Advanced GPU Volume Rendering for Virtual Endoscopy

Arno Krüger[1], Christoph Kubisch[1], Gero Strauß[2], and Bernhard Preim[1]

[1]Department of Simulation and Graphics, Otto-von-Guericke-University of Magdeburg, Germany
[2]ENT Department, University Hospital of Leipzig, Germany

Abstract

For difficult cases in endoscopic sinus surgery, a careful planning of the intervention is necessary. Virtual endoscopy enables the visualization of the operating field and additional information, such as risk structures and target structures to be removed. The Sinus Endoscopy system provides the functional range of a virtual endoscopic system with special focus on a realistic representation. Furthermore, by using direct volume rendering, we avoid time-consuming segmentation steps for the use of individual patient datasets. However, the image quality of the endoscopic view can be adjusted in a way that a standard computer with a modern standard graphics card achieves interactive frame rates with low CPU utilization. Thereby, characteristics of the endoscopic view are systematically used for the optimization of the volume rendering speed. As a small standalone application it can be instantly used for surgical planning and patient education. The system was used for preoperative planning in 102 cases, provides useful information for intervention planning (e.g., anatomic variations of the Rec. Frontalis), and closely resembles the intraoperative situation.

1. Introduction

Minimally invasive endoscopic procedures are gaining importance, since they lead to a reduced trauma and hospitalization duration. Endoscopic interventions are challenging for the surgeon due to the indirect and limited view and the difficult eye-hand coordination. The surgeon has to infer the complex spatial relations solely based on a view at a two-dimensional screen and cannot use palpation for orientation and navigation. Therefore, virtual endoscopy (VE) systems have been developed in order to simulate these interventions either for training purposes or for planning an actual intervention based on the CT or MRI data of the patient. Such VE systems are already used in different areas, e.g., in pituitary gland surgery and other neuroendoscopic interventions [NWF*04, BSG*01] or for bronchoscopy [BMF*03]. In general, surgery planning is considerably more difficult to support than training, since the large variety of data from the clinical routine has to be processed efficiently and robustly, instead of using only one carefully prepared dataset.

Functional endoscopic sinus surgery (FESS) is a minimally invasive intervention, which is applied in order to treat patients with extended mucosal swellings in the paranasal sinuses [Llo88]. This procedure represents a huge advantage for the patient, taking into account that open surgery would lead to severe cicatrices. These interventions are frequently performed. In selected cases, they are risky and difficult to perform. In this paper, we present an endoscopy system targeted at the special requirements of FESS interventions. The presented system called *Sinus Endoscopy* is based on CT datasets which are routinely acquired for diagnosis and preoperative planning. It is optimized to run on off-the-shelf hardware or notebooks, but also provides higher visual quality on modern and more powerful computers. All volume rendering steps are directly implemented on the GPU to reduce the CPU workload.

2. Previous and Related Work

The diagnostic value of VE for the diagnosis of sinus diseases was investigated in [Rog01, BVB*04, HPI*00]. The representation of 3D information is realized by volume or surface rendering. The 3D models are used to generate images and videos of different anatomical structures from the view of an endoscope for diagnostic purposes. Comparisons between a virtual and real endoscopy point out that the anatomical structures and variations of the sinuses are recognizable in the 3D model (cf. [HPI*00]).

Different prototypes have been developed for the training and simulation of FESS (e.g., [PNT*05, MKT*07]). Besides a realistic representation of the structures, the design is focused on realism and faithfulness. Such training systems are too expensive and require too much preprocessing time for the regular planning in clinical settings (cf., [MKT*07]). Furthermore, an exact simulation, e.g., of tissue deformation, is not essential for the task of intervention planning. The STEPS system [NWF*04] supports the planning of endoscopic tumor operations to the brain using sinus cavities as access. It also provides a collision detection with force feedback navigation, which is useful for the orientation of the surgeons. However, in the STEPS system the entry to the brain only uses the healthy sinuses in a direct way, where no swollen or pathologic structures occur.

3. Medical Background

In sinus surgery, minimally invasive FESS techniques are common [KWM93]. With the *Sinus Endoscopy* system we aim at an enhancement of the conventional intervention planning on 2D images with the possibility to perform a VE preoperatively and directly with the clinical data. To achieve this goal, segmentation steps are avoided to cope with the limited time in the clinical routine. ENT surgeons stated that the additional planning time for VE should not exceed two minutes. FESS is a frequently accomplished intervention, but very risky in selected cases, e.g., if important anatomical landmarks were removed during earlier operations. Unusual anatomical features (stationary skullbase) as well as closeness to risk structures (e.g., N. opticus or A. carotis interna) can further increase the risk level. A similar spatial representation with VE can support the intraoperative orientation as a preparation step and help finding structural features that cannot be easily seen on the usual 2D CT slices. A minimization of the risks mentioned above is already possible through the 3D view of a VE. The quality of planning would even be enhanced with a segmentation of the mentioned risk structures and a combined visualization. However, this adds additional time to the planning process which is often not available.

For surgical planning, CT data are acquired, because they deliver a good representation of the bony anatomy and the mucous membrane changes, and they enable the radiologist to assess the severity and the localization of chronically phlogistic sinus diseases. Nose polyps and possible sequelae can also be located exactly. A spiral CT with an axial 1 mm slice distance is currently the optimal resolution. In clinical datasets also larger slice distances up to 3 mm occur. Datasets often show closed airways by mucous, polyps or other pathologic variations, depending on the diagnostic finding. This is a big challenge for a VE system and has not been tackled so far.

4. Requirements

Surgeons need a realistic visualization of the nasal anatomy to recognize the individual shape of the patient during the pre-operative planning. One goal of *Sinus Endoscopy* was to enable surgeons to quickly load and browse the data (to fulfill the estimated planning time <2 minutes). For the records of the patient's case it is useful to archive the data for later viewing to support comparisons of volume datasets or documentation with screenshots or animations. The presentation of the diagnosis to the patient is another reason for a realistic, but slightly stylized imagery being used. The rendering system of *Sinus Endoscopy* takes the following aspects into account:

Realistic visualization: Illumination and depth cues via texturing of the tissue surrounding the sinuses enhance the shape recognition. Other shading effects, such as wetness and the secretion level inside the nose, should be graded to present structural information in a way that is well known from real endoscopy. The renderer should enable the integration of modes with greater realism, or the opposite, stronger stylization.

Usability: We avoid image segmentation, since it takes too long for regular surgical planning (cf. [PNT*05, MKT*07]). For documentation and planning purposes, the possibility to draw sketches on the tissue during the endoscopy should be integrated. Usability also means that the system can easily be used on consumer class hardware.

Customizations: The CT Hounsfield units might slightly vary depending on the case, thus the system should allow interactive changes of the levels of density that serve as thresholds to solid tissue (app. -230 HU), secretion and air. This gives enough flexibility for an instantly useable visualization that can yet be reproduced by defining default values. It is also useful to cope with small passages due to swollen or pathology structures, but if the cavities are totally closed we cannot fly through them. Users might also prefer different parameters of the rendering (e.g., wetness level or secretion color) and adapt parameters to enhance, e.g., the brightness of the monitor.

Currently, no system for VE fulfills all criteria simultaneously, especially not the fast and easy use. The nasal sinuses are an area with both large hollow shapes, and fine labyrinths of channel systems. Furthermore, density values are caused by diseases affecting the secretion transport. This leads to a challenging rendering problem. The STEPS system is the only (commercially) available system for ENT and neurosurgery planning, but comes as a plug-in for a radiological workstation. This comes along with an overhead of GUI elements, which is not mentioned in the very good STEPS interface. Still, the rendering here is optimized for look behind the wall applications and no natural look of the tissue is possible.

5. Renderer Description

The *Sinus Endoscopy* system makes use of the latest technology to generate perspective images at realtime frame rates as long as datasets fit directly into the video memory. This limitation has not been an issue in clinical routine (usually $<$200 slices with 512$\times$512 pixel). The image shading was tailored towards realism and is realized using ray-casting. At first, the secretion layer is detected and its density is accumulated. Finally, the ray stops when finding tissue, which is represented as textured surface. To give further shape cues, a specular wetness effect is applied.

Ray casting is employed to combine volume rendering for secretion accumulation with isosurface rendering for the mucosa. With advancements in pixel shading capabilities the current generation hardware allows ray traversal within a single pass. Stegmaier et al. [SSKE05] uses such a single pass ray traversal for volume rendering. Thus, it does not require complex setups anymore, which used multiple draw-calls to benefit from speed enhancing principles, such as early ray termination seen in [KW03]. As ray casting classifies pixels at runtime, the user can interactively change thresholds for secretion and tissue classification.

Illumination and final coloring in *Sinus Endoscopy* is performed via deferred shading (cf. [HSS*05]). The main volume rendering pass gives results, such as the depth of hard tissue in viewspace, density values or other attributes for each pixel of the final image. The composition and shading is performed in another pass to get the final image. This allows a flexible customization of the shading, and also the use of enhanced attribute buffers in between.

Sinus Endoscopy was developed using the *Luxinia* 3D engine as platform (http://www.luxinia.de). The *Luxinia* API offers a rich functionality to aid the rapid-prototyping of 3D games and applications. OpenGL is the rendering backend of *Luxinia*, and *Cg* was used for programming the graphics hardware. With the fast scripted application prototyping it was possible to implement various VR techniques to perform speed measurements and to build and refine prototypes with low programming effort.

6. Performance Measurements

Tests have been carried out on four hardware configurations. The interactivity mostly varies on how much empty-space has to be skipped. The timings presented are averages in a flight into the nose, starting inside the front tip, with consistent values on maximum view distance and sample step size. The volume sizes did not significantly affect the performance, as hardware efficiently takes care of sampling large 8-bit single channel volume textures. We employ a full dataset (512$\times$512$\times$128) and a cropped version (256$\times$256$\times$64). On a standard PC with a modern GPU always more than 30 fps are possible on highest quality settings. This comes along with a typical CPU utilization of 10-15%. This value does not depend on the size of the dataset, as long as the data fits into the GPU memory.

7. Clinical Evaluation

A study at two clinical sites was accomplished to achieve final parameter values, to test the usability and robustness in general, and to compare the intraoperative views with the preoperative planning. To prepare the clinical study, we carefully developed a robust prototype for use in the routine (Fig. 1). In both cases a standard PC (with low end graphics card: nVidia geForce 8600 GS, 512MB) was used with an existing big wall-mounted plasma display as a secondary screen.

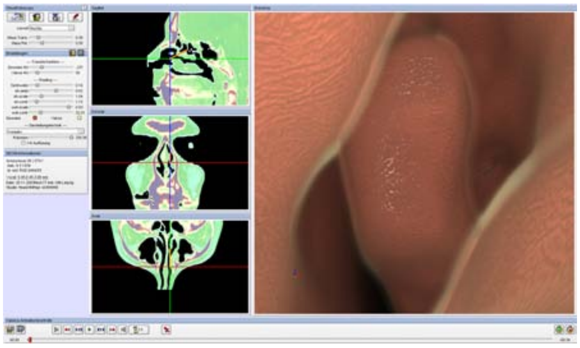

Figure 1: *Strongly reduced user interface for clinical evaluation. On the left side a patient information box was added.*

So far, the system was used for preoperative planning of sinus surgery in 102 cases. There is a trend to a better understanding of the patient individual anatomy and of the planned intervention compared to the traditional planning with 2D slices. Due to the very individual anatomy of this structure, the investigation of the Rec. Frontalis benefits from the system. The similarity between the preoperative Virtual Endoscopy and the real anatomy in the intervention was assessed on a 5 point Likert scale (1 represents identity and 5 no correspondence). An average score of 2.21 confirms a good correspondence.

Furthermore, it turned out that the *Sinus Endoscopy* system can be used quickly ($<$2min), and the remaining rendering parameters were judged as useful. Real endoscopic screens and devices also have various controllers to enhance the video quality. The variation of the parameter secretion level is useful for less experienced surgeons, and patients. The nose functions can be simulated and convey the understanding why a small secretion level can already close the main cavity of the nose. It could also be observed that important landmarks, e.g., the Concha nasalis medialis, are clearly visible in the VE. Furthermore, additional features of the patient anatomy are visible using the VE system together with the orthogonal 2D views. The natural look of the renderings was evaluated as a key feature of the system. Only with such a rendering the patient can be convinced–more abstract visualizations cannot accomplish this. To avoid misinterpretations the look is still artificial enough and the surgeons stated that it is definitely not a real endoscopic image and cannot be overrated. A more detailed description of the evaluation and the rendering techniques was published in [KKSP08].

8. Conclusion and Future Work

We presented a virtual endoscopy application that integrates state-of-the-art rendering techniques and integrates realistic textures to inform the patient. The system is dedicated to plan Functional Endoscopic Sinus Surgeries and is in clinical use since more than 100 cases so far. Using GPU-based volume rendering greatly decreases the CPU workload and enables existing computers in hospitals to use the *Sinus Endoscopy*. The estimated time of approx. 2 min for additional planning was reached by the possibility of loading CT datasets and visualization with direct volume rendering without any further steps. The rendering techniques presented here can be used efficiently with a variety of GPUs. With this approach, significantly more frames per second (min. 20 fps) than necessary for interactive framerates (10–15 fps) can be achieved, even on GPUs from previous generations (GeForce 7). The *Sinus Endoscopy* system has also been used for virtual endoscopy of the inner ear (Fig. 2) and could render those datasets instantly with a high similarity to the anatomy. The methods presented here can probably be applied to other areas, e.g., virtual bronchoscopy. Adapting the textures is the major issue.

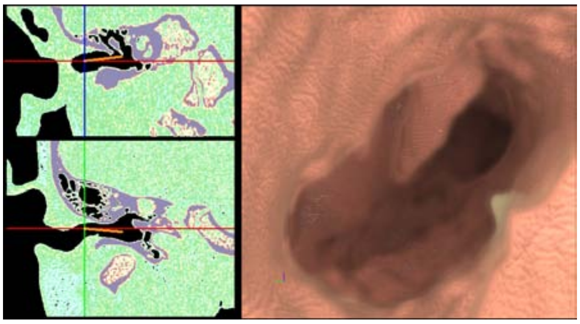

Figure 2: *The system can also be used to explore other hollow organs such as the inner ear that could not be accessed with real endoscopes.*

References

[BMF*03] Bartz D., Mayer D., Fischer J., Ley S., del Rio A., Thust S., Heusse C., Kauczor H., Strasser W.: Hybrid Segmentation and Exploration of the Human Lungs. In *Proc. of IEEE Visualization* (2003), pp. 177–184.

[BSG*01] Bartz D., Strasser W., Gürvi O., Freudenstein D., M., Skalej: Interactive and Multimodal Visualization for Neuroendoscopic Interventions. In *Proc. of Symposium on Visualization* (2001), pp. 157–164.

[BVB*04] Bisdas S., Verink M., Burmeister H. P., Stieve M., Becker H.: Three-Dimensional Visualization of the Nasal Cavity and Paranasal Sinuses: Clinical Results of a Standardized Approach Using Multislice Helical Computed Tomography. *Journal of Computer Assisted Tomography 28*, 5 (2004), 661–669.

[HPI*00] Han P., Pirsig W., Ilgen F., Gorich J., Sokiranski R.: Virtual Endoscopy of the Nasal Cavity in Comparison with Fiberoptic Endoscopy. *Europ. Archives of Oto-Rhino-Laryngology 257*, 10 (2000), 578–583.

[HSS*05] Hadwiger M., Sigg C., Scharsach H., Bühler K., Gross M.: Real-Time Ray-Casting and Advanced Shading of Discrete Isosurfaces. In *Proc. of Eurographics* (2005), pp. 303–312.

[KKSP08] Krüger A., Kubisch C., Strauss G., Preim B.: Sinus Endoscopy - Application of Advanced GPU Volume Rendering for Virtual Endoscopy. *IEEE Transactions on Visualization and Computer Graphics 14(6)* (2008), 1491–1498.

[KW03] Krüger J., Westermann R.: Acceleration Techniques for GPU-based Volume Rendering. In *Proc. of IEEE Visualization* (2003), pp. 287–292.

[KWM93] Klimek L., Wenzel M., Mösges R.: Computer-Assisted Orbital Surgery. *Ophtalmic Surgery 24*, 6 (1993), 411–417.

[Llo88] Lloyd G. A. S.: *Diagnostic Imaging of the Nose and Paranasal Sinuses*. Springer, 1988.

[MKT*07] Moral A. I., Kunkel M. E., Tingelhoff K., Rilk M., Wagner I., Eichhorn K. W. G., Bootz F., Wahl F. M.: 3d endoscopic approach for endonasal sinus surgery. In *Proc. of IEEE Engineering in Medicine and Biology Society, Lyon, France* (2007), pp. 4683–4686.

[NWF*04] Neubauer A., Wolfsberger S., Forster M.-T., Mroz L., Wegenkittl R., Bühler K.: STEPS - An Application for Simulation of Transsphenoidal Endonasal Pituitary Surgery. In *Proc. of IEEE Visualization* (2004), pp. 513–520.

[PNT*05] Pössneck A., Nowatius E., Trantakis C., Cakmak H., Maass H., Kühnapfel U., Dietz A., Strauss G.: A Virtual Training System in Endoscopic Sinus Surgery. In *Proc. of CARS* (2005), pp. 527–530.

[Rog01] Rogalla P.: Virtual Endoscopy of the Nose and Paranasal Sinuses. In *Virtual Endoscopy and Related 3D Techniques*, Rogalla P., van Scheltinga J. T., Hamm B., (Eds.). Springer, 2001, pp. 17–39.

[SSKE05] Stegmaier S., Strengert M., Klein T., Ertl T.: A Simple and Flexible Volume Rendering Framework for Graphics-Hardware based Raycasting. In *Proc. of Intern. Workshop on Volume Graphics* (2005), pp. 187–195.