1. Introduction

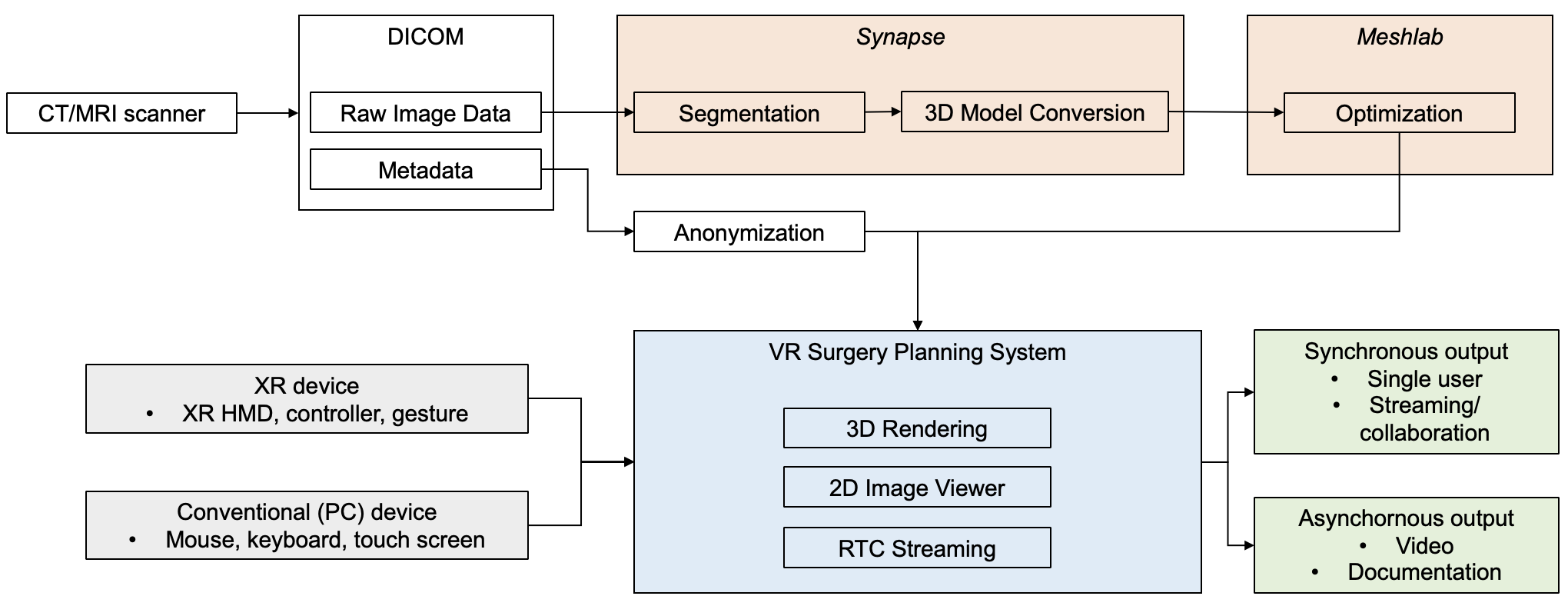
Planning for complex surgical procedures presents numerous challenges and difficulties, primarily due to the intricate and variable nature of human anatomy. The success of such interventions heavily relies on the surgeon's ability to anticipate and navigate these complexities, underscoring the importance of integration of advanced imaging and planning tools that can provide a detailed and accurate representation of the patient-specific anatomy[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[7-11], improvements in surgical decision-making[12], and reductions in operative times[13, 14] across multiple surgical subspecialties[15].

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[16, 17]. 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[18].

In this work, we develop a VR surgical planning system. This system allows multiple users to examine the patient organ model reconstructed from computed tomography (CT) dataset and collaborate on forming a preoperative plan in real time. Also we describe a protocol to process patient-specific image datas into 3D models for immersive interaction in virtual environment. *To demonstrate the use cases, performance, and efficacy, we have conducted prospective pilot study involveing ??? physicians with complex cardiothoracic pathology undergoing surgery.*

1. System Design and Implementation

Our proposed pipeline takes the imaging data from CT and generates a 3D model for viewing in virtual reality. It involves processing steps to segment the content of the images and reconstrct the anatomy for the patient. The resultant 3D models will be further modified and then imported into our VR surgical planning system supporting immersive visulization and intuitive interaction. The user can assess the system either by extended reality or conventional devices. See Fig ???. for schematic representation of our workflow and system architecture.

* 1. Medical Image Acquisition

Volumetric data acquired from computer tomography (CT) scanners was output in the Digital Imaging and Communication (DICOM) format. The slice thickness was set to ??? mm for acquisition protocol, and all images were reconstructed into ??? 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

To enable real-time collaboration, education and general communication purposes, we developed a streaming feature allowing users without HMDs to join the peroperative 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. Methods

We deisgn a pilot study with ??? participants including ??? attending surgeons and ??? residents. The purpose of the study was to perform an initial validation of the system and the recorded data rather than characterize the performance of the participants. Written informed consent was obtained from all patients as they were included for VR collaborative surgical planning with the system desrcibed above. After the introduction and familiarization to the system, all participating physicians then evaluated the patient-specific models as the main user with unlimited time. Every participant would also additionally join a session using smart phones and participate online. This study was approved by the ???. Informed consent was obtained from all participants, including physicians and patients.

1. Results

The presented pipeline requires approximately an hour from importing raw data to presentation of 3D models in the VR system. This time estimate comes from running the program on the aforementioned computing resources and device.

The segmentation and visual fidelity of the end product was verified in both conventional 2D displays and HMDs, which are rated functionally accurate by all partcipants. The results for one patient are shown in Figure ??? and video ???.

1. Discussion

Surgical interventions for complex pathologies are highly intricate, requiring precise planning to optimize outcomes while preserving critical structures. These challenges necessitate advanced preoperative planning solutions that enable detailed visualization and interaction with patient-specific anatomy. Our virtual reality collaborative preoperative planning system addresses these needs by proposing a workflow on reconstructing patient-specific 3D anatomic models from 2D image data and implementing such a VR system for collaborative interaction and annotation of these virtual models in an immersive environment.

The quality of the input data directly afftced the fidelity of the 3D reconstrctions in virtual environment[22, 23]. To avoid loss of details in the 3D models, acquisition and processing parameters of CT/MRI data needed to be caliberated and standrized. Slice thickness of CT has been shown as one of the primary factors affecting 3D model resolution and quality, with multiple studies proposed a threshold of maximum of 1.25 mm[23, 24]. As a result, we adopted a similar setting for input quality selection in our study.

The segmentation process is one of the time and resource critical steps of generating anatomically accurate models. Manual segmentation by trained physicians or technians has been extensively adopted in previous studies with acceptable accuracy[8, 25, 26]; however the workload of manual tracing limited its efficiency, cost-effectiveness, and reproducibility. Semi-automatic or automatic segmentation aim at replacing manual labor with computational workload. Methogolodies including thresholding, neural network, or hybridization of machine learning algorithm have been reported in segmenting normal tissues or pathologies across different regions. Semi-automatic segmentation alleviates the manual workload by producing segments of different organs efficiently, while preserving the flexibility of manual editing in cases with rare anatomical variation or complex pathology. As shown in our study, intergration of semi-automatic segmentation into generation of 3D-VR models has been reported feasible and clinically useful for preoperative planning[11, 27]. A fully automatic process to segment multiple structures within a region of interest can possibly further improve the effiency and facilitate streamlining the process into a executable pipeline[28]. However, there is still limited evidence of feasibility of incoporating such strategy into clinical planning.

Earlier studies on preoperative planning for thoracic tumors primarily focused on generating 3D anatomical models from CT and MRI data and displaying them on conventional 2D devices[29, 30]. However, reliance on 2D displays limited the depth perception and interactive capabilities necessary for comprehensive evaluation and planning. More recently, several studies explored in the application of virtual reality (VR) and immersive visualization technologies for preoperative planning for intrapulmonary or thoracic tumors[11, 27, 31-33]. VR systems demonstrated a positive impact on surgical strategy and surgeon confidence with favorable utility[7, 11, 33].

Our study was the first to assess the use of 3D-VR system in surgical planning for complex thoracic and report our early results on the system usability, feasibility and clinical applicability in selected patients.

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