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REVIEW ARTICLE

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From static web to metaverse: reinventing medical education in the post-pandemic era

Kadriye O. Lewis[a], Vitaliy Popov[b] and Syeda Sadia Fatima[c]

[a]Children's Mercy Kansas City, Department of Pediatrics, UMKC School of Medicine, Kansas City, MO, USA; [b]Department of Learning Health Sciences, University of MI Medical School, Ann Arbor, MI, USA; [c]Department of Biological and Biomedical Sciences, The Aga Khan University, Karachi, Pakistan

ABSTRACT

The World Wide Web and the advancement of computer technology in the 1960s and 1990s respectively set the ground for a substantial and simultaneous change in many facets of our life, including medicine, health care, and medical education. The traditional didactic approach has shifted towards more dynamic and interactive methods, leveraging technologies such as simulation tools, virtual reality, and online platforms. At the forefront is the remarkable evolution that has revolutionized how medical knowledge is accessed, disseminated, and integrated into pedagogical practices. The COVID-19 pandemic also led to rapid and large-scale adoption of e-learning and digital resources in medical education because of widespread lockdowns, social distancing measures, and the closure of medical schools and healthcare training programs. This review paper examines the evolution of medical education from the Flexnerian era to the modern digital age, closely examining the influence of the evolving WWW and its shift from Education 1.0 to Education 4.0. This evolution has been further accentuated by the transition from the static landscapes of Web 2D to the immersive realms of Web 3D, especially considering the growing notion of the metaverse. The application of the metaverse is an interconnected, virtual shared space that includes virtual reality (VR), augmented reality (AR), and mixed reality (MR) to create a fertile ground for simulation-based training, collaborative learning, and experiential skill acquisition for competency development. This review includes the multifaceted applications of the metaverse in medical education, outlining both its benefits and challenges. Through insightful case studies and examples, it highlights the innovative potential of the metaverse as a platform for immersive learning experiences. Moreover, the review addresses the role of emerging technologies in shaping the post-pandemic future of medical education, ultimately culminating in a series of recommendations tailored for medical institutions aiming to successfully capitalize on revolutionary changes.

KEY MESSAGES

1. The evolution of medical education from the Flexnerian era to the digital age provides valuable insight into how medical education has evolved and adapted to changing social needs, technological advancements, and educational paradigm shifts (Education 1.0, Education 2.0, Education 3.0, Education 4.0).
2. The transition from static web to metaverse applications (Virtual Reality, Augmented Reality, and Mixed Reality) has brought about transformative changes in medical education merging physical and virtual reality, where users interact in real-time to have immersive and interactive learning experiences.
3. Metaverse platforms enable external collaboration among medical learners, faculty educators, and other healthcare professionals from various parts of the world without the limitations of physical distance allowing them to exchange insights, discuss cases, and learn from diverse perspectives, including opportunities for collaborative research.
4. Developing strategic implementation plans can help ensure that institutions and faculty educators can harness the benefits of emerging technologies while proactively addressing potential challenges, ensuring a well-rounded and effective learning experience for future medical professionals.

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CONTACT Kadriye O. Lewis kolewis@cmh.edu Children's Mercy Kansas City, Department of Pediatrics, UMKC School of Medicine, 2401 Gillham Road, Kansas City, MO 64108, USA

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Introduction

As technology has progressed over the years, it has gradually found its indispensable place within the field of medical education. This integration began to take shape sometime after the release of the Flexner Report in 1910 [1]. When the Flexner Report was written, technology, especially in the context of education, was not as developed and widespread as it is today. The report's scope was primarily concerned with the structure of medical schools, their facilities, faculty qualifications, curriculum content, and the standardization of medical education [2,3]. Thus, the focus was on addressing shortcomings related to medical school quality, education content, and training methods at the time, rather than examining technology integration into medical education. As we all know, technology's role in education was not as significant during that historical period. However, the development of computer technology in the 1960s and the World Wide Web (WWW) in the early 1990s paved the way for a profound and simultaneous transformation across various dimensions of education, medical practice, and healthcare delivery. A growing reliance on computers and interconnected communication within medical centers has led to an increase in the importance of biomedical computing experts, which contributes significantly to the provision of quality health care and health data administration. Furthermore, in today's digital world, technology plays a crucial role in medical education, with simulation-based training, virtual patient scenarios, electronic health record systems, and other digital tools enhancing medical learners' and other healthcare professionals ' learning experiences [4–7].

Much progress has been made with the progression of Internet technologies from a static and one-way information Web 1.0 platform to an interactive, personalized, and intelligent Web 4.0 network over the past three decades. As a result, fundamental changes took place creating new value in shaping the learning experiences of medical professionals and students, and promoting flexible, accessible, and personalized medical education through e-learning or online courses [8]. Moreover, following the COVID-19 pandemic, a significant amount of attention has been paid to e-learning in medical education. With the closure of educational institutions and restrictions on in-person teaching, medical education quickly transitioned to online platforms and institutions rapidly adopted e-learning strategies to ensure continuity of education [9,10]. This radical shift necessitated the development and implementation of more e-learning solutions such as self-paced interactive modules, online courses, virtual lectures, webinars, podcasts, blogs, social media content, and other digital learning resources [11,12]. However, medical professionals have found it difficult to adapt to the sudden switch to an online environment with an unfamiliar mode of teaching, due to their lack of knowledge about how they can meet the educational needs of their learners. Having no substitute plan for the 'traditional' classroom approaches of teaching and learning, they encountered challenges such as communication difficulties, learner assessment and evaluation, use of technology tools, online experience, anxiety or stress associated with the pandemic, time management, and technophobia [13]. Furthermore, not knowing various e-learning modalities, technological and pedagogical affordances, and disciplinary differences are overlooked with respect to e-learning instructional design, course delivery format, and selecting suitable technology or learning management systems. Being an expert in the area of online learning field, the first author (KOL) received multiple requests and/or questions from faculty educators internally and externally regarding their challenges and how they can efficiently conduct online teaching. She even prepared an 'E-learning: Survival guide for medical educators' [14]. While all these challenges are present, the transition from Static Web 1.0 to the metaverse holds immense promise in transforming how medical professionals are trained, educated, and engaged in ongoing learning.

Metaverse is a 3 Dimensions-based (3D), dynamic immersive, and interconnected virtual space where learners can interact with each other and digital content in real-time. Unlike Static Web 1.0, which primarily focuses on one-way information dissemination, the metaverse introduces elements of virtual reality (VR), augmented reality (AR), and mixed reality (MR) to create a multifaceted learning experience [15]. The metaverse is a composite term, combining 'meta' and 'universe,' referring to a parallel or virtual environment intricately interconnected with the physical world and this concept has been popularized in science fiction, specifically in the 1992 novel 'Snow Crash' written by Neal Stephenson [16]. In the book, the metaverse is depicted as a massive virtual reality-based successor to the Internet, where people can immerse themselves in a virtual world using specialized technology. As the concept continues to evolve, it holds significant promise in revolutionizing how we engage with digital content and interact with others. The use of metaverse or Meta platforms provides a new level of technological and pedagogical flexibility for developing medical professionals' competencies that include patient care, medical knowledge, procedural training, interprofessional teamwork, diagnostic reasoning, and critical thinking.

In brief, several innovations and the adoption of emerging technologies have become an integral part of modern education, opening new possibilities for medical learners and educators worldwide [17]. The massive changes brought by COVID-19, the explosive growth of recent artificial intelligence (AI), and the new teaching modalities still have lingering effects and seem to have a long-term impact on an entire generation of our learners. It is evident that the world we once knew has changed, and we should leverage these changes to advance medical education. At this point, we need to understand the evolving structure of Web and immersive technologies, including their potential and how to employ them in the learning design of medical education. Furthermore, due to the increasing complexity of technologies from the static Web to the metaverse, medical educators/faculty need in-depth information to be knowledgeable to take a proactive approach in their educational practices, especially to create a contingency plan for unexpected interruptions such as the COVID-19 pandemic. Thus, the purpose of this review paper is three-fold: (1) To explore the impact of Web evolution on medical teaching and curricular levels, examining how each generation of the Web has influenced curriculum design, content delivery, assessment methods, and competency-based medical education. (2) To examine how the metaverse has revolutionized medical education, specifically the integration of VR, AR, and MR technologies in medical curricula and their potential to enhance practical skills training. (3) To discuss the benefits, challenges, and opportunities of these emerging technologies in shaping the future of medical education in the post-pandemic era.

Transformation of medical education over the years

Medical education has undergone a significant transformation and evolution over the years, including the Flexner Report in 1910, the use of scientific methodology that led to the emergence of evidence-based medicine in the early 1960s [18], and the digital revolution in recent years. Initially, the Flexner era brought significant improvements in shaping the modern medical education system in the United States by establishing higher standards, promoting scientific rigor, and ensuring the production of well-trained physicians [1–3]. Its impact is still felt today, and the process of implementing significant changes is continuously evolving by embracing technological advancements, and innovative pedagogical approaches, promoting interdisciplinary collaboration, and fostering compassionate and competent medical professionals. Several key factors have contributed to these changes, shaping the way medical knowledge is taught, medical professionals are trained, and patient care is delivered. To understand and track the drastic changes, we need to look at the Flexner era (Early Twentieth Century) and the Modern era (Twenty-first Century). Table 1 below highlights some of the key differences in medical education between these two eras, focusing on changes in curriculum, teaching methods, clinical training, patient interaction, and the integration of technology and research.

The most noticeable advancements in the Modern era placed greater emphasis on diversity/inclusion, global health, interprofessional education, technology integration, and a lifelong commitment to learning. All these changes reflect a shift towards more learner-centered, evidence-based, interdisciplinary, and patient-focused approaches, addressing the changing needs of healthcare and society.

The evolution of the World Wide Web and its impact on medical education

Since the invention of personal computers (PCs) in the 1980s, the WWW has continued to evolve from Web 1.0 to Web 4.0, including the growing amount of data that is exchanged and coordinated using digital technologies like artificial intelligence (AI), the Internet of Things (IoT), cloud computing, and cognitive computing [8,19]. These different phases and versions of the Web represent major shifts in the way people interact with the Internet and the technology-enhanced services offered to them. In the medical education concept, each generation of the Web has influenced curriculum design, content delivery, assessment methods, and competency-based medical education. Table 2 presents descriptions of the four generations of the Web and their learning paradigms [8,19,20,21].

Note: IoT-enabled devices or objects can range from everyday devices like smartphones, smartwatches, and home appliances to more specialized equipment used in industries, such as environmental sensors, medical devices (e.g. fitness trackers, smart insulin pumps), AirTag beacons, traffic management systems and industrial machinery [19,22,23]

It is important to note that the transition from one Web phase to another is not strictly linear, and different elements of each phase can coexist. The concept of

Table 1. Key aspects of medical education during the Flexner era and Modern era.

Key Aspects	Flexner Era (Early Twentieth Century)	Modern Era (Twenty-first Century)
Standardization	Lack of standardized educational requirements	Stringent standards and accreditation for medical schools
Curriculum Structure	Standardized, lecture-based curriculum	Integration of basic and clinical sciences with a more flexible schedule and competency-based curriculum
Teaching Methods	Traditional, didactic lectures with a strong emphasis on basic sciences (e.g. lectures, textbooks, and laboratory work)	Technology-enhanced, simulations, virtual patients. (e.g. patient-centered approach)
Learning Approach	Didactic lectures and passive learning	Active learning, problem-based learning, and case-based learning
Clinical/Practical Training	Limited clinical exposure during the early years and less clinical experience	Extensive clinical rotations, clerkships, and simulation-based training
Patient Interaction	Limited patient interaction during preclinical years	Early patient contact and continuity of care
Patient-Centered Care	Limited emphasis on patient-centered care	Focus on patient-centered care, empathy, and effective communication
Evidence-Based Medicine	Limited focus on scientific rigor	Emphasis on evidence-based medicine and critical appraisal skills
Interprofessional Education	Minimal emphasis on interprofessional education and interdisciplinary collaboration	Focus on teamwork and collaboration among healthcare professionals
Technology Integration	Limited use of technology in education	Integration of advanced medical technologies, simulation tools, digital resources, virtual learning, and telemedicine.
Lifelong Learning	Limited emphasis on continuous professional development and lifelong learning	Emphasis on continuous professional development and lifelong learning
Diversity and Inclusion	Lack of diversity in medical schools	Focus on diversity, inclusion, and cultural competency
Global Health Perspective	Limited focus on global health and public health issues	Emphasis on global health awareness and understanding of health disparities
Assessment and Evaluation	Summative, high-stakes exams	Competency-based and performance-based assessments and evaluation (formative and summative), including continuous feedback and reflection
Research	Limited emphasis on research	Greater emphasis on evidence-based medicine and research opportunities

Table 2. Evolution of the WWW from Web 1.0 to Web 4.0.

Web Version	Learning Paradigm
Web 1.0 (1990–2000: Information Centric Static Web)	• *Traditional*Content was primarily static and text-based, with limited interactivity. • Medical education websites served as information repositories, providing course materials, lecture notes, and references. • Online medical journals became accessible, allowing researchers and students to access scientific publications. • Web 1.0 lacked dynamic engagement and collaboration, offering mostly one-way communication.
Web 2.0 (2000–2010: People-Centric Social Web/ Read-and-Write Web)	• *Social Learning*The advent of Web 2.0 brought interactivity and user-generated content to the web. • Social media platforms emerged, enabling medical professionals to connect, share knowledge, and engage in discussions. • Medical education shifted toward more interactive learning experiences through multimedia content, online forums, blogs, wikis, and collaborative learning.
Web 3.0 (2010–2020: Machine-Centric Semantic Web)	• *Personalized Learning*Web 3.0 aimed to make the web more intelligent, context-aware, and personalized. • In medical education, this phase focused on incorporating smarter search engines and improved knowledge retrieval. • Learning platforms used semantic technologies to deliver personalized learning pathways and recommendations based on learners' preferences and performance. • VR and AR are integrated into e-learning for immersive experiences.
Web 4.0 (2020–2030: Agent-Centric Symbiotic Intelligent Web)	• *Immersive Learning*Web 4.0 is an extension of the concept that envisions a more intelligent, autonomous, and adaptable web. • In medical education, Web 4.0 leverages artificial intelligence (AI), machine learning, and big data analytics to deliver advanced learning experiences. • AI-driven virtual tutors and conversational agents help guide learners, answer questions, and provide personalized feedback. • Virtual and augmented reality technologies create immersive simulations for medical training, enhancing practical skills and decision-making. • IoT-enabled devices create a pervasive learning environment that allows for seamless integration of digital and physical learning spaces.

Web 4.0 is still evolving, and its full realization remains the subject of ongoing research and innovation. As indicated in Table 2, potential applications in medical education include virtual patient simulations, personalized learning algorithms, and AI-driven diagnosis and treatment recommendations. Moreover, telemedicine and telehealth could be seamlessly integrated into Web 4.0, enhancing access to medical expertise and remote learning opportunities. It is obvious that Web 4.0 continues to develop and has not yet reached its full

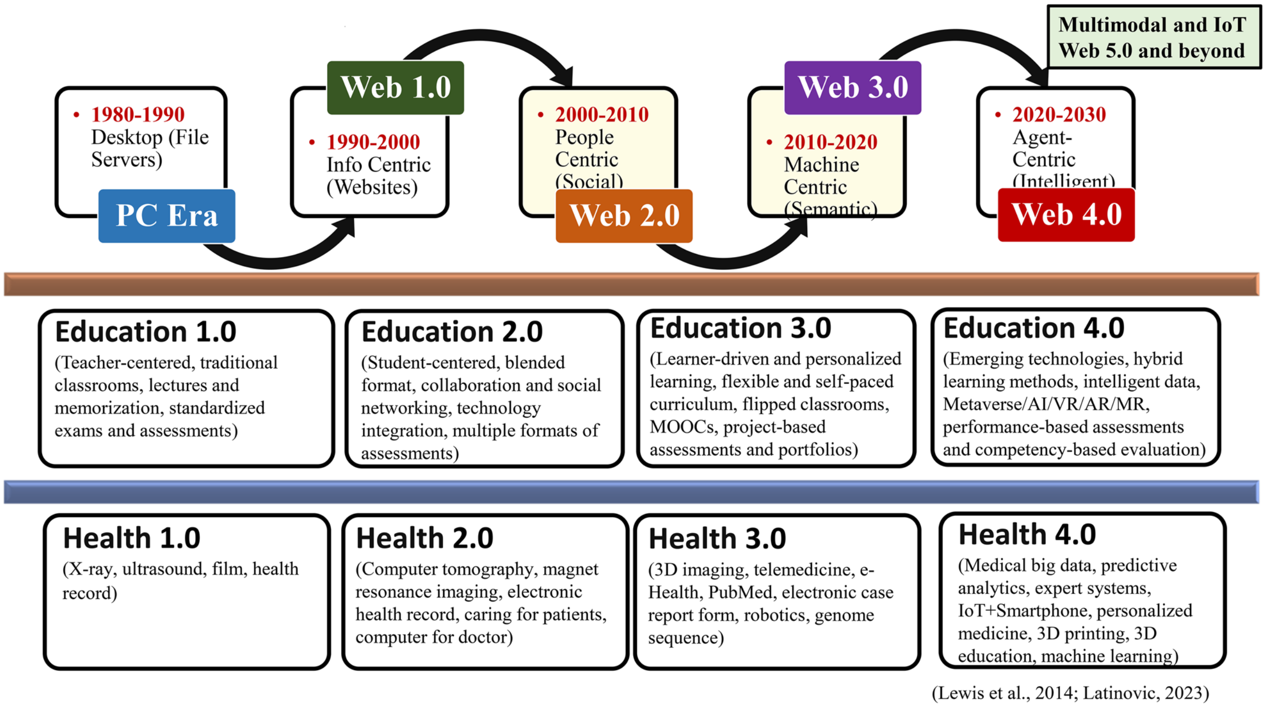

Figure 1. Evolution of the Web, education and healthcare.

potential. As an extension to Web 4.0, Web 5.0 is emerging to be a sensory and emotive capabilities, allowing users to engage with the Internet through immersive experiences that evoke and respond to human emotions [19,24,25]. All these advancements in technology have created a different version of education.

The evolution of education from Education 1.0 to Education 4.0

Both Internet technologies and education are evolving, and their developments or advancements always influence and complement each other as a response to the changing needs of education and learners. The Internet serves as a catalyst for the digitalization and distribution of educational content, promotes distant learning methods for interactive and collaborative learning, and creates new avenues for knowledge access to produce a whole new educational experience [26]. The evolution of education is evidence of humankind's capacity for innovation, adaptation, and acceptance of change in all its forms. Every stage of education, from traditional classrooms to the digital frontier, has shaped the way we learn, teach, and interact with knowledge. Education 1.0 established the foundation, Education 2.0 fulfilled the demands of industrialization, and Education 3.0 tapped into the potential of the digital era [27]. On the other hand, the progression from Education 1.0 to Education 4.0 somewhat draws parallels with the industrial revolution eras, specifically Industrial 1.0 to Industrial 4.0. While this analogy is often used to describe the evolution of education in response to technological advancements, the concept of parallelism is not perfect because education is a complex and multifaceted system influenced by various factors, including societal needs, cultural shifts, and pedagogical advancements. However, both industrial evolution and education demonstrate a parallel path toward the transitions from Health 1.0 to Health 4.0 due to the changing nature of technological advancements and toward more intelligent, innovative, and technologically integrated approaches [28]. Figure 1 illustrates how the Web, education, and healthcare have evolved over the years (Figure 1).

As we enter the era of Education 4.0, individualized/personalized learning experiences are being driven by cutting-edge technology, which is also fostering a culture of constant improvement [29]. Table 3 provides an overview of the main attributes associated with four generations of educational eras, highlighting distinctions in learning design across each phase.

As seen in Table 3, the variations and salient features in each generation's approach illustrate the remarkable advancements and how our teaching and learning design have changed over the years. Medical education is no different and the evolution of medical education is a continuous process. Recognizing the potential and benefits of internet-based technology, medical institutions have developed a variety of

Table 3. Major traits of the four educational generations.

Elements	Education 1.0	Education 2.0	Education 3.0	Education 4.0
Teaching Methods	Teacher-centered instruction	The transition toward student-centered learning	Learner-driven and personalized learning	Integration of emerging technologies and data-driven insights
Pedagogical Differences	Rote learning and memorization	Increased emphasis on collaboration and communication	Shift towards critical thinking, problem-solving, and creativity	Personalized and adaptive learning experiences
Technology Integration	Limited use of technology	Integration of multimedia resources and interactive tools	Online resources, open educational resources, MOOCs	AI, VR, AR, gamification
Curriculum Design	Fixed curriculum	Blended format of traditional and digital methods	Flexible and self-paced curriculum	Blended and flipped classroom models
Assessment and Evaluation	Standardized exams and assessments	Multiple formats of assessments including multimedia projects	Project-based assessments, portfolios	Learning analytics, performance-based formative assessments, and competency-based evaluation. Simulation-based assessments, electronic portfolios (ePortfolios), longitudinal integrated clerkships (LIC)

approaches to enable more learner-centered and individualized types of more accessible education [8]. Thus, today's medical education has been trying to leverage technology-enhanced learning methods that represent metaverse concepts such as virtual simulations, virtual reality, augmented reality, mixed reality, and e-learning modules to facilitate interactive and immersive learning experiences for medical professionals and students. Some of the novel assessment methods in medical education include milestones assessments, objective structured clinical examinations, simulation-based assessments, electronic portfolios, and team-based assessments [30–35]. These methods represent advancements compared to previous methods prevalent in Education 1.0–3.0 because they provide standardized and structured evaluations of clinical skills, offer realistic and immersive learning experiences, allow for continuous tracking of student progress, and emphasize teamwork and interprofessional collaboration, ultimately improving the preparation of students for real-world medical practice. Their use may facilitate a more comprehensive and objective assessment of students' abilities and enhance their learning outcomes.

The evolution from Web 2D to Web 3D: Implications for medical education

Through continuous technological advancements, virtual worlds have evolved from 2 Dimensions (2D) to 3 Dimensions (3D) that support virtual technologies [15]. 2D technology-enhanced learning refers to the use of two-dimensional digital media to deliver educational content. This can include text, images, videos, presentations, and interactive elements. On the contrary, 3D technology-enhanced learning utilizes three-dimensional digital media to create immersive and interactive educational experiences [36]. It goes beyond flat images and text, presenting content in a more lifelike and engaging manner. While both methods utilize technology, they offer different ways of presenting and interacting with educational content as illustrated in Table 4.

Both 2D and 3D technology-enhanced learning have their unique advantages and are often used in combination to create comprehensive and engaging educational experiences. While 2D learning is more accessible and widely used, 3D learning offers a more immersive and interactive approach, particularly suitable for medical education that benefits from hands-on exploration and visualization. For example, 3D learning can facilitate interactive anatomy lessons, enabling learners to explore and interact with detailed digital anatomical models for better understanding and retention of complex structures. The evolution of 3D virtual worlds will be an ongoing advancement since the potential for 3D virtual worlds is enormous to provide more realistic and interactive learning experiences in virtual spaces.

Metaverse and its applications in medical education

The origin of the metaverse can be traced back to science fiction literature as mentioned above, but the development of the metaverse concept and its application in medical education is a gradual progression that builds on advancements in technology, pedagogical approaches, and the desire to create more immersive and effective learning experiences. At this point, the integration of metaverse technologies into medical education and practices is still an emerging field with

Table 4. Differences between traditional 2D content and 3D Web-based content.

Characteristics	Traditional 2D Content	3D Web-Based Content
User Interface	Text-based interfaces	Immersive and realistic environments where users can interact with objects, avatars, and the environment in a more natural and intuitive manner.
Remote Learning and Collaboration	Collaboration through learning management systems, which is 2D technology-enhanced learning (e.g. asynchronous participation in discussion board activities, completing assignments, online forums, video conferencing)	Remote collaboration and global knowledge sharing (e.g. learners from different locations or countries collaborating in a 3D virtual anatomy lab)
Engagement and Motivation	Low level of engagement or motivation (e.g. reading case descriptions in a textbook)	Higher level of engagement and motivation through immersion and hands-on learning (e.g. an interactive 3D scenario where learners diagnose and treat virtual patients, and/or interact with objects and scenarios for physical manipulation and exploration)
Accessibility and Flexibility	Universal accessibility of educational content from anywhere with an Internet connection (e.g. self-paced learning, and accessible to certain disabilities)	Customizable 3D modules for different learning needs, including simplified interfaces
Personalization	Less adaptable due to standardized curriculum with fixed progression	Adaptable to individuals' learning preferences and paces through an adaptive learning platform adjusting difficulty based on a learner's performance
Spatial Visualization	Limited depth and perspective (e.g. 2D anatomical diagram of the heart)	Enhanced 3D representation for accurate spatial understanding and visualization skills (e.g. 3D interactive model of the human heart, allowing learners to rotate, zoom, and dissect for detailed spatial understanding of complex structures or concepts.)
Interactivity	Limited interactivity and graphical fidelity (e.g. static images illustrating surgical steps, text-based materials, video lectures, educational animations, interactive slides, interactive quizzes, and online assessments)	Interactive exploration, manipulation, and simulations such as virtual surgery simulation with haptic feedback where learners can perform steps of a procedure in a realistic virtual setting and observe outcomes in real-time Use of conversational agents, also known as chatbots, that simulate human interactions through text or verbal communication
Realism	Limited realism and graphs representing medication effects	Realistic simulations and procedures such as simulating a patient's response to medication with physiological changes visible in a 3D model
Dynamic Processes	Lack of dynamic representation of dynamics (e.g. series of 2D images depicting muscle contraction)	Effective representation of dynamic processes over time such as an animated 3D representation of muscle contraction and relaxation during the cardiac cycle
Depth and Perspective	Limited angles and perspectives (e.g. a flat diagram of a neuron and its connections)	Multi-angle views for complex structures when exploring a 3D model of a neuron to understand synapse connections from multiple angles
Holistic Understanding	Limited to specific views (e.g. viewing isolated 2D images of blood vessels)	Comprehensive view of structures and scenarios (e.g. exploring an immersive 3D environment of the human circulatory system)
Complexity	Simpler, quicker representation (e.g. simplified 2D diagram of brain structures)	In-depth and complex learning experiences (e.g. virtual 3D dissection of a complex anatomical structure like the brain)
Familiarity	Familiar format for many learners (e.g. traditional textbooks and diagrams)	Transitioning from traditional 2D textbooks to 3D interactive modules, requires adjustment for learners accustomed to 2D

great potential. Furthermore, these technologies have the capability to enhance medical training, improve patient care, and advance medical research.

The metaverse is not limited to a single technology or platform but refers to a network of interconnected virtual spaces that exist within the broader spectrum of interactive and immersive digital experiences. These technologies include VR, AR, and MR that form the components of Extended Reality (XR), seamlessly integrating various digital and interactive experiences into a cohesive digital universe [36–38]. While sharing certain similarities, each component of XR possesses distinctive characteristics, as well as unique pedagogical and technological affordances within this evolving digital landscape.

As technology advances, these three concepts can be combined to create more comprehensive educational experiences. For example, a medical learner might use VR to explore the human body, and then switch to AR to practice a surgical procedure on a physical model. This may give more learning opportunities in a variety of activities across multiple virtual and/or physical spaces. Another example can be virtual physician-patient interactions through metaverse applications mimicking and complementing standardized patient simulations. Physicians use AR and MR to examine patients, discuss diagnoses, and recommend treatments through remote consultations and telemedicine services. We can expand these examples to include collaborative medical conferences in virtual reality and medical training scenarios in shared virtual environments [9,39]. Overall, VR, AR, MR, and the metaverse are interconnected concepts that utilize 3D technology to create immersive and interactive experiences (Table 5). Each term represents a different level of immersion and interaction with the digital and

Table 5. Immersive technologies.

Technology type	Description	Medical applications
Virtual Reality (VR)	VR creates a completely immersive digital environment that isolates users from the physical world. Users wear VR headsets to be fully immersed in a simulated 3D environment. An immersive virtual reality system tracks a learner's movement and projects it onto the virtual environment. The three-dimensional virtual environment that offers real-time visual, aural, haptic, and/or kinesthetic input is interacted with by the learner [40]. VR provides a sense of presence, making users feel as if they are physically present in the virtual world. VR is primarily used to create immersive experiences, training simulations, gaming, and entertainment where users can interact with the digital environment and with each other.	• *Anatomy Visualization*: Learners can explore 3D anatomical models in a fully immersive environment, allowing them to understand complex structures better than traditional 2D methods [36]. • *Training Simulations*: VR enables trainees and surgeons to practice surgeries in a controlled and risk-free environment, enhancing their skills and decision-making. This VR environment also provides learners with real-time feedback regarding their performance and techniques applied [45]. • *Patient Interaction*: Medical trainees can engage with virtual patients, gaining experience in (collaborative) diagnostic reasoning, patient communication, and empathy.
Augmented Reality (AR)	AR overlays digital information to enhance the real world by adding digital elements such as text, images, or 3D objects, to the user's surroundings. Users experience a blend of the physical and digital worlds while still being aware of their real-world surroundings [38]. AR is often experienced through smartphones, tablets, smart glasses, or other devices with cameras [15].	• *Anatomical Learning*: AR can project virtual images onto physical models or cadavers, providing additional insights and annotations during dissections. • *Medical Imaging*: AR can be used to display 3D images from medical scans directly onto a patient's body, aiding in visualization and surgical planning. • *Training for Medical Procedures*: AR can guide medical students through procedures by overlaying step-by-step instructions onto the patient or medical equipment.
Mixed Reality (MR)	MR combines elements of both VR and AR, allowing digital objects to interact with the real world and vice versa [15]. Users can interact with and manipulate both real and virtual objects. MR headsets, like Microsoft's HoloLens, enable users to see and interact with digital content as if it exists in the same space as the real world.	• *Hybrid Simulations*: Combining physical simulators or mannequins with virtual elements allows for complex and realistic medical scenarios and procedural training • *Team Training*: VR and AR can simulate scenarios that involve coordination among medical teams, promoting teamwork and communication skills, such as emergencies.

physical worlds, with the metaverse being a more comprehensive concept that envisions a network of interconnected virtual experiences.

Benefits and challenges of the use of metaverse in medical education

The concept of a metaverse in medical education, which involves using virtual and augmented reality technologies to create immersive and interactive learning environments, has the potential to revolutionize how medical education is delivered. The use of the metaverse in medical education has several benefits and creates new opportunities that may be grouped under the following categories.

1. *Learner Engagement*: Traditional educational methods usually fail to maintain students' attention and interest, which results in passive learning. The metaverse, on the other hand, increases learner engagement with dynamic, interactive information that suits a variety of learning preferences and needs. We can foster different types of engagement such as academic, behavioral, cognitive, and affective engagement [41] Through gamification, simulations, and interactive scenarios, learners can actively participate in the learning process, making education more enjoyable and effective. In particular, gamification principles that can elevate engagement and learning in metaverse applications include providing clear challenges, a personalized scoring/reward system, and individual pathways for learners to progress through the material and achieve mastery over time. Additional gamification strategies may enable social connections between learners, incorporating storytelling elements, allowing avatar customization, and building in surprises/secrets for learners to discover. The decision-making processes can be gamified to provide immediate feedback and consequences, fostering a dynamic learning environment. This pedagogical integration aligns seamlessly with the principles of Education 4.0, emphasizing adaptive, personalized, immersive, exploratory, collaborative, and technology-driven learning experiences [42]. Research is still needed to optimize the balance between gamification and actual learning outcomes in next-generation medical training.
2. *Immersive Learning Experiences*: The metaverse allows medical learners to immerse themselves in realistic 3D environments, such as virtual hospitals or surgical suites, providing hands-on experience without the risks associated with real-world practice. This level of immersion fosters experiential learning, allowing learners to apply theoretical knowledge in practical scenarios. As a result, learners can build confidence, hone their patient care skills, and develop a

deeper understanding of complex concepts, ultimately translating into better-prepared medical professionals.

3. *Personalized Learning and Skill Development*: The metaverse can adapt to individual learning preferences and paces, providing customized learning experiences that cater to each learner's needs. Medical learners can practice a wide range of clinical skills and procedures in a safe and controlled virtual environment. This can accelerate skill acquisition and improve muscle memory before performing procedures on real patients.
4. *Novel Assessment and Evaluation Methods Coupled with Metaverse Applications:* The collection of discrete, nuanced, and real-time data on trainee or team processes (such as behavior, visual attention, speech analysis, and emotional arousal) that unfold over time and that have previously been difficult or impossible to observe is now possible with the help of new high-fidelity sensor technology and computational models [43]. Real-time team behavioral data collection can uncover significant correlations, spot patterns, and give each member personalized, learner-specific feedback. Multimodal learning analytics has the potential to prepare the next generation of healthcare professionals to provide patients with the best care possible.
5. *Collaboration Opportunities and Accessibility*: The metaverse enables medical professionals from around the world to collaborate and learn together in shared virtual spaces, fostering a global community of learners and experts. This platform breaks down geographical barriers, making education accessible to individuals around the world. Learners from remote or underserved areas can access high-quality education without the need to relocate. Moreover, the metaverse enables unprecedented opportunities for external or global collaboration. Medical students, practitioners, and experts who are physically separated or from different countries can come together in shared virtual spaces to exchange knowledge, discuss cases, and collaborate on research projects [44,45]. This diverse and international perspective enriches learning, exposes learners to different healthcare systems, and encourages a broader understanding of medical practices. Other benefits can be listed as follows:

- Learners can connect with leading experts and educators from different parts of the world, accessing insights and knowledge that might not be readily available locally.
- Collaborating with peers and mentors from diverse backgrounds enhances cultural competency and prepares future professionals to deliver patient-centered care in a globalized environment.
- Global collaboration in the metaverse can spur joint research initiatives and inspire creative solutions to medical problems that require a range of skills.

6. *Cost Efficiency*: Metaverse-based approaches have the potential to greatly expand access and lower delivery costs per student for simulated clinical training. However, institutions must weigh the upfront investments needed in both technology infrastructure and human capital required to build and sustain these next-generation platforms. Specifically, current best practices involve manikin-based medical simulation which is limited by the availability of adequate facilities (physical, space, equipment), human resources, and scheduling challenges in many community, rural, and under-resourced hospitals, leading to inequity in access to training and contributing to disparities in care [46]. In contrast, the metaverse offers a promising solution with an average headset cost of $430 [47], allowing populations worldwide to access remote training at their convenience and at a fraction of the cost associated with conventional medical simulation training. However, to maintain the overall cost-effectiveness of this approach, institutional IT support and infrastructure costs must be carefully managed. The metaverse also excels in learner assessment by providing cost-effective automatic scoring and learning algorithms with real-time feedback [48]. This not only enhances the educational experience but also allows learners to access medical content from anywhere, reducing the need for physical presence in a specific location. This aspect is particularly valuable for remote or underserved areas. While prioritizing cost efficiency for individual learners is crucial, adopting a holistic approach that considers both individual and institutional perspectives becomes essential for the successful and sustainable integration of the metaverse in medical education (Table 5).

We listed multiple benefits of metaverse applications in medical education, but some several challenges and obstacles must be carefully addressed to ensure successful implementation. Some of the key challenges include:

1. *Technical Limitations and Access:* Not all learners may have access to the necessary hardware and high-speed internet required for seamless metaverse interactions, creating potential disparities in access, and learning opportunities. High-performance computers or devices, fast internet connections, and compatible peripherals (such as VR headsets) are often needed for seamless interactions. Technical limitations could hinder widespread adoption, especially in regions or communities with limited access to advanced technology.
2. *Content Quality and Accuracy*: Ensuring that the content within the metaverse is accurate, up-to-date, and aligned with established medical standards is crucial to avoid misinformation. In medicine, precision is critical, and inaccuracies in simulations or scenarios could lead to improper training and potentially harm patient safety. At this point, encouraging collaborative content development fosters unity in simulation creation while this collaboration helps the establishment of consistent standards through standardization, working with accreditation bodies and professional organizations to uphold consistency, accuracy, and quality. Furthermore, robust peer review processes, quality assurance frameworks, and ongoing professional development help preserve the integrity of the content and keep faculty educators current in their teaching. Other strategies may include transparent reporting of the education recourses, fact-checking mechanisms, periodic content updates, informed by subject matter experts to create a dynamic framework for maintaining high-quality, accurate metaverse-integrated content in medical education.
3. *Faculty and Learner Training:* Transitioning from traditional teaching methods to the metaverse can be challenging for both faculty educators and learners. Faculty need training in the new technology, and pedagogical knowledge for effective design principles and content delivery, while learners may require time to adapt to the new learning environment and tools [49].
4. *Existing Curricula and Resistance to Change*: Incorporating metaverse experiences seamlessly into existing medical curricula can be challenging and require careful planning. Further, resistance to adopting new technologies and methods is a common challenge. Some faculty or institutions may be hesitant to embrace the metaverse due to concerns about disrupting established teaching practices or a lack of familiarity with the technology.
5. *Lack of Human or Physical Interaction*: Traditional medical education often involves strong mentor-learner relationships and interpersonal interactions that might be less prominent in virtual learning environments. The metaverse, while immersive, may not fully replicate the tactile and emotional aspects of real-world patient interactions (e.g. lack of the emotional and human aspects of face-to-face interactions). As we all know, patient care relies on empathy and interpersonal skills, and overreliance on virtual experiences could potentially lead to a loss of these crucial attributes.
6. *Data Privacy and Security Concerns*: Effectively managing sensitive medical data within virtual environments requires robust security measures to protect patient confidentiality and ensure compliance with medical privacy regulations [38]. Collecting and processing user data within the metaverse raises privacy and security concerns, given the inherent sharing of personal information, behaviors, and interactions. To address these challenges, a multifaceted strategy is crucial, beginning with the establishment of stringent security standards to safeguard sensitive data and maintain the integrity of educational platforms. This effort is necessary for digital partnership [50] and collaborative engagement among academic institutions, IT companies, and cybersecurity specialists for continuous assessment and improvement of the security infrastructure. It is also critical to raise awareness and instruct users on cyber-security recommended practices. This covers users who interact with the metaverse for educational reasons, such as faculty instructors and learners. Creating a combination of security-focused platform engineering, comprehensive governance policies, widespread culture and training programs, advanced monitoring systems, and collaborative expert teams may go a long way toward making the learning environment safer and upholding stakeholders' trust.
7. *Learner Data Accuracy and Reliability of AI Algorithms:* This involves addressing biases, ensuring transparency in AI decision-making, and regularly validating and updating algorithms to align with evolving medical knowledge and practice standards. There is a need to establish clear

guidelines and standards for using AI-driven assessments to ensure fair and equitable evaluation of learners' competence and performance.

8. *Legal and Ethical Issues*: Medical education strongly emphasizes the value of ethical judgment. Medical learners should be taught how to address ethical challenges and the benefit of having informed discussions about how to approach ethical dilemmas and make judgments [48]. The metaverse introduces complex legal and ethical considerations. Therefore, issues related to medical liability, informed consent for simulated procedures, and the boundaries of medical practice in virtual environments need careful thought and regulation.
9. *Maintenance and Updates*: The metaverse requires consistent maintenance, updates, and technical support to ensure a seamless user experience. Failing to address technical glitches or keep content current could lead to frustration and hinder learning outcomes.
10. *Cost Implications*: Metaverse technologies can be costly to develop, implement, and maintain. The initial investment in hardware, software, content creation, and ongoing updates can strain the budgets of institutions or individuals with limited financial resources. The cost could become a significant barrier to entry for both learners and faculty.

In summary, the adoption of the metaverse in medical education offers numerous benefits, from immersive learning to global collaboration. However, addressing technology barriers, ensuring content quality, and managing human interaction and data security challenges are critical for its successful implementation. Addressing these challenges requires a multifaceted approach that involves collaboration between technology developers, educators, policymakers, and regulatory bodies. Finding solutions to technical, financial, ethical, and accessibility concerns is crucial to realizing the full potential of the metaverse in medical education. In addition, Table 6 provides a comprehensive comparison of the benefits and challenges associated with the specified dimensions of using the metaverse in medical education.

Case studies and examples of metaverse applications

We have compiled a selection of ten case studies that showcase the innovative spirit and underscore the potential for transformative learning experiences in medical training and education (see Supplementary Appendix 1). Through these initiatives, the impact on learner satisfaction and performance became evident, reinforcing the metaverse's role in shaping the future of medical education. The metaverse has proven transformative, particularly in the field of anatomy and surgical training [50–58] and patient outcomes [60]. Some examples of the use of AR in surgery can be coupled with better performance of the actual surgical procedure itself and can overlay patient-specific anatomical information obtained from imaging scans, such as in spinal surgeries [61,62], transrectal prostate biopsy [63], renal surgery [63–66]. Other platforms are also available for teaching colonoscopies, such as GI Mentor™ and EndoVR™ (CAE Healthcare, the old AccuTouch®, Immersion) [68], hysteroscopies such as EssureSim [69], and complicated tibial shaft fracture surgical techniques [70]. Further, virtual patients and immersive technologies are integrated into medical curricula, significantly enhancing learning experiences. Various medical schools, including NYU Langone Health Grossman School of Medicine and Stanford University, leverage VR and AR for anatomy education and surgical training, contributing to improved skills, learner satisfaction, and performance [71].

In the context of treatment options, the metaverse, particularly through VR, proves effective for therapeutic goals in various medical conditions such as phobias, anxiety disorders [72], rehabilitation [72–76], Parkinson's disease [78], pain management and Angelman syndrome, a genetic neurological disorder resulting in cognitive and neuromuscular impairments [79]. Integrating metaverse applications enhances learner engagement, nurtures clinical decision-making proficiencies to advance patient care, and bridges theoretical knowledge with practical implementations in medical training.

In addition, the metaverse plays a role in public awareness, with applications like the Immersive Nutrition Game and the Whyville platform demonstrating its potential for health education [80,81]. These platforms engage users in virtual environments to promote understanding of health consequences, encourage informed decision-making, and even facilitate public health campaigns. Moreover, the metaverse extends beyond clinical applications to support integrative medicine and mindfulness practices (e.g. yoga and guided meditation), contributing to overall wellness using the Roblox metaverse [82]. Overall, the metaverse emerges as a transformative force with the potential to revolutionize medical education, treatment options, and public awareness across diverse aspects of the medical field.

Table 6. Benefits and challenges of the use of metaverse.

Categories	Benefits	Challenges
Learner Engagement	• Increasing engagement and interaction with dynamic, interactive content material • Allowing the use of active learning through gamification, simulations, and interactive scenarios	• Maintaining the educational quality of the content • Taking measures to prevent overstimulation
Immersive Learning Experiences	• Providing hands-on experience with realistic fully immersive 3D environments • Developing skills through experiential learning	• Financing high initial costs for producing immersive media • Dealing with technical problems, such as incompatibility of equipment
Personalized Learning	• Allowing virtual practice of skills in a safe environment • Creating personalized educational opportunities	• Overcoming the learning curve for some learners • Maintaining security and privacy of data
Assessment and Evaluation	• Obtaining personalized feedback and real-time data collection • Monitoring and analyzing learning analytics (intelligent data) to identify areas for improvement	• Maintaining data privacy and ethical considerations • Ensuring the accuracy and consistency of the data
Collaboration Opportunities	• Promoting global collaboration and a range of viewpoints among medical students, practitioners, and experts • Having access to experts worldwide	• Removing language and cultural barriers • Adapting or managing time zone differences
Cost Efficiency	• Providing remote training at a reasonable cost • Reducing the need for physical presence	• Providing all learners with access and affordability • Keeping cost-effectiveness through careful management of institutional IT support and quality in balance
Technical Limitations and Access	• Enabling access for remote or underserved areas • Tailoring to varying learning needs and preferences	• Having access to high-quality hardware and a reliable network • Helping users who are not familiar with the new technology
Content Quality and Accuracy	• Having access to an extensive collection of up-to-date medical content and resources	• Ensuring the quality and accuracy of educational materials and resources
Faculty and Learner Training	• Offering training opportunities for faculty and staff • Teaching learners how to use digital technology effectively	• Handling reluctance to modify conventional teaching approaches • Providing faculty with sufficient training and support
Existing Curricula and Resistance to Change	• Embracing innovation in both teaching methods and content • Integrating metaverse applications into the curriculum	• Overcoming resistance from educators and institutions • Combining cutting-edge technology with traditional teaching techniques
Lack of Human or Physical Interaction	• Reducing the need for physical infrastructure • Fostering a sense of community and social interaction	• Dealing with the shortcomings of virtual interactions • Responding to worries or concerns about possible isolation and disconnection
Data Privacy and Security Concerns	• Keeping learner data private and secure • Complying with legal and ethical guidelines for managing data	• Preventing possible data breaches and cyberattacks • Building and maintaining secure metaverse platforms
Learner Data Accuracy and Reliability of AI Algorithms	• Generating data-driven insights for personalized learning that contribute to better model training	• Eliminating biases by ensuring accurate data collection and analysis
Legal and Ethical Issues	• Adhering to ethical standards and best practices • Assessing compliance with data protection and privacy regulations	• Navigating complex legal and ethical frameworks • Resolving potential conflicts between stakeholders
Maintenance and Updates	• Preserving continuous improvement of educational content • Keeping current with the most recent advancements in medical research and information	• Managing updates without disrupting ongoing education • Balancing the workload of content creators and faculty
Cost Implications	• Reducing the need for physical infrastructure costs • Exploring cost-effective metaverse platforms	• Assuring sustainable long-term financing structures for education and training • Providing funding for the implementation of the metaverse

Emerging technologies and reshaping the future of medical education in the post-pandemic era

In response to the growing demand for training medical professionals in VR and AR environments, a software platform [83] was developed to simplify the creation of Interactive Mixed Reality (IMR) scenarios. These scenarios aim to replicate clinical settings by integrating patient physiology, emotions, and team dynamics. Overcoming the complexity associated with incorporating such parameters, the IMR platform combines elements like 360-degree video recording, annotated knowledge content, and assessment questionnaires into IMR scenarios. A sepsis prevention education scenario was created to demonstrate how this software accelerates novice students' clinical exposure. The efficacy of IMR technology was evaluated through a study involving 28 novice students, with feedback collected using NASA-TLX and system usability scale questionnaires. This software advancement represents a step towards streamlining the development of VR-based medical education content, offering a promising tool for enhancing medical training [83].

Similarly, another theoretical model to teach the cardiovascular system and interventional procedures, termed CardioVerse, was developed [84]. CardioVerse opens a world of opportunities within the metaverse. It brings new ways of learning about diseases, preventive strategies, and diagnostic accuracy. It has many uses, especially in improving doctor visits, helping with heart treatments, and changing medical education. While there will be challenges in areas like security, technology, laws, and rules, using unique tokens to secure patient information might be a way to solve this issue.

As metaverse technology evolves, we expect more advanced and realistic virtual environments, simulations, and AI-driven patient interactions. A comprehensive framework for metaverse-based medical education may include the following.

- *Virtual Medical Campuses*: Institutions can establish virtual campuses within the metaverse, replicating real-world medical facilities, classrooms, libraries, and laboratories.
- *Simulation Centers*: Advanced simulations can provide realistic medical scenarios, enabling learners to practice skills and decision-making in a controlled environment.
- *Global Networks*: Virtual conferences, seminars, and collaborative spaces can facilitate networking and knowledge-sharing among learners and professionals worldwide.
- *Continuous Assessment*: AI-powered assessments can provide real-time feedback, allowing learners to track their progress and make informed adjustments to their learning strategies.

The metaverse can help prepare learners for the challenges of practicing medicine in the twenty first century and beyond by providing access to immersive virtual environments, global collaboration opportunities, and continuous feedback. However, careful planning, collaboration with technology experts, professional development of faculty members, and ongoing evaluations are essential for ensuring the success of this endeavor. Challenges such as the need for robust technical infrastructure, ethical considerations surrounding AI-driven patient interactions, and potential overreliance on virtual environments should also be considered.

In addition, navigating the dynamic landscape of technological evolution in medical education requires a strategic approach beyond the adoption of the latest innovations. Therefore, it is important to recognize that the objective is not only to adopt the latest technologies but also to leverage them effectively for educational enhancement. We believe that the process of learning will always require effortful thinking, and technology is powerful yet merely a tool to foster this process. While predicting a potential level of the need for advanced technology in medical education remains challenging, the overarching goal is to establish educational frameworks that evolve in harmony with technological progress, always emphasizing technology as a tool to meet the changing needs of healthcare as well as to enhance learning outcomes, patient care, and the overall educational experience.

Recommendations for medical institutions

This section provides recommendations for effectively incorporating the metaverse into the medical education curriculum. These recommendations are based on the best practices in curriculum development [85,86] and emerging research in this field.

Step 1: foundational work

Developing a metaverse curriculum involves careful planning and preparation to ensure its success. The following foundational work should be performed diligently:

- *Readiness or Needs Assessment*: Readiness or needs assessment is a critical step as a starting point for any project, program, or initiative. While a readiness assessment focuses on evaluating the readiness and capacity for change or implementation, a needs assessment uncovers the specific requirements and deficiencies and/or identifies specific gaps, necessary conditions, resources, skills, and support. Both assessments play crucial roles in decision-making, planning, and resource allocation in various contexts.
- *Collaboration with Stakeholders*: Collaboration with stakeholders such as faculty educators, learners, industry partners, and technical experts is a key element in designing and implementing successful educational programs like metaverse. By fostering collaboration with these stakeholders, we can address the needs, expectations, and expertise of all parties involved, which helps create a well-rounded and comprehensive curriculum. This collaborative approach not only enhances the quality of the curriculum but also leads to higher engagement, better outcomes, and a more positive learning experience.

By undertaking these initial tasks, we set a solid foundation for the development of a successful and impactful metaverse curriculum.

Step 2: curriculum design and development process

Designing and developing a curriculum for a metaverse environment requires input from various stakeholders to ensure its effectiveness and relevance for specific medical disciplines. Here are the essential tasks for each party:

- *Faculty Educators*: As content experts and agents of change, faculty educators should define the scope of the metaverse curriculum, including the topics and skills to be covered. Their insights ensure that the curriculum aligns with educational goals and pedagogical strategies.
- *Instructional Designers*: Instructional designers, who specialize in technology-enhanced learning, play a crucial role in creating a cohesive, effective, and engaging learning experience that would harness the capabilities of virtual environments for educational purposes. They can organize the metaverse curriculum into modules or units and outline learning outcomes for the greatest interactive learning experiences using the best instructional design principles, theoretical concepts, pedagogical tactics, and appropriate assessment strategies.
- *Evaluation and Assessment Specialists*: Including evaluation and assessment specialists in the development of a metaverse curriculum ensures that the assessment and evaluation strategies are aligned with desired learning outcomes and the overall curriculum goals, promote effective learning, and provide valuable insights into learner progress and engagement.
- *Learners*: The input from learners as the end users and the target learner population contributes to a curriculum that is academically rigorous and impactful for their personal and professional growth. Their involvement also helps tailor the curriculum to their specific needs and learning preferences by selecting the best pedagogies for an effective educational environment.
- *Ethics Experts*: When dealing with sensitive medical content, we need specific guidelines and protocols for using AI-driven patient interactions and virtual scenarios ethically. At this point, including ethics experts in the curriculum development process ensures that learners are not only gaining technical skills but are also equipped with a deep understanding of ethical considerations, fostering responsible and ethical professionals within the metaverse context. Ethics experts can also guide the development of metaverse scenarios involving AI-driven patient interactions to ensure that patient privacy, confidentiality, and other ethical dilemmas are well-constructed and maintained even in virtual environments.
- *Technical Experts and Industry Partners*: Incorporating technical experts and industry partners in the development of a metaverse curriculum plays a critical role in translating the educational vision into a functional and engaging metaverse curriculum. They are familiar with metaverse platforms, VR, AR, and other related technologies that would help select appropriate metaverse platforms, tools, and technologies based on the nature of the curriculum. Their expertise ensures that the technological aspects align with the pedagogical goals, creating a seamless and impactful learning environment for learners and faculty educators. In addition, depending on the subject area, we can consult relevant industry professionals' insights to ensure that the curriculum aligns with real-world applications and industry trends.

Other important stakeholders would be research and development teams, institutional leaders, and community partners depending on the needs. By involving a diverse group of stakeholders, we gather insights from multiple perspectives, ensuring that the curriculum design is comprehensive, effective, and meets the needs of all parties involved. This collaborative approach results in a curriculum that is well-rounded, engaging, and aligned with the goals of metaverse-based education.

Step 3: curriculum implementation

The implementation stage is a critical phase for a metaverse curriculum because it is the point at which the carefully designed curriculum is put into action in a real setting. This stage allows learners to engage with content/learning materials, apply knowledge, and develop skills within an immersive virtual environment. However, the following are the essential steps to take before the actual implementation of the full curriculum with the end users:

- *Professional Development*: Faculty educators should be trained in technology and pedagogical efficiency to become more proficient in using metaverse tools, platforms, and related technologies. Institutions can offer ongoing training workshops and webinars to help faculty, staff, and learners develop their metaverse teaching and learning skills, emerging technologies, and instructional design principles specific to virtual environments. Professional development activities can be designed to foster a sense of community where educators can share best practices and learn from each other.

- *Learner Orientation*: An effective orientation session should start with a guided tour that shows learners how to move around, access resources, engage with avatars or virtual objects, and perform basic interactions. This session should also cover expectations that would maximize the learning experience within the metaverse. In this way, learners can navigate the metaverse curriculum with confidence and enthusiasm.
- *Piloting Curriculum*: Piloting a curriculum involves implementing it on a small scale before introducing the curriculum to a wider audience. This test run helps us identify possible problems, gather feedback, and make necessary adjustments. At the same time, piloting provides faculty educators with a hands-on experience of how the curriculum works in real practice settings.
- *Implementation At Scale*: Deploying the metaverse curriculum to a large number of learners on a widespread basis requires robust infrastructure to support the Extended Reality (VR, AR, and MR) environment and ensure uninterrupted access for users. Continuous monitoring and evaluation allow for feedback-driven improvements and the identification of best practices to enhance the learning experience and gains in the metaverse.

The immersive nature of the metaverse environment has the potential to significantly enhance learner engagement and motivation. As learners become more invested in their learning experiences, they can develop practical skills and competencies through the interactive and dynamic nature of the curriculum. During the implementation stage of metaverse-based medical education, it is crucial to address global disparities in access to technology and resources. This obstacle to equality requires collaborative efforts from various stakeholders, including governments, educational institutions, and technology providers. Strategies such as providing affordable access to the necessary infrastructure, fostering international partnerships, and developing tailored solutions for different regions can contribute to a more inclusive implementation. Moreover, prioritizing inclusion is crucial to preventing additional gaps in medical education, especially in light of the special conditions of developing countries. We may aim for a more equal integration of the metaverse in medical education globally by fostering international collaboration and conversations towards solutions. In addition, collecting data on learner interactions, engagement, and performance during the implementation stage provides valuable insights into the effectiveness of the curriculum. This data-driven approach informs decisions for future iterations, ensuring continuous improvement and adaptation to diverse learning needs.

Step 4: evaluation and continuous improvement

Evaluating a metaverse curriculum is a systematic process to measure its effectiveness, capture learner satisfaction, identify areas for improvement, and ensure that the intended learning outcomes are achieved (e.g. knowledge, skills, and competencies). This evaluation provides valuable insights into the impact of the curriculum on learners, faculty educators, and the overall educational process. Moreover, it fosters a culture of continuous improvement based on data-driven insights, ensures alignment with educational goals, and enhances the overall quality of the learning experience within the virtual environment. Finally, ongoing evaluation helps us explore innovative ways to update the curriculum content and pedagogical approaches based on emerging trends and metaverse-based technologies.

By following these steps, we can design, implement, and evaluate a metaverse curriculum that effectively engages learners and prepares them for the evolving digital landscape.

Conclusion

The evolution of medical education from the Flexnerian era to the present time has been marked by the integration of advanced technologies catalyzing a significant revolution, including the metaverse, which has expanded learning opportunities, enriched the educational experience, and transformed medical training into dynamic, immersive, and multidimensional learning opportunities. As we addressed in this review paper, the advent of the WWW ignited a revolution in access to medical information, reshaping how medical students and professionals acquire knowledge. The transition from traditional Education 1.0 to dynamic

Education 4.0 ushered in new paradigms of learning, emphasizing adaptability and digital fluency. The emergence of the metaverse has already presented a paradigm shift, offering innovative and interactive platforms moving from the static Web 2D to the immersive Web 3D that bridge the gap between theoretical learning and practical application.

The transition from static Web platforms to immersive metaverse environments promises to revolutionize medical learning. The metaverse offers immersive simulated environments that can provide impactful experiential learning at scale. Integrating virtual, augmented, and mixed reality facilitates experiential learning through real-time simulations that merge physical and digital worlds. This interactivity promotes competencies like clinical reasoning, communication, teamwork, and empathy. Educators can leverage these technologies to create inclusive medical simulations that adapt to diverse learning needs. The personalized practical experiences refine clinical skills and decision-making capabilities in safe settings. As we have provided examples from case studies across various medical disciplines, the metaverse has the power to provide medical learners with hands-on experiences, collaborative learning environments, and realistic simulations. These examples underscore the metaverse's capacity to revolutionize medical education and better prepare future healthcare professionals for the complexities of real-world practice. Furthermore, international collaboration is also made possible by the metaverse, allowing learners and experts from all over the world to connect at any time, from anywhere. This expands professional networks and perspectives, bringing together diverse skills and knowledge to enrich medical education. The metaverse also facilitates telemedicine and global outreach to underserved communities.

While metaverse offers immersive, interactive, and captivating learning experiences that have the potential to completely transform medical education, certain aspects of medical education could be difficult to completely replace or require careful thought when incorporating the metaverse. Especially, there may be no substitute for the fundamental components of hands-on practical clinical experience, the diversity of real patients, essential skills like physical examinations and communication, emotional intelligence, ethical dilemmas, and the nuances of interprofessional/multidisciplinary collaboration. Therefore, a balanced approach should be adopted in order to avoid misuse of the metaverse while maintaining the essential components of practical training.

As we look ahead to the post-pandemic era, emerging technologies will play a significant role in shaping the future of medical education. The lessons learned from the pandemic's impact on education underscore the importance of blended learning approaches, where virtual and physical experiences are thoughtfully integrated. Medical institutions must embrace these changes, redefining their strategies to ensure learners are equipped with the skills and competencies demanded by a rapidly evolving healthcare landscape. However, thoughtfully addressing access barriers, content accuracy, data privacy, legal concerns, and ethical issues is vital for the successful implementation of metaverse-based solutions. Developing strategic plans through stakeholder collaboration helps institutions harness benefits while mitigating challenges. Careful planning, faculty development, and collaboration between educators, technologists, and policymakers are key. Gradually transitioning from static Web learning models to more interactive, personalized, and immersive platforms can bridge theory with practice and enhance the quality of medical education.

In brief, medical institutions must adopt a proactive approach, embracing emerging technologies to reshape medical learning and practice. Realizing the full potential of innovations requires investing in cutting-edge technology infrastructure, fostering collaboration between faculty educators and technologists, designing adaptive curricula, and integrating contemporary teaching methods/instructional approaches all in alignment. As technology progresses, medical education must also continue to reinvent itself, adapting creative solutions to transform how the next generation of physicians are prepared to meet society's evolving healthcare needs. In this way, medical institutions can pave the way for a future where medical education not only keeps pace with technological innovation but also becomes a cornerstone of groundbreaking healthcare delivery. Finally, in this comprehensive review, our focus has been primarily on the diverse landscape of metaverse applications, encompassing simulations, virtual reality, augmented reality, and mixed reality experiences tailored for medical education. Our analysis did not include an exploration of Multi-user Virtual Environment (MUVE), Large Language Programs (LLPs), mobile learning, metaverse-related social networking, and collaboration tools. To provide a more holistic perspective, future research could delve into how those programs and tools are integrated into metaverse platforms in terms of accessibility, adaptability, and scalability in the evolving landscape of medical education.

Authors contributions

KOL played a pivotal role in the conception and design of this review paper. All authors were actively involved in drafting and revising the manuscript, and they collectively approved the final version for submission. We all conducted extensive literature searches, gathered relevant research articles, and synthesized the information to form the core content of the review. VP contributed to providing comprehensive insights into the main context of the overall structure and coherence of the paper, ensuring the logical flow of ideas and a cohesive presentation. SSF focused on analyzing case studies and practical applications, enhancing the paper's real-world relevance. The first author's leadership in the design of this paper and drafting, coupled with the valuable contributions of co-authors, led to the production of a comprehensive and informative review on the evolution of medical education from the static Web to the metaverse.

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ORCID

Kadriye O. Lewis http://orcid.org/0000-0001-5947-409X
Vitaliy Popov http://orcid.org/0000-0003-2348-5285
Syeda Sadia Fatima http://orcid.org/0000-0002-3164-0225

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