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Abstract:

Objectives:

Virtual reality (VR) is an increasingly valuable teaching tool, but current simulators are not typically clinically scalable due to their reliance on inefficient manual segmentation. The objective of this project was to leverage a high-throughput and accurate machine learning method to automate data preparation for a patient-specific VR simulator used to explore preoperative sinus anatomy

Methods:

An endoscopic VR simulator was designed in Unity to enable interactive exploration of sinus anatomy. The Saak transform, a data-efficient machine learning method, was adapted to accurately segment sinus CT scans using minimal training data, and the resulting data was reconstructed into 3D patient-specific models that could be explored in the simulator.

Results:

Using minimal training data, the Saak transform-based machine learning method offers accurate soft-tissue segmentation. When explored with an endoscope in the VR simulator, the anatomical models generated by the algorithm accurately capture key sinus structures and showcase patient-specific variability in anatomy.

Conclusions:

By offering an automatic means of preparing VR models from a patient's raw CT scans, this pipeline takes a key step towards clinical scalability. In addition to preoperative planning, this system also enables virtual endoscopy—a tool that is particularly useful in the COVID-19 era. As VR technology inevitably continues to develop, such a foundation will help ensure that future innovations remain clinically accessible.

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Development of a Machine Learning-Enabled Virtual Reality Tool for Preoperative Planning of Functional Endoscopic Sinus Surgery

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Methods An endoscopic VR simulator was designed in *Unity* to enable interactive exploration of sinus anatomy. The Saak transform, a data-efficient machine learning method, was adapted to accurately segment sinus CT scans using minimal training data, and the resulting data was reconstructed into 3D patient-specific models that could be explored in the simulator.

Results Using minimal training data, the Saak transform-based machine learning method offers accurate soft-tissue segmentation. When explored with an endoscope in the VR simulator, the anatomical models generated by the algorithm accurately capture key sinus structures and showcase patient-specific variability in anatomy.

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Keywords

Computed Tomography

Introduction

The novel coronavirus disease 2019 (COVID-19) pandemic has thrust patients and healthcare workers into a vulnerable state. Faced with this global crisis, the medical field must embrace new technologies to advance education and patient care.^{1,2} Stay-at-home orders, widely implemented during the early phase of the pandemic, resulted in a dramatic decrease in the feasibility of in-person examinations. The subsequent increase in video and telehealth visits during this time period suggests the need for alternative, safer, and no-contact methods for examining patients, to avoid delays in diagnosis and treatment.

Virtual reality (VR) offers tremendous potential in the medical field, especially for inherently visual-spatial exercises like diagnostic and surgical endoscopy.³⁻⁵ Sinus anatomy is intricate and variable, with close proximity to critical neurovascular structures.⁶⁻⁸ Preoperative planning and innovative intraoperative image guidance systems presently rely on 2D CT planes that may not offer the most intuitive visualization of anatomy.⁹⁻¹²

In otolaryngology, VR has demonstrated efficacy as a teaching tool for students, residents, and surgeons to hone procedural skills.¹³⁻²⁶ While such innovations showcase VR's potential, current simulators rely on laborious manual image segmentation—the identification of different components in an image—and are thus not clinically scalable.²⁰ Machine learning methods offer

the potential to automate high-quality image segmentation, addressing a significant hurdle of clinical VR.²⁷⁻³⁰

Existing machine learning methods like convolutional neural networks (CNNs) have shown promise as a segmentation tool across a variety of modalities but require a large volume of high-quality annotated data, as observed in previous studies centered around sinus segmentation.³¹⁻³³ True clinical applicability demands a more data-efficient alternative.³⁴

Subspace approximation with augmented kernels (Saak) is a novel transformation that offers a fully reversible and data-efficient means of feature extraction.^{35,36} Equipping the Saak transform with a classifier produces an automatic image segmentation algorithm capable of operating with minimal training data. We previously developed this method and studied its ability to segment intricate light sheet fluorescence microscopy images, finding that Saak transform-based machine learning consistently outperformed a CNN, particularly with lower numbers of training images.³⁶

In this study, we leverage data-efficient machine learning to create a VR tool for patient-specific surgical planning.⁵ Our Saak transform-based method automatically segments soft tissue and bone from sinus CT scans to allow operators to explore a patient's unique anatomy in the VR domain.

Materials and Methods

Preparation of training data

All data collection for this study received IRB approval. We obtained DICOM files for 3 patients' sinus CT scans with identification stripped for confidentiality purposes. Subjects were selected from a pool of preoperative candidates for functional endoscopic sinus surgery. Both the soft and bony tissues of all 548 axial images, between 100-200 per CT scan, were annotated in *Amira* to establish ground truth for training and validation purposes.

Segmentation algorithm

We used MATLAB to extract and trim each axial slice from the raw CT scan DICOM files to 350x350 windows encompassing the airspace structures. We then used randomly selected images and their manually segmented labels to train our Saak-based machine learning algorithm, consisting of a multi-stage Saak transform—based on principle component analysis (PCA)—and a random forest classifier. The model segmented all desired anatomic structures at once for each axial slice. We ran the trained model to segment each CT scan such that training data did not overlap with testing data.

Validation of segmentation

The Saak-based method was validated using randomly selected, non-overlapping axial images from the CT datasets. We calculated intersection over union (IOU) and dice similarity coefficient (DSC) of the segmentation results of our algorithm trained with 3, 6, and 9 training images.

VR Demo

After obtaining segmented data, we reconstructed the 3D object in *Amira* 6.1 and generated, compressed, and exported a surface model to *Autodesk Maya* for scaling and smoothing. We

developed our VR demo in *Unity* using models exported from *Maya*. We finalized all steps in *Maya* and *Unity* with educational licenses.

We used an Acer Windows Mixed Reality Headset (Acer) as the VR viewer and an educational-purpose license version of Unity 5.5 (Unity Technologies) as the development engine. In a new *Unity* project, we imported the patient's 3D reconstructed head and mounted a probe with a virtual endoscopic camera. We enabled user control of the probe using either Acer Windows Mixed Reality Controllers or keyboard inputs and computed its coordinate position for mapping to 2D slices of the CT scan. Finally, we designed a *Unity* canvas that contained windows for the probe's location and the endoscopic camera's display. The outline of our VR pipeline is outlined in figure 1.

Results

Automatic Segmentation

We compared the Saak transform segmentation results of soft tissue (Fig. 2, blue) and bone (Fig. 2, red) with the ground truth (Fig. 2, white). Under the condition of 3, 6, and 9 training images, the DSC of soft tissue was 0.94 ± 0.05 , 0.96 ± 0.04 , and 0.98 ± 0.01 , respectively, while the intersection over union IOU was 0.89 ± 0.09 , 0.92 ± 0.07 , and 0.97 ± 0.02 . In comparison to soft tissue segmentation, bone images had DSCs of 0.30 ± 0.06 , 0.66 ± 0.10 , and 0.6 ± 0.07 and IOUs of 0.44 ± 0.08 , 0.49 ± 0.11 , and 0.44 ± 0.08 across the same numbers of training images.

VR Model

The automatic segmentation results enabled us to explore each patient's sinus anatomy in our *Unity* VR model with functionality to augment the user's experience. In the digital reconstruction, we examined the nares and nasal cavity to view the orifice of the maxillary sinus, ethmoid air cells, frontal sinus, nasopharynx, and any obstructions along the pathway with real time mapping of our location (Fig. 3A-B) to corresponding 2D slices of a CT scan. At any point during the exploration, we could toggle between soft tissue and bone views to assess the degree of mucosal obstruction (Fig. 3C-F). Our investigative trajectory was also traced during the virtual endoscopy, and tissue and bone boundaries were overlaid on the 3D path to assess the user's proximity to sensitive structures such as the lamina papyracea.

We performed virtual endoscopy on 2 patients with significant sinus disease and captured parallel views. In addition to the frontal sinus, we visualized the alar cartilage (Fig. 4A, E), nasal cavity (Fig. 4B, F), nasopharynx (Fig. 4C, G), maxillary sinuses, and ethmoid air cells (Fig. 4D, H). All structures were identifiable both through the navigation system and through the endoscopic camera's view. These perspectives allowed us to compare the obstructions and varying landmark locations between these patients (Fig. 4.).

Discussion

Both anatomic abnormalities and low conceptual expertise of the surgeon are cited as risk factors for increased complication rates in endoscopic sinus surgeries.³⁷ As VR enables a more intuitive, 3D visualization of anatomic features compared to traditional 2D CT scan views, our model has the potential to address both of these issues. Our framework offers the novel ability to automatically process and view a patient's unique anatomy in the VR domain. While existing

VR models serve as teaching tools, the scalable patient-specific nature of our model broadens its application to preoperative planning, virtual endoscopy, and education. The mapping feature, inspired by the intraoperative image-guidance systems in practice today, further enhances the identification and understanding of landmarks.

The primary advantage of the Saak transform over other machine learning methods is its data-efficiency. We were able to generate viable 3D sinus reconstructions using as few as 3 training images, meaning that users can tailor the algorithm to their specific segmentation needs with a minimal amount of manually labeled data. We assessed the accuracy of our Saak-based segmentation method with qualitative and quantitative measures. In addition to strong DSC and IOU values, the soft tissue segmentation results had minimal visible noise, avoiding unnecessary surface vertices in the final model that would otherwise affect the performance of the VR demo. Bone segmentation was less accurate, likely due to the limitations of generating manually labeled training data around difficult to visualize structures like the ethmoid air cell walls. However, while highly precise soft tissue segmentation is essential for an effective VR model, less accurate bone segmentation still enables the clear visualization of contours needed to identify the probe's relative position. The 6 and 9 training sizes were more effective in producing a bony anatomy model, but all training sizes provided a similarly effective soft tissue VR experience.

This study provides a foundation for future innovations in the VR domain. Adding interactive functionality such as the ability to cut or debride tissue would build on this foundation and allow trial runs of a surgery.

Both the machine learning and virtual reality aspects of this study present limitations. Our Saak-based method functions well with consistent scan settings but is not designed to simultaneously handle images with multiple different windows and contrast profiles. However, the data-efficient nature of the Saak transform allows any user to tailor the performance of the algorithm for their scan standards using only minimal training data, preserving its clinical applicability.

Second, our VR model, like most others, is built using surface meshes rather than space-occupying voxels due to computational constraints. This makes deformation or manipulation of the object more challenging, limiting the realism of functional endoscopic sinus surgery simulators. Nevertheless, the fundamental framework of applying automatic segmentation to the VR domain is broadly applicable and will remain relevant even as voxel-based VR technology improves.

Conclusion

This study found that Saak transform-based machine learning automatically generated accurate, patient-specific VR models. Beyond preoperative planning, automatic segmentation and visualization of scans in VR may pave the way for virtual endoscopy and other remote alternatives to diagnostic exams, addressing major challenges presented by the COVID-19 era. Future research into the automatic segmentation of additional anatomic structures and the interactive mechanics of VR will reinforce the clinical applicability of this technology.

Funding and Conflicts of Interest

The authors declare no conflict of interest. The authors have no other financial disclosures.

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Figure 1. Segmentation and VR Pipeline: (A) The axial slices of a raw CT scan are passed to (B) the Saak transform-based machine learning algorithm, which has been trained with manually labeled images. The algorithm produces segmented slices of (C) soft tissue and (E) bone which are stacked and processed to generate (D-F) 3D meshes that can be ported to (G) the prebuilt *Unity* VR user interface for interactive anatomical exploration.

Figure 2. Qualitative and Quantitative Comparison of Segmentation Results: (A-B) The Saak transform-based method's soft tissue (blue) and bone (red) segmentation results overlaid with the ground truth (white) for 2 axial slices of a CT scan. (C-D) The DSC and IOU results of our automatic segmentation method for soft tissue and bone computed using 24 randomly selected validation image sets.

Figure 3. Functionality of the VR Interface: (A) The three-paned *Unity* user interface displaying the mapped location of the probe, the probe's camera feed, and the 3D model in which the probe is deployed (MS: Maxillary Sinus, NP: Nasopharynx). (B-F) A view of the frontal sinus showing user ability to toggle between tissue (C, D) and bone (E, F) views and control the brightness of the probe's light. (G-I) A 3D tracer enables the user to view the probe's path. Bone and tissue can be toggled on and off to observe proximity of the path to other structures like the orbits.

Figure 4. Labeled Anatomical Features: (A-D) Selected views of one patient's anatomy. (E-H) Parallel views in second patient highlighting anatomical differences. The first patient has a narrower nasal cavity (B) due to obstruction compared to the second patient (F). While the natural orifice of the maxillary sinus is normally located above the inferior turbinate (C), the second patient has a passageway below the turbinate from previous surgery (H).



