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COMMENT

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Metaverse-powered basic sciences medical education: bridging the gaps for lower middle-income countries

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ABSTRACT

Background: Traditional medical education often lacks contextual experience, hindering students' ability to effectively apply theoretical knowledge in real-world scenarios. The integration of the metaverse into medical education holds great enormous promise for addressing educational disparities, particularly in lower-middle-income countries (LMICs) accompanied by rapid technological advancements. This commentary paper aimed to address the potential of the metaverse in enhancing basic sciences education within the constraints faced by universities in LMICs. We also addressed learning design challenges by proposing fundamental design elements and a suggested conceptual framework for developing metaverse-based teaching methods.The goal is to assist educators and medical practitioners in comprehensivley understanding key factors in immersive teaching and learning.
Discussion: By immersing medical students in virtual scenarios mimicking real medical settings and patient interactions, the metaverse enables practice in clinical decision-making, interpersonal skills, and exposure to complex medical situations in a controlled environment. These simulations can be customized to reflect local healthcare challenges, preparing medical students to tackle specific community needs. Various disciplines, including anatomy, physiology, pharmacy, dentistry, and pathology, have begun leveraging the metaverse to offer immersive learning experiences, foster interdisciplinary collaborations, and facilitate authentic assessments. However, financial constraints pose a significant barrier to widespread adoption, particularly in resource-limited settings like LMICs. Addressing these challenges is crucial to realizing the full potential of metaverse technology in medical education.
Conclusion: The metaverse offers a promising solution for enhancing medical education by providing immersive, context-rich learning experiences. This paper proposes a conceptual framework and fundamental design elements to aid faculty educators and medical practitioners in effectively incorporating metaverse technology into their teaching methods, thus improving educational outcomes in LMICs.

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Metaverse; medical education; lower middle-income countries; virtual reality; augmented reality; authentic assessment; universal design of learning; metaverse learning design; ADDIE model; instructional design

KEY MESSAGES

- The metaverse offers a transformative pathway for basic sciences medical education in lower-middle-income countries (LMICs) through leveraging 3D human replicas, virtual dissection, laboratories, and simulations.
- A metaverse-based learning design may easily combine a variety of learning theories, instructional design models, and/or conceptual frameworks, including constructivism, the ADDIE model, universal design, and minimalism.
- Unlocking the full potential of VR and AR in basic sciences medical education for LMIC universities requires collaborative synergy among educators, policymakers, and technology developers, with a crucial emphasis on equitable access and resource allocation.
- Despite the immense promise held by metaverse-powered education, it is crucial to address issues surrounding technology accessibility, learning design challenges, and implementation barriers in LMICs as we provide guidance to educators and practitioners worldwide.

Introduction

The Metaverse, a term originating from the fusion of 'meta,' signifying beyond or virtuality, and 'verse,' denoting universe or world, refers to a Virtual Reality space [1]. Its inception can be traced back to the 1992 science fiction novel Snow Crash [2], where the term was first coined, stemming from the amalgamation of 'meta' and 'universe'. More often, the Metaverse is described as a Virtual Reality (VR) environment where users may

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communicate with other users and interact with computer-generated settings. The Metaverse adds a layer of experiential depth and sensory richness to enhance our interactions with the physical world, rather than replacing it. The goal is to combine physical and digital worlds in a way that produces value and benefits for both [3]. This concept originally pertained to a Virtual Reality accessible through terminals and wearable devices such as VR goggles or VR headsets. Key technologies that actualize the Metaverse include Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR). VR creates digitally simulated environments mirroring the real world, utilizing specialized equipment like VR headsets and treadmills, fostering user interaction with virtual content. Augmented reality (AR) overlays digital data onto the physical world. By employing devices such as smartphones, tablets, or AR goggles, AR projects supplementary information like anatomical components and equipment onto real-world settings. Similarly, Mixed Reality (MR) encompasses combinations of AR and VR, [1].

Basic sciences, including anatomy, physiology, biochemistry, pharmacology, pathology, and microbiology form the cornerstone of medical practice. Typically, these subjects are taught during the preclinical years through a variety of integrated teaching, learning, and assessment methods [4]. Given the complexity of human body systems in diagnosing and treating diseases, conventional approaches often lack the integration necessary for effectively linking basic sciences concepts to clinical applications [5]. In line with the principles of Education 4.0, which emphasizes immersive learning, the metaverse represents a forward- thinking pedagogical approach. It aligns with contemporary educational needs, promoting discovery-based learning rooted in constructivist principles. This approach emphasizes active learner engagement, interaction with the environment, and the significance of social interaction in knowledge construction [6].

As mentioned above, the Metaverse integrates the core principles of Education 4.0 by transcending temporal and spatial limitations, enabling personalized learning journeys, fostering adaptable learning frameworks, and prioritizing continuous improvement over episodic assessments [7]. The emergence of the metaverse, coupled with the characteristics and preferences of Generation Z (DOB:1995-2012) and Generation Alpha/iGeneration (DOB: 2013–2025) is reshaping teaching pedagogies, presenting new demands and opportunities [8,9]. To meet the learning preferences of these generations, educators must embrace learner-centric models that emphasize personalization, collaboration, and experiential learning, all qualities inherent in the Metaverse. A recently coined concept of an 'Edu-Metaverse' gives glimpse to the near future whereas the Metaverse will conveniently provide an open and inclusive learning and teaching space [10].

Applying the Metaverse to medical and health professional education presents a unique opportunity to enhance learning experiences, improve access to quality education, and bridge geographical disparities. However, like any technological advancement, there are notable advantages and challenges, especially concerning Low- and Middle-Income Countries (LMICs). A bibliometric analysis examined the patterns and evolution of Metaverse-related research by analyzing over 45,000 relevant papers published from 2012 to 2021. The analysis revealed that those countries such as United States, Canada, China, Germany, United Kingdom, France, Portugal, Slovenia, Switzerland, Thailand, Turkey, the Netherlands, Norway, Spain, Taiwan, Singapore, Australia, and New Zealand were the primary contributors to Metaverse research, with no LMIC universities identified in the study [11,12].

LMICs encounter numerous challenges in their medical education systems, including limited access to quality education due to resource constraints, inadequate infrastructure, overcrowded classrooms, and a shortage of skilled faculty [13–16]. The metaverse holds promise in addressing several of these issues, enabling access to medical education by providing virtual classrooms and immersive learning environments. This ensures standardized, up-to-date, and engaging education for medical students regardless of their geographical location. In many LMICs, medical students struggle to gain exposure to diverse and challenging clinical scenarios, essential for honing diagnostic and problem-solving skills [17]. Moreover, these regions often face health crises, infectious diseases, and public health emergencies, augmenting the need for well-prepared medical professionals [18]. The metaverse can offer a wide array of virtual patient cases, allowing medical students to practice clinical decision-making, encounter complex medical situations, and refine their interpersonal skills.

As technology continues to reshape education, the integration of metaverse applications holds tremendous potential. However, there are certain challenges to consider from design to implementation process. Through this commentary, we aimed to explore the potential of the metaverse in improving basic sciences education and the limitations of LMIC universities. We also provided fundamental learning design elements with a suggested conceptual framework for designing metaverse-based teaching to aid faculty educators and medical practitioners in understanding the key variables in immersive teaching and learning.

Potential application of metaverse in Basic sciences education

3D Human replicas and virtual dissection

Utilizing 3D human replicas, the metaverse introduces an interactive approach to teaching clinical anatomy and understanding complex anatomical structures. Traditional reliance on cadaveric sections often limits manipulation due to their inherent fragility. However, the introduction of 3D-printed models overcomes these constraints, enhancing kinesthetic learning experiences and overall engagement. For example, projects like generating a 3D-printed localized intracerebral aneurysm using digital imaging and communications (DICOM) foster an appreciation for structural pathologies that are otherwise challenging to attain [19], while tools like the Holonomy Software enable visualization of human anatomy without cadavers, aiding in deep learning [20]. Integration of educational games within the metaverse allows the infusion of scientific concepts into an engaging narrative. Medical students participate in puzzle-solving, quests, and progression through different levels [21]. Virtual dissections offer precise control and understanding of anatomical structures.

Virtual laboratories and simulations

In the metaverse, virtual science labs provide a secure environment for hands-on experimentation, allowing students to manipulate objects, mix substances, and observe reactions while mastering essential principles of human body systems and diseases. Interactive simulations help medical students understand complex physics concepts, like the behavior of blood flow in vessels by experimenting with pressure-volume curves in cardiac cycles and blood circulation. Educators can become virtual entities within the metaverse, offering lessons in full-body form, demonstrating anatomical structures, movements, and concepts with real-time interaction that enhances online learning [21]. This approach can effectively be applied through distance learning, increasing access to education, and enhancing learning experiences. Virtual classroom design and real-time collaboration *via* video conferencing increase flexibility, accessibility, and cost effectiveness by eliminating geographical barriers and by allowing medical students to participate in learning activities at their own pace.

In-situ learning and authentic assessment

'In-situ learning' and 'authentic assessment' focus on evaluating students' skills in meaningfully, and emphasizing real-world, practical, and contextual learning experiences [22]. The metaverse situates medical students in authentic environments like hospitals, sports fields, adding realism to their learning. Simulated workplaces within the metaverse prepare medical students for their future professional endeavours. The metaverse can revamp assessment methodologies by enabling medical students to present, discuss, and be evaluated on concepts within a realistic 3D environment, regardless of their physical location. Virtual field trips to simulated disaster control sites or common injuries provide a low-cost solution to enhance hands-on learning experiences in medical education.

Interdisciplinary learning within the metaverse

The metaverse seamlessly combines multi-disciplinary information and models diverse body systems, offering an avenue for integrating complex medical concepts effectively. This integrated approach empowers medical students to traverse traditional disciplinary boundaries that exist between academic disciplines, such as anatomy, physiology, pathology, and pharmacology. As a result, a comprehensive understanding of diseases and their far-reaching clinical implications is fostered, underscoring the potential of this holistic educational paradigm. Virtual 'stations' and dynamic group formations within the metaverse accommodate small and large groups of medical students for discussions, problem-based learning, and team-based learning sessions, without being constrained by physical classroom limitations.

Reproducible contextual clinical scenarios

In medical education, the metaverse serves as a safe and interactive space for repeating critical clinical scenarios. Immersive videos recreated using omnidirectional cameras can simulate emergency care situations and contextual clinical cases for later viewing by medical students, overcoming constraints such as in-person attendance limitations (evident, for instance, during the COVID-19 pandemic). This innovation facilitates teaching and practicing challenging clinical scenarios, providing meticulous feedback to medical students engaged in patient interviews, and disseminating highly specialized technical skills [23]. Ultimately, this bridges the gap between theoretical understanding and practical expertise, creating more competent medical professionals [24]. Additionally, it reduces pain perception and underscores the importance of using metaverse both as a learning tool and clinical aid [25].

Challenges in implementing the metaverse

Common challenges:

- Technical challenges arise in both developing and applying the metaverse in medical education, particularly in managing medical data. Ethical concerns encompass issues such as privacy, data security, and equal access [26]. These concerns, including security and privacy of medical data, interoperability, biases, validation, ethical content usage, are universal. For example, the collection of user data may inadvertently capture personal information, raising significant privacy and surveillance issues [27]. Potential solutions include leveraging blockchain technology and Non-Fungible Tokens (NFTs) to enable digital information ownership, addressing cybersecurity concerns [28]. In addition, content creation and sharing raise questions about data ownership and usage restrictions, necessitating clear guidelines to prevent ambiguity or plagiarism [29].
- The use of the metaverse may trigger psychological consequences such as "Post VR sadness" and "VR Hangover" indicating temporary shifts in mood or the onset of disorders due to prolonged VR/AR headsets use. Understanding these effects is crucial for safeguarding learners' well-being. Extended use can lead to VR sickness/Motion sickness, characterized by eye fatigue, nausea, and dizziness [30].
- Ensuring inclusivity within the metaverse poses a multifaceted challenge. Medical students with visual or hearing impairments may encounter barriers, necessitating thoughtful learning design considerations to ensure equitable learning experiences for all.

LMIC specific challenges

- A significant hurdle arises from the financial implications associated with the widespread adoption of the metaverse. Successful implementation not only requires high-speed internet connectivity (5G and fiber-optic) but also entails acquiring expensive headsets and accompanying accessories. This financial barrier could hinder broad utilization of the metaverse, especially for individuals lacking the resources to embrace this advanced technological ecosystem. In LMICs, where medical education expenses are already significant, integrating the metaverse could exacerbate the financial burden. This unintended consequence might counteract the desired educational benefits by limiting accessibility for a significant portion of prospective learners [1,21,31].
- Connectivity stands as a cornerstone of virtual education. However, challenges such as dropped connections can disrupt lessons, disproportionately affecting those with limited access to reliable internet or technology. Universal internet access, hardware availability, and electricity access remain far from realized across numerous LMICs, with uneven availability and subpar quality of services. These limitations, marked by frequent outages, pose a considerable hurdle to the seamless flow of teaching sessions. This situation could inadvertently favor individuals with better connectivity, revealing challenges related to access disparities. Disadvantaged communities might struggle to access this technology, potentially rendering it counterproductive [19,31].
- The learning curve associated with the metaverse demands attention, particularly for individuals with limited familiarity with advanced technology. This challenge is notably accentuated in LMICs, where widespread access to technological resources is limited. Some medical students might find the transition to learning through head-mounted displays distracting, while others might even experience cyber-sickness, requiring a delicate balance in providing effective virtual learning environments.
- Adoption of the metaverse may face hesitation due to its disruption of traditional teaching methods, which have remained the status quo for decades. Medical educators must consider local customs, beliefs, and disease patterns. Generic metaverse content might not always align with the specific healthcare needs of different regions. Addressing this challenge involves facilitating educators' transition while acknowledging the uncertainties associated with this transformative shift. Furthermore, providing training to educators in LMICs might be resource intensive.

Discussion

Technology-driven changes in medical education have transformed the way medical students learn, healthcare professionals train, and healthcare is delivered. This evolution, fueled by innovations like Artificial intelligence (AI) and digital imaging, brings about precision education that caters to multi-channel learning to suit the distinct learning preferences [19].

In LMIC universities students have limited access to medical facilities, educators, and traditional resources as compared to the developed world. The integration of metaverse in basic sciences education can help overcome this disparity and increase accessibility and inclusivity. It can provide equitable access to high-quality resources and expert knowledge. For example, limited exposure to cadaveric dissections due to ethical concerns limit learning opportunities [32]. These technologies allow learners to engage in lifelike cadaveric dissections and explore complex physiological changes that would be difficult to replicate with real patients [33]. It may be an ethical alternative to cadaver labs as it can provide virtual dissection experiences to multiple students simultaneously.

Another significant issue that the metaverse can help address is the lack of real-life clinical cases. By offering a repository of realistic virtual clinical experiences, the metaverse fills a crucial gap, enhancing the quality of medical education in LMICs and better preparing future healthcare professionals for the intricacies of real-world patient-centred medical education [34]. Students from diverse backgrounds can collaborate on medical cases, share insights, and engage in problem-solving exercises, fostering a sense of community and expanding perspectives.

The metaverse can provide medical students with immersive experiences, allowing them to explore intricate anatomical structures, visualize disease processes, and interact with medical simulations in a lifelike environment through virtual labs, and interactive models and simulations. This can cause enhanced engagement, better understanding, and retention of knowledge. It can also provide opportunities for LMIC students to engage with clinical and educational content from the developed world, thus enabling them to access the latest advancements in medical knowledge and practices. Through distance learning, virtual collaborations with institutions and experts around the globe, LMIC students can participate in lectures, seminars, and case discussions, gaining exposure to diverse perspectives and best practices in healthcare delivery. They can learn from the experiences of healthcare professionals in different healthcare systems, gaining insights into innovative approaches to patient care, medical research, and healthcare management.

Diverse teaching methods (flipped classrooms, problem-based learning, team-based learning, peer-assisted learning, theoretical discussions, interaction with virtual patients, and practicing procedures on them) can thus not only be adapted to suit various curricular needs but can also be used to personalize learning experiences for individual students. It can also be useful for medical students with disabilities since it can provide visual and tactile learning experiences.

In previous studies conducted in developed countries, students reported that metaverse integrated into online platforms facilitated resource sharing and enabled collaborative learning regardless of geographic barriers. It helped them in overcoming physical and time constraints. Using techniques like team-based learning within the metaverse aided in the development of skills in clinical reflection, collaboration, and communication. It also improved engagement and knowledge retention [35,36]. A systematic review and meta-analysis revealed that both virtual and augmented reality offer viable alternatives to conventional teaching methods in health sciences and medical courses [37] anatomy, physiology [38], and pharmacy education [39,40]. In a previous study conducted by our group [41], we examined the impact of mental rotation (MR) training and the utilization of three-dimensional (3D) software in medical student education. Ninety-Seven% students regarded technology-assisted learning as highly effective in instructional methods, and that the application of 3D software surpassed the utility of traditional plastic models. This outcome suggested that educational software founded on 3D technologies has the potential to serve as a valuable pedagogical tool, accommodating students with varying levels of mental rotation abilities. Based on these findings, we can also speculate that for the GenZ learners anywhere in the globe, the metaverse provides a flexible, self-paced environment that is suitable for remote learners. Table 1 provides an overview of metaverse platforms for reference *(please note that this list is not exhaustive)*. The metaverse can provide a platform for continuous learning, enabling professionals to stay current with medical advancements.

To effectively harness the metaverse's potential, a collaborative effort between policymakers, educators, and technology developers is paramount. Policymakers should prioritize the allocation of resources toward the development and implementation of metaverse-enabled educational platforms [42]. Capacity building and training programs for medical educators in LMICs need to be offered to familiarize them with metaverse technologies and effective pedagogical practices for utilizing them in medical education. This could include workshops, seminars, and online courses tailored to the needs of educators in LMICs [42]. These trained educators can then develop the educational content within the metaverse that is culturally sensitive and relevant to the healthcare challenges faced by LMICs. For example, clinical cases could be made of malnutrition,

Table 1. Metaverse platforms and their possible application in Basic sciences medical education.

Metaverse Platform	Uses in Medical Education	Cost Effectiveness	Learning Curve	Technical Requirements	Potential for Integration	Licenses	Equipment	Limitations and Other Information
Second Life	Medical simulations, virtual clinics, role-playing scenarios	Variable pricing, free option	Moderate	Standard PC, Broadband Internet	Offers versatile scenarios, may require scripting for customization	Proprietary	PC or Mac, Internet connection	Can be resource-intensive, may have a learning curve for users unfamiliar with virtual worlds
OpenSimulator	Custom medical simulations, virtual environments	Free and open source	Moderate	Server setup, technical expertise	Highly customizable, open-source nature	Open source	Server, PC, or Mac clients	Requires technical expertise to set up and customize
Unity3D	Developing VR/AR medical apps, simulations, interactive content	Varies (free for personal use, paid for commercial)	Moderate to High	Programming skills, hardware for testing	Highly flexible for creating custom experiences	Proprietary	PC or Mac, VR/AR hardware	Requires programming skills or development resources
Unreal Engine	Creating high-quality medical VR experiences, simulations	Varies (free for personal use, royalty-based for commercial)	Moderate to High	Programming skills, hardware for testing	Realistic visual quality, suitable for complex scenarios	Proprietary	PC, VR hardware	Like Unity, programming skills or development resources required
Microsoft HoloLens	AR-based medical education, anatomical visualizations	Hardware cost: High	Low to Moderate	Standalone AR headset	Offers Mixed Reality experiences; limited field of view	Proprietary	Microsoft HoloLens	Limited field of view and high initial cost
Oculus Rift	Medical VR simulations, immersive training	Hardware cost: Moderate	Moderate	High-end PC, Oculus Rift	Provides high-quality VR experiences	Proprietary	Oculus Rift, High-end PC	Requires a compatible computer
HTC Vive	Medical VR simulations, interactive training	Hardware cost: Moderate	Moderate	High-end PC, HTC Vive	Offers room-scale VR experiences	Proprietary	HTC Vive, High-end PC	Requires a compatible computer
Magic Leap	Medical AR applications, anatomy visualization	Hardware cost: High	Low to Moderate	Standalone AR headset	Offers unique spatial computing	Proprietary	Magic Leap	High initial cost; limited adoption
Visible Body	An interactive 3D anatomy app offering detailed visualizations of the human body's systems.	High-quality 3D models, interactive animations, quizzes, cross-sectional views, clinical correlations, and AR views.	Medical education, anatomy learning, professional training	iOS, Android	Varies by subscription	Engaging 3D visuals, in-depth anatomical exploration, valuable resource.	PC or Mac, Internet connection Subscription cost, complexity for non-medical users	License Cost
Touch Surgery	Surgical training app providing step-by-step simulations and educational content.	Surgical simulations, procedure tutorials, videos, assessments, and case sharing.	Surgical education, skills development	iOS, Android	Free, in-app purchases	Hands-on surgical practice, access to expert content.	In-app purchases for premium content	–
SimX	VR simulation platform for medical training, allowing learners to practice clinical scenarios.	Immersive VR scenarios, team-based training, real-time feedback, and customizable cases.	Medical education, clinical training, team collaboration	VR platforms, web	Contact for pricing	Realistic clinical simulations, customizable scenarios.	Requires VR hardware, potential cost barriers	–
Proximie	Augmented reality platform connecting remote experts to surgical procedures in real-time.	Live AR surgical assistance, remote collaboration, annotations, telestration.	Surgical education, remote collaboration	iOS, Android	Contact for pricing	Real-time expert guidance, remote collaboration.	Dependent on network connectivity, potential costs	–
HoloPatient	AR app for medical education, offering interactive patient scenarios and simulations.	Interactive AR patient scenarios, case simulations, and medical training.	Medical education, clinical simulations	iOS, Android	Free, in-app purchases	Immersive AR patient encounters, practical training.	In-app purchases for premium content, limited scope	–

(*Continued*)

Table 1. Continued.

Metaverse Platform	Uses in Medical Education	Cost Effectiveness	Learning Curve	Technical Requirements	Potential for Integration	Licenses	Equipment	Limitations and Other Information
Medieval	Medical visualization platform using AR and AI to aid in planning and performing surgeries.	AR visualization, surgical planning, 3D reconstructions, AI-assisted insights.	Surgical planning, medical visualization	iOS (HoloLens), Android	Contact for pricing	Surgical precision, AI-powered insights.	Relies on specific hardware (HoloLens), potential costs	–
SeeingVR	Visual impairment simulation for training	Varies	Low to Moderate	VR hardware, compatible PC	Immersive simulation	Subscription	VR hardware, PC	Requires VR hardware, subscription costs
Anatomage Table	Interactive 3D anatomy exploration	High	Low	Anatomage Table Hardware	Detailed anatomical view	Proprietary	Anatomage Table	Requires specific hardware
AR Dental Simulator	Dental training and simulations in AR	Moderate	Low	AR-capable device	Interactive training	Subscription	AR-capable device	Subscription cost

tuberculosis, polio etc. This can help increase acceptability thus minimizing delayed adoption attributable to inertia of traditional methods of pedagogy. Increased acceptability will help level the learning curve to some extent [43]. This could lead to partnerships and knowledge exchange between medical institutions in LMICs and those in higher-income countries in the development and implementation of metaverse-based medical education programs. This could involve partnership arrangements, research collaborations, and faculty exchanges.

Technology developers play a crucial role in designing user-friendly, accessible, and adaptable metaverse tools that cater to the specific challenges of LMIC environments. The development of more affordable and accessible AR devices, the establishment of standards for AR content development, and further research on the effectiveness of AR in clinical practice is also an area worth exploring. Advocacy for the development of open-access platforms and resources for metaverse-based medical education that are freely available to educators and learners in LMICs needs to be catered. This could help overcome financial barriers to access and ensure equitable distribution of educational materials.

Developing mobile-friendly versions of metaverse applications and educational content to accommodate learners who may not have access to desktop computers or high-end VR hardware may also be helpful in extending the reach. Mobile devices are more prevalent in LMICs help overcome difficulties associated with obtaining expensive hardware thus providing a more accessible means of accessing educational resources. Engaging with local communities and stakeholders in LMICs to gather feedback on the usability and effectiveness of metaverse-based medical education solutions can inform the iterative development and improvement of these technologies to better meet the needs of users in LMICs.

Advocacy for supportive policies at the national and international levels that prioritize investment in digital infrastructure and educational technology in LMICs could involve lobbying governments, international organizations, and donor agencies to allocate resources towards improving access to metaverse technologies for medical education [42].

Perspectives from medical students in envisioning the future

As medical students and authors of this commentary (SSBZ and UA), we are intrigued by the potential of the metaverse to revolutionize medical education. We envision it as a powerful tool for enhancing our understanding of complex anatomical structures, molecular biology, and physiological processes. By immersing ourselves in 3D environments, we believe we can deepen our grasp of pathologies and medical interventions in ways traditional methods cannot match. The integration of VR and AR simulations holds promise for refining our practical skills. Through virtual dissections and interactions with simulated patients, we anticipate a more hands-on approach that will better prepare us for clinical practice.

One of the most compelling aspects of the metaverse is its capacity for personalized learning. With features like repetition tools, formative assessments, and immediate feedback, we anticipate improved knowledge retention compared to the traditional teaching and learning. However, as enthusiastic as we are about these prospects, we also recognize the potential drawbacks. The current assessments methods often fail to adequately evaluate technical skills and deeper understanding. The metaverse presents an opportunity to address this deficiency by allowing educators to assess learners in authentic, real- world scenarios. Yet, we cannot ignore the concerns surrounding increased screen time and potential social isolation. While the metaverse offers unparalleled educational opportunities, we must remain vigilant to ensure it does not exacerbate existing trends toward reduced face-to-face interaction. In addition, we acknowledge that not all students may readily adapt to these new technologies. Issues such as eyestrain, technical difficulties, and the learning curve associated with navigating virtual platforms could hinder the educational experience for some learners. Therefore, we advocate for a balanced approach. The metaverse should complement, rather than replace, traditional educational methods. By integrating both approaches, we can ensure that students benefit from both the strengths of each, resulting in a more holistic learning experience. As future physicians, it is essential that we embrace innovation while also safeguarding the social and educational well-being of our peers.

Learning design in the metaverse

Learning design is a systematic and intentional process of planning, organizing, and creating effective learning experiences for learners [44]. It involves the careful consideration of various elements, strategies, and pedagogical approaches to facilitate the acquisition of knowledge, skills, and competencies. Learning design goes beyond simply delivering content; it focuses on shaping the entire learning experience to maximize engagement, understanding, and retention. In the metaverse's context, learning design is the process of creating educational experiences and content tailored for virtual, immersive, and interconnected digital environments.

To our knowledge, metaverse learning design models or immersive learning design are still emerging fields and limited studies are available in literature. Kapp and O'Driscoll [45] outlined a comprehensive 3D learning architecture as a "Metaverse Learning Design Model" that consists of four layers: principles, macrostructures, archetypes, and sensibilities. This four-layer model brings value by providing practitioners with a structured basis for making well-informed decisions regarding what layer or layers are best suited and aligned to achieve the desired learning outcomes cohesively and harmoniously. A systematic review study conducted by Won et al. [46] adapted Chris Dede's [47] immersive interface design framework to examine how learning in immersive VR was designed in contemporary educational studies. This framework includes four categories of design attributes: (1) sensory (representational fidelity that combines vision and graphics, sound, and haptic feedback), (2) actional (user control of the experience and virtual body movement), (3) narrative (roles, contextual stories, learning activities, challenging tasks, and achievements), and (4) social features of learning (interaction with peers, and collaborative activities). These categories reflect the multidimensional nature of immersive VR learning design, where sensory fidelity, user interaction, narrative elements, and social aspects all contribute to the overall effectiveness of the learning experience. Effective design within these categories can lead to more engaging and impactful VR-based learning experiences, making them valuable tools in education and training.

Based on the existing learning theories and instructional design models, practitioners are adapting or creating learner-centred innovative pedagogies such as the three 'gogies' (Heutagogy, Peeragogy, and Cybergogy) to optimize immersive learning and teaching [48]. Metaverse learning design requires a robust instructional design framework that should incorporate various learning theories or conceptual frameworks to create effective and engaging learning experiences within a virtual, immersive, and interconnected digital universe. To design engaging in meaningful activities, constructivist learning theory combined with minimalism would align well with the dynamic and immersive nature of VR, AR, and MR technologies. Constructivism emphasizes active learning/engagement and hands-on experiences [49–51]. Minimalism focuses on delivering essential information concisely and efficiently [52,53]. In medical education, this could involve presenting key concepts, procedures, and information that are directly relevant to clinical practice and the learning outcomes that align with the learners' needs. By removing unnecessary details, learners can quickly grasp and retain essential information. By avoiding information overload and presenting only essential concepts, learners can better focus on constructing their understanding without being overwhelmed by extraneous details.

Several theories and conceptual frameworks can be seamlessly integrated into metaverse-based learning environments. Some of the examples would be

Table 2. A Sample ADDIE model for creating a metaverse-enriched curriculum.

Steps	Description	Expected Challenges	Potential Solutions
Analysis	• ***Needs Assessment:*** Identify educational needs and goals. **This assessment is to obtain** what skills or knowledge students need to gain from the metaverse learning experience. **This assessment also helps to determine learning objectives regarding** what learners should be able to do after completing the metaverse instructional experience**. The objectives should be written using measurable action verbs that should** align with different learning levels of Bloom's Taxonomy, from basic 'knowledge' acquisition to higher-order thinking (evaluation) to ensure comprehensive learning outcomes [66–68]. • ***Learner Analysis:*** Examine the characteristics of learners and/or the target audience's background, including their prior knowledge, learning preferences, learners' familiarity with VR, AR, and MR technologies as well as any challenges or constraints that may impact their engagement with the Metaverse. • ***Resource Analysis:*** Assess available resources and technology.	• Identifying specific Metaverse learning objectives. • Access to Metaverse-ready hardware and software.	• Collaborate with subject matter experts and technology staff. • Conduct needs assessment or gap identification surveys or interviews with learners or the targeted population. • Seek funding or grants for necessary technology if applicable.
Design	• ***Curriculum Design:*** Create a blueprint or a detailed curriculum outline that organizes the content into logical sections, and outlines the structure, interactions, and assessment strategies. • ***Assessment Design:*** Create assessments and evaluation criteria to measure student progress and achievement (e.g. Determine how to assess students' mastery of Metaverse-related concepts and skills). • ***Metaverse Integration:*** Determine Metaverse integration strategies. • *Curriculum Alignment:* Align the design with learning theories/pedagogical principles, interactivity, and assessment/evaluation strategies to maximize educational effectiveness.	• Integrating Metaverse experiences effectively. • Balancing immersive experiences with traditional content.	• Pilot Metaverse tools and gather feedback. • Use established pedagogical principles. • Consider accessibility and inclusivity.
Development	• ***Content Creation:*** Gather content and resources to create immersive 3D models, programming interactive simulations, designing avatars, and sources of multimedia such as videos and animations. • ***Technology Implementation:*** Set up technical infrastructure and/or choose the right technology platform (VR headsets, AR-enabled devices, or web-based tools). • ***Prototype Development:*** Develop prototypes for testing to bring the design concept to life in a functional and immersive metaverse environment as well as provide a user-friendly experience with easy navigation.	• Technical challenges in building Metaverse elements. • Ensuring scalability and reliability.	• Collaborate with experienced Metaverse developers. • Use established Metaverse platforms. • Conduct a pilot test with a small group of learners to identify any usability issues or areas for improvement. • Work with developers or technical staff if any technical glitches are experienced.
Implementation	• ***Training:*** Provide training to instructors, facilitators, and students to guide them through the content and technology effectively. • ***Delivery:*** Begin delivering the curriculum setting up the technical infrastructure, providing access to learners, and ensuring that the learning environment operates smoothly. • ***Support:*** Maintain ongoing support and on-demand troubleshooting.	• Learning curve for using Metaverse tools. • Technical issues during live sessions. • Student engagement in virtual environments.	• Offer workshops, tutorials, and on-demand technical support. • Have technical support available during classes. • Gamify the learning experience for engagement.
Evaluation	• ***Formative Evaluation:*** Continuously assess and gather feedback to obtain information related to content review, including instructional materials for accuracy, relevance, and effectiveness in conveying the concepts of VR, AR, and MR. • ***Summative Evaluation:*** Conduct a summative evaluation to measure achievement (e.g. the effectiveness of the metaverse learning experience in achieving its intended outcomes). This may include learner assessments, feedback surveys or focus group interviews, data analytics tracking, and qualitative observations. • ***Revision and iteration:*** Iterate and revise the curriculum (e.g. The data collected informs refinements and improvements to enhance the learning experience continually.).	• Limited data on Metaverse learning outcomes. • Misalignment between goals and outcomes. • Resource constraints for revisions.	• Collect intelligent data on user interactions and progress. • Adjust goals and objectives based on assessment results. • Seek additional funding for improvements if applicable.

the ADDIE Model [54], David Kolb's Experiential Learning Model [55], John Keller's ARCS model [56], Robert Gagne's Nine Events of Instruction [57], SAM Model [58], Siemens' Connectivism [59], Lave's and Wenger's Situated Learning Theory [60], and Constructivist 3D Learning Environment Model [61,62]. Through a thoughtful approach, all these theories or models can be combined and customized to create a tailored approach to create effective and engaging learning experiences within the metaverse. However, medical educators/practitioners must be familiar with the principles of learning design and the integral elements of pertinent theories of learning. This knowledge equips them to dismantle potential barriers that may arise when applying metaverse technology to teaching and learning.

In this section, we present essential design principles aimed at equipping educators and practitioners worldwide with a valuable guide to address challenges and construct productive learning environments within the metaverse. To achieve successful learning design and implementation, we have adopted the ADDIE instructional design model, renowned for its versatility and widespread utilization in the development of technology-enhanced learning experiences [54,63–65].

(a) Components of the design elements system

As discussed earlier in this paper, the basic components of the design elements are virtual environments that serve as dynamic, interactive spaces that replicate real-world scenarios, offering learners the opportunity to engage with knowledge in a three-dimensional and immersive manner. Identity and avatars allow for personalization and self-expression, enabling individuals to experiment with different virtual personas and engage with others within the metaverse. Problem-based scenarios foster critical thinking and decision-making by presenting learners with challenging, real-world situations. Collaborative spaces transcend geographical boundaries, facilitating teamwork and social learning. Resource exploration empowers learners to access a diverse array of digital materials, enabling them to tailor their learning experiences to their unique needs and interests. These design elements collectively form a valuable roadmap for educators and practitioners to navigate the evolving landscape of metaverse-based learning.

(b) Design process

Due to the systematic and iterative approach of the ADDIE model (Analysis, Design, Development, Implementation, and Evaluation), practitioners and educators can create engaging, pedagogically sound, and inclusive learning experiences that leverage the unique capabilities of the metaverse to create effective and impactful learning experiences. We have used this model to create a framework as shown in Table 2. We also presented a comprehensive overview of the key components and considerations necessary to design and implement educational experiences within the emerging metaverse in an effective and efficient manner in an appendix (See Supplemental Appendix 1).

Conclusion

Embracing the metaverse's potential in LMIC medical education institutes requires a comprehensive approach to address the multifaceted challenges. By proactively navigating privacy concerns, financial barriers, discomfort, learning curve, and other obstacles, educators and institutions can create a transformative educational landscape that fosters inclusivity, innovation, and equitable learning opportunities. The metaverse instructional design model presented in this paper encapsulates a comprehensive approach to harnessing the potential of immersive virtual environments for medical education. This model underscores the importance of meticulous analysis, thoughtful design, and careful consideration of learner needs and access. It advocates for the seamless integration of digital equity, user-friendly interfaces, and accessible communication modes to ensure that the metaverse becomes a truly inclusive learning space. By addressing the learning curve, and technical barriers, and fostering interactivity, educators and designers can pave the way for engaging and effective metaverse-based education. In a rapidly evolving educational landscape, the metaverse presents a powerful platform for innovation and student-centered learning. Embracing the recommendations outlined in this design model empowers educators to create transformative and equitable learning experiences. These technologies hold promise in transforming medical education, enabling learners to immerse themselves in intricate anatomical structures and radiological interpretations in ways previously unattainable. Yet the most important challenges that may arise by implementing these tools could be reduced face-to-face communications, cost limitations, educational, and user attitude challenges, and lack of contextualization.

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Author contributions statement

SSF played a pivotal role in the conception and design of this review paper. All authors conceptualized, performed a literature search, drafted, and revised the manuscript. SSBZ and UA crafted the students' voice section based on their experiences and literature searches. KOL also provided significant intellectual expertise and offered valuable insights into instructional design theories, which greatly enriched the content of this commentary paper. All authors reviewed and approved the final version of the manuscript for submission.

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