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

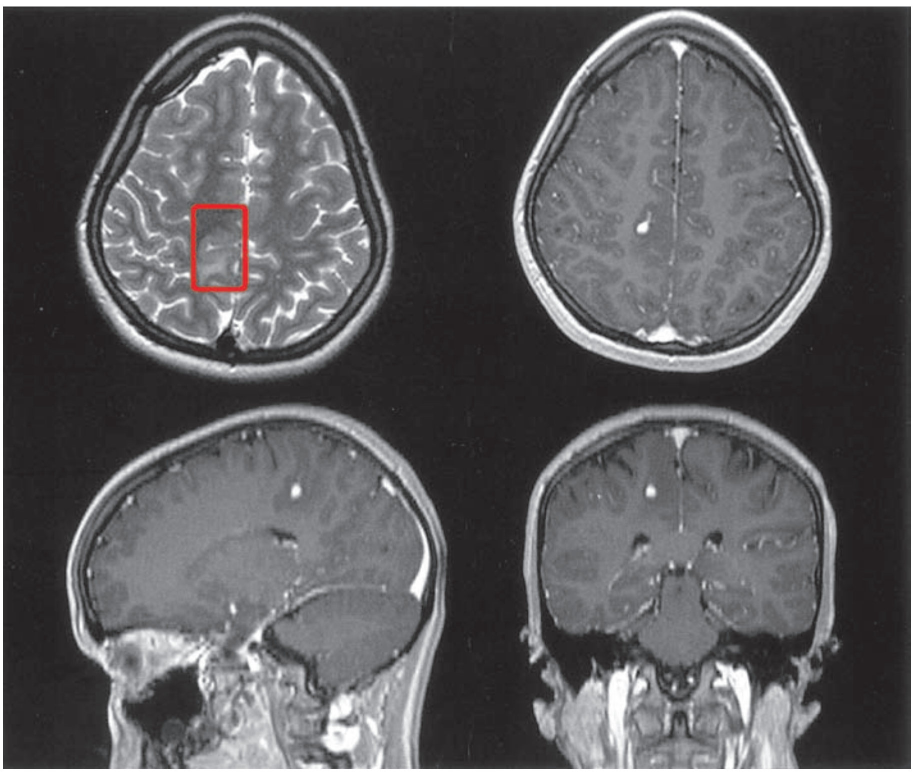

Fig. 5 An infantile desmoganglioma in the right postcentral region of a 14-year-old patient. The T2-weighted MRI (upper left comer) shows that the lesion centers around a sulcus. In the depth, nodular contrast-enhancement in T1-weighted images points to a histologically dubious portion of the tumor

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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