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Navigation as a tool to visualize bone-covered hidden structures in transfrontal approaches

JOERG SCHIPPER, M.D., WOLFGANG MAIER, M.D., IAKOVOS ARAPAKIS, M.D., UWE SPETZGER*, M.D., R. LASZIG, M.D.

Abstract

A retrospective analysis of 10 patients was performed to evaluate navigation systems in extranasal frontal skull base surgery. When performing a craniotomy following a bicoronal skin incision, the surgeon has to calculate the extent of the frontal sinus to avoid unnecessary damage to the dura or mucoceles later. Due to surgical morbidity including compression of the frontal lobe, many skull base surgeons have refused to use such an approach. Malformation or bone-destruction complicates the identification of the borders and increases the risk of side-effects. Navigation systems can be an alternative for calculating the frontal sinus outlines during surgery. In the authors' surgical procedure two different navigation systems were used. Conventional surgery using the transfrontal, transbasal or subcranial approach consisting of trepanation and craniotomy were performed, while the navigated surgical procedure was evaluated.

The analysis showed that computer-assisted surgery (CAS) is applicable to extranasal frontal skull base surgery. In comparison to X-ray beam-controlled craniotomy, CAS is beneficial as it constitutes a non-invasive instrument of quality management. Furthermore, the analysis indicated that under the guidance of a navigation system a precise pre-surgical simulation is available in order to perform an optimal craniotomy and reconstruction of the frontal skull base.

Key words: Surgery, Computer-Assisted; Frontal Sinus

Introduction

Computer-assisted surgery (CAS) is a well-accepted technique in skull base surgery. However, it is still debated whether CAS is really necessary or is only a sophisticated artificial tool.[1–7] CAS has been introduced in sinus surgery, and it is now extensively used in reconstructive bone surgery where, for instance, it is used for precise and reproducible implant surgery such as hip implantation or in various neurosurgical procedures.[8–14] The advantage lies in the detailed pre-operative planning by simulation, precisely controlled drilling and exact surgical orientation that is possible. In addition, navigation is an alternative to an intra-operative X-ray beam, computed tomography (CT) or magnetic resonance imaging (MRI) for the identification of fine bone-covered structures.

In skull base surgery, in many cases, fine structures of interest to the surgeon are hidden and embedded in the bone. To avoid surgical morbidity and to reduce surgical trauma by an unnecessarily wide approach, the surgeon would prefer to go straight to the target field. However, generally in skull base surgery the characteristic vital nerve and vessel structures often do not allow such a straight surgical strategy. If the skull base surgeon cannot identify the target field at the beginning of surgery because of the covering bone, he has to explore anatomical landmarks for his intra-surgical orientation first, which will extend the surgical corridor. This can be a time-consuming procedure and can increase the surgical trauma. Therefore, CAS can be a helpful instrument for the identification of bone-embedded and hidden anatomical structures such as the frontal sinus in frontal skull base surgery.[15,16]

CAS is an alternative intra-surgical indirect imaging system for seeing through the covering bone and evaluating the underlying target fields. A form of CAS that guarantees intra-operative correlation of the pre-surgical imaging data with the surgical site agrees with radiological intrasurgical imaging systems in such cases. An intra-operative ultrasound, CT or MR image will be recommended when the surgeon himself changes the pre-surgically scanned anatomical situation, thus causing dislocation of vital structures.[17–19]

The aim of this retrospective analysis was to

From the Department of Otorhinolaryngology, Head and Neck Surgery, University of Freiburg Medical School, and the Department of Neurosurgery*, Klinikum Karlsruhe, Germany.
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investigate the scope, limitations and benefits of CAS in extranasal approaches to the frontal skull base. This report deals with the precise identification of the frontal sinus in frontal skull base surgery using the transbasal approach of Derome,[20,21] the subcranial approach of Raveh[22,23] or the classic transfrontal approach of Unterberger.[24] The authors report their experience of CAS in frontal skull base surgery and demonstrate that intra-operative navigation can improve the effect of the surgical procedure and can reduce surgical morbidity.

Patients and method

A set of three different transfrontal approaches on 10 patients (further details see Table I) with various disorders of the frontal skull base was performed with the assistance of the Stryker-Leibinger NavigationSystem® (Freiburg, Germany) or the BrainLAB VectorVision2®, (München, Germany). Both navigation systems are optic electronic devices. Patients exhibited different malignant lesions at the anterior skull base such as adeno- or squamous cell carcinoma or aesthesioneuroblastoma and benign tumours such as epidermoid tumours or mucoceles (Table I). Due to the pathology and extent of lesions and location and shape of the frontal sinus, a transbasal approach according to Derome,[20,21] a subcranial approach according to Raveh,[22,23] a transfrontal approach according to Unterberger[24] or a combination of all three were indicated in an interdisciplinary conference with colleagues from the department of neurosurgery (Table II). Pre-operatively, CT and MRI scans were performed to characterize the extent of the lesions. To avoid double investigations for the imaging procedure, these CT and MRI scans were performed as a three-

TABLE I

PATIENTS INCLUDED IN THE RETROSPECTIVE ANALYSIS ON COMPUTER ASSISTED TRANSFRONTAL SURGERY

Patient, Sex, Age	Diagnosis	Surgical approach	CAS	Registration procedure	Obliteration of the frontal sinus
1, M, 59	Aesthesioneuroblastoma Kadish C, Hyams II	Transbasal	Yes	Surface matching	Yes
2, M, 34	Mucocele of the frontal sinus	Transfrontal	Yes	Surface matching	No
3, M, 36	Squamous cell carcinoma of the anterior ethmoid with infiltration of the frontal lobe of the brain	Transbasal	Yes	Surface matching	Yes
4, F, 28	Recurrence of a chrondrosarcoma of the anterior ethmoid with infiltration of the frontal lobe of the brain	Transbasal	Yes	Surface matching	Yes
5, M, 50	Epidermoid limited to the right frontal sinus	Transfrontal	Yes	Surface matching	No
6, F, 78	Aesthesioneuroblastoma Kadish C, Hyams II	Transbasal	Yes	Surface matching	Yes
7, F, 39	Adenocarcinoma of the anterior ethmoid without infiltration of dura of the frontal skull base	Subfrontal/ transbasal	Yes	Upper jaw mould	Yes
8, M, 60	Adenocarcinoma of the anterior ethmoid with infiltration of the frontal lobe of the brain	Transbasal	Yes	Surface matching	Yes
9, F, 35	Aesthesioneuroblastoma without infiltration of the dura of the frontal brain	Subfrontal	Yes	Upper jaw mould	No
10, F, 44	Aesthesioneuroblastoma Kadish C, Hyams II	Transbasal	Yes	Surface Matching	Yes

F = female, M = male

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TABLE II

INDICATION AND DESCRIPTION OF SURGICAL INTERVENTIONS PERFORMED IN THIS INVESTIGATION

	Classic transfrontal	Subcranial	Transbasal
Designation of surgery	Unterberger[24]	Raveh *et al.*[22]	Derome *et al.*[20]
Indication	Dura intact	Dura intact	Dura infiltrated
Procedure	Transdural–extraethmoidal	Infradural–intraethmoidal	Transdural–intraethmoidal

dimensional data set for navigation. The CT scan was performed to evaluate the bony lesions and the MRI scan to visualize possible lesions of the dura or frontal brain. If the lesions were endonasally visible by an endoscope or microscope, a biopsy was taken pre-surgically.

In lesions that were limited only to the frontal sinus without destroying its rear wall, a classic transfrontal approach was performed. In cases where the lesions infiltrated the anterior ethmoid and invaded the frontal lobe of the brain, a trans-basal approach was recommended, or a sub-cranial approach, if the dura of the frontal skull base was still intact (Table II). In the case of a trans-basal approach, a small frontal sinus would require a stronger elevation and compression of the frontal lobe. Therefore, to avoid unnecessary compression of the frontal lobe, a sub-cranial approach was required if the frontal sinus seemed to be too small and the dura was thought to be intact.[23] In cases with an enlarged frontal sinus a trans-basal approach was considered to explore the base of the frontal sinus and the anterior ethmoid. The exact approach was planned and simulation of the trajectories was performed in the 3D-data set of all patients pre-surgically.

A numeric three-plane data set of 1-mm slices of a spiral single slice CT scanner ProSpeed®, General Electric (Milwaukee,USA) with table projection 2 mm, reconstruction interval 1 mm and gantry angle 0 degree by a resulting pixel size of 0.49 mm, or corresponding MRI slices of Magnetom Vision Advanced® (Siemens, Erlangen, Germany) in one case of the patient's head (including the nose and auricles down to the C2 vertebral level) and, in two cases of patients with an additional upper jaw splint, were transferred into the navigation system work station via the local intranet network. If both CT and MRI images were available simultaneously, an image fusion was performed. In the simulation mode of the navigation system the surgeon can outline the contours of the tumour borders in the MRI data set. Image fusion allowed the authors to visualize the contours of the tumour borders in the CT data set as well. For surgery, all patients' heads were fixed in a Mayfield® clamp. For the registration procedure titanium markers of the upper jaw splint or the surface-matching procedure were used (Table I).

Results

The aim of CAS in frontal skull base surgery was to perform a controlled tumour resection and obtain an early identification of the bone-covered course of the frontal sinus, as well as to determine the optimal point of trepanation and the size of the craniotomy.

The time period required for calibration and registration was found to be between seven and 14 minutes for both navigation systems. The time required for the registration procedure amounted to four and 5.5 min when upper jaw splint markers were used (*Cases 7* and *9*, Table I). Thus, this method was much faster than the surface-matching procedure, which was eight to 10.5 minutes *(Cases 1–6, 8, 10,* Table I). For surface matching a set of several points of the forehead's surface (nose, both orbits, upper forehead) was detected by a pointer system. The upper jaw splint was individually made for every patient and had to be manufactured at the onset of the diagnostic trial, i.e. before the imaging procedure was performed. The imaging data set would have to be repeated if the upper jaw splint had been made, creating additional costs and X-ray investigations for the patient. At the beginning of the diagnostic imaging procedure, however, it is often not clear if such a surgical frontal skull base intervention will be mandatory or not. The cost for an upper jaw splint manufactured by the department of oral-maxillo-facial-surgery is approximately €10. However, the surface-matching procedure is more comfortable for the patient and more commonly used. Both companies, Stryker-Leibinger and BrainLAB, have improved their registration device for surface matching to make the registration procedure faster and less prone to errors. For the registration procedure of the BrainLAB system, a contact-free laser pointer device may be used instead of a hand-held pointer instrument.

As calculated by the computer navigation systems, a mean registration accuracy of 0.7 mm was obtained for the surface-matching procedure and of 0.4 mm for the upper jaw splint registration device. The reproducibility of the surface-matching registration procedure was 87 per cent (tested five times), whereas that of the upper jaw mould 94 per cent (tested five times). During surgery, in two cases the registration failed (maybe by moving the patient tracker fixed at the Mayfield® clamp), and the registration had to be repeated after the patient's head had been opened surgically. This was only possible by using the surface-matching procedure, otherwise the sterile cover of the operation field would have had to be refixed, an additional time consuming procedure. In these two cases a new accuracy of 0.9 and 0.8 mm was obtained, as indicated by the navigation systems. The measurement of the intra-operative accuracy, as evaluated using anatomical landmarks (interfrontal septum, upper tip of the nasal septum followed by resection of the anterior ethmoid, supraorbital foramen), yielded deviations of 1.2–3.4 mm. The

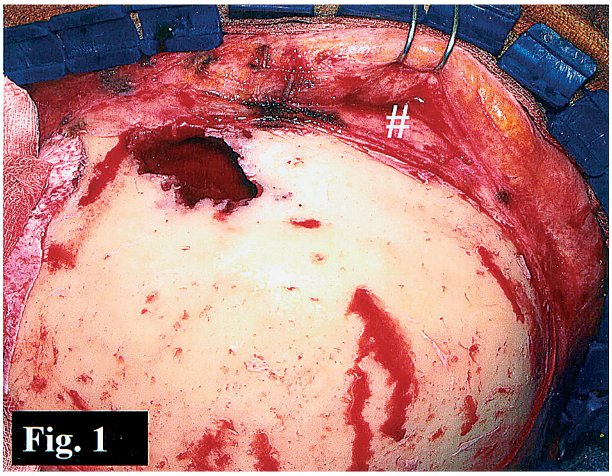

FIG. 1

Surgeon's view of the upper forehead following removal of the skin flap by a bicoronal skin incision (*Case 10*, Table I). The lesion on the left side of the upper forehead demonstrates that the tumour had already invaded the anterior wall of the frontal sinus. # = glabella.

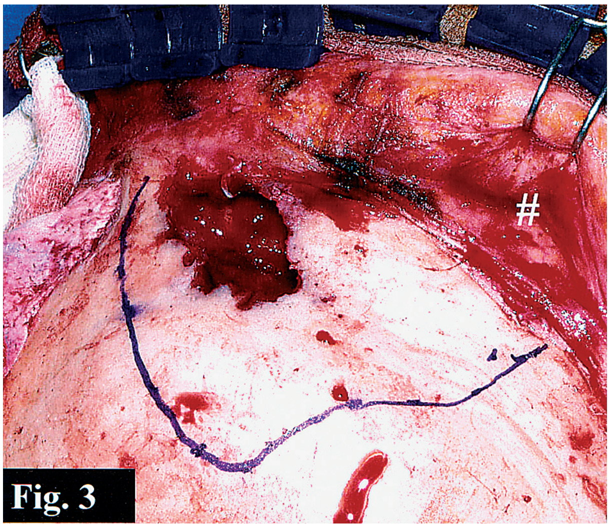

FIG. 3

Surgeon´s view of the upper forehead: the tumour´s borders are marked with respect to the frontal sinus by use of navigation (*Case 10*, Table I). # = glabella.

deviation increased as the distance from the registration plane of the forehead increased.

In all patients, a bicoronal skin incision was performed preserving an anterior pedicled galea-periost flap (Figure 1). The bicoronal skin incision was used because of the good cosmetic results. The scar was hidden in the hair zone and no further changes due to surgery were seen. The skin flap was pushed forward by retractors. The forehead was covered by a sterile and visible patch, so that another registration procedure could be performed during surgery.

In *Case 10* (Table I) the aesthesioneuroblastoma had already infiltrated the anterior wall of the frontal sinus, the frontal brain lobe and destroyed the anterior ethmoid. The patient showed an enlarged frontal sinus. Thus, because of extension of the frontal sinus and tumour invasion into the frontal brain requiring an extended basal duraplasty, a trans-basal approach was chosen. When looking at the bony upper forehead (Figure 1), it was impossible to differentiate between the borders of the tumour and of the frontal sinus. The navigation system indicated the tumour borders through the covering bone and the side walls of the frontal sinus (Figure 2). Thus, it was possible to demonstrate the position of the underlying structures before opening the bone. The borders of the tumour were marked with respect to the enlarged frontal sinus (Figures 2 and 3) and the craniotomy was performed with an oncological security zone of 1.5 cm (Figure 4). Further surgical steps were performed as already described by Derome.[21] In this case the tumour had already infiltrated the anterior wall of the frontal sinus.

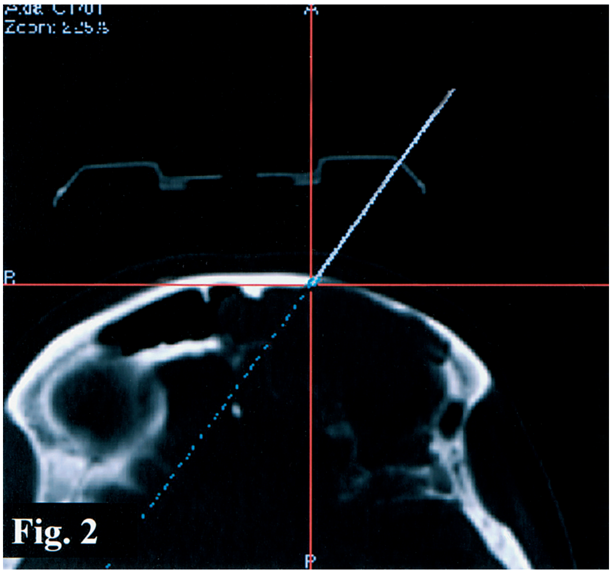

FIG. 2

Axial CT scan (*Case 10*, Table I): navigation controlled marking of the borders of the tumour and the frontal sinus.

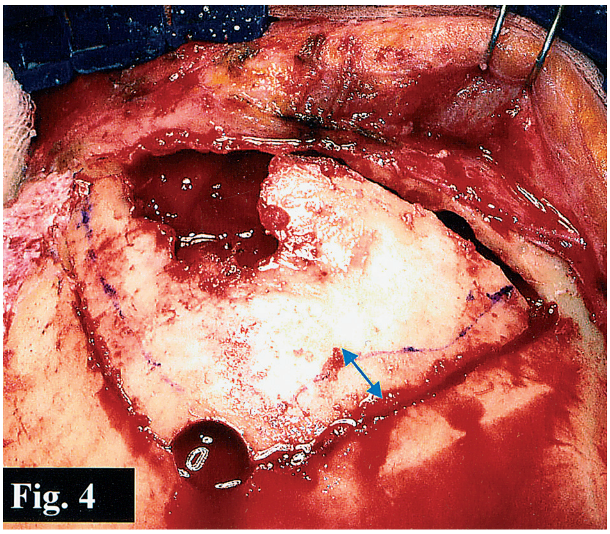

FIG. 4

Forehead following the craniotomy with an oncological security distance of 1.5 cm to the marked tumour's borders (*Case 10*, Table I).

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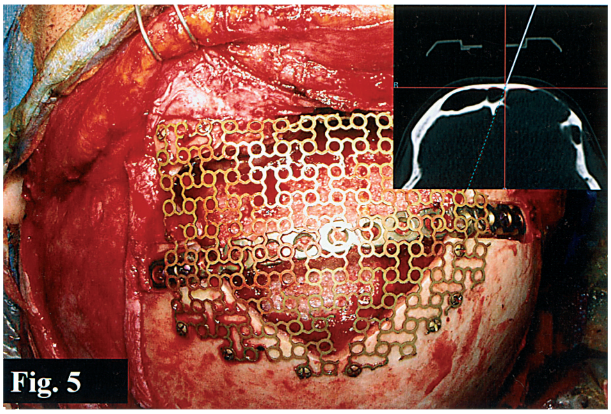

FIG. 5

After complete resection of the tumour the reconstruction is performed with a mesh and a plate composed of titanium. Both devices are shaped during surgery according to the pre-operative skull form (*Case 10*, Table I) with the assistance of navigation.

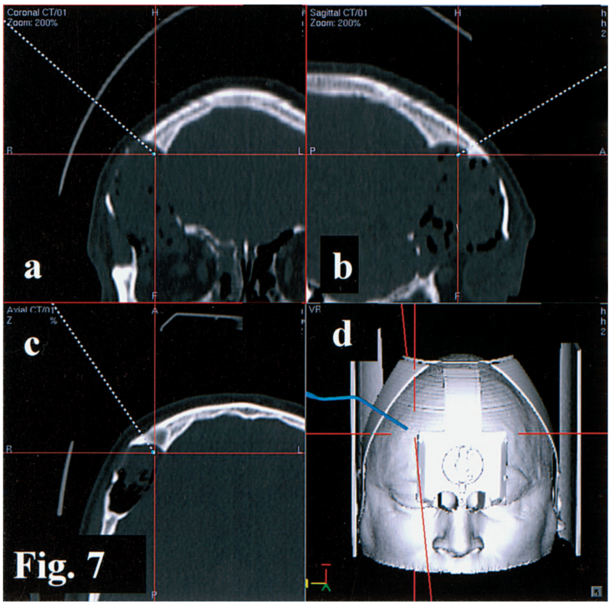

FIG. 7

Corresponding CT scan to Figure 5. (*Case 5*, Table I). (a) coronal, (b) sagittal, (c) axial, (d) 3-D volume model. The broken line shows the position of the pointer for evaluating the borders of the tumour.

Therefore, this bone could not be used for reconstruction. Instead, titanium mesh was used that was shaped according to the original surface by use of navigation and additional support by an osteosynthesis plate Compact 2.4 Unilock®, Synthes (Umkirch, Germany) (Figure 5). However, the use of navigation in the reconstruction procedure was also helpful in such frontal skull base approaches. The sterile cover of the operating field makes it impossible to evaluate the original shape of the splanchnocranium for forming the titanium mesh implant. Furthermore, the shape of the splanchnocranium is individual and not completely symmetrical, which complicates adequate reconstruction.

In another case with a benign tumour (*Case 5*, Table I), which was histologically proven by a pre-surgical biopsy, the authors tried to preserve the integrity of the frontal sinus and prevent iatrogenic damage to the dura. Following the bicoronal skin incision, the borders of the tumour and of the frontal sinus (Figures 6 and 7 (a)–(d)) were marked using navigation. A craniotomy was performed at the marked lines (Figure 8) and the tumour was resected with preservation of the dura (Figure 9). As already demonstrated in the previous case, a titanium mesh was used for closing the lesion of the anterior wall of the frontal sinus. The titanium mesh was shaped under control of the navigation system to reproduce the original surface of the anterior wall of the frontal sinus. The mesh was fixed with titanium screws. The frontal sinus was closed without any further protection of the uncovered dura at the resected rear wall of the frontal sinus.

The navigation tool was used in a similar manner for the subcranial approach. The main goal of the surgical procedure was to explore the frontal skull

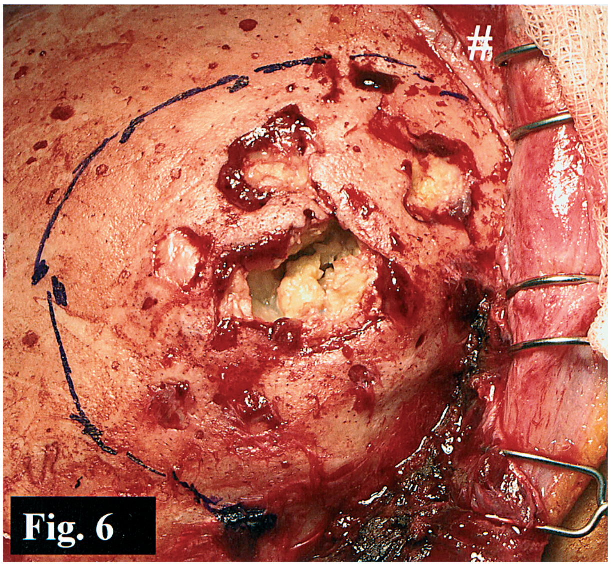

FIG. 6

Surgeon´s view of the upper forehead following a bicoronal skin incision: the tumour borders are marked with respect to the frontal sinus by use of navigation (*Case 5*, Table I).

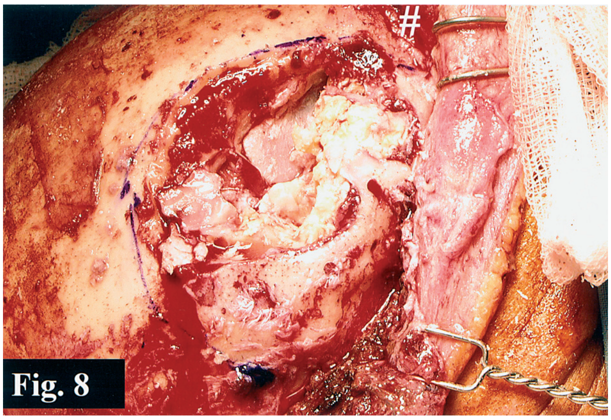

FIG. 8

View of the upper forehead after a navigation-controlled craniotomy (*Case 5*, Table I) up to the tumour. # = glabella.

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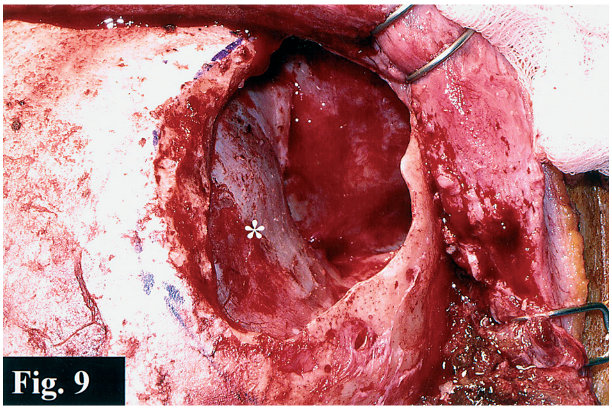

FIG. 9

Upper forehead after tumour removal (*Case 5*, Table I). * = uncovered dura after removal of the back wall of the frontal sinus.

base from the lower side without damaging the dura. Navigation indicates to the surgeon where he has to expect the level of the frontal skull base. Thus, he can determine the optimal level and size of the craniotomy in respect to the form of the frontal sinus (Figure 10 (a)–(d)) without damaging the dura or the frontal lobe (Figure 11). The craniotomy was performed using an Aesculap craniotome® (Tuttlingen, Germany) in one piece in order to guarantee that it would fit well when pushed back into the surgical corridor during the reconstruction and closing procedure.

The surgical procedure using a variation of the trans-frontal approach was successfully performed by navigation.

Discussion

Extensive developments have taken place in the last 20 years in skull base surgery that would have seemed impossible years ago. The operating microscope, new surgical approaches and techniques and, above all, the use of modern imaging techniques have been the major influences. Rapid advances in computer technology – specifically, three-dimensional reconstruction of data generated by CT or MRI have led to considerable improvements in the visualization of anatomy and pathological anatomy. However, partial and significant changes may occur in the patient's anatomy subsequent to imaging, and intra-operative correlation of these regions with the pre-operatively obtained imaging data may remain difficult in view of the restrictions in visibility.

Almost 50 years ago, Unterberger[24] described a transfrontal approach by resecting the anterior wall of the frontal sinus following a bicoronal skin incision. In the absence of an osteosynthesis procedure, at this time reconstruction of the upper forehead was not performed. Nowadays, the transfrontal approach of Unterberger has been modified by pushing back the resected bone of the anterior wall and fixing it with osteosynthesis plates. However, for this modified transfrontal approach the surgeon needs precise intra-operative orientation of the frontal sinus, which is sometimes deformed by the pathology, in order to avoid opening of the neurocranium.

Since the transbasal approach was described by Derome[21] in 1985, a controversy has arisen with respect to surgical morbidity and late effects due to mucoceles resulting from surgery.[25] To reduce morbidity and to optimize craniotomy with respect to the frontal sinus, an intra-operative X-ray beam or fluoroscopy were used. Such devices required additional tools for protection against X-ray beams which impeded the surgeon. In 1993, Raveh[22] proposed a so-called subcranial approach for tumours of the frontal skull base to avoid elevation and compression of the frontal lobe as in the trans-basal approach. But as with the transbasal approach the difficulty for the surgeon was in evaluating the

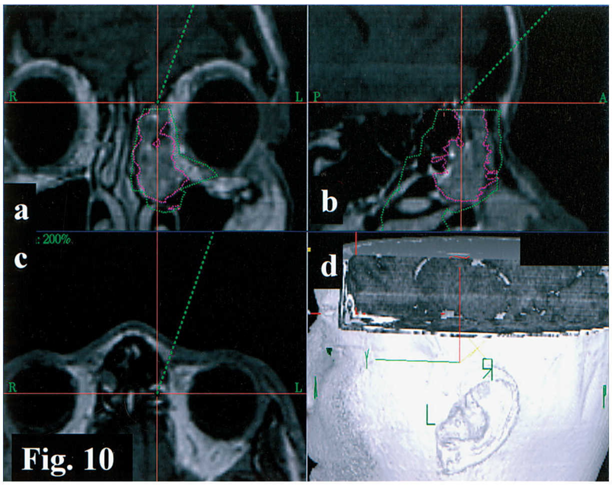

FIG. 10

3-D data set of an MRI scan (*Case 9*, Table I). (a) coronal, (b) sagittal, (c) axial, (d) 3-D volume model. The broken lines show the position of the pointer for evaluating the borders of the tumour for a subcranial approach and demonstrating the border of the tumour in the CT scan, visualized by image fusion with MRI.

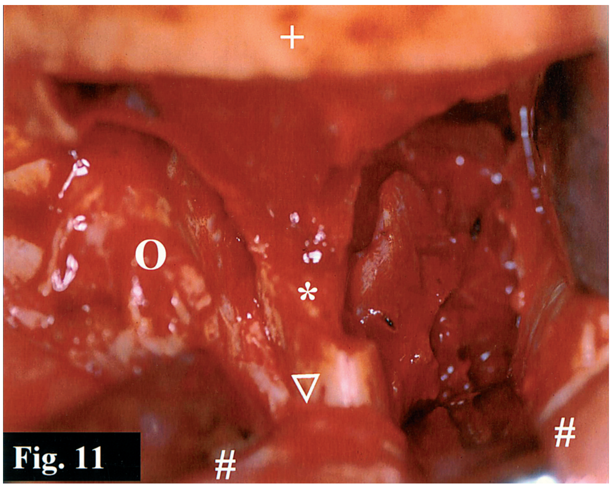

FIG. 11

View of the frontal skull base after navigation-controlled removal of the bony frontal skull base of the frontal sinus by a subcranial approach (*Case 9*, Table I). * = nasal septum; ∇ = mucosa of the posterior nasal septum; o = medial wall of the maxillar sinus; # = dura of the frontal brain; + = part of the upper bony anterior wall of the frontal sinus.

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invisible extension of the frontal sinus and of the pathology covered by bone to create an optimal craniotomy. Furthermore, one-piece craniotomy was recommended to secure a well-fitting piece of bone that could be repositioned for a good cosmetic result in the closing procedure.[26]

The rapid development of 3-D image-processing systems has greatly enhanced the surgeon's ability to visualize cross-sectional spatial anatomy.[15,19,27] CAS was not a favoured method in the early days, but rapid advances in electronic data processing and electronic systems have subsequently led more and more to a routine application of this device in the field of skull base and neurosurgery.[13,14,28] In the authors' surgery, navigation systems with optic electronic devices are preferred as they tend to be more accurate than electromagnetic devices.[29] In this retrospective investigation of 10 patients following all types of transfrontal approach, various applications of CAS in skull base surgery were analysed. It was demonstrated that navigation could optimize the craniotomy and minimize morbidity. Meanwhile, the identification of the borders of skull base malignancies or of critical landmarks by navigation has come to be a common procedure as well as navigation-controlled drilling of implantation beds or positioning of implants.[2,4,7,10,12,14] Thus, this navigation-controlled procedure combining the drilling of the forehead bone to create the surgical corridor and simultaneously preparing for reconstruction was further development in CAS. This is a new tool showing how navigation can support and secure the surgeon's procedures. The preparation time for activating the navigation system of about 10 min including the time period for the registration procedure while the patient is under general anaesthesia is acceptable in a total duration of surgery of about five hours. Surface matching is a very reliable, practicable registration procedure, which is neither time-consuming nor prone to error, that can be performed by a less experienced person.

The bicoronal skin incision does not allow the use of a head frame. Titanium screws as bone anchored markers are too uncomfortable for patients and will be refused. The only alternative to surface-matching procedures in such surgical approaches resulting in a comparable accuracy is the use of an upper jaw splint. The error associated with cutaneous markers is unacceptably high.[30] In the event of dislocation, both navigation systems used in our departments allow a re-evaluation of the registration procedure by surface matching or by definition of several intra-operative anatomical landmarks. The former was shown with an excellent accuracy in two cases, in which accidental dislocation of the tracker happened during the surgical procedure. The authors' experience showed that this situation, occurring in two out of 10 cases in their series, is not rare and the surgeon should be prepared for it, otherwise he will lose a lot of time or the chance of navigation-guided surgery.

CAS allows the surgeon to mark the borders of the pathological process of the frontal sinus or of the resection line directly on the bone. This was impossible in the past when using a mobile X-ray system, because the surgeon had to transfer his impression from the X-ray image to the bone, with a high failure rate. An intra-operative CT or MRI scan would be the only alternatives. Both are very expensive. In addition, intra-operative CT scanning needs a high irradiation dose, whereas MRI requires an open tomograph as well as a need to avoid all magnetic instruments inside the operating theatre. Furthermore, CAS offers information about the thickness of the bone at this surgical point of the forehead to the surgeon performing the craniotomy and shows him where he has to expect the sagittal venous sinus. Thus, he can directly change the position of the craniotome to get an optimal result for the resected bone, minimizing side-effects.

- **This is a relatively small retrospective series of patients with frontal sinus malignancy treated surgically with the additional help of using a computer-assisted navigation system**
- **The authors suggest that the additional facility offered by this system aids planning the craniotomy and facilitates reconstruction**

Conclusion

CAS can provide sufficient precision and reproducibility in frontal skull base surgery and may help to optimize the surgical corridor in transfrontal approaches and the reconstruction procedure for a good functional and cosmetic result.

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Address for correspondence:
Joerg Schipper, Assoc. Prof., M.D.,
Universitaets-HNO-Klinik Freiburg,
Killianstrasse 5,
D-79106 Freiburg, Germany.

Fax: +49-761-2704111
E-mail: schipper@hno1.ukl.uni-freiburg.de

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