Chapter

The Virtual Operating Field – How Image Guidance can Become Integral to Microneurosurgery

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1.1 Introduction

In neurosurgery, layers of soft tissue, bone, and parenchyma conceal vital structures, landmarks, and the targeted lesion. Guiding an approach to a lesion with the help of computed tomography (CT), magnetic resonance imaging (MRI), or ultrasound images of the anatomy of a patient enables avoidance of accidental damage and the definition of a clear surgical corridor in individually uncharted territory. Today, surgical image guidance based on three-dimensional (3D) volumetric data has become part of the routine in most neurosurgical centers around the world.

There is a concurrent trend in medical disciplines toward augmenting interventions by virtual reality, the envisioned ideal being a virtual stereoscopic view on the surgical field and beyond before the first cut and throughout the operation [14, 23, 35]. Image-based, stereoscopic virtual reality models are used to plan surgical procedures and for teaching purposes in neurosurgery and temporal bone dissection [11, 17, 19, 20, 34, 38, 41]. However, image guidance in neurosurgery, synonymously termed "neuronavigation," has yet to become an integral part of most neurosurgical procedures. While this would be desirable considering the need to anticipate functional and morphological obstacles in the surgical path in individual cases, there are several prerequisites that will have to be met before navigation in neurosurgery will come to be seen as ordinary as navigation in today's automobiles. This chapter briefly explores the history and current development in the field and offers an outlook into the future of neurosurgical image guidance.

1.2 History

The history of neuronavigation can be traced back to the roots of stereotaxis with a Cartesian coordinate system devised by Clarke and Horsley at the beginning of the last century [1]. Image-guided frameless stereotaxis became feasible through the integration of high-speed computers in the 1990s. The first clinical trials were accompanied by concerns about spatial accuracy and ease of application of the technology in the operating theater. Hardware and software were designed by various research groups and even with the first commercially available systems, data transfer, segmentation of morphological structures, and registration procedures were cumbersome and time consuming. Bone-anchored fiducials under local anesthesia often had to be applied a day before surgery, and scanning protocols for CT had to be adjusted to meet the requirements of the specific navigation system. The acquired data had to be saved to digital tapes or magneto-optical discs, and often tedious pre-processing ensued in order to reformat files to make them readable for the system.

Today, the accuracy of most image-guidance systems, as assessed by target registration error, is well documented and usually acceptable with mean values below 2 mm [4, 16, 22, 29, 33, 44, 48], except for targets located remote to the fiducials used for registration or cases where very few fiducials are valid [46]. MRI images can be corrected for object-induced and spatial distortion [40, 45]. Adhesive skin markers and surface registration have replaced bone-anchored fiducials for most intracranial procedures. Data transfer is made by local area networks that connect workstations in the operating theater directly with those in the radiology department. Workflow control allows for intuitive use of the navigation software, making the setup in the operating room fast and easy.

1.3 State of the Art

Three-dimensional stereoscopic guidance has been developed with the goal of allowing the surgeon to explore radiological imaging information in situ [10, 12, 13, 23] by overlaying an image onto the microscopic view. It still has a long way to go with computation capacity, accuracy [24], and visual perception of depth in 3D images [15].

However, with improving image quality, coregistration of various image modalities, and 3D volumetric image rendering in real-time, image guidance today is capable of providing nonstereoscopic, color-coded models that match closely the individual anatomy of the real surgical field and relieves the surgeon of the task of mental reconstruction of tri-axial images on a routine basis [3, 35, 39].

Although ultrasound is being employed increasingly for image guidance [2, 6, 18, 21, 30, 36, 42, 43], MRI (1.5 and 3 Tesla), CT, and CT angiography remain the primary imaging technologies to create volumetric data sets.

CT is usually performed in the axial orientation with a slice thickness of 1 mm and an ultra-high algorithm. For arterial and venous CT angiography in tumor patients, the first bolus of 40 ml intravenous contrast medium is sufficient to visualize enhancing tumors. For vessel depiction, it may be followed by a further 60 ml, administered at a fast rate, after an individual delay determined by a bolus test [47].

Today, MRI is usually performed on 1.5 Tesla or 3 Tesla scanners. A higher field strength is superior for functional imaging, but imaging is also more prone to motion artifacts, especially in regions around the brainstem.

Axial T1-weighted 3D magnetization prepared rapid gradient echo (MPRAGE; TR/TE/T1 11.08/4.3/300 ms, flip angle 15°, band width 130 Hz/pixel, effective slice thickness 1 mm, pixel size 1.2×0.9 mm) with or without intravenous contrast medium (0.1 mmol/kg body weight gadolinium-DTPA) are usually sufficient for MRI guidance. This sequence is acquired in just over 7 min minutes.

For improved imaging of the temporal bone and the cortical surface in the temporal fossa, an axial T2-weighted constructive interference in steady state (CISS) sequence (TR/TE/flip angle 17/8.08ms/70°ms, effective slice 0.7 mm pixel size 0.6×0.45 mm acquisition time 7 min 51 s) has been applied in selected cases, especially when the lesion is located in a cistern or in the ventricles. Data can be transferred to an image-guidance system via a local area network or passed onto the system using portable storage media. Navigation software should be capable of rendering high-resolution, pseudo-3D images that can be interactively rotated in real time.

There is no limitation for image guidance with respect to the pathologies involved. Even in an extensive subdural hematoma, it may be helpful in placing several burr holes at precisely determined locations.

The decision making for the surgical strategy including the approach and the stepwise exclusion of the lesion is usually designed by the surgeon in advance. However, in some cases, image guidance may be employed to modify and adapt these strategies to avoid approach-related morbidity or to define an optimal surgical corridor. The

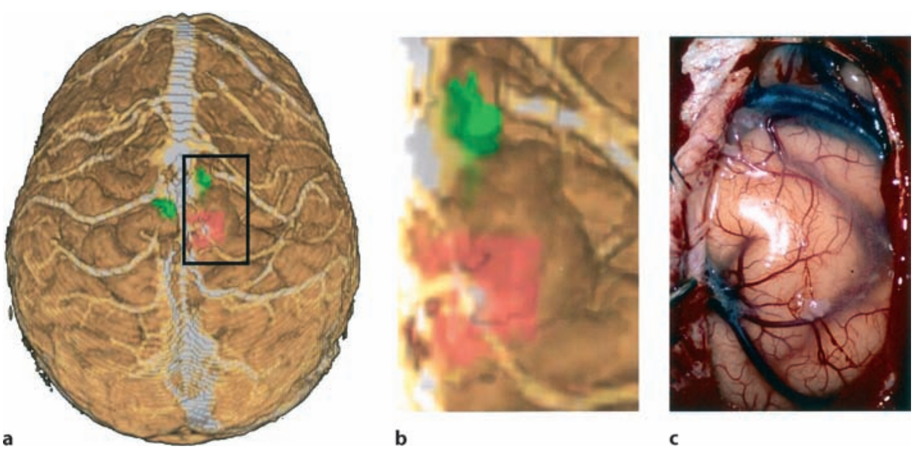

Fig. 1 **a** "Helicopter view" of the lesion and the motor areas for the left (*green*; pushed anteriorly) and right foot (*pink*) in a three-dimensional (3D) rendering created from magnetization prepared rapid gradient echo sequences and functional magnetic resonance imaging (fMRI) on the image-guidance system. **b** The virtual operating field (VOF, "driver seat view") showing the cortical surface and veins, the lesion, and the adjacent motor areas (*shaded*). Note that the latter two are exclusively seen in the VOF, but not in the real field. **c** Only the veins and the cortical surface can be recognized after the parasagittal craniotomy. Image injection of the VOF with a tumor outline and functionally significant areas can greatly enhance the real operating field in cases like this

segmentation and the creation of volumes of interest from the imaging data containing the landmark anatomical structures in the surgical path will usually be carried out by the neurosurgical team and only occasionally by an experienced neuroradiologist. A virtual "fly through" or "fly around" movie may be generated to simulate the major surgical steps in the planned procedure using the individual imaging data of the patient ("helicopter view", Fig. 1a). Again, the surgical strategy may be adjusted whenever an improved surgical approach could be derived from these visualizations.

Several volumes of interest may be selected and color-coded to create a volumetric image that contains all of the anatomical landmarks that would also appear in the real operating field. This image – the "virtual operating field" (VOF) – on advanced image-guidance systems can be interactively rotated to match the orientation of the real surgical field, as seen through the microscope (Fig. 1). Surfaces may gradually be rendered translucent in the image to allow a view of the lesion in relation to more superficial morphologic landmarks (Figs. 1–3, "driver seat view"). The VOF should ideally be zoomed to the size of the real microscopic field, and both views may be displayed on a

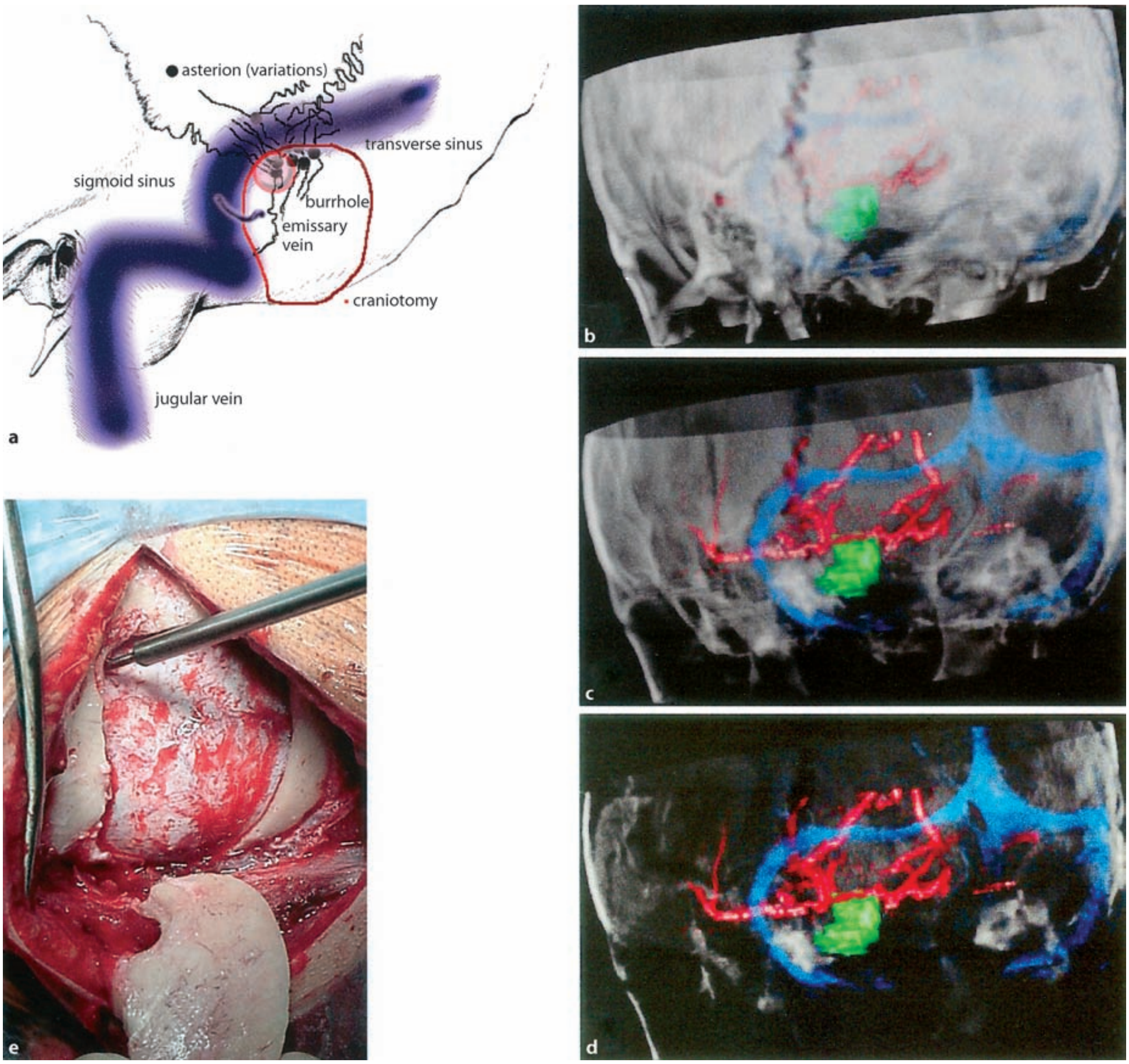

Fig. 2 **a** Anatomical landmarks for the lateral suboccipital approach. Note the variability of the location of the asterion around the sinus transition. **b** 3D rendering of the bone sutures of the posterior fossa with the navigation system. **c,d** Gradual transparency modulation of the bone allows for a look through the posterior fossa. The borders of the venous sinuses (*pink*) become clearly visible so that they can be used as landmarks themselves, replacing the asterion as a historical landmark. The circle of Willis is also shown in the images (*blue*). **e** After a burr hole has been placed just below the transverse-sigmoid junction, an osteoplastic lateral suboccipital craniotomy is carried out

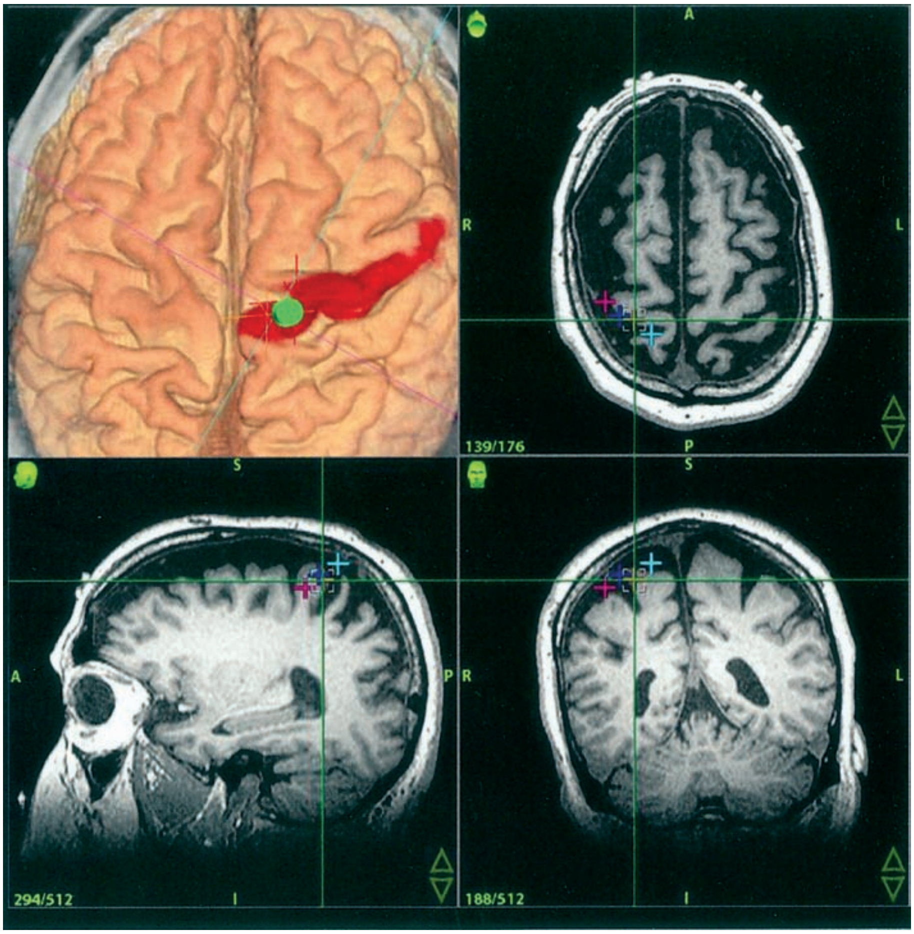

Fig. 3 Image guidance with 3D renderings (upper left) and tri-axial MRI in a patient with intractable thalamic pain during implantation of a motor cortex stimulator. The visualization of the cortical surface with its gyri and sulci is clearly superior in the volumetric 3D rendering. The motor strip has been segmented manually based on fMRI images of the patient. The virtual probe points – just as the real one – to a previously defined electrode location

video monitor or in the ocular of the surgical microscope simultaneously. Depending mostly on the quality of the imaging data and the level of the human computer interface (intuitive software, computer skills of the surgeon), image rendering may take between 15 min and 2 h.

In the operating room, the patient's head is registered either with five to ten adhesive skin fiducials and a pointing probe (which may be substituted by the microscope in some settings), or with a device and algorithm for surface detection. Most systems today are based on infrared transmission employing a camera for detection of a digital reference frame and the instruments (Fig. 4).

The digital reference frame may be attached to the head holder, to the operating table, or directly to the head of the patient. It is kept visible by the camera by draping it with a transparent bag or by mounting it sterile on an appropriate extension. After registration, a quick check should be performed to assess the accuracy of the registration by targeting a well-defined landmark (e.g., the nasion or the outer ear canal).

The quality of VOF images related to their closeness to reality will obviously depend on the quality of the primary data set. A contrast-enhanced target located adjacent to the bone and targets located in the middle fossa or at the craniocervical junction may pose difficulties because of decreased tissue contrast and MRI distortion. Also, due to the smaller sulci and the lesser amount of cerebrospinal fluid contained in the subdural space, it is usually harder to depict the surface of the temporal lobe cortex in 3D renderings.

The surgical approach is facilitated by VOF images by showing hidden landmarks like the transverse and sigmoid sinus in a retrosigmoid route (Fig. 2). Gradual modulation of the opacity of surfaces in VOF images allows for visualization of hidden anatomical structures, and for relating those structures to more superficial land-

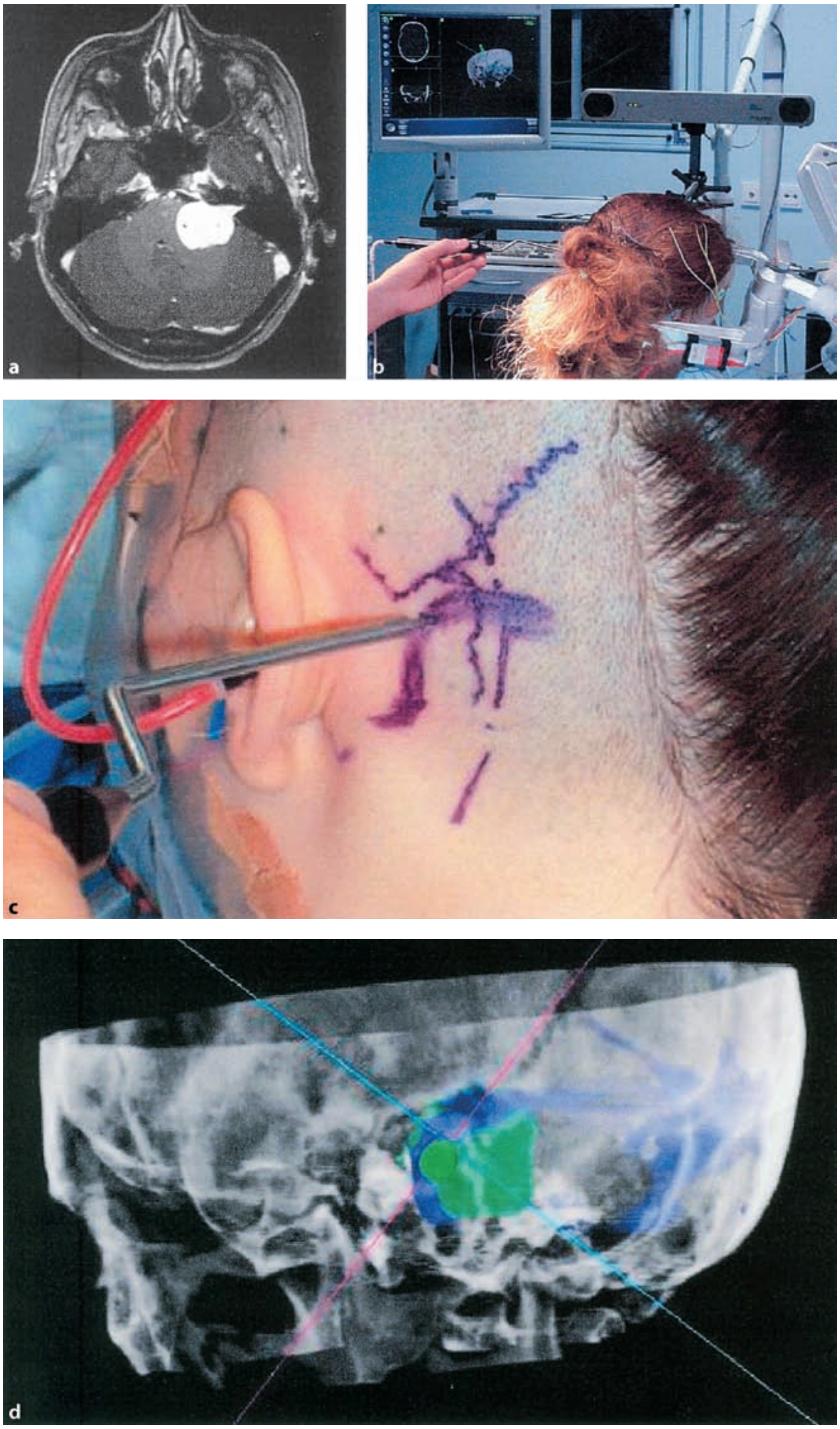

Fig. 4 **a** Gadolinium-enhanced, T1-weighted axial MRI of a vestibular schwannoma on the left side. The primary data for image-guidance in this particular case were obtained from both a MRI and spiral computed tomography. **b** Semisitting position of the patient for the retrosigmoid approach. The infrared camera of the image-guidance system is placed low on the side of the lesion so that it can "see" the probe. **c** The course of the transverse and sigmoid sinuses and the bone sutures meeting at the asterion have been drawn to the skin with a surgical marker. **d** Corresponding image on the navigation screen with the virtual probe pointing to the transverse sigmoid transition

marks that were already within the surgeon's view (like the asterion in Figs. 2 and 4).

With 3D renderings there is no need for the surgeon to mentally reconstruct the surgical anatomy from two-dimensional scans. Compared to tri-axial two-dimensional images, orientation is significantly faster and more comprehensive with VOF images (Figs. 1–3). This becomes more apparent when irregular-shaped structures like the dural sinuses, the basal arterial circulation, the bone of the skull base, tumor borders, and the cortical surface are involved or when the operating field was rotated into an unusual orientation [35].

The advantages of image guidance multiply when functional and/or histological characteristics are added to a VOF. Figure 3 shows how functional image-guidance aids can be in the placement of epidural electrodes for motor cortex stimulation in intractable pain. The morphological outline of the precentral gyrus can be easily and safely traced in 3D images if functional data are available. Precise electrode implantation with this guidance is greatly facilitated, even with the dura remaining closed throughout the procedure [5].

Similar advantages have been reported for subdural placement of electrode grids in patients with epilepsy, for detection of the origin of focal seizure activity [25, 37]. Some brain tumors, even though they reach the surface of the cerebral cortex, do not show any demarcation to normal brain parenchyma (Figs. 1 and 5).

However, if a tumor is well delineated on T2-weighted MRI (Fig. 5), its outline can be mapped or overlaid onto the cortical surface in a VOF. This is especially useful if the tumor is located adjacent to a functionally eloquent area and, therefore, resection has to be restricted precisely to the tumor limits in order to avoid intolerable morbidity. Functional imaging provides further information that would not be available in the real surgical field without neuronavigation (Fig. 1).

The functional anatomy can be shifted or distorted by the tumor. This is especially important when fiber tracking by diffusion tensor imaging is employed. The pyramidal tract may be considerably displaced and then returned to its normal position as tumor resection progresses. Under these circumstances of major brain shift, MRI scans acquired prior to the procedure would not be reliable during surgery. It has been shown that intraoperative functional MRI is feasible with the same protocols that are used outside the operating theater. The combination of neuronavigation and intraoperative functional MRI offers additional safety in these cases [8, 26–28]. Multimodal imaging may also improve the reliability of

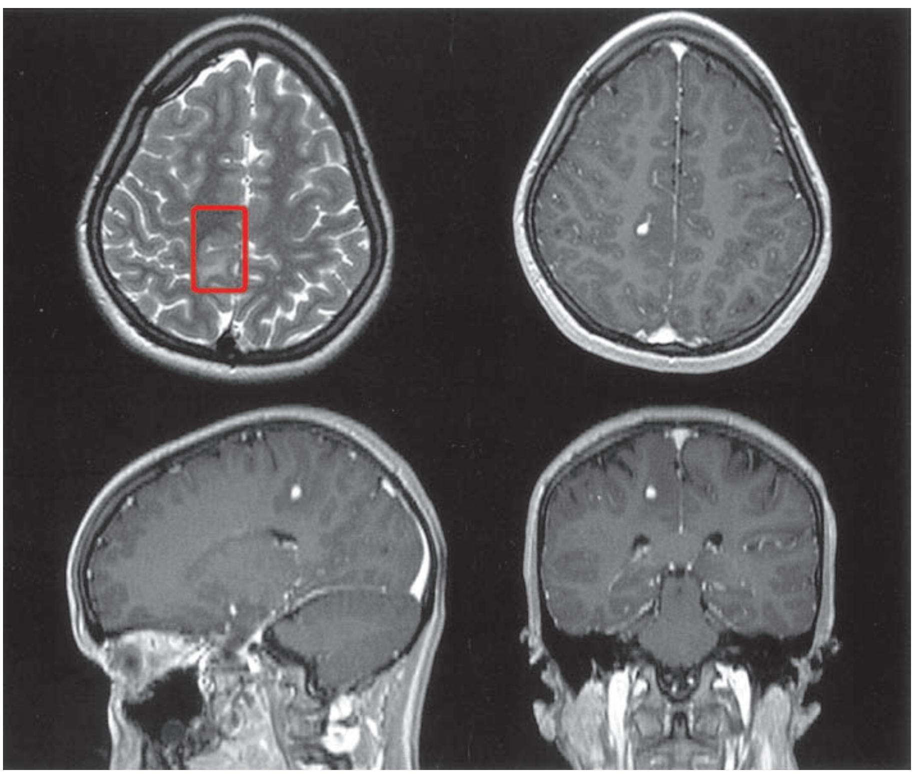

Fig. 5 An infantile desmoganglioma in the right postcentral region of a 14-year-old patient. The T2-weighted MRI (upper left comer) shows that the lesion centers around a sulcus. In the depth, nodular contrast-enhancement in T1-weighted images points to a histologically dubious portion of the tumor

functional information, especially with respect to the language areas of the cortex [7].

Zooming in the virtual images in order to enlarge the detail to the size of the surgical field reduces the amount of information presented at a time to the required minimum, steadying the surgeon's focus of attention (Fig. 1).

Individual, patient-specific anatomy can be visualized in the VOF down to a resolution of about 2 mm for well-delineated structures. In general, all morphological structures that are readily discernable in primary imaging data can be also detected in virtual 3D models of the surgical situs. Using image fusion techniques, bony surfaces, embedded vessels, and different types of soft tissue along the surgical path, both in front of and beyond the lesion, can be identified in a single image, which in turn can be rotated to match the view through the microscope onto the real surgical field.

Stereoscopic images are not obtained as easily, but they have the decisive advantage of conveying information on depth along the *z*-axis [9, 10, 16, 32, 38], which can only be captured in tri-axial images with volumetric pseudo-3D rendering.

Smaller and less discernable structures, such as most cranial nerves, are not well delineated in routine images. Electrophysiological monitoring is still by far the most effective tool for early identification of the cranial nerves.

1.4 Outlook

Microneurosurgery depends on 3D, stereoscopic information on the surgical field delivered through the microscope. A "virtual microscope" operating in 3D space that uses stereoscopic radiographic images of the patient's anatomy would be an ideal instrument to plan these procedures and to obtain on-line information beyond the operating field during surgery. While several problems remain to be resolved [15, 24, 31], true 3D imaging, on a routine basis will probably be performed by taking advantage of stereoscopy in the future.

Overlay of a VOF that virtually matches the surgical field will certainly augment the surgeon's capacities. While anatomical knowledge and experience still remain the most crucial factors affecting the surgical result, virtual reality can provide additional information about elements in the operative field that are beyond the superficial layer and invisible through the operating microscope.

Although now in extensive clinical use, image guidance still is often perceived as an intrusion into the operating room [31]. In our experience, image guidance is best accepted when additional preparation time is minimal and the VOF is adjusted to the size and orientation of the real surgical field containing relevant landmarks without redundant information.

The following list is a brief compilation of essential prerequisites that, according to the literature and to our own experience,, will have to be met in order to turn image guidance into an integral part of most microneurosurgical procedures.

1. Accuracy: Image guidance needs to be precise. Geometric distortions in imaging procedures have to be corrected before the data are taken to the operating room.
2. Easy and speedy applicability: Imaging, data transfer, segmentation, intraoperative setup, and registration combined should require minimal additional time.
3. Image fusion: Multimodal images must be easily coregistered and combined in a single image.
4. Truly stereoscopic 3D images: Stereoscopic visualization improves perception and enhances the ability to understand complex 3D anatomy.
5. Interactivity: The practical benefit of 3D display is increased considerably when the size and orientation of the VOF corresponds to the real microscopic view of the surgical field. Different perspectives of the field (driver's seat view, helicopter view) should be optional. With respect to the limitation of the VOF, less may often be more, since the surgeon will only appreciate relevant information on the surgical field in view under the microscope.
6. Transparency: The possibility of seeing through surfaces by gradually rendering them translucent is advantageous, since landmarks at different depths along the surgical path can be correlated to one another.
7. Integration of the functional characteristics of tissue: Data from functional MRI, including fiber tracking by diffusion tensor imaging as well as, for example, positron emission tomography, electroencephalography, magnetoencephalography, and spectroscopy, should all be made available in images used for intraoperative guidance.
8. Intraoperative correction for tissue shift: In procedures involving major mass extraction or massive drainage of cerebrospinal fluid, an intraoperative update of the images by MRI, CT, ultrasound, or surface tracking should be available.
9. High spatial image resolution: While spatial resolution on MRI has increased over the years, it is difficult to discern objects smaller than 2 mm in size. Since spatial resolution and tissue contrast are crucial for the creation of true 3D images that match the view provided by microscopic magnification, this is an issue that will have to be addressed in the future.

Image guidance based on 3D images will never substitute precise anatomical knowledge and surgical experience, because systematic and accidental technical errors occur and the depiction of anatomical detail is limited by the resolution of imaging techniques. There is little doubt, however, that the VOF will become a very real part of the microsurgical situs and it is hard to see why the two should not be intimately entwined in the near future.

1.5 Summary

Image guidance in neurosurgery – the technique of guiding an approach to a lesion with the help of computed tomography (CT), magnetic resonance imaging (MRI), or ultrasound images of the anatomy of an individual patient – is no longer a novelty. Accuracy validation has been established and advances in both hardware and software have rendered the technology user-friendly and almost intuitive in routine applications. Image acquisition, data transfer, and intraoperative patient registration take only a few minutes to accomplish. The whole procedure is noninvasive and in many surgical approaches, there is no particular need to compensate for brain shift.

Still, image-guidance in neurosurgery (neuronavigation) has not yet evolved into such an omnipresent instrument (e.g., like the microscope), although it does have similar potential considering the constant desire to see beyond tissue barriers in the surgical path in an ever variable, individual, anatomical environment.

In order to be successful, neurosurgeons must develop a thorough comprehension of complex, three-dimensional (3D) anatomy. Current radiological methodology – namely tomography – for everyday purposes has reduced the dimensions available in a single image to two, leaving the surgeon to mentally reconstruct a 3D structure from two-dimensional images in multi-axial planes.

There is a clear discrepancy between today's radiological routines and the challenges of surgical practice described in what could be called "the two-dimensional dilemma." This dilemma is being dissolved only slowly and gradually, but it is obvious that neurosurgery, with its dependence on spatial visual orientation, would be among the specialties that will take the helm in leading medicine into a new era of 3D image guidance.

Technologically, it is already possible to reconstruct a virtual, true 3D model of the operating field with translucent surface modulation and an optional "fly-through" video mode to the target structure from tomographic or ultrasound images. This model can be enhanced by CT–MRI image fusion and by adding functional characteristics, obtained from functional imaging or neurophysiological studies, to the morphology. Complex anatomical structures like the cortical surface, the tortuous course of cerebral vessels, or the outline of the paranasal sinuses can be easily visualized in such a model and recognized by the surgeon at a glance. Comprehension is greatly facilitated as compared to routine mental reconstruction of tri-axial images. It is also possible to simulate depth in a stereoscopic version of such a virtual operating field (VOF) and to zoom in and out according to the magnification of the microscope. The technology of tomorrow will allow for higher spatial resolution to capture very small objects (like small vessels) in the image.

Once stereo images like this can be projected into the microscope and overlaid onto the real operating field, in the view of the surgeon, without requiring much additional effort, image guidance is likely to become an integral part of most microneurosurgical procedures. Supported by sound anatomical knowledge, creating a VOF for any given surgical approach in an individual patient can greatly enhance the capabilities of a neurosurgical team.

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