1. Introduction

Cardiothoracic surgery epitomizes the complexity and precision required in surgical interventions. These procedures often involve intricate anatomical structures and necessitate meticulous preoperative planning to mitigate risks and improve outcomes. The high stakes associated with cardiothoracic surgeries demand detailed visualization and precise execution, as even minor errors can have profound consequences. Therefore, the integration of advanced imaging and planning tools for patient-specific preparation is critical in enhancing surgical accuracy and patient safety[1].

Virtual reality (VR) offers a promising solution to the challenges inherent in complex surgery planning[2-5]. By providing immersive, three-dimensional (3D) visualizations of patient-specific anatomy, VR enables surgeons to interact with and manipulate anatomical models in a immersive nature. This interactive capability allows for a more thorough visuospatial conversion from two-dimensional (2D) images, optimizing strategic planning. Supported by advancements in computing power and hardware[6], applications of VR in preoperative planning have demonstrated clinical benefits for both patients and physicians, including changes in preoperative planning[7-10], improvements in surgical decision-making[11], and reductions in operative times[12, 13] across multiple surgical subspecialties[14].

Integration with communication technologies can further enhance the convenience and accessibility of preoperative planning. The flexibility provided by enabling real-time interaction between multidisciplinary teams ensures that critical insights and decisions can be made without the need for all team members to be physically present in the same location[15, 16]. The combination of virtual reality with network communication can facilitate mutual understanding and collaboration among surgical team members, which is crucial for both patient outcomes and physician efficiency[17].

[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.

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.[18]

*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, an open-source 3D mesh processing software, MeshLab (version 2023.12), was utilized[19]. The STL files were imported into MeshLab and first underwent a series of cleaning operations, including the removal of duplicated vertices, unreferenced vertices, and zero-area faces to enhance the mesh integrity. Then, quadric edge collapse decimation targeting a 50% reduction in face count was applied to reduce the polygon count while preserving essential geometric features[20]. Laplacian smoothing was applied to ensure balanced surface smoothness. Normals were recomputed to correct any lighting and shading inconsistencies using weighted normal calculation. Finally, isolated mesh components were removed, with the 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, we developed our software using the Unity 3D engine (Unity Technologies, San Francisco, CA, version 2020.3) and integrated it with the Meta XR All-in-One SDK (version 60). We employed the Universal Rendering Pipeline (URP) from Unity, which facilitated optimized graphics performance across various platforms, including mobile devices, PCs, and head-mounted displays (HMDs) utilized in our study.

The software was deployed on an Omen 16 laptop (HP Inc., Palo Alto, California) featuring an Intel® Core™ i7-12700H CPU at 2.30 GHz, 16 GB of RAM, and an NVIDIA® GeForce™ RTX 3070 graphics card. For an immersive virtual reality experience, we used the Meta Quest Pro and Meta Quest 3 HMDs (Meta, Menlo Park, California), along with their corresponding controllers. The Meta Quest Pro offers 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 enhances these specifications with a resolution of 2064 x 2208 pixels per eye, a refresh rate of up to 120 Hz, and a field of view of 110 degrees. These devices provided stereoscopic visualization and interaction, dynamically adjusting the medical image data according to the user's movements and positional changes. During software operation, the HMD was connected to the computer via the built-in link functionality of the Meta Quest models.

* 1. User Interaction and Interfaces

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

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

A concurrent 2D slice image viewer was developed for comparison and correlation between 3D models and conventional medical images, including CT and MRI. A virtual cutting plane on the 3D models represented the corresponding level of the slice (Fig ???) and translated accordingly when the user scrolled 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 the system, an update was sent to the corresponding server, then the server multicasts all the updates to other clients.[21] Audio from main user could also be broadcasted to remote audiences.

* 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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