

Intra-Operative Virtual Endoscopy for Image Guided Endonasal Transsphenoidal Pituitary Surgery

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Abstract Purpose. Virtual endoscopy has already proven its benefit for pre-operative planning of endoscopic pituitary surgery. The translation of such a system into the operating room is a logical consequence, but only a few general intra-operative image guided systems providing virtual endoscopic images have been proposed so far. A discussion of related visualization and interaction problems occurring during sinus and pituitary surgery is still missing.

Methods. This paper aims at filling this gap and proposes a system that integrates an existing virtual endoscopy system originally designed for pre-operative planning of pituitary surgery with a professional intra-operative navigation system. Visualization and interaction possibilities of the pre-operative planning system have been extended to fulfill the special requirements to the system if used for intra-operative navigation of endonasal transsphenoidal pituitary surgery.

Results. The feasibility of the system has been successfully tested on one cadaver and 12 patients. The virtual endoscopic images were found useful (1) during the endonasal transsphenoidal approach in cases of anatomic variations and for the individually tailored opening of the sellar floor, and (2) during tumor resection for respecting the internal carotid artery. The visualization of hidden anatomical structures behind the bony walls of the sphenoid sinus during the sellar phase of the surgery has been found most beneficial.

Discussion. According to our data, intra-operative virtual endoscopy provides additional anatomical information to the surgeon. By depicting individual anatomical varia-

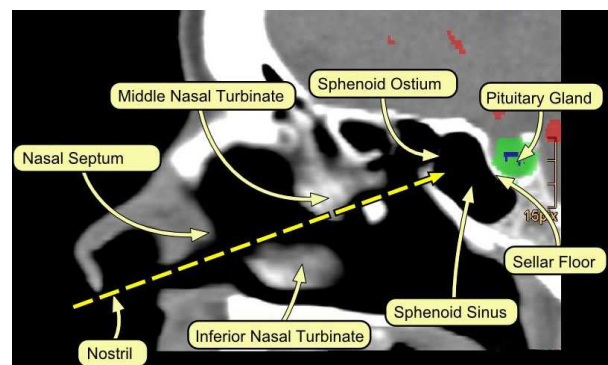


Fig. 1 The endonasal transsphenoidal approach: The endoscope is inserted from nostril towards the sphenoid sinus passing the inferior and middle nasal turbinates and the sphenoid ostium.

tions in advance, it may add to the safety of this frequent neurosurgical procedure.

Keywords virtual endoscopy · image guided intervention · pituitary surgery

1 Introduction

Endoscopic surgery of the pituitary gland is a well established minimally invasive technique for the treatment of pituitary adenomas. The endonasal transsphenoidal approach using a rigid endoscope [3] (see Figure 1) requires a high experience level of the surgeon due to the limited field of view of the endoscope and the complex patient individual anatomical structure of the paranasal sinuses that make orientation difficult. The presence of critical structures that might not be harmed under any circumstances in close proximity to the adenoma, like the brain, optical nerves, eyeballs, internal carotid arteries and the pituitary gland itself, induce an additional level of complexity to the procedure.

Careful planning of the intervention based on pre-operative CT and/or MR data of the patient helps to reduce the risk during the intervention by identifying pathologies, anatomical variations and critical structures. Basic planning systems provide tools for image registration, segmentation, and MPR (Multi-Planar Reformation) viewing. Additional computational support is provided by virtual endoscopic views

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mimicking the real endoscopic image based on pre-operative image data, and a camera model reproducing the optical properties of the endoscope. Virtual endoscopy allows pre-operative simulation of the approach by virtual navigation through the paranasal sinuses and additional visualization of hidden critical structures supporting the surgeon to decide pre-operatively on the optimal surgical strategy.

The second option for risk reduction is the use of intra-operative navigation systems providing reliable information on the actual location of the tip of the endoscope and other instruments in relation to the patient based on pre-operative CT and/or MR data. These systems generally provide tracked MPR views, display of segmented structures, markers indicating an available pre-operative plan and eventually a non-perspective 3D view of the data set. However, none of the listed conventional visualization methods allows the direct visual comparison of endoscopic image and pre-operative data.

The combination of intra-operative navigation with virtual endoscopy is a logical consequence from this observation. Main benefit of the connection of tracking information with virtual endoscopic images is the possibility to establish a direct local relation of virtual and real endoscopic images and to visualize the pre-operatively defined critical structures not visible in the real image. Especially in non-standard cases this additional information can support the decision process of the surgeon during the procedure.

While potential benefits of intra-operative virtual endoscopy for pituitary surgery are obvious, and a high correspondence of virtual and real endoscopic images has been reported [14], virtual endoscopy has not yet been established for endonasal approaches in the operating room (OR).

Careful analysis of existing virtual endoscopy systems reveals a possible explanation for this observation: General virtual endoscopy systems provide images based on the given pre-operative data without taking the specific approach and the current intra-operative situation into account. In practice, such systems often fail to generate stable and meaningful virtual images during all phases of endonasal transsphenoidal approaches which substantially limits the usefulness and acceptance of the system.

Main reason for these visualization problems are the narrow cavities the endoscope has to cross and slight differences between the available pre-operative images and the current intra-operative situation.

These differences can be caused by inaccurate tracking information induced by a slight flexibility of the endoscope, but they are present even if patient and pre-operative data are perfectly registered and the position of real and virtual endoscope match with high precision:

- During the nasal phase of the surgery tissue might be slightly deformed in comparison to the pre-operative data: it might be more or less swollen, compressed or shifted by the inserted instruments (Figure 2 (a)).
- During the sphenoid phase structures are less deformable and mainly modified by resection: the sphenoid ostium is opened, septa and bone are removed (Figure 2 (c)).

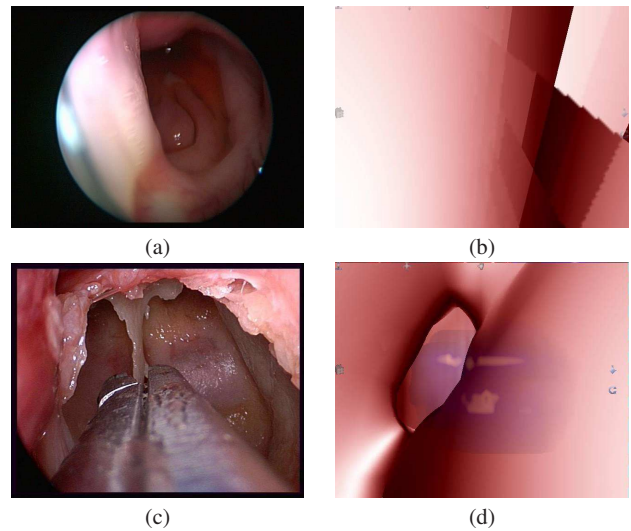


Fig. 2 Typical situations in endonasal pituitary surgery where corresponding real and virtual endoscopic images are not comparable.

The first situation might result in a complete loss of sight in the virtual endoscopic image if the virtual camera is located inside virtual tissue while the real endoscope shows a clear image of the nasal pathway (Figure 2 (b)). In the second situation removed tissue is still present in the pre-operative data and occludes in the virtual image the sight on structures already visible in the real endoscopic image (Figure 2 (d)).

This paper proposes a virtual endoscopy system specialized on the intra-operative guidance of endonasal transsphenoidal approaches to the pituitary gland. The system is based on an existing planning system for endonasal transsphenoidal pituitary surgery and a professional intra-operative navigation system. Thus, this work focusses mainly on the intra-operative use of the virtual endoscopy system. The approach specific core visualization problems described above are addressed and several additional features facilitating the intra-operative use of the system are proposed. The feasibility and benefits of the extended virtual endoscopy system have been assessed and discussed based on 12 clinical cases.

2 Related Work

An excellent general introduction to virtual endoscopy, including an overview on different rendering techniques, academic and commercial systems, and application fields has been published by Bartz [1].

First proposed virtual endoscopy systems for visualization of paranasal sinuses based on patient image data used specialized hardware [19] or generated off-line fly-throughs along a pre-defined path [14] due to the limited computational power. The visualization of more recent systems is based on highly optimized software [11] or GPU based [7] raycasting algorithms that allow to add more realism, like realistic lightening or wetness, without losing interactivity. Dominating render mode today is direct iso-surface rendering, a techniques that directly generates a virtual endoscopic image based on individual patient data without

pre-processing of the images and generation of intermediate geometry. Variations of this technique are spatially restricted direct volume rendering [11] and combinations of direct iso-surface and direct volume rendering. The geometric representation of the paranasal sinuses plays a secondary role in the pre- and intra-operative setting as exact segmentation of the paranasal sinuses in computed tomography images is an extremely time consuming task [15, 17], and flexibility and quality of the direct representation is higher. A comparison of direct and indirect rendering techniques of paranasal sinuses has been given by Rogalla [13].

In addition to the correct simulation of the endoscopic view, a clear visualization of critical structures as background objects is the most important feature for pre-operative planning systems for sinus and pituitary surgery and is part of most cited systems. Other described features of planning systems include linked MPR views, navigation aids, annotation possibilities and PACS (Picture Archiving and Communication System) integration. A detailed discussion of virtual endoscopy for paranasal sinuses has been recently published by Kettenbach et al. [5].

Intra-operative guidance of endoscopic procedures has already been proposed with the availability of the first intra-operative navigation systems. For sinus and pituitary surgery different strategies to fuse pre-operative data and intra-operative images have been published: fusion of real endoscopic images with outlines [2, 12] or 3D representations of pre-segmented objects [4]; the combination of non-perspective 3D rendering of the whole head with cutting planes following the tip of the endoscope and visualization of the viewing frustum [20]; recording and registration of intra-operative images to provide reconstructed views in case of total loss of sight due to hemorrhage [16, 6]. Systems using virtual endoscopic images directly for intra-operative guidance of sinus surgery are rare. Lapeer et al. [8] proposed a system, that enhances a real endoscopic image directly by fusing it with the corresponding virtual view. Deformation of tissue and the related discrepancy between real and endoscopic images has been discussed only in connection with endoscopy simulation systems for training purposes [19].

Mayberg et al. [9] describe the use of the commercially available intra-operative navigation system Cbyon IGS for image guided pituitary surgery. Cbyon IGS provides parallel display of virtual and real endoscopic images. The system is designed for the intracranial approach and uses a direct volume rendering method which is not capable of visualizing surface anatomy of nasal cavities.

To the best of our knowledge there exists no paper discussing the complete set-up of a virtual endoscopy system for intra-operative guidance of endonasal pituitary surgery including a detailed discussion of related visualization, interaction, and hardware problems.

3 Materials

This section shortly describes the two systems that have been combined, adapted and extended to build navSTEPS

- the system for virtual endoscopy based image guided endonasal pituitary surgery being subject of this paper.

3.1 STEPS - Pre-operative Planning of Endonasal Transsphenoidal Pituitary Surgery

STEPS [11, 18] has been developed for pre-operative planning and simulation of endonasal transsphenoidal pituitary surgery. It provides the software basis of navSTEPS: Surgery planning and pre-operative exploration of patient data is still done using the original system, whereas additional visualization and interaction paradigms have been developed for its intra-operative use.

STEPS has been implemented as PlugIn of a professional radiological workstation (ImpaxEE, AGFA Healthcare) inherently providing PACS integration, slice and MPR views of image data, and professional registration and segmentation tools. It covers the whole planning workflow including automatic and semi-automatic mutual information based rigid registration of available MR and CT data; manual and semi-automatic segmentation of critical structures on MR and/or CT data; interactive data exploration based on enhanced MPR views and a virtual endoscopic view of nasal cavities and paranasal sinuses including background visualization of pre-segmented structures; data annotation; planning of the optimal access to the sphenoid sinus and the location for the opening of the sellar floor (Figure 3).

The virtual endoscopic view is rendered directly and in real time from the CT data, i.e. no segmentation of the nasal cavities and paranasal sinuses and generation of intermediate geometry is required. Two different render modes are available: A direct first-hit iso-surface rendering based on a pre-defined, but adjustable, iso-value that displays the shape of the rendered cavities, and a constrained direct volume rendering that allows the direct visualization of tissue characteristics (i.e. the difference between mucosa and bone) encoded in the CT image. The fusion of virtual endoscopic views and rendered critical structures shown as background objects is done on the fly and provides highly interactive and flexible 3D images.

Optical parameters of the virtual endoscope like opening angle, viewing angle, barrel distortion and roll can be chosen to obtain comparable images of the virtual endoscopic view and the real endoscopic image. A set of orientation and navigation aids helps finding the optimal path to the sphenoid sinus and allows the validation of the chosen iso-value. The system also provides a simulation of the opening of the sellar floor including color coded indication if critical structures would be damaged or not.

A detailed description of STEPS can be found in [10, 11]. The system is not commercially available, but under clinical evaluation. Results have been published by Wolfsberger et al. [18].

3.2 StealthStation®- Intra-Operative Navigation

The second basic component of navSTEPS is the image-guided navigation system StealthStation® by Medtronic.

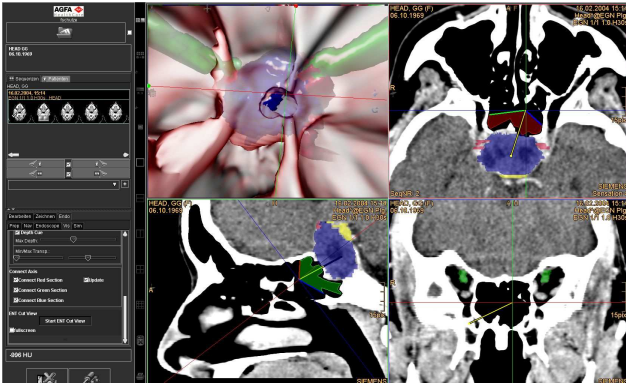


Fig. 3 Screenshot of STEPS showing the planning and simulation of the opening of the sellar floor. The tumor and the internal carotid arteries are shown as background objects in the virtual view and appear color coded in the MPR. The tip of the virtual endoscope is located at center of the MPR, a projection of the line of sight is indicated on each section by a yellow arrow. The color coded frustum on the MPRs restricted by the rendered iso-surface provides a tool to directly compare the shown virtual endoscopic image with the original data.

A StealthStation® delivers real-time feedback on patient anatomy, instrument position, and therapy placement for both procedure planning and intra-operative confirmation. The system optically tracks the endoscope and up to four additional tools during the intervention. A software interface to the StealthStation® can be realized using the StealthLink® research portal that provides access to information like the patient space/image registration transformation and the tool positions.

4 navSTEPS - System Overview

navSTEPS combines the visualization, simulation and planning capabilities of STEPS with the tracking information of the navigation system.

To integrate both systems an additional communication layer has been implemented using StealthLink®. Customized calibration procedures for external and internal camera parameters guarantee the comparability of real and virtual endoscopic images. Visualization, planning and interaction possibilities have been extended for intra-operative use.

navSTEPS supports the whole work flow consisting of four phases: acquisition, planning, setup, and intervention. The user interface is designed in a way that each phase is mapped to its own specialized working environment providing computational assistance for all tasks of the respective phase. The following paragraphs give a workflow oriented overview of navSTEPS.

4.1 Data Acquisition

For pre-operative planning and conventional image guided navigation of endoscopic pituitary surgery CT (512*512 axial, 100-200 slices), a T1-weighted MR and a MR angiography data is acquired.

The CT data provides, besides information on the location of bony structures, clear air-tissue boundaries required to generate high quality virtual endoscopic images. The MR

datasets contain information on tumor location and extend, pituitary gland, optical nerves, and cysts (T1 weighted MR) and about the internal carotid arteries (MR angiography).

4.2 Data Pre-Processing and Parameter Adjustment

navSTEPS integrates the whole functionality of the original STEPS to prepare the available image data for later generation of patient specific virtual endoscopic images: MR and CT data are registered, and critical structures are segmented and stored as binary masks. The pre-selected iso-value of -500 HU for surface reconstruction can be adjusted with respect to important thin structures affected by the partial volume effect. Endoscope parameters like the opening angle can be chosen according to the real setup during the intervention. (See Section 3.1 for further details.)

4.3 Intervention Planning

navSTEPSs main tool for patient individual pre-operative planning of the approach to the pituitary gland is the virtual endoscopic view enhanced by color coded critical structures that is also part of the original STEPS. It allows the surgeon a pre-operative simulation of intra-operative situations that can help to avoid or to be prepared to critical situations. (Section 3.1 and related literature). The exact procedure for pre-operative planning of the intervention highly depends from the experience level of the surgeon, the individual anatomical situation and pathological findings of the patient.

For the intra-operative use, navSTEPS extends the visual guidance functionality of STEPS by so called waypoints that can be placed directly in the MPR of the pre-operative data to mark important landmarks like the sphenoid sinus ostium along the path.

To assure a free view to the sellar floor, which is needed during the most important phase of the intervention, a clipping plane (Section 5.2.2) can be defined pre-operatively that can be enabled during the intervention.

4.4 Setup

The intra-operative setup consists of an endoscope, an intra-operative navigation system, and a PC which runs the extended virtual endoscopy software navSTEPS. Figure 4 shows how the system is assembled in the OR.

At the beginning of the intervention the intra-operative navigation system is initialized by registration of the physical patient space to the pre-operative CT and/or MR images. Passive tracking targets are clamped on the endoscope and a second tool (e.g. the suction) which acts as a pointer. Both tools are calibrated using the standard procedure provided by the navigation system.

After completion of the setup of the navigation system, the same CT data is loaded into navSTEPS together with the pre-segmented background objects and pre-operatively defined additional parameters.



Fig. 4 Intra-operative setup: Endoscope monitor (1), intra-operative navigation system (2), navSTEPS monitor (3), patient (4), endoscope (5).

A calibration step ensuring the comparability between real and virtual endoscopic image concludes the setup phase. (See Section 5.1 for implementation details.)

4.5 Intervention

All visualization capabilities of STEPS are fully available during the intervention. navSTEPS extends this functionality by providing additional features to handle the intra-operative visualization and interaction requirements for the application.

Reduced User Interaction. While STEPS was designed as highly interactive system, navSTEPS takes the interaction constraints during surgery into account like reduced moving space of the surgeon, sterility, and time constraints. The intra-operative system is almost interaction free: Currently only an eventually pre-operatively defined clipping plane has to be activated by one single mouse click or by using a foot switch.

Global Orientation Through Enhanced MPR Views. navSTEPS constantly acquires the current position of the endoscope and the pointer and updates all tracked views of the application accordingly. Global orientation is supported by the available MPR view that is steered per default by the tip of the endoscope but automatically switches to the tip of the pointer if present. This feature allows an intuitive exploration of structures close to the pointer directly on the original image data.

Local Orientation by Relation of Virtual and Real Endoscopic Images. The virtual endoscope follows the tip of the real endoscope and provides the corresponding virtual view based on the pre-operative data. The navigation system acquires the position of the endoscope with high precision, but tracking errors introduced by the technical properties of the endoscope (see Section 5.1.4) and the differences between the real intra-operative situation and the pre-operative images (see Section 5.2) make the exact match of the virtual and the real endoscopic image virtually impossible. Nevertheless, the high quality of the virtual images allows the surgeon to establish the relationship between the virtual endoscopic image and the intra-operative situation by direct visual comparison of anatomical land-

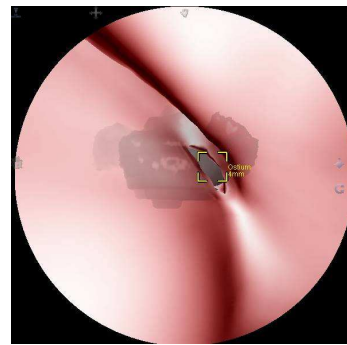


Fig. 5 Waypoint marker at the ostium. Segmented structures, adenoma, pituitary gland and carotid artery are already visible in the background.

marks. navSTEPS additionally enables the surgeon to directly control spatial relationships by using the pointer: The tool is visible in reality in the real endoscopic image and is displayed as cross hair in the virtual image.

To generate meaningful virtual endoscopic images during all stages of the surgery navSTEPS provides two mechanism to overcome the visualization problems associated with the differences between pre-operative data and intra-operative situation: (a) Especially during the nasal phase, where tissue is flexible and mucosa might be more or less swollen, it can easily happen that the virtual endoscope is placed within virtual tissue. navSTEPS automatically recognizes such a situation and applies a modified rendering algorithm that still generates a meaningful image. (b) Pre-operatively defined clipping plane(s) can be activated by mouse click or foot switch to easily handle tissue removal mainly during the sphenoid phase of the surgery. (See Section 5.2 for implementation details.)

Visual Guidance by Waypoint Marker. Pre-operatively defined waypoints are visualized as square overlays (see Figure 5) and guide the surgeon towards relevant landmarks. Additionally the name of the waypoint and the distance to the endoscope tip is displayed next to the marker.

Localization of Critical Structures During the Sphenoid and Sellar Phase. STEPS visualizes previously segmented structures that are generally hidden in the real endoscopic image as colored overlays on the MPR views and as background objects directly in the virtual endoscopic image (see Figure 3). navSTEPS combines these images with the navigation information of the real endoscope and the pointer. In this way it effectively supports the surgeon in localizing critical structures behind the occluding tissue and/or bone. This feature is especially important during the critical sphenoid and sellar phases of the surgery when the surgeon has to determine the optimal position for the opening of the sellar floor. An example is given in Figure 6.

5 Implementation Details

5.1 Camera Model and Calibration

The endoscope and additional tools are calibrated to the navigation system by measuring two positions, the tip p_{tip}^{tool} and the hind p_{hind}^{tool} with a special calibration device. This

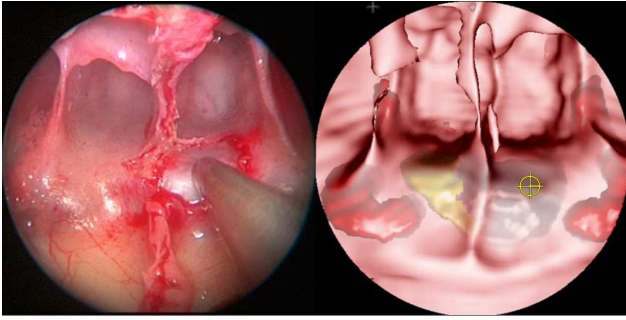


Fig. 6 Left: Real endoscopic view on the sellar floor. The suction tool visible in front is used as pointer. Right: Corresponding virtual endoscopic view with background objects and crosshair indicating the position of the tip of the pointer above the adenoma (gray). The pituitary gland is displayed as yellow structure and the carotid arteries are indicated in red.

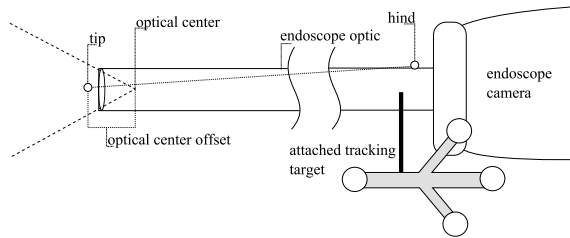


Fig. 7 Endoscope Assembly

positions are defined in tool space, i.e. in the coordinate system of tracking target which is attached to the tool. The navigation system updates continuously a matrix T_{tool}^{image} which allows to transform from tool to image (CT data) space.

$$p^{image} = T_{tool}^{image} p^{tool} \quad (1)$$

For simple pointing tools the two resulting positions in image space are sufficient, however driving a virtual endoscope requires more attention. The endoscope used for endonasal transsphenoidal surgery consists of two parts: A long and thin monocular rigid optic and the video camera (see Figure 7), neither the position of the optical center nor the orientation can directly be derived from the measured points. Thus, a camera calibration has to be performed in two ways. First, camera position and orientation (extrinsic parameters) have to be corrected. Second, the intrinsic camera parameters have to correspond with the parameters of the real endoscope.

5.1.1 Extrinsic Camera Parameters

Based on the tip and hind position a virtual camera is defined in tool space such that the optical center is located at the tip and the viewing direction is aligned to the axis defined by tip and hind. However since the tip position is measured in front of the lens and the hind position is most likely off the optical axis (see Figure 7) further corrections are required to mimic the real endoscope. The roll angle (rotation around the optical axis) is an additional parameter that must be adjusted.

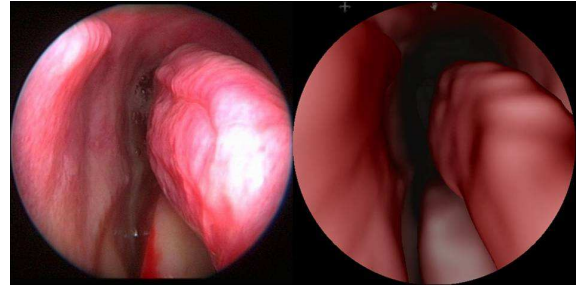


Fig. 8 Intra-operative and virtual image of the inferior turbinate.

Therefore a correction transformation C is inserted into Equation 1 which can be used to transform the virtual camera from tool to image space:

$$p^{image} = T_{tool}^{image} C p^{tool} \quad (2)$$

The correction transformation C is assembled from a translative part which moves the tip into the optical center and a rotational part which corrects viewing direction and roll angle. Scaling or shear transformations are not allowed.

5.1.2 Intrinsic Camera Parameters

For intrinsic camera calibration only the field of view v_{fov} is estimated so far. More complex visual behavior like radial distortion can be visualized by the rendering system but is not used since these parameters are not captured at the moment (see Section 5.1.3).

5.1.3 Calibration Procedure

To define the final camera model, the correction transformation C and the field of view v_{fov} have to be estimated.

Currently a simple manual calibration is used that requires the definition of the field of view, which is generally known for the used endoscope, and the alignment of the roll angle. The pre-defined position for the optical center is 3mm behind the measured tip (see Figure 7) and generally does not need further adjustment.

In our clinical study we used the inferior nasal turbinate as a reference to define and verify the chosen roll angle (see Figure 8), because this structure can be reached in an unproblematic way and has a characteristic appearance.

5.1.4 Endoscope Related Errors

The connection between the optic and the camera is designed to make a fast interchange of optics possible and allows the rotation of both parts against each other. This construction imposes problems building a virtual camera model because the intra-operative navigation system is only able to track the camera body or the endoscope lens. The tracking target is attached onto the endoscope optic in our setup. If the camera is rotated against the lens, the calibration (at least the rotational part along the viewing axis) is invalidated.

Another source of errors is the optic itself. Especially long and thin build types can be bend easily applying little force which can result in positional errors of several millimeters.

5.2 Occlusion Handling

Besides of the extrinsic tracking errors described in the previous section, there are mainly three situations in which the real patient anatomy differs from the anatomy captured pre-operatively:

1. The CT images were acquired hours or days before the surgery and do not represent the current anatomical state which likely has changed due to natural swelling.
2. Deformation of mucosa.
3. During surgery tissue and bony structures are resected.

Differing real and virtual anatomical structures pose several problems. There are two situations where the virtual view can be highly different to the endoscopic view. First, if large displacements of soft structures occur during surgery due to (de-)swelling, compression or shift, the tip of the endoscope is placed inside the virtual tissue and the default first-hit-raycasting algorithm is not capable to produce a meaningful image. Second, if the surgeon has removed a layer of tissue, it will still be visible in the virtual view and may block the view.

Both classes of problems cannot be avoided. Nevertheless the system must provide a meaningful view especially on critical structures in any situation. To achieve this we propose two different strategies:

- The use of a robust rendering algorithm which provides meaningful images even if the conventional rendering approach would be occluded or show artifacts (see Section 5.2.1).
- A simple clipping system to effectively handle occlusion problems related to tissue removal. (see Section 5.2.2).

5.2.1 Transparent Backface Rendering

The virtual endoscopic images are generated by a first-hit raycasting algorithm. The algorithm computes the color for each pixel by tracing a ray through the volume until the underlying value exceeds the chosen iso-value. Starting from this position the exact intersection with the iso-surface and the corresponding normal is computed which is used to shade the pixel. This basic algorithm works fine as long as the tracing starts at a position with a value below the given iso-value (which is case of virtual endoscopy generally anatomically outside any tissue). If the optical center of the virtual endoscope is located inside virtual tissue, the tracing procedure will stop immediately and the algorithm does not longer deliver useful images.

Transparent Backface Rendering extends the original first-hit raycasting algorithm in a way that it still generates meaningful images if the virtual camera is placed slightly inside the tissue: If the value at the beginning of the ray already overshoots the threshold, the modified casting procedure searches for the first point along the ray with an iso-value below the given threshold (the "exit point"). From this point on the basic direct iso-surface raycasting is performed. Ray R_1 in figure 9 (a) illustrates how the algorithm

finds the intersection with the correct iso-surface I_1 by first searching for the exit point O_1 .

The limitation of this straightforward approach is depicted by tracing ray R_2 : If the search for the exit point is not restricted, the hidden cavity (I_2) not accessible by the real endoscope might become visible. This problem has been solved by introducing a maximal search distance d_{max} that limits for each ray the tolerated distance from p^{eye} to O_i . d_{max} has been chosen $\leq 10mm$. This range generally covers the small differences between real and pre-operative data caused by swelling, tissue removal, slight tissue shifts and/or tracking errors.

To clearly indicate that the virtual endoscope lies inside virtual tissue, and that the virtual images differ from the current real situation, the pixel color is dimmed proportional to the distance d_i .

Figures 9 (1st row) (b)-(d) shows a typical situation. The endoscope is pressed against the nasal septum at the left side (b). This results in a deformation of the tissue which allows the virtual camera to be located inside the virtual nasal septum. (c) shows the result of the default first-hit ray-caster rendering which generates no usable result. Figure (d) depicts the the improved algorithm. The middle nasal turbinate is clearly visible however not deformed as in the real view.

5.2.2 Clipping

Clipping is one way to guarantee visibility to important structures in the virtual endoscopic image if tissue and/or bone have been removed during surgery to advance the endoscope (e.g. opening of the sphenoid ostium to access the sphenoid sinus) or to get a clear view to important structures (e.g. removal of septa in front of the sellar floor).

The original STEPS provides sophisticated tools to simulate tissue and bone removal, but for intra-operative use the required user interaction is far too complex. To reduce user-interaction to a minimum, navSTEPS implements virtual removal of tissue as a simple clipping plane. Two interaction metaphors have been realized: pre-defined- and interactive clipping.

Pre-defined clipping is setup in the pre-operative planning phase by defining a fixed clipping plane. During intervention only enabling/disabling of this clipping plane is possible.

Figure 9 (2nd row) shows an example where the clipping plane has been placed in front of the sellar floor. If activated, the virtual endoscopy generates comparable images to the real endoscopic view and allows the localization of the tumor and other critical structures.

Interactive intra-operative clipping has been realized by using the pointer (e.g. suction) tool to define the clipping plane (see Figure 10 (left)). The clipping plane is constructed at the tip position of the suction perpendicular to the connection vector between eye position and pointer tip (Figure 10 (middle)) and is activated by using a footswitch.

Additional *cylindrical clipping* provides a clipping mechanism that emulates opening of sinuses, removal of septa and bone (Figure 10 (right)).

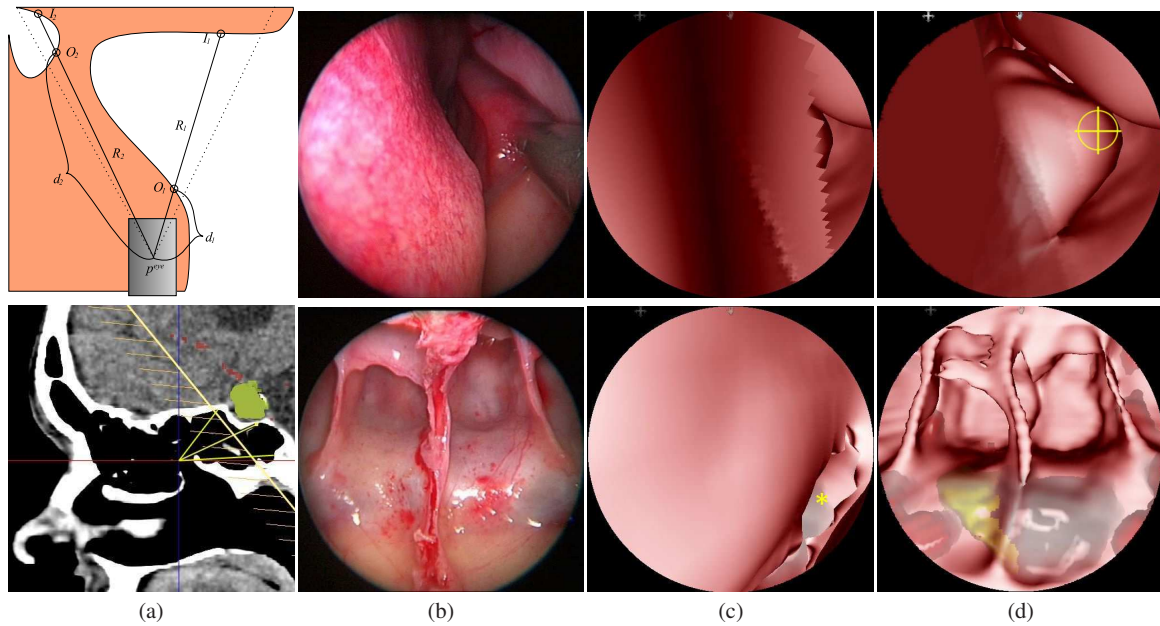


Fig. 9 (Top row) Transparent backface rendering: (a) Algorithm. (b) Intra-operative endoscopic view. The endoscope touches the nasal septum on the left. The middle nasal turbinate is visible on the right side (deformed by the suction). (c) Pure iso-surface raycasting resulting in a complete loss of sight because the virtual camera is located inside the nasal septum. (d) Transparent backface rendering provides sight on most of the anatomy. The middle nasal turbinate is clearly visible (however the turbinate is not deformed as in the real endoscopic view). (Bottom row) Clipping: (a) Sagittal CT, the endoscope is located in front of the sphenoid ostium facing towards the sellar floor. The clipping plane is depicted as a yellow line running through the sphenoid sinus. (b) Intra-operative endoscopic image with a clear view on the sellar floor because the septum around the sphenoid ostium has been resected. (c) Virtual image without clipping. The sphenoid ostium is visible in the lower right corner (marked with *). (d) Clipping is activated. The rendering provides a clear view on the sellar floor, matching the real endoscopic view.

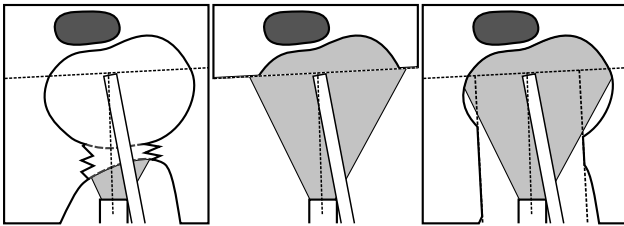


Fig. 10 Interactively controlled clipping. The surgeon has opened a paranasal sinus. The view of the virtual endoscope is still blocked because the image is generated based on pre-operative CT data (left). With the tip of the suction a clipping plane is defined to enable a view into the cavity (middle). A cylindrical clipping shape can be used to simulate the opening more realistically (right).

6 Results

The system has been tested so far in one cadaver study and twelve clinical cases.

Preparation Time. Pre-operative planning using the original STEPS needs about 13 minutes including image registration, segmentation and anatomy exploration. The additionally required planning steps for intra-operative use provided by navSTEPS (placing of the clipping plane and waypoints) takes at maximum two minutes.

The intra-operative setup of navSTEPS (connection of PC and StealthStation, start of the system, loading of pre-operative images and pre-defined parameters) and the calibration of the virtual camera requires maximally 5 minutes of additional time.

Feasibility. The feasibility of navSTEPS has been assessed by the performing neurosurgeon (S. Wolfsberger) in relation to the clinical features of the individual case. Fig-

ures 11 - 14 shows examples of the use of navSTEPS in all stages of an endonasal transsphenoidal approach to the sellar floor.

The results of the evaluation based on the twelve clinical cases are listed in table 1. The virtual endoscopic images were found useful:

1. During the approach.

- (a) In cases of anatomic variations: The transnasal approach to the sphenoid sinus can be hindered by various individual anatomic variations such as septal deviations and spurrs, bullous turbinates and post-surgical scarring all narrowing the nasal cavities. The virtual endoscopy system was able to navigate the surgeon to the sphenoid ostium even in the case of a narrow nasal corridor by means of the waypoint system and the visibility of anatomical structures through the extended rendering algorithm (see Table 1, case number 9, Figure 11).
- (b) For individually tailored opening of the sellar floor: During the sphenoid phase of the procedure it is crucial for complete tumor resections to maximize the opening of the sellar floor in cases of large adenomas. The lateral extension of such an opening is defined by the siphon of the internal carotid arteries. The available clipping mechanisms provided in all cases a clear view to the sellar floor. In combination with the visualization of the internal carotid artery hidden behind the bony walls of the sphenoid sinus navSTEPS was able to safely guide the surgeon during sellar floor opening (see table 1 cases 1, 4,6-11, Figure 13). In cases of small sellar lesions, an indi-

<i>no.</i>	<i>pathology</i>	<i>size</i>	<i>PS extension</i>	<i>invasive</i>	<i>anatomic variation</i>	<i>resection</i>	<i>benefits of navSTEPS</i>
1	NF	2.5	yes	yes	firm tumor consistency	subtotal	Position of ICA during opening of sellar floor. Position of ICA during parasellar tumor removal.
2	ACTH	1.0	no	no	presellar sinus	complete	Projection of PG, tumor and ICA on thick bony sellar floor during drilling.
3	PRL	1.0	no	no	cystic tumor	complete	Localization of cyst for tailored sellar floor opening.
4	NF	2.0	no	no	firm tumor consistency	complete	Position of ICA during opening of sellar floor.
5	Rathke's cleft cyst	2.5	no	no	cystic	cyst drainage	Localization of cyst for tailored sellar floor opening and cyst puncture.
6	PRL	1.5	yes	no	parasellar extension	complete	Localization of PG and tumor for tailored sellar floor opening. Localization of ICA during parasellar tumor removal.
7	NF	3.0	no	no	multiseptated sphenoid sinus	complete	Position of ICA during opening of sellar floor.
8	cranio-pharyngeoma	3.0	no	yes	cystic	subtotal	Position of ICA during opening of sellar floor.
9	NF	3.0	no	no	narrow nasal corridor	complete	Nasal anatomy for maximum opening of sphenoid sinus. Position of ICA during opening of sellar floor.
10	NF	2.5	no	no	-	complete	Position of ICA during opening of sellar floor.
11	GH	1.5	no	no	nasal septum deviation, bullous concha	complete	Nasal anatomy for maximum opening of sphenoid sinus. Position of ICA during opening of sellar floor.
12	Hypophysitis	1.0	no	no	-	biopsy	Localization of PG and lesion for tailored sellar floor opening and biopsy.

Table 1 ACTH: adrenocorticotroph-cell adenoma, GH: growth-hormone-cell adenoma, ICA: internal carotid artery, NF: endocrine non-functioning adenoma, PG: pituitary gland, PRL: prolactinoma

vidually tailored opening of the sellar floor is necessary to optimally expose the tumor while maintaining the function of the normal pituitary gland. The virtual endoscopy system was able to visualize the pathology in relation to the pituitary gland behind the bony walls of the sphenoid sinus. With this information, the surgeon was able to place his approach through the sellar floor in an optimal position (see Table 1, cases 3,6,12, Figure 14).

2. During tumor resection for respecting the internal carotid artery.

In cases of tumor extension lateral to the internal carotid artery (parasellar extension), the virtual endoscopy system was able to provide the surgeon with the information about the position of the artery in relation to the tumor, thereby increasing the safety of this challenging task and maximizing tumor resection (see Table 1, cases 1 and 6, Figure 14).

Accuracy. The accuracy as been checked by correlation of the insertions of the nasal and sphenoid septation between the live and virtual endoscopic and neuronavigation images was always in the standard range of the navigation system - i.e. 2 mm both at the beginning and during later stages of the procedure.

Usability. The usability of the system was analyzed for the intra-operative situation. Well received by the surgeons was the fact that the systems requires almost no additional interaction (activating the clipping plane is the only exception) after the setup. The direct coupling of the virtual camera to the real endoscope makes it possible for the surgeons

to do their work as usual and just go back to the new visualization if additional information is needed without any additional effort.

7 Discussion and Future Work

The potential benefit of intra-operative virtual endoscopy for image guided endonasal transsphenoidal pituitary has been discussed in many publications and is mainly undisputed. The limited acceptance of such systems in the OR is basically based on the visualization problems induced by the specific anatomy of the nasal cavities, correspondence problems, and tracking errors.

navSTEPS, the system presented and tested in this paper, is a highly specialized solution addressing the two main visualization problems that hamper the acceptance and use of virtual endoscopy for image-guided endonasal transsphenoidal pituitary surgery in the OR. The analysis of the twelve clinical cases performed with the system have shown that it is possible to create meaningful virtual endoscopic images through all stages of the surgery and that the system can add to the safety of the procedure.

Some currently existing technical problems may be solved in the future with the availability of new innovations regarding the technical equipment: With the next generation of endoscopes the weaknesses of current endoscopes might be improved and it will become possible to integrate a reliable automatic camera calibration method into navSTEPS.

In the future the use of navSTEPS for other paranasal sinus interventions will be evaluated. In this case interac-

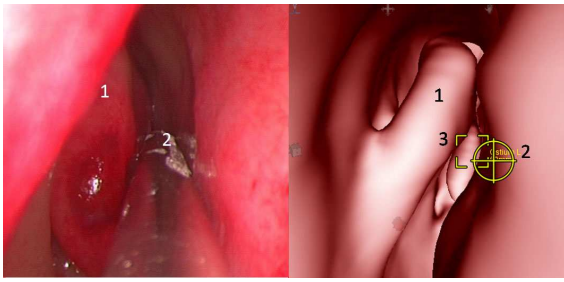


Fig. 11 Virtual and real image of the tip of middle turbinate (1), suction (2), trajectory to sphenoid ostium (3). Note that the middle turbinate is deformed to the left.

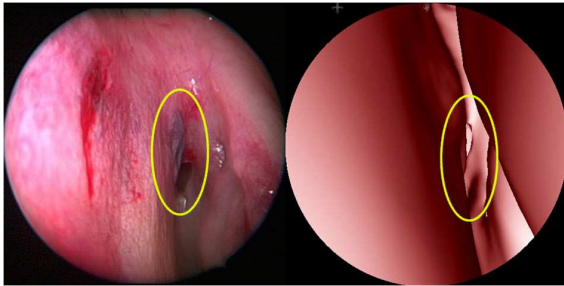


Fig. 12 Corresponding intra-operative and virtual image of the sphenoid ostium (marked in both views)

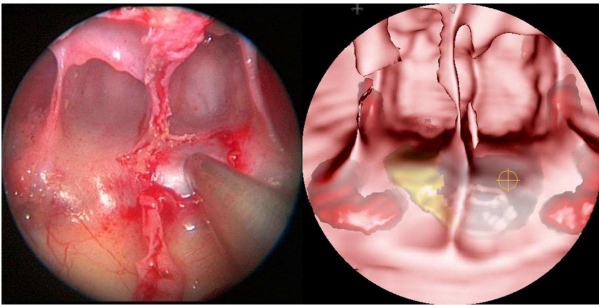


Fig. 13 The activated clipping plane provides free view to the sellar floor with suction.

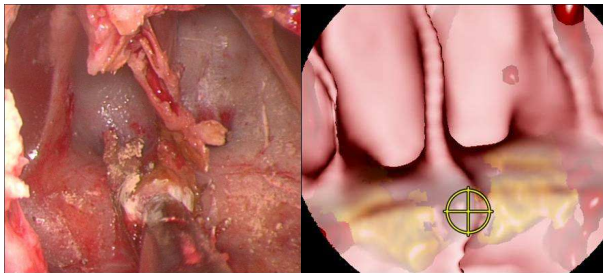


Fig. 14 Tailored opening of the sellar floor superficial to the adenoma with a high speed drill. The crosshairs in the virtual image indicate the position of the suction tool placed on the drilled opening.

tive clipping techniques and other methods which allow the surgeon to control visibility get even more important and need extensive evaluation.

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