1. Introduction

<intro>

[VR and Cardiothoracic surgery]

The advent of virtual reality (VR) technology has revolutionized various fields, including medicine and surgery, by offering immersive three-dimensional (3D) visualization capabilities that surpass traditional two-dimensional (2D) imaging. This innovative technology provides enhanced depth perception and dynamic interaction, enabling surgeons to visualize and interact with anatomical data in unprecedented ways. The integration of VR into medical practice promises to transform preoperative planning, particularly in the context of complex and intricate procedures such as cardiothoracic surgeries.

Cardiothoracic surgeries are among the most challenging in the medical field due to the intricate structures and vital functions of the heart and thoracic cavity. Preoperative planning for these procedures requires a meticulous understanding of the spatial relationships within the patient's anatomy. Traditional imaging techniques, while invaluable, often fall short in providing the depth and detail necessary for optimal surgical planning. Studies have shown that up to 25% of cardiothoracic surgical complications could be mitigated with better preoperative planning (Smith et al., 2021). This highlights the critical need for advanced imaging technologies that can enhance spatial comprehension and surgical precision.

[Statistics]

In recent years, the integration of virtual reality (VR) technology into medical practice has revolutionized preoperative planning by offering unprecedented 3D visualization and interaction with patient-specific anatomical data. This transformative approach has seen a significant surge in adoption, dramatically increasing the number of VR-related research publications across a wide array of specialties. For instance, a systematic review identified a remarkable rise in VR applications in cardiothoracic (38%), general surgery (21%), neurosurgery (19%), oral and maxillofacial surgery (10%), orthopedic surgery (4%), otorhinolaryngologic surgery (4%), plastic surgery (2%), and urology (2%). VR provides an immersive environment where surgeons can explore complex anatomical structures from multiple angles, enhancing their spatial understanding and decision-making capabilities. Recent advancements in VR hardware and software have significantly improved the fidelity and usability of these systems, making them more accessible and practical for clinical use. Despite the growing body of evidence supporting VR's efficacy in enhancing surgical outcomes—demonstrating its effectiveness in altering surgical plans in 33% to 95% of cases depending on the specialty—the technology remains underutilized in many medical institutions. This research article introduces a novel VR system designed for preoperative planning, showcasing its capabilities, clinical applications, and potential benefits in improving surgical precision and reducing operative times. By addressing both the technical and clinical aspects, this study aims to contribute to the growing literature on VR in medicine and provide a comprehensive evaluation of its impact on surgical planning processes. As VR technology continues to evolve, its integration into preoperative planning is poised to become a standard practice, benefiting a broad spectrum of surgical disciplines.

[Characteristic of VR for general surgery purpose]

Virtual reality offers a solution to these challenges by bridging the gap between 2D images and actual 3D anatomical structures. Immersive 3D visualization allows surgeons to perceive depth cues and spatial relationships more effectively, which is crucial for understanding complex anatomical configurations. Dynamic interaction with the VR environment enables the viewing of structures from multiple angles and scales, providing a comprehensive perspective that static images cannot offer. Additionally, VR's embodied interaction feature integrates the user’s movements, offering vestibular and proprioceptive feedback that mimics natural interactions with real volumes. This enhances the surgeon's spatial understanding and reasoning, which are critical for accurate preoperative planning.

[Collaboration]

Virtual reality (VR) platforms integrated with conventional communication devices significantly enhance the convenience and accessibility of preoperative planning. Real-time communication through smartphones, tablets, and computers allows medical professionals to connect to VR meetings from virtually anywhere. For instance, a surgeon can join a VR preoperative planning session using a smartphone, participating in detailed discussions and manipulations of the surgical site in 3D. This flexibility ensures that critical insights and decisions can be made collaboratively without the need for all team members to be physically present in the same location. Additionally, this integration facilitates the inclusion of specialists from different geographical locations, promoting a multidisciplinary approach to surgical planning. By combining VR with conventional communication technologies, healthcare providers can ensure comprehensive, efficient, and flexible preoperative collaboration, ultimately improving surgical precision and patient outcomes.

1. Related Works
2. System Design and Implementation

Our

* 1. Medical Image Acquisition

Volumetric data acquired from computer tomography (CT) scanners was output in the Digital Imaging and Communication (DICOM) format. To minimize loss of resolution quality during following 3D models production, a minimal slice thickness of 1.00 mm was chosen for scanning protocol.[1]

*Maximal resolution computed tomographic (CT) angiography of the head and neck was performed (Siemens SOMATOM Definition Edge). A slice thickness of 0.6 mm with 0.31 mm increment was applied, and data were reconstructed with 0.4 mm images. CT venography was performed similarly with 20 seconds delay after the arterial phase. Images were acquired from the recipient during one of the multiple preoperative clinical encounters. Upon arrival of the donor to our institution, our urgent facial VCA image acquisition protocol was activated in collaboration with the radiology department.*

*examinations were done using six scanners (Brilliance iCT 256, Philips Healthcare [Best, Netherlands]; Sensation 64 and SOMATOM Definition AS+, Siemens Healthcare [Forchheim, Germany]; Aquilion one, Toshiba [Tochigi, Japan]; Revolution CT and LightSpeed VCT, GE Medical system, [Milwaukee, WI, USA) with 100, 120, 130 kV, or automatic mA control without extra noise reduction processes. The slice thickness was 0·7–1·5 mm, and image size was 512×512 pixels. The portal venous scan was obtained at 70–80 s after intravenous administration of contrast medium. The volume of the contrast medium (mL) was determined by multiplying the bodyweight (kg) by 1·5, with an upper limit of 150 mL. All images were reconstructed into 5 mm slices for subsequent interpretation and analysis.*

* 1. Segmentation and Virtual Reality Object Generation

The DICOM images were anonymized and then imported into a commercially available medical imaging workstation, Synapse 3D (Fujifilm, Tokyo, Japan), for 3D visualization, segmentation, and 3D model generation. Skin, bones, vascular structures, bronchi, bronchopulmonary segments, and tumors (if present) were segmented from the CT datasets semiautomatically using built-in extraction functions in Synapse 3D Viewer and Lung Analysis Resection applications. Additional segmentation of small branches and border modification were performed manually by assigning or deleting pixels in the image dataset to the corresponding desired anatomic structures. Isolation of submodels (e.g., isolating a rib from the bone models) was also conducted by manually dividing the segmented data. During manual refinement, the CT image data with adjustable window settings and a 3D volumetric rendering of the segmented region were both available to the operator for optimal evaluation and stereoscopic visualization. After segmentation, texture mapping was applied to define surface texture and color information of the segmented data. The resulting data were then exported into a standard tessellation language (STL) file format.

* 1. Model Optimization

To optimize the mesh representation of the 3D models, a open-source 3D mesh processing software, MeshLab (version 2023.12), was utilized[2]. The STL files were imported into MeshLab, and first underwent a series cleaning operations, including the removal of duplicated vertices, unreferenced vertices, and zero-area faces to enhance the mesh integrity. Then quadric edge collapse decimation with a targeting a 50% reduction in face count was applied, to reduce the polygon count while preserving essential geometric features[3]. Laplacian smoothing was applied to ensure a balanced surface smoothness. Normals were recomputed to correct any lighting and shading inconsistencies using weighted normal calculation. Finally, isolated mesh components were removed with a minimum component size set to 10% of the overall model diameter. The optimized meshes were then exported in OBJ format for integration into our VR surgery planning system.

* 1. VR Environment Development

For the presentation and interaction with the 3D models, our software was developed based on the Unity 3D engine (Unity Technologies, San Francisco, CA, version 2020.3) with the Meta XR All-in-One SDK (version 60). The universal rendering pipeline (URP) made by Unity was adopted and allowed for optimized graphics across different platforms, from mobile devices, PCs, to head-mounted displays included in our study.

The software was installed and run on an Omen 16 laptop (HP Inc., Palo Alto, California) with Intel® Core™ i7-12700H CPU with 2.30 GHz, 16 GB Rapid Access Memory and NVIDIA® GeForce™ RTX 3070 graphic card. For immersive virtual reality experience, we employed the Meta Quest Pro and Meta Quest 3 (Meta, Menlo Park, California) head-mounted displays (HMDs), with their associated controllers. The Meta Quest Pro features a resolution of 1800 x 1920 pixels per eye, a refresh rate of 72/90 Hz, and a field of view of 106 degrees. The Meta Quest 3 improves upon its precedent with a higher resolution of 2064 x 2208 pixels per eye, refresh rate of up to 120 Hz, and a field of view of 110 degrees. These devices provided stereoscopic visualization and interaction via dynamic adjustment of medical image data to the movement and changes in position of the user. During the execution of the software, the HMD was tethered to the computer utilizing the built-in link functionality of Meta Quest models.

* 1. User Interaction and Interfaces

As handheld controllers provided a more intuitive approach to interact within a 3D virtual reality setting compared to conventional 2D controls, we employed and implemented several interaction functions on the Meta Quest Touch Pro Controllers and Meta Quest 3 Touch Plus Controllers. Also, an intuitive Graphical User Interface (GUI) was developed as a menu for segmented regions of the 3D models, anonymized patient profile, and quick assess to certain functions (Fig ???). The core interactions implemented in our system included

* Continuous translation in all six degree of freedom (6DoF)
* Continuous rotation in all three degree of ratational freedom (3DoF)
* Selective visibility and transparency of individual segmented regions of the model
* Measurements of omnidirectional linear distance on the volume by placing the start and end points
* Marking and drawing on the volume freely

A concurrent 2D slice image viewer was developed for comparison and and correlation between 3D models and conventional medical images including CT and MRI. A virtual cutting plane on the 3D models represented the corresponing level of the slice (Fig ???) and translated accordingly when the user scrolls through the images.

* 1. Synchronous Sharing (RTC)

To enable real-time collaboration, education and general communication purposes, we developed a streaming feature allowing users without HMDs to join the peropeartive planning system using conventional input devices and built-in browsers. Based on web real-time communication (WebRTC), an extended reality (XR) cloud streaming service and a server were set up. When the main user interacted with and updated the system, an update was sent to the corresponding server, then the server multicasts all the updates to other clients.[4]

* 1. Asynchronous Demonstration and Portable End Products

* 1. Study Participants
  2. Clinical End Point and Qualitative Assessment

1. Results
   1. Case Series
   2. Usability Studies
2. Discussion

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