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Summary

Recent advances in imaging techniques (MRI), electrical source imaging and image processing algorithms (co-registration) have increased the success rate of preoperative localization of epileptogenic zones. This information can be transferred into image-guidance systems (neuronavigation) and utilized intraoperatively during epilepsy surgical procedures. More precise implantation of subdural or depth electrodes can be achieved for invasive monitoring. Improved tailored resections or disconnections can be performed. Intraoperative MR or digital photography can also be used to control the precise extent of tailored procedures. Used alone or in combination, these technological tools should improve the confidence and safety of epilepsy surgery, particularly in cases of non-lesional epilepsy. However, the permanent dialogue between the epileptologist and the neurosurgeon, possibly during the surgery itself, as well as a better comprehension of epileptogenic diseases, remain a key factor in the success of epilepsy surgery

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Key words: Epilepsy surgery, image-guided surgery, brain mapping

Utilisation de l'imagerie préopératoire pour la chirurgie de l'épilepsie

Les progrès récents réalisés en technique d'imagerie (IRM), l'imagerie de localisation de sources et les algorithmes d'analyse d'image (co-registration) ont augmenté le taux de succès de la localisation préopératoire des zones épileptogènes. Ces informations peuvent être transférées dans des systèmes de guidage par l'image (neuronavigation) et utilisées en salle d'opération durant les procédures de chirurgie de l'épilepsie. Il en résulte l'implantation plus précise d'électrodes sous-durales ou profondes pour le monitoring invasif et des résections ou déconnexions plus ciblées. L'IRM ou la photographie digitale peropératoires peuvent être utilisées pour contrôler l'extension d'une résection ciblée. Utilisés seuls ou de manière combinée, ces outils technologiques devraient améliorer la qualité et la sûreté de la chirurgie de l'épilepsie, particulièrement dans les cas de chirurgie non lésionnelle. Toutefois, le dialogue permanent entre l'épileptologue et le chirurgien, aussi durant la chirurgie, de même qu'une meilleure compréhension des maladies épileptogènes restent un facteur clé contribuant au succès de la chirurgie de l'épilepsie.

Mots clés : Chirurgie de L'épilepsie, neuronavigation, cartographie cérébrale

Präoperative Bildgebung bei Epilepsiechirurgie

Kürzliche Fortschritte in der MRI-Bildgebungstechnik, des „electrical source imaging“ und bei Algorithmen der Bildverarbeitung (Ko-Registrierung) haben die Erfolgsrate bei der präoperativen Lokalisation von epileptogenen Zonen erhöht. Diese Information kann in Bildgebungs-gesteuerte Verfahren (Neuronavigation) übertragen und intraoperativ während epilepsiechirurgischer Eingriffe verwendet werden. Damit erreicht man eine genauere Implantation von subduralen oder Tiefenelektroden für das invasive Monitoring und eine verbesserte Kontrolle von massgeschneiderten Resektionen oder Durchtrennungen. Auch die digitale Bildgebung oder ein Intraoperatives MRI dient der Kontrolle des genauen Ausmasses massgeschneiderter Eingriffe. Diese technologischen Verfahren, allein oder in Kombination angewandt, sollten das Vertrauen in die und die Sicherheit der Epilepsiechirurgie verbessern, insbesondere bei nicht-läsionellen Zellen. Der permanente Dialog zwischen Epileptologen und Neurochirurgen, der auch während des Eingriffs selbst möglich ist, bleibt ebenso wie ein besseres Verständnis der epileptologenen Erkrankungen ein Schlüsselfaktor für den Erfolg epilepsiechirurgischer Eingriffe.

Schlüsselwörter: Epilepsiechirurgie, Neuronavigation, Kartographie des Gehirns

Introduction

Success of epilepsy surgery relies on a precise determination and localization of the epileptogenic zone (EZ). While mesial temporal lobe epilepsies are treated successfully when hippocampal sclerosis is present, non-lesional and/or extra-temporal epilepsies are still challenging and still need invasive tools like subdural grids or depth electrodes to achieve accurate localization of EZ in some cases. With the recent advances in anatomical (MRI) and functional imaging (SPECT, PET, fMRI) coupled with electroencephalography and powerful signal processing tools (electrical source imaging), an increasing number of lesions and/or brain regions with epileptogenic activity are becoming localizable with more accuracy. The information obtained during the pre-operative evaluation should be fully and reliably transferred and utilized in the operative theatre in order to increase the precision of surgical resective or disconnective procedures while minimizing the risks of neurological deficits. Image-guided surgery has had a rapid development in the previous years and proved to be a useful adjunct in the neurosurgical practice, especially for the surgery on small and deep-seated lesions in eloquent regions. We present here our experience in the development and utilization of the preoperative multimodal imaging as well as the recent technical advances in image-guidance that allow the precise and tailored resection or disconnection of a predetermined epileptic focus.

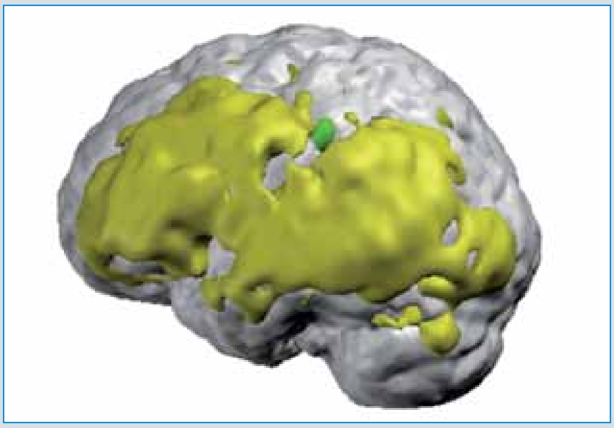

Figure 1: Co-registration of PET, subtraction ictal SPECT (SISCOM) and MRI: 50 year-old patient with partial motor seizures. The MRI revealed a discrete left parietal abnomality suggestive of dysplasia. PET (yellow) and SISCOM (green) co-registered with the MRI showed a focal interictal hypometabolism and ictal hyperperfusion that was concordant with the MRI abnormality.

Multimodal imaging and image co-registration

Multimodal imaging is essential during the presurgical evaluation of epileptic patients as it provides not only information on the localization and precise extent of epileptogenic malformations or lesions, but also information on normal and epileptogenic brain function, especially in non-lesional cases. Besides the standard use of CT, SPECT and PET images, recent advances in magnetic resonance imaging (high-field MRI) has certainly contributed to improve the resolution of anatomic (T1-, T2-weighted, FLAIR sequences) images, leading to a dramatic decrease of the so-called cryptogenic (or non-lesional) cases of focal epilepsy (figures). The use of high-field MRI has lead to the localization of brain functional regions with higher accuracy (fMRI) as well as the development of new applications, like the assessment of memory or the localization of abnormal epileptogenic brain function when coupled with EEG (EEG triggered fMRI). The exploration of diffusion properties of intracellular water by diffusion tensor imaging (DTI) has provided access to exquisite information on normal and possibly aberrant fiber tract localization and direction (see the paper by Vulliémoz et al. in this issue).

Parallel development of signal processing tools has lead to the emergence of electrical source imaging, which allows to consider the spatial and temporal localization of epileptic foci from the distribution of scalp EEG recordings through inverse solutions algorithms.

Powerful and reliable co-registration algorithms are needed to integrate complementary preoperative or intraoperative (when images are treated by image-guided systems) information provided by multimodal imaging [1]. Co-registration is essential for accurate spatial assessment of EZ and eloquent brain areas either by non-invasive multimodal imaging **(Figure 1)** or by subdural or depth electrodes when invasive monitoring is required **(Figures 2 and 3)**. The respective position of such electrodes is obtained from post-implantation CT or MR images; such "virtual electrodes" are co-registered with the pre-implantation MR images. Spatial mapping of EZ and eloquent brain areas can be carefully carried out from these implanted electrodes **(Figure 4)**. The combined 3D volume can also be transferred and rendered on image-guided systems for tailoring resection/disconnection of EZ [2, 3].

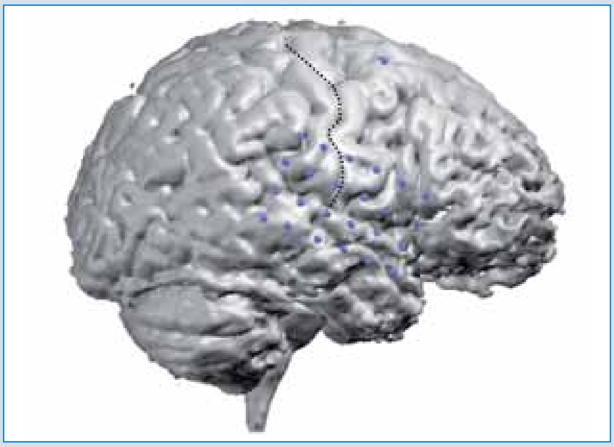

Figure 2: Co-registration of a CT-scan after implantation of a subdural grid (blue dots) and the preoperative 3D MRI.

Image-guided surgery (neuronavigation)

The term "neuronavigation" refers to the frameless image-guidance methods that allow the real time localization, during surgery, of the position of the instruments in relation to the preoperative imaging. Such techniques are widely used for the surgery on small or deep-seated lesions in order to follow a most direct and

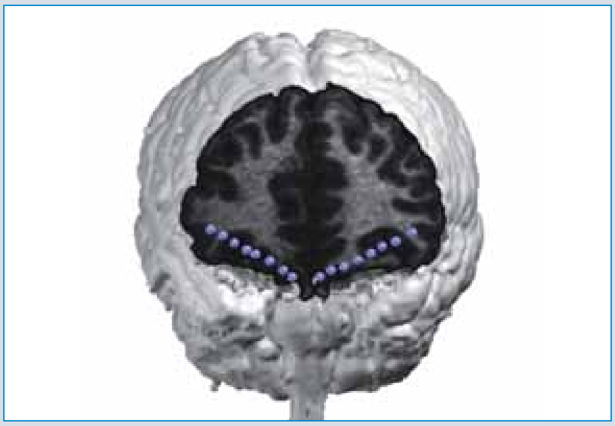

Figure 3: Co-registration of a CT-scan after implantation of a depth electrode (blue dots) in the orbitofrontal regions and the preoperative 3D MRI.

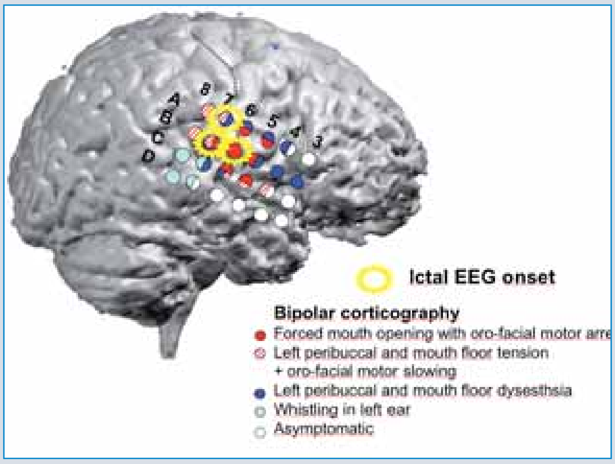

Figure 4: Co-registration of electrodes, EEG, corticography and MRI: The precise location of the intracranial electrodes is assessed by CT scan, co-registered to MRI. The dots indicate the position of the electrode contacts. The EEG telemetry allows recording of the ictal onset zone (yellow). Bipolar stimulation of the intracranial contacts allows mapping of the eloquent cortex (color-coded for motor and sensory) for optimal surgical planning.

less harmful trajectory to reach the desired target. Regarding epilepsy surgery, integration of multimodal imaging is crucial for guidance of subdural grids and/or depth electrodes placement to achieve precise localization of EZ and for mapping the eloquent brain areas during invasive recordings. The accuracy of depth electrodes placement with neuronavigation appears sufficient and the absence of a stereotactic frame allows the placement of subdural electrodes at the same operation [4, 5]. Multi-modality image-guided systems are also useful regarding surgical planning of therapeutic procedures, including the choice of center/extent of craniotomies and guidance of superficial as well as deep tailored resections/disconnections, rendering procedures minimally invasive. This is particularly true in cases of non lesional epilepsy, multiple lesions/EZ or if an EZ is located in an eloquent brain area, in order to optimize the extent of EZ resection [3, 6, 7] while minimizing the risks of neurological damage and the need for re-resection at least in temporal lobe epilepsy surgery [8].

During selective amygdalo-hippocampectomy, neuronavigation is very useful to precisely define the place and extent of craniotomy, find the opening site of limen insulae and guide the white matter trajectory to enter the anterior portion of the temporal horn of the ventricle **(Figure 5)**, limiting the risk of postoperative visual field deficit and limiting the extent of the necessary opening of the sylvian fissure or the transcortical approach [9]. Taking some precautions on account of brain collapse, neuronavigation can also serve to measure the length of the hippocampal resection, in order to tailor or standardize the hippocampectomy [10]. Moreover, when temporal lobectomy is associated with amygdalo-hippocampectomy, neuronavigation helps to tailor the posterior extent of the temporal resection. When periinsular hemispherotomy is considered, neuronavigation is very useful to find the lateral ventricle, reduce the risk of entering the contralateral hemisphere during the callosotomy and guide the approach for disconnecting the fimbria/fornix from the posterior aspect of the corpus callosum.

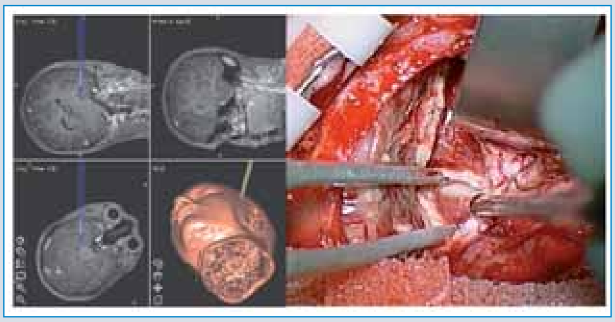

Figure 5: Image-guidance system showing the localization of the temporal horn of the ventricle (left) and the corresponding intraoperative view of the opened ventricle (right).

Although a precise per-operative localization of the target is achievable at the beginning of surgery, neuronavigation is subject to errors due to the shift and distortion of the brain as surgery progresses through the combined effect of cerebral resection and gravity. A study by Wurm et al. concluded that the surgical navigation was useful for tailoring the craniotomy and the cortectomy but was less reliable for the verification of the resection boundaries in the white matter. It was also useful to report the electric focus on the anatomic structures [11]. The utilization of per-operative neuronavigation may also have the potential of reducing the complication rate. However, the safer maximization of the resection allowed by neuronavigation does not replace completely the utility of electrocorticography. Thus, the combination of neuronavigation and electrocorticography appears to be an efficient solution of obtaining a precise lesionectomy as well as insuring a sufficient resection of the epilectogenic tissue in order to achieve a better seizure outcome [12].

Per-operative MRI

Per-operative MRI is another recent advance in image-guided surgery. It allows the repeated verification of the position of a lesion, the exclusion of the persistence of a residue of the lesion and, overall, the direct visualization of the brain in its current status and position. The image is present and brain shift is therefore not a concern. For epilepsy surgery, per-operative MRI can be an interesting adjunct to evaluate and maximize the extent of resection of the epileptic focus **(Figure 6)**. As the extent of resection of the temporo-mesial structures correlates with outcome, per-operative MRI has been used during anterior temporal lobectomies and selective amygdalo-hippocampectomies to verify the extent of resection, revealing that an unresected residue of amygdala or hippocampus was often left by the surgeon [13]. The per-operative identification and resection of such potentially epileptogenic residual tissue is obviously of great interest to optimize seizure control after a single surgery.

In fact, in epilepsy, the lesion is often not visible on T1-weighted and hardly visible of T2-weighted and FLAIR images, limiting the interest of the current low-field per-operative MRI systems. However, the co-registration of the pre-operative high-field T2 and FLAIR images with the T1 images and the utilization of the fused images during surgery along with a neuronavigation system is an effective solution to accurately target the epileptic focus in diagnostic and resective epilepsy surgery [15].

Digital photography

A simple digital picture of the exposed cortex during epilepsy surgery can be of great help in planning a resective or disconnective surgery [16]. If per-operative mapping (somato-sensory evoked potentials and/or direct cortical stimulation) and electro-corticography are performed during the surgery, the epileptologist can report the identified eloquent areas as well as the primary and secondary epileptogenic zones on the picture and thus in relation with the cortical surface landmarks **(Figure 7)**. A global neurosurgical map is thus created, allowing the epileptologist to plan a tailored combination of cortical resections and subpial transsections, and aiding and orienting the neurosurgeon who, at any time as the surgery progresses, can refer to this original and undistorted map [16]. Such pictures can also be taken at the time of subdural strips and grids implantation for invasive presurgical work-up, where a more complex map, including language and cognitive functions, will be created during the pre-operative investigations **(see Figures 2 and 4)**. The digital picture is then sufficient to precisely localize the subdu-

Figure 6: Intraoperative MRI coupled with image-guidance system (left) and acquired image showing the extent of a lesion resection (right)

However, an extensive resection implies an increased risk of new neurological deficits. The combination of functional neuronavigation with per-operative MRI appears therefore as an elegant solution to obtain an up-to-date combined anatomical and functional information for guidance; the position of the eloquent cerebral regions are displayed in superimposition in the operative field, thereby minimizing the risk of encroaching on the functional brain regions [14]. This combined approach has been used in epilepsy surgery with low-field and high-field MRI systems but the latter proved clearly superior in epilepsy surgery by its better image quality and more advanced imaging possibilities [14].

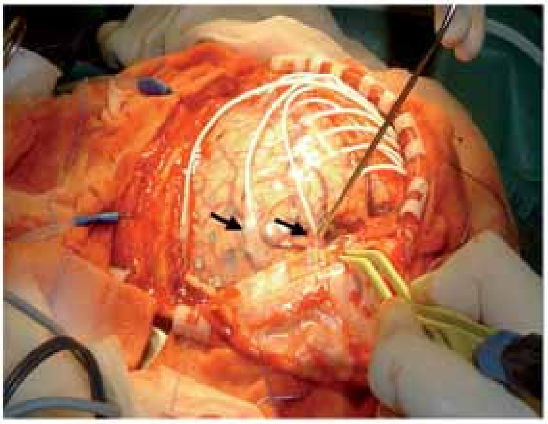

Figure 7: 2 year-old boy with symptomatic partial status epilepticus in the context of an extensive left posterior dysplasia. Per-operative view of a subdural grid of 8x8 contacts on the parieto-occipital cortex. The black arrows indicate additional interhemispheric subdural strips of 8 contacts.

ral strips and grids contacts in order to manually report their position onto a 3D rendered view of the cortical surface obtained from the pre-implantation MR [17]. This new 3D volume, combining precise anatomy and electrodes position, can now serve as a template onto which the results of the electrophysiological evaluation can be transferred to each electrode location; this integrated dataset can finally be fed into a neuronavigation system to display, during the surgery, the electrophysiological information in relation with the cortical surface [17].

Conclusion

Multimodal imaging, image co-registration and the use of image-guidance techniques have increased the confidence and safety of epilepsy surgery, particularly in cases of non-lesional epilepsy. The recent insights in anatomical and functional imaging gleaned during the preoperative evaluation as well as the significant developments of signal (EEG) and image (co-registration algorithms) processing tools have provided information of higher accuracy regarding the localization of epileptogenic zones and the mapping of functional brain areas. This information can easily be displayed on image-guided systems in the operative theatre and, coupled with intraoperative electrophysiological monitoring, appears to be helpful to tailor the surgery and hence improve the outcome while minimizing neurological deficits. However, despite these advances, the permanent dialogue between the epileptologist and the neurosurgeon, possibly during the surgery itself, as well as a better comprehension of epileptogenic diseases, remain a key factor in the success of epilepsy surgery.

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