REVIEW

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Digital Twins in Healthcare and Their Applicability in Rhinology: A Narrative Review

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Digital twins were initially introduced in the aerospace industry, but they have been applied to the medical field in the 2020s. The development of the Internet of Things, sensor technology, cloud computing, big data analysis, and simulation technology has made this idea feasible. Essentially, digital twins are virtual representations of real-world data that can generate virtual outcomes related to a patient based on their actual data. With this technology, doctors can predict treatment outcomes, plan surgery, and monitor patients' medical conditions in real time. While digital twins have endless potential, challenges include the need to deal with vast amounts of data and ensure the security of personal information. In the field of rhinology, which deals with complex anatomy from the sinus to the skull base, the adoption of digital twins is just beginning. Digital twins have begun to be incorporated into surgical navigation and the management of chronic diseases such as chronic rhinosinusitis. Despite the limitless potential of digital twins, challenges related to dealing with vast amounts of data and enhancing the security of personal data need to be surmounted for this method to be more widely applied.

Keywords: Digital twins; Digital technology; Telemedicine; Mobile health; Healthcare.

INTRODUCTION

Technological advances have brought forth a revolutionary concept in healthcare known as "digital twins" [1]. Dr. Michael Grieves initially introduced the concept of a digital twin in 2002. It is a digital model that depicts a physical entity or system using dynamic software models and sensor data to analyze and anticipate its real-time status and future behavior [2]. This innovative methodology in medicine utilizes computational models to comprehend the biological development of diseases, from the molecular level to the level of organs. In recent years, the concept of digital twins has gained considerable attention in the healthcare community, with numerous studies showcasing its potential for improved precision and personalization in medicine.

Rhinology has long been challenging for both surgeons and patients due to the complex anatomy, proximity to critical neurovascular structures, and diverse physiology of this region. The introduction of digital twin technology is expected to provide a new solution for rhinologists, offering a powerful tool to enhance patient care and outcomes.

This narrative review article aims to provide a comprehensive overview of digital twins in healthcare and their applicability in rhinology. The review covers the evolution and development of digital twin technology, its current state-of-the-art applications, and future directions for research. Additionally, this article provides a detailed analysis of the current literature on the use of digital twins in rhinology, including both the advantages and limitations of this technology. Ultimately, this review endeavors to furnish insights into the future application of digital twins in healthcare and their potential to enhance the field of rhinology and otolaryngology.

METHODS

A literature search was conducted on PubMed and Google Scholar using the keywords "digital twins," "digital healthcare"

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and "surgery." The search was restricted to English-language literature only, and studies related to the rhinology field (chronic rhinosinusitis [CRS], allergic rhinitis, sleep medicine, rhinoplasty, or sleep medicine) were selected. After identifying and removing duplicates, the resulting articles were screened by title and abstract, then critically evaluated for relevance and quality by the primary author. The review primarily included original articles, but also featured selected editorials and review articles from key opinion leaders. A snowballing strategy was used to identify additional relevant studies by screening the citations of the selected articles.

DISCUSSION

A brief history of digital twins

There was a lack of research or reports related to digital twins in the 2000s, even after the concept of digital twins was publicized. At the time, the technology required to enable the creation of digital twins had not yet been developed, resulting in a lack of studies or reports on the topic in the following decades.

However, with the steady advancement of basic technology, the National Aeronautics and Space Administration in the United States formalized the active implementation of digital twin technology in aerospace applications in 2012 [3]. Subsequently, in 2014, Grieves [4] published a white paper outlining the potential use of digital twin technology for conceptualization, comparison, and collaboration at actual manufacturing sites. Furthermore, with rapid advances in the Internet of Things (IoT), sensor technology, cloud computing, big data analysis, and simulation technology, research on digital twin technology has seen a marked increase in publications since 2017 (Fig. 1), and the term "digital twins" began appearing on the Gartner hype cycle, which is a graphical representation of how market expectations and acceptance of a new technology change over time. The digital twin first appeared in the Gartner hype cycle for emerging technologies in 2017, where it was positioned in the "innovation trigger" phase (https://www.gartner.com/smarterwithgartner/top-trends-in-the-gartner-hype-cycle-for-emerging-technologies-2017). At that time, digital twins were considered an emerging technology with the potential to transform various industries, including manufacturing, transportation, and healthcare. However, digital twins have come a long way since their emergence in the Gartner hype cycle in 2017. Today, they are no longer considered an emerging technology, but rather a mainstream one that has demonstrated its benefits across various applications. In recent years, digital twin technology has seen growing adoption across various fields, such as manufacturing, aerospace, energy, automotive, building and construction, and healthcare.

The concept of digital twins in healthcare

In the healthcare field, early on, significant efforts were made to understand the biology of diseases through computational models that span from the molecular to the organ level [5].

Digital twins are virtual copies produced by real-world processing data [6]. They can also be seen as a gateway connecting the real and digital worlds through shared data, which is called a digital thread [7-9]. A patient's clinical, demographic, genomic, or psychosocial data are sent to the digital world. Simultaneously, the patient's condition is evaluated in the real world based on data values transmitted in this digital thread [10]. In addition, the data transmitted through the digital thread can be stored in a large-scale data storage or disease registry built for future research (Fig. 2).

These efforts align with the concept of digital twins, which could potentially improve precision and personalization in medicine by addressing the uncertainty and variations that arise from individual patients.

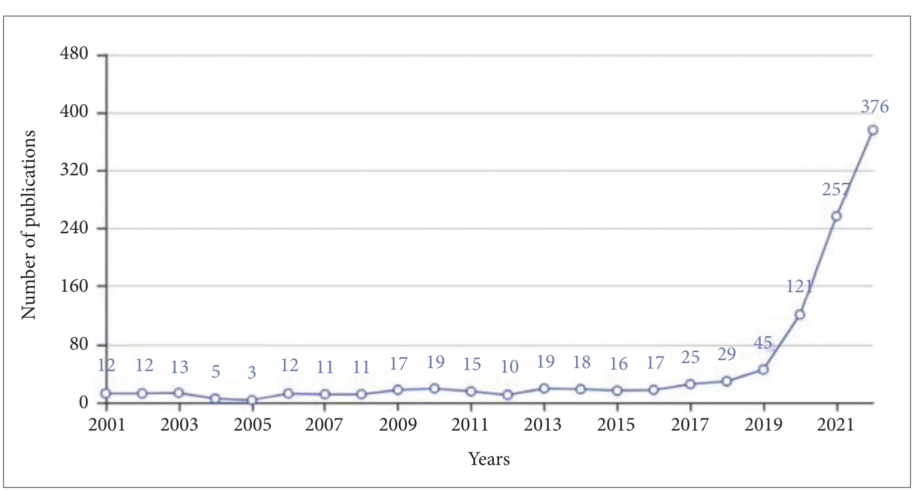

Fig. 1. The number of published papers related to digital twins searchable on PubMed has skyrocketed since 2017.

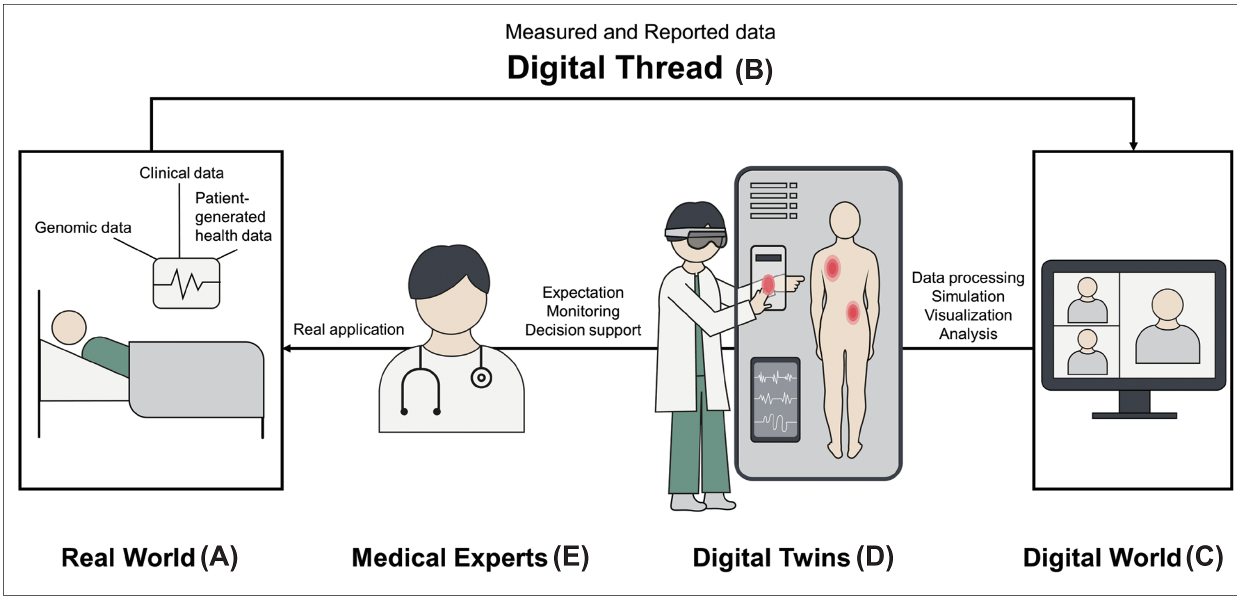

Fig. 2. The process from real-world data to digital twins for personalized healthcare. A: Any real-world data generated by a patient can be collected. In general, data from patients can be classified into three types: genomic data, clinical data, and patient-generated health data. B: A digital thread refers to a connection of shared data between the real world and the digital world. C: These data are transmitted to the digital world. D: Based on this information, we can create a digital replica, also known as a digital twin. A digital twin that mirrors a patient's distinct characteristics allows for expectations for treatments that would be administrated to a real patient. This makes it possible to predict the patient's individual outcome. E: This method is used to provide decision support to medical experts.

Case studies of digital twins in healthcare

Patient monitoring

Digital twin technology offers a range of applications for patient monitoring, including the management of chronic conditions, patient care coordination, and remote telemedicine thanks to the development of IoT and sensor technology. By creating a digital representation of a patient's physical and physiological state, healthcare professionals can use sensor data and other information to understand a patient's real-time status, predict potential health changes, and take proactive actions [11].

For instance, digital twins can be used to continuously track and analyze a patient's vital signs, such as heart rate, blood pressure, and oxygen saturation, and to monitor the progression of their condition over time [12]. This enables healthcare professionals to identify patterns and trends that may indicate changes in a patient's condition and take appropriate action to address any issues that arise. Because lung elastance is different for each patient who needs mechanical ventilator care in an intensive care unit, unintended lung injuries may occur even in similar settings. Zhou et al. [13] created a virtual patient based on the patient's data and predicted changes in specific ventilator settings. This method showed a high level of accuracy in predicting lung changes and contributed to reducing lung damage in each patient.

Surgical planning and simulation

Preoperative computed tomography (CT) and magnetic resonance imaging (MRI) scans are commonly used in modern healthcare to create detailed images of a patient's anatomy. These images can be used to create a digital model of the patient's anatomy, which can then be used as the basis for digital twins. Digital twins can be used by surgeons to plan the surgical approach, identify potential problems, and predict outcomes before surgery takes place [14]. This can help to reduce the risk of complications and optimize the surgical outcomes.

Digital twins can be utilized to simulate surgical procedures, providing a safe and controlled environment for surgeons to enhance their skills. This can be accomplished by developing a virtual reality representation of the patient's anatomy, with which the surgeon can interact using specialized tools such as haptic devices [15]. This can enhance the surgeon's dexterity and precision, and decrease the learning curve for new techniques. For example, osteotomy is typically performed using a minimal external incision, which requires the surgeon to rely on his or her sense of touch and perform the operation without direct visual guidance. Although experienced surgeons are skilled in this technique, it can be challenging for beginners to determine the exact location and extent of the required incisions for osteotomy. To overcome this learning curve, preoperative practice with the aid of a digital twin model can be employed before the actual surgery (Fig. 3).

Reconstructing preoperative images has become a standard process for understanding patient-specific anatomy, but those attempts were not common in the 2000s. A case was reported in the *New England Journal of Medicine* in 2000 in which surgical planning was performed with MRI scans taken during pregnancy for the separation of conjoined twins [16]. While this concept was relatively unfamiliar even in the 2000s, it has been actively introduced into the field of surgery. As a result, efforts to create a virtual environment that simulates the actual surgical situation have been proceeding rapidly. While digital twins were initially limited to understanding anatomy through image reconstruction, they have evolved towards constructing an environment that closely resembles the actual surgical situation with the development of tactile instruments and virtual systems.

Digital twins in rhinology

The digital era has also begun in the rhinology field. The concept of digital twins means providing personalized care to patients based on medical data. Cutting-edge technologies, such as artificial intelligence (AI), machine learning, sophisticated three-dimensional (3D) modeling, and extended reality, have a significant impact on medical decisions and are also available in rhinology. There are a few examples of digital twins that have been currently utilized in the rhinology field (Fig. 4).

Virtual patient-specific models for navigation

Functional endoscopic sinus surgery (FESS) has become more precise and safer with the development of navigation devices. FESS navigation is also becoming more accurate, but surgeons want to display major structures on the endoscope screen during FESS in real time [17]. A case has been reported wherein a technology that fused preoperative CT images and endoscopic images during surgery with augmented reality was developed at the cadaver level. The researchers created a virtual model with preoperative CT images and overlaid the 3D model on the actual patient's surgical images. During surgery, critical structures that must be avoided (e.g., the optic nerve) are displayed on an endoscopic screen. This display is anticipated to enhance the safety of the surgical procedure and facilitate the training of novice surgical trainees utilizing this system.

Real-time monitoring technology–focusing on mobile healthcare

Mobile healthcare technology has a prominent position in chronic disease. Bodini et al. [18] identified five digital therapeutics for asthma and chronic obstructive pulmonary disease patients. They developed a mobile application for patients and cloud-based software for recording the count of

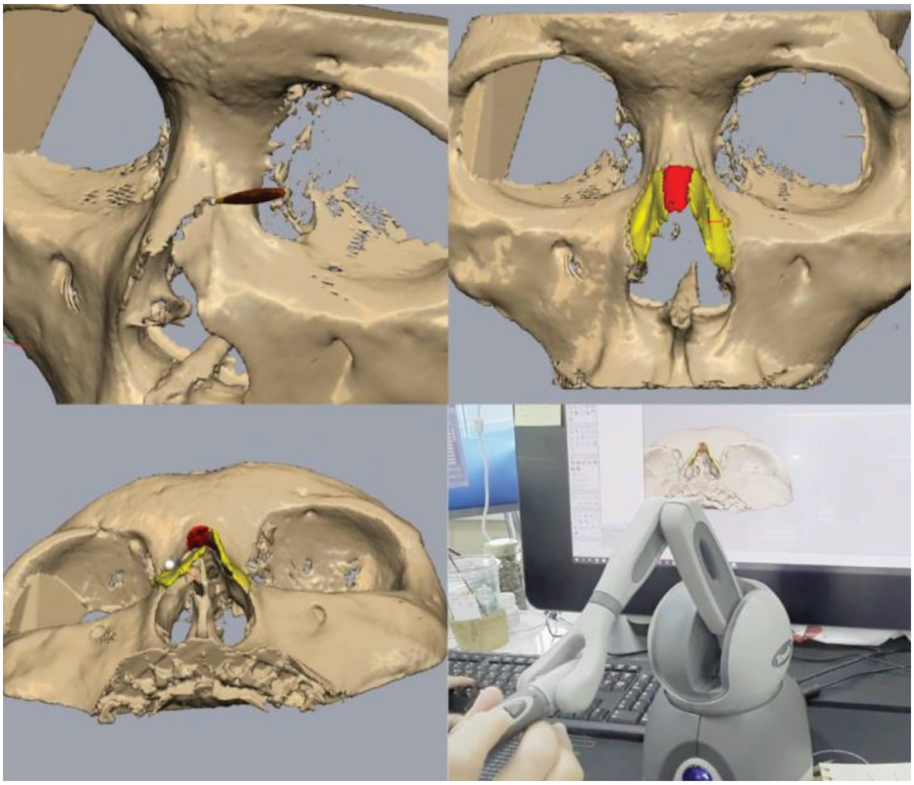

Fig. 3. Surgeons can perform an osteotomy on a digital twin that has been created based on a real patient's image with a haptic device before the real surgery (unpublished data, Jung, 2023).

inhaler use and patient's symptoms, providing alerts for the use of the inhaler, and transferring information from the sensor. It also transmits the patient's information to healthcare providers, including doctors.

Similarly, the European Forum for Research and Education in Allergy and Airway Diseases developed an application called mySinusitisCoach in 2017. This application monitors the symptoms of CRS patients in real time and provides the patient with a degree of symptom control and treatment options. In addition, these data are also shared with doctors, who can use the data to provide optimized treatment to patients [19].

In the field of otolaryngology, digital twins have been used to manage infectious diseases such as coronavirus disease 2019 (COVID-19) in addition to the management of chronic diseases. Furthermore, digital twins have been utilized in vaccine design, which took a relatively short time to conduct clinical trials [20]. However, the most important role of the COVID-19 pandemic was that telemedicine was introduced faster than expected. In a situation where face-to-face treatment was limited due to the pandemic, patients became more accustomed to sending their medical information through a device, and the collection of this data helped establish a virtual clinic.

Sleep is an area where digital twins need to be applied. A study to select patients with sleep-breathing disorders using a mobile device has already been conducted [21]. We are gathering patients' sleep data related to continuous positive airway pressure (CPAP) use and polysomnography, which can be fully utilized as a digital thread. A sleep specialist can provide real-time feedback on CPAP problems that occur during sleep. If a virtual model is made with digital twins, we can predict problems when starting CPAP in advance. This will make it possible to improve patients' adaptation periods more quickly.

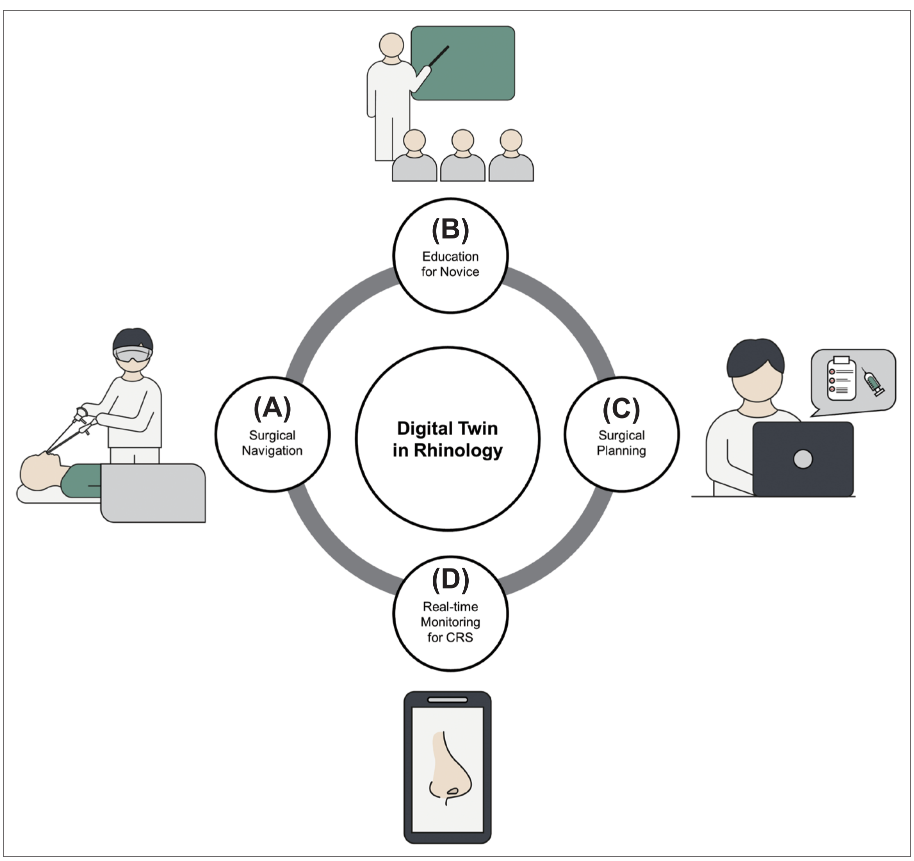

Fig. 4. Digital twins in rhinology. A: Augmented reality technology, which fuses preoperative computed tomography (CT) images and endoscopic images during surgery, has been developed to display major structures on an endoscope screen in real-time, enabling safer surgery and assisting surgeons. B: Patient-specific digital twin models for novice training provide real-time feedback without limitations on time or space and ensure patient safety during actual operations. C: Preoperative CT scans and magnetic resonance imaging can be used to create digital twins of a patient's anatomy, which can help surgeons plan surgical approaches, simulate procedures, and enhance their skills in a safe and controlled environment. As a result, the risk of complications can be reduced and surgical outcomes optimized. D: Digital twins have been utilized in the management of infectious diseases, vaccine design, and sleep-breathing disorders. The collection of patient data during the pandemic has led to the introduction of telemedicine. There have also been attempts to utilize mobile healthcare in chronic rhinosinusitis patients.

Education for novices

As standards for patient ethics are gradually strengthened, it is becoming difficult for novices to receive sufficient training to reach the learning curve. FESS is the most common type of surgery performed in the rhinology department, and the hurdles seem relatively high due to the complicated sinus anatomy and the use of various angle scopes. In addition, sufficient training is required because damage to major structures can lead to serious complications. Given that FESS is an endoscopic surgical procedure, it presents an opportunity for the creation of educational models utilizing virtual reality technology (Fig. 5). The Neurorhinological Surgery group developed a mixed-reality simulator and presented a technique in which trainees train on a patient-specific model using a device capable of real-time tracking [22]. As a result, trainees can practice with the same patient model as the actual patient, receiving real-time feedback on the surgical process without time and space limitations. Above all, it is possible to secure the patient's safety during the actual operation with a sufficient period to achieve proficiency.

Digital twins are a breakthrough concept that will play a paramount role in medical management and treatment in the future, but there are matters of concern. First, we should always keep the issue of data availability in mind because digital twins are a concept based on data. The privacy and ethical use of data must be fundamental to the development of digital twins. It is possible to access and utilize healthcare data based on such premises. In addition, it is currently possible to collect massive amounts of data, but formalization and standardization of data are required to make data usable. However, the automatic processing of such data has not been technically perfectly feasible yet. Technological development should also progress to utilize digital twins in healthcare more actively.

Reprocessed data with digital twins can be helpful in clinical decision-making, but physicians should not use it as an absolute criterion. For instance, if an AI model recommends an optimal treatment that boosts a patient's survival rate, the physician must contemplate whether this choice can also enhance the patient's quality of life. Consequently, when evaluating digital twin models, it is imperative to consider the patient's preferences alongside other factors.

CONCLUSION

Digital twins have the potential to revolutionize the healthcare industry by offering solutions to multiple challenges, in-

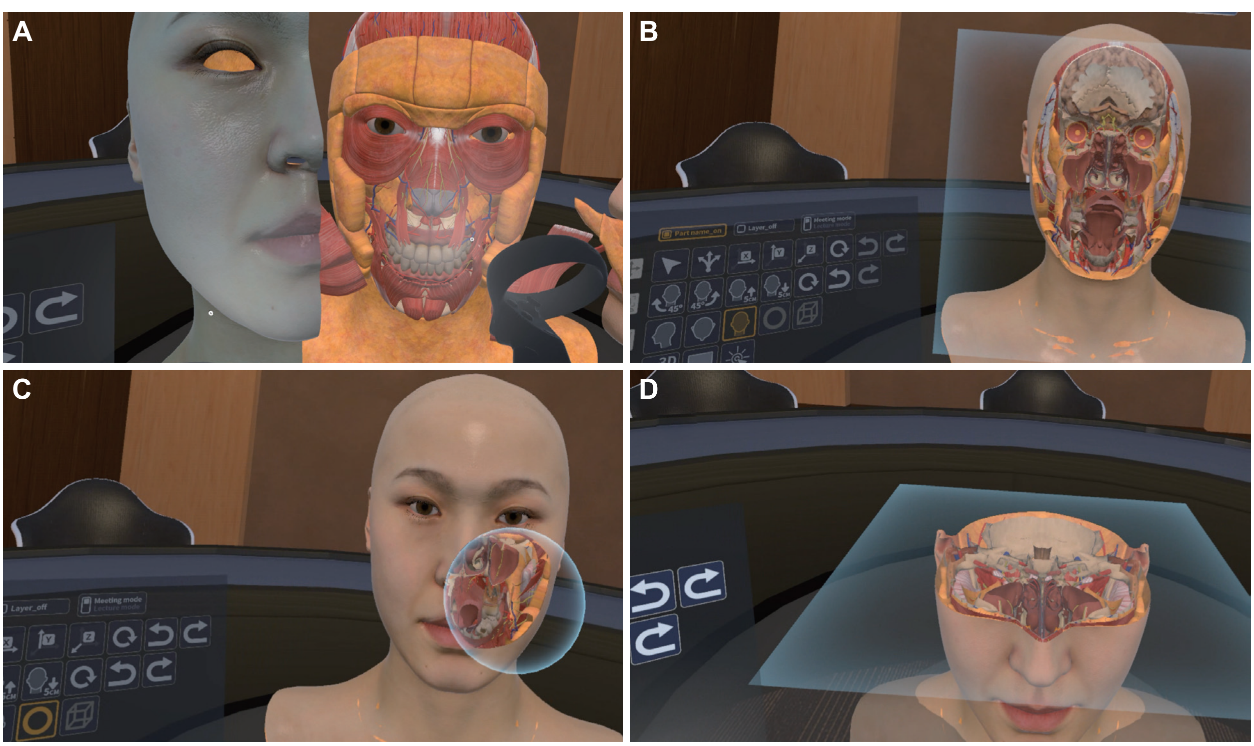

Fig. 5. Unveiling three-dimensional (3D) sinonasal anatomy for enhanced preoperative planning and spatial orientation. The illustration represents a 3D model of the sinonasal anatomy, created using a patient's computed tomography image (A). The (B) coronal, (C) endoscopic magnified, and (D) axial cuts of the model can be viewed in 3D, allowing for a comprehensive understanding of the patient's anatomy prior to surgery while wearing a head-mounted display. The major structures such as muscles, vessels, and nerves are also displayed, which is useful for spatial orientation (unpublished data, Jung, 2023).

cluding emerging infectious diseases, telemedicine, and the need to reinforce medical ethics standards. Within the realm of rhinology, digital twin studies are still in the nascent stages, and various applications of the concept are yet to be explored. These studies involve real-time marking of critical anatomy during endoscopic surgery based on preoperative imaging, the use of virtual models for training purposes, and the implementation of mobile healthcare for CRS patients. Despite the potential benefits, research on digital twins for sleep medicine, rhinoplasty, and sinonasal cancer remains relatively limited.

Ethics Statement

Not applicable

Availability of Data and Material

Data sharing does not apply to this article as no datasets were generated or analyzed during the study.

Conflicts of Interest

The authors have no potential conflicts of interest to disclose.

Author Contributions

Conceptualization: all authors. **Formal analysis:** Minhae Park, Namkee Oh. **Investigation:** Minhae Park, Namkee Oh. **Methodology:** Minhae Park, Namkee Oh. **Project administration:** Minhae Park. **Supervision:** Yong Gi Jung. **Validation:** all authors. **Visualization:** Minhae Park, Yong Gi Jung. **Writing—original draft:** Minhae Park, Namkee Oh. **Writing—review & editing:** all authors.

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