(4):e0266462. doi: 10.1371/journal.pone.0266462.

2. Price WN, Cohen IG. Privacy in the age of medical big data. Nature medicine. 2019 Jan;25(1):37-43. doi: 10.1038/s41591-018-0272-7.

3. Kuo TT, Kim HE, Ohno-Machado L. Blockchain distributed ledger technologies for biomedical and health care applications. Journal of the American Medical Informatics Association. 2017 Nov 1;24(6):1211-20. doi: 10.1093/jamia/ocx068.

4. Dubovitskaya A, Novotny P, Xu Z, et al. Applications of blockchain technology for data-sharing in oncology: Results from a systematic literature review. Oncology. 2020 Dec 3;98(6):403-11. doi: 10.1159/000504325.

5. Uddin M, Salah K, Jayaraman R, et al. Blockchain for drug traceability: Architectures and open challenges. Health informatics journal. 2021 Apr;27(2):14604582211011228. doi: 10.1177/14604582211011228.

6 Gomasta SS, Dhali A, Tahlil T, et al. PharmaChain: Blockchain-based drug supply chain provenance verification system. Heliyon. 2023 Jul 1;9(7). doi: 10.1016/j.heliyon.2023.e17957.

7. Cong LW, He Z. Blockchain disruption and smart contracts. The Review of Financial Studies. 2019 May 1;32(5):1754-97. doi: 10.1093/rfs/hhz007.

8. Seaberg RW, Seaberg TR, Seaberg DC. Use of blockchain technology for electronic prescriptions. Blockchain in Healthcare Today. 2021;4. doi: 10.30953/bhty.v4.183.

9. Hughes L, Dwivedi YK, Misra SK, et al. Blockchain research, practice and policy: Applications, benefits, limitations, emerging research themes and research agenda. International journal of information management. 2019 Dec 1;49:114-29. doi: 10.1016/j.ijinfomgt.2019.02.005.

10. Sapra N, Shaikh I, Dash A. Impact of proof of work (PoW)-based blockchain applications on the environment: A systematic review and research agenda. Journal of Risk and Financial Management. 2023 Mar 31;16(4):218. doi: 10.3390/jrfm16040218.

11. Gulia P, Gill NS, Yahya M, et al. Exploring the Potential of Blockchain Technology in an IoT-Enabled Environment: A Review. IEEE Access. 2024 Feb 26;12:31197-227. doi: 10.1109/access.2024.3366656.

12. Marais A, Adams B, Ringsmuth AK, et al. The future of quantum biology. Journal of the Royal Society Interface. 2018 Nov 30;15(148):20180640. doi: 10.1098/rsif.2018.0640.

13. Tuszynski JA. From quantum chemistry to quantum biology: a path toward consciousness. Journal of Integrative Neuroscience. 2020 Dec 30;19(4):687-700. doi: 10.31083/j.jin.2020.04.393.

14. Torday JS. Quantum Mechanics predicts evolutionary biology. Progress in biophysics and molecular biology. 2018 Jul 1;135:11-5. doi: 10.1016/j.pbiomolbio.2018.01.003.

15. Bordonaro M. Quantum biology and human carcinogenesis. Biosystems. 2019 Apr 1;178:16-24. doi: 10.1016/j.biosystems.2019.01.010.

16. Bisiani J, Anugu A, Pentyala S. It’s Time to Go Quantum in Medicine. Journal of Clinical Medicine. 2023 Jul 5;12(13):4506. doi: 10.3390/jcm12134506.

17. Bryce RA. What next for quantum mechanics in structure-based drug discovery?. Quantum Mechanics in Drug Discovery. 2020:339-53. doi: 10.1007/978-1-0716-0282-9_20.

18. Yu CJ, Von Kugelgen S, Laorenza DW, et al. A molecular approach to quantum sensing. ACS central science. 2021 Apr 20;7(5):712-23. doi: 10.1021/acscentsci.0c00737.

19. Ur Rasool R, Ahmad HF, Rafique W, et al. Quantum computing for healthcare: A review. Future Internet. 2023 Feb 27;15(3):94. doi: 10.3390/fi15030094.

20. Mintz Y, Brodie R. Introduction to artificial intelligence in medicine. Minimally Invasive Therapy & Allied Technologies. 2019 Mar 4;28(2):73-81. doi: 10.1080/13645706.2019.1575882.

21. Katta MR, Kalluru PK, Bavishi DA, et al. Artificial intelligence in pancreatic cancer: Diagnosis, limitations, and the future prospects—A narrative review. Journal of Cancer Research and Clinical Oncology. 2023 Aug;149(9):6743-51. doi: 10.1007/s00432-023-04625-1.

22. Rajkomar A, Oren E, Chen K, et al. Scalable and accurate deep learning with electronic health records. NPJ digital medicine. 2018 May 8;1(1):1-0. doi: 10.1038/s41746-018-0029-1.

23. Topol EJ. High-performance medicine: the convergence of human and artificial intelligence. Nature medicine. 2019 Jan;25(1):44-56. doi: 10.1038/s41591-018-0300-7.

24. Bender A, Cortés-Ciriano I. Artificial intelligence in drug discovery: what is realistic, what are illusions? Part 1: Ways to make an impact, and why we are not there yet. Drug discovery today. 2021 Feb 1;26(2):511-24. doi:10.1016/j.drudis.2020.10.010.

25. Alowais SA, Alghamdi SS, Alsuhebany N, et al. Revolutionizing healthcare: the role of artificial intelligence in clinical practice. BMC medical education. 2023 Sep 22;23(1):689. doi: 10.1186/s12909-023-04698-z.

26. Arnold MH. Teasing out artificial intelligence in medicine: an ethical critique of artificial intelligence and machine learning in medicine. Journal of bioethical inquiry. 2021 Mar;18(1):121-39. doi: 10.1007/s11673-020-10080-1.

27. Morley J, Machado CC, Burr C, et al. The ethics of AI in health care: a mapping review. Social Science & Medicine. 2020 Sep 1;260:113172. doi: 10.1016/j.socscimed.2020.113172.

28. Laspro M, Groysman L, Verzella AN, et al. The use of virtual reality in surgical training: Implications for education, patient safety, and global health equity. Surgeries. 2023 Nov 29;4(4):635-46. doi: 10.3390/surgeries4040061.

29. Prunoiu VM, Popa D, Serbulea M, et al. Augmented reality in surgical oncology. A literature review. Chirurgia. 2022 Oct 1;117:517-25. doi: 10.21614/chirurgia.2785.

30. Aulagnier J, Hoc C, Mathieu E, et al. Efficacy of AccuVein to facilitate peripheral intravenous placement in adults presenting to an emergency department: a randomized clinical trial. Academic Emergency Medicine. 2014 Aug;21(8):858-63. doi: 10.1111/acem.12437.

31. Hoffman HG, Doctor JN, Patterson DR, et al. Virtual reality as an adjunctive pain control during burn wound care in adolescent patients. Pain. 2000 Mar 1;85(1-2):305-9. doi: 10.1016/s0304-3959(99)00275-4,

32. Dinh A, Yin AL, Estrin D, et al. Augmented reality in real-time telemedicine and telementoring: scoping review. JMIR mHealth and uHealth. 2023 Apr 18;11:e45464. doi: 10.2196/45464.

33. Laver KE, Lange B, George S, et al. Virtual reality for stroke rehabilitation. Cochrane database of systematic reviews. 2017(11). doi: 10.1002/14651858.cd008349.pub4.

34. Górski F, Łabudzki R, Żukowska M, et al. Experimental evaluation of extended reality technologies in the development of individualized three-dimensionally printed upper limb prostheses. Applied Sciences. 2023 Jul 10;13(14):8035. doi: 10.3390/app13148035.

35. Samant S, Bakhos JJ, Wu W, et al. Artificial intelligence, computational simulations, and extended reality in cardiovascular interventions. Cardiovascular Interventions. 2023 Oct 23;16(20):2479-97. doi: 10.1016/j.jcin.2023.07.022.

36. Logeswaran A, Munsch C, Chong YJ, et al. The role of extended reality technology in healthcare education: Towards a learner-centred approach. Future healthcare journal. 2021 Mar 1;8(1):e79-84. doi: 10.7861/fhj.2020-0112.

37. Baniasadi T, Ayyoubzadeh SM, Mohammadzadeh N. Challenges and practical considerations in applying virtual reality in medical education and treatment. Oman medical journal. 2020 May;35(3):e125. doi: 10.5001/omj.2020.43.

38. Liang S. Distributed Computer Function Assisted Evaluation Based on Virtual Reality. Procedia Computer Science. 2023 Jan 1;228:477-85. doi: 10.1016/j.procs.2023.11.054.

39. Karami M. Semantic web: a context for medical knowledge discovering and sharing. Frontiers in Health Informatics. 2018 Jun 10;7:2. doi: 10.24200/ijmi.v7i0.145.

40. Machado CM, Rebholz-Schuhmann D, Freitas AT, et al. The semantic web in translational medicine: current applications and future directions. Briefings in bioinformatics. 2015 Jan 1;16(1):89-103. doi: 10.1093/bib/bbt079.

41. Haque AB, Arifuzzaman BM, Siddik SA, et al. Semantic web in healthcare: a systematic literature review of application, research gap, and future research avenues. International Journal of Clinical Practice. 2022;2022(1):6807484. doi: 10.1155/2022/6807484.

42. Cardoso J, Sheth A. The Semantic Web and its applications. InSemantic Web Services, Processes and Applications 2006 Oct (pp. 3-33). Boston, MA: Springer US. doi: 10.1007/978-0-387-34685-4_1.

43. Pinto-Coelho L. How artificial intelligence is shaping medical imaging technology: A survey of innovations and applications. Bioengineering. 2023 Dec 18;10(12):1435. doi: 10.3390/bioengineering10121435.

44. Baqa H, Truong NB, Crespi N, et al. Semantic smart contracts for blockchain-based services in the Internet of Things. In2019 IEEE 18th International Symposium on Network Computing and Applications (NCA) 2019 Sep 26 (pp. 1-5). IEEE. doi: 10.1109/NCA.2019.8935016.

45. Mohammed O, Benlamri R. Developing a semantic web model for medical differential diagnosis recommendation. Journal of medical systems. 2014 Oct;38:1-8. doi: 10.1007/s10916-014-0079-0.

46. de Mello BH, Rigo SJ, da Costa CA, et al. Semantic interoperability in health records standards: a systematic literature review. Health and technology. 2022 Mar;12(2):255-72. doi: 10.1007/s12553-022-00639-w.

47. Patra JK, Das G, Fraceto LF, et al. Nano based drug delivery systems: recent developments and future prospects. Journal of nanobiotechnology. 2018 Dec;16:1-33. doi: 10.1186/s12951-018-0392-8.

48. Begines B, Ortiz T, Pérez-Aranda M, et al. Polymeric nanoparticles for drug delivery: Recent developments and future prospects. Nanomaterials. 2020 Jul 19;10(7):1403. doi: 10.3390/nano10071403.

49. Han X, Xu K, Taratula O, et al. Applications of nanoparticles in biomedical imaging. Nanoscale. 2019;11(3):799-819. doi: 10.1039/c8nr07769j.

50. Chaudhury K, Kumar V, Kandasamy J, et al. Regenerative nanomedicine: current perspectives and future directions. International journal of nanomedicine. 2014 Sep 1:4153-67. doi: 10.2147/ijn.s45332.

51. Kausar A, Ahmad I, Maaza M, et al. Self-Healing Nanocomposites—Advancements and Aerospace Applications. Journal of Composites Science. 2023 Apr 7;7(4):148. doi: 10.3390/jcs7040148.

52. D'elia E, Eslava S, Miranda M, et al. Autonomous self-healing structural composites with bio-inspired design. Scientific Reports. 2016 May 5;6(1):25059. doi: 10.1038/srep25059.

53. Thwala LN, Ndlovu SC, Mpofu KT, et al. Nanotechnology-based diagnostics for diseases prevalent in developing countries: current advances in point-of-care tests. Nanomaterials. 2023 Mar 31;13(7):1247. doi: 10.3390/nano13071247.

54. Najahi-Missaoui W, Arnold RD, Cummings BS. Safe nanoparticles: are we there yet?. International journal of molecular sciences. 2020 Dec 31;22(1):385. doi: 10.3390/ijms22010385.

55. Desai N. Challenges in development of nanoparticle-based therapeutics. The AAPS journal. 2012 Jun;14(2):282-95. doi: 10.1208/s12248-012-9339-4.

56. Devi VK A, Shyam R, Palaniappan A, et al. Self-healing hydrogels: Preparation, mechanism and advancement in biomedical applications. Polymers. 2021 Oct 31;13(21):3782. doi: 10.3390/polym13213782.

57. Brochu AB, Craig SL, Reichert WM. Self-healing biomaterials. Journal of Biomedical Materials Research Part A. 2011 Feb;96(2):492-506. doi: 10.1002/jbm.a.32987.

58. Sanyal S, Park S, Chelliah R, et al. Emerging Trends in Smart Self-Healing Coatings: A Focus on Micro/Nanocontainer Technologies for Enhanced Corrosion Protection. Coatings. 2024 Mar 8;14(3):324. doi: 10.3390/coatings14030324.

59. Wu J, Xue W, Yun Z, et al. Biomedical applications of stimuli-responsive "smart" interpenetrating polymer network hydrogels. Materials Today Bio. 2024 Feb 10:100998. doi: 10.1016/j.mtbio.2024.100998.

60. Speck O, Speck T. An overview of bioinspired and biomimetic self-repairing materials. Biomimetics. 2019 Mar 20;4(1):26. doi: 10.3390/biomimetics4010026.