TECHNICAL NOTE - FUNCTIONAL NEUROSURGERY - EPILEPSY

Three-dimensional neuronavigation in SEEG-guided epilepsy surgery

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Abstract

Objectives Epilepsy surgery is mainly cortical surgery and the precise definition of the epileptogenic zone on the complex cortical surface is of paramount importance. Stereoelectroencephalography (SEEG) may delineate the epileptogenic zone even in cases of non-lesional epilepsy. The aim of our study was to present a technique of 3D neuronavigation based on the brain surface and SEEG electrodes reconstructions using FSL and 3DSlicer software.

Patients and methods Our study included 26 consecutive patients operated on for drug-resistant epilepsy after SEEG exploration between January 2015 and December 2017. All patients underwent 1.5 T pre-SEEG MRI, post-SEEG CT, DICOM data post-processing using FSL and 3DSlicer, preoperative planning on 3DSlicer, and intraoperative 3D neuronavigation. Accuracy and precision of 3D SEEG reconstruction and 3D neuronavigation was assessed.

Results We identified 125 entry points of SEEG electrodes during 26 operations. The accuracy of 3D reconstruction was 0.8 mm (range, 0–2 mm) with a precision of 1.5 mm. The accuracy of 3D SEEG neuronavigation was 2.68 mm (range, 0–6 mm). The precision of 3D neuronavigation was 1.48 mm.

Conclusion 3D neuronavigation for SEEG-guided epilepsy surgery using free software for post-processing of common MRI sequences is possible and a reliable method even with navigation systems without a brain extraction tool.

Keywords Neuronavigation · Three-dimensional reconstruction · Cortical topography · Cortical relief · Eloquent cortex · Epilepsy surgery

Introduction

Epilepsy surgery is mainly cortical surgery and the precise definition of the epileptogenic zone on the complex cortical surface is of paramount importance. Stereoelectroencephalography (SEEG) may delineate the epileptogenic zone even in cases of non-lesional epilepsy. Projection of the epileptogenic zone on the intraoperative cortical surface remains a neurosurgical challenge. The transition from slices to three-dimensional (3D) imaging gets surgeon and neurologist closer to the reality. Neurosurgeons are used to transforming slices in volumes and surfaces but this mental process is dependent on the physician's qualities, experience, and lesion localization and may be a source of errors. Neuronavigation is used to improve our orientation in the intracranial space. The important development in MR neuroimaging and different post-processing software reveals new opportunities for pre-surgical planning and intraoperative 3D neuronavigation in epilepsy surgery. The automatic segmentation tools in the present neuronavigation systems provide a simple but frequently an imperfect way to reconstruct the brain surface and electrodes' contacts. The aims of our study were to present and to analyze the accuracy of a technique of 3D neuronavigation based on brain surface and SEEG electrodes reconstructions using FSL and 3DSlicer software.

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Material and methods

Material

Our study included 26 consecutive patients operated on for drug-resistant epilepsy after SEEG exploration between January 2015 and December 2017. All patients underwent 1.5-T pre-SEEG MRI, post-SEEG CT, DICOM data post-processing using FSL and 3DSlicer, preoperative planning on 3DSlicer, and intraoperative 3D surface neuronavigation using Stryker navigation system (NAV3).

Methods

Imaging

All pre-SEEG MRI was conducted using a 1.5-T scanner (GE Signa Excite Hdxt, with 8HRBRAIN coil). The following imaging sequences were obtained in all cases: sagittal T2 cube (isotropic, voxel size $1.0 \times 1.0 \times 1.0$ mm), sagittal FLAIR cube (isotropic, voxel size $1.0 \times 1.0 \times 1.0$ mm), and axial 3D T1 SPGR (voxel size $1.0 \times 1.0 \times 1.4$ mm) without contrast and after gadolinium enhancement (0.1 mmol/kg). Our technique of SEEG electrode implantation was described previously [1]. CT scan without contrast enhancement was performed after SEEG electrodes' implantation (GE, BrightSpeed, helical mode, 256 slices, 1.25-mm-slice thickness).

Post-processing pipeline

DICOM data were imported and processed through FSL and 3DSlicer running on a MacBook Pro 2 GHz Intel Core i7 (Apple Computer, Inc., Cupertino, California). Post-processing included the following steps:

1. Importation of DICOM series (sagittal T2 cube, sagittal Flair cube, axial 3D T1 SPGR, axial 3D T1 SPGR with contrast enhancement and post-SEEG CT) in 3DSlicer.
2. Conversion of DICOM series to NifTi format and exportation.
3. BET (brain extraction tool) using FSL that allowed obtaining image volumes containing only the brain volume striping out scalp, skull, and dura. The BET of FSL was performed separately for Flair, T2, T1 without contrast, and T1 with contrast imaging. The BET tool may be applied with a different fractional intensity threshold. Smaller values give a larger brain outline estimation. Flair sequence brain extraction provides the best cortical reconstruction (Fig. 1).
4. Creation of T2 skull mask using FSL and the terminal command: bet X.nii X_betted.nii—a will which produces different masks and meshes: outskin, outskull, inskull, and brain.

5. Visualization of the intracranial SEEG using T2 inskull_mask, post-implantation CT, and the terminal command: fslmaths Electrodes_CT.nii–mas T2_inskull_mask.nii subtracted_Electrodes.nii.
6. Grayscale model maker tool of 3DSlicer was used for creating a 3D model of the electrodes. Thresholding of 2000 was applied in order to exclude non-metal structures and to reconstruct electrodes' contacts (Fig. 2).
7. Importation of brain extracted NifTi files on the 3DSlicer platform and preoperative planning using the volume-rendering tool, slice visibility on 3D imaging, and background foreground layer mixture (Fig. 3).
8. Exportation of brain extracted (BE) DICOM series using Create a DICOM series in 3DSlicer.
9. Importation of BE DICOM series in Stryker navigation system (NAV3).

Accuracy assessment

The accuracy of 3D SEEG reconstruction was assessed measuring the difference between the distance of the entry point of the electrode and a close sulcal point visible on the brain surface after performing craniotomy and the same distance on the 3D reconstruction in 3D Slicer (Fig. 4). The precision of 3D reconstruction was measured using the standard deviation (SD) of these values.

The accuracy of 3D neuronavigation was assessed measuring the Euclidean distance between the tip of the pointer when pointing the center of the entry point on the multiplanar and 3D image and the real entry point on the brain surface (Fig. 5). The precision of the neuronavigation was assessed using the SD of these values.

Results

We identified 125 entry points of SEEG electrodes during 26 operations. The accuracy of 3D reconstruction was 0.8 mm (range, 0–2 mm) with a precision of 1.5 mm. The accuracy of 3D SEEG neuronavigation after the dural opening was 2.68 mm (range, 0–6 mm). The precision of 3D neuronavigation was 1.48 mm.

Discussion

3D brain surface reconstructions

The seminal work of Nakajima et al. from 1997 proposed the application of image handling software and

Fig. 1 3D cerebral surface reconstructions using different MRI sequences. **a** Flair. **b** T2. **c** T1. **d** T1 with contrast enhancement
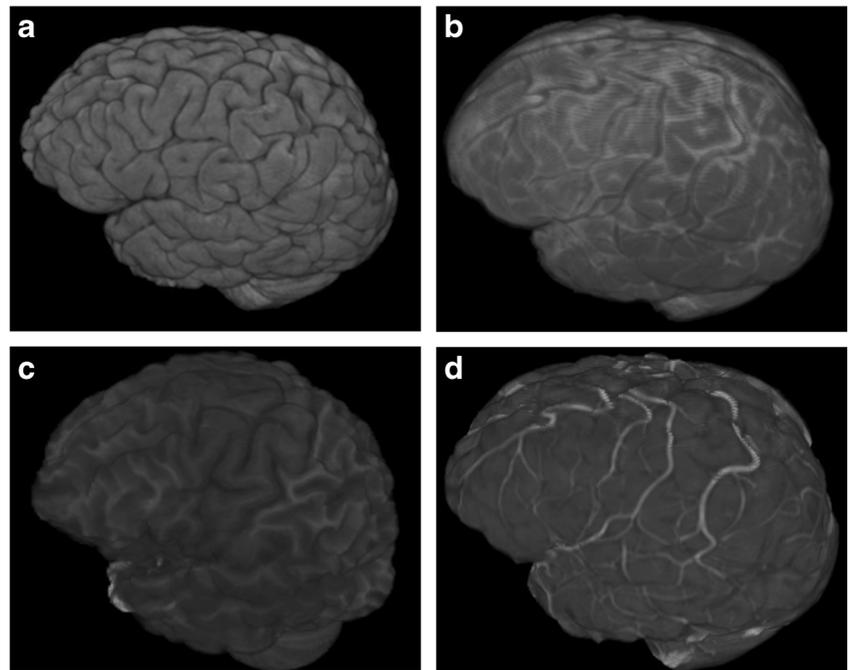
personal computer for three-dimensional cortico-vascular reconstruction using the technique of paste and overlaid slices [2]. Hattingen et al. used a curved multiplanar reformatting technique to create a 2-dimensional image

Fig. 2 Grayscale model maker tool of 3DSlicer for creating a 3D model of the electrodes
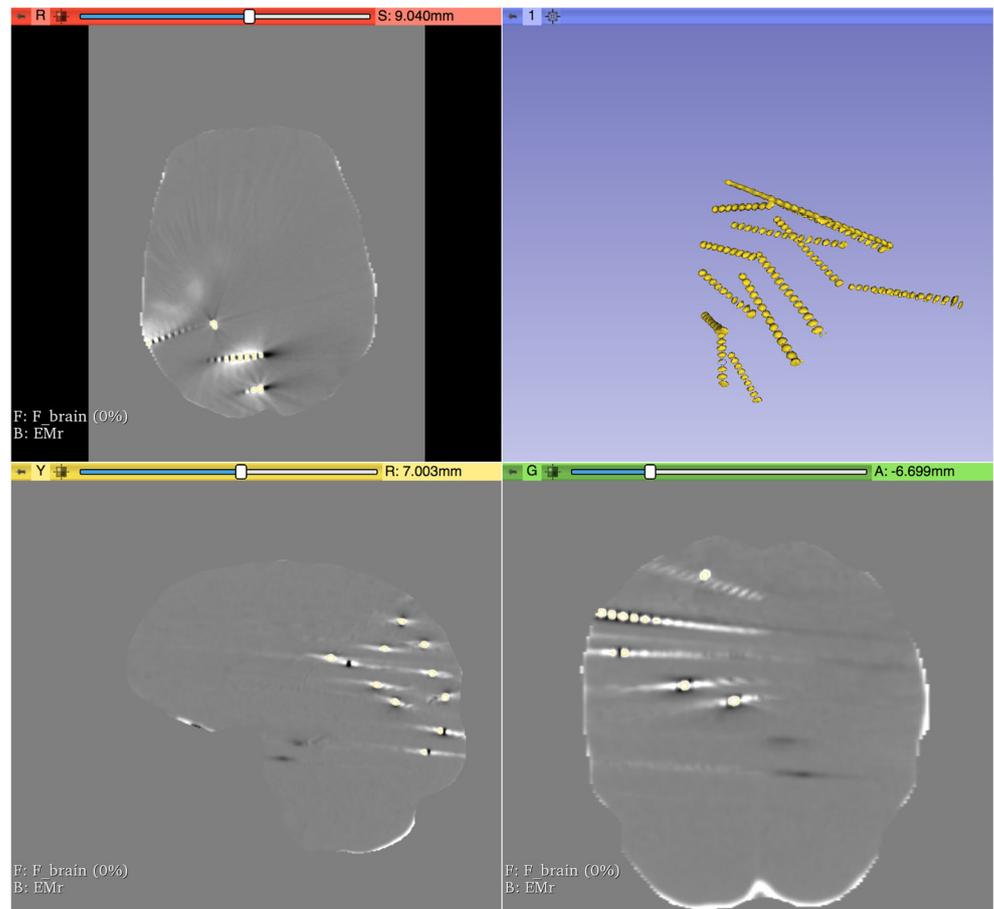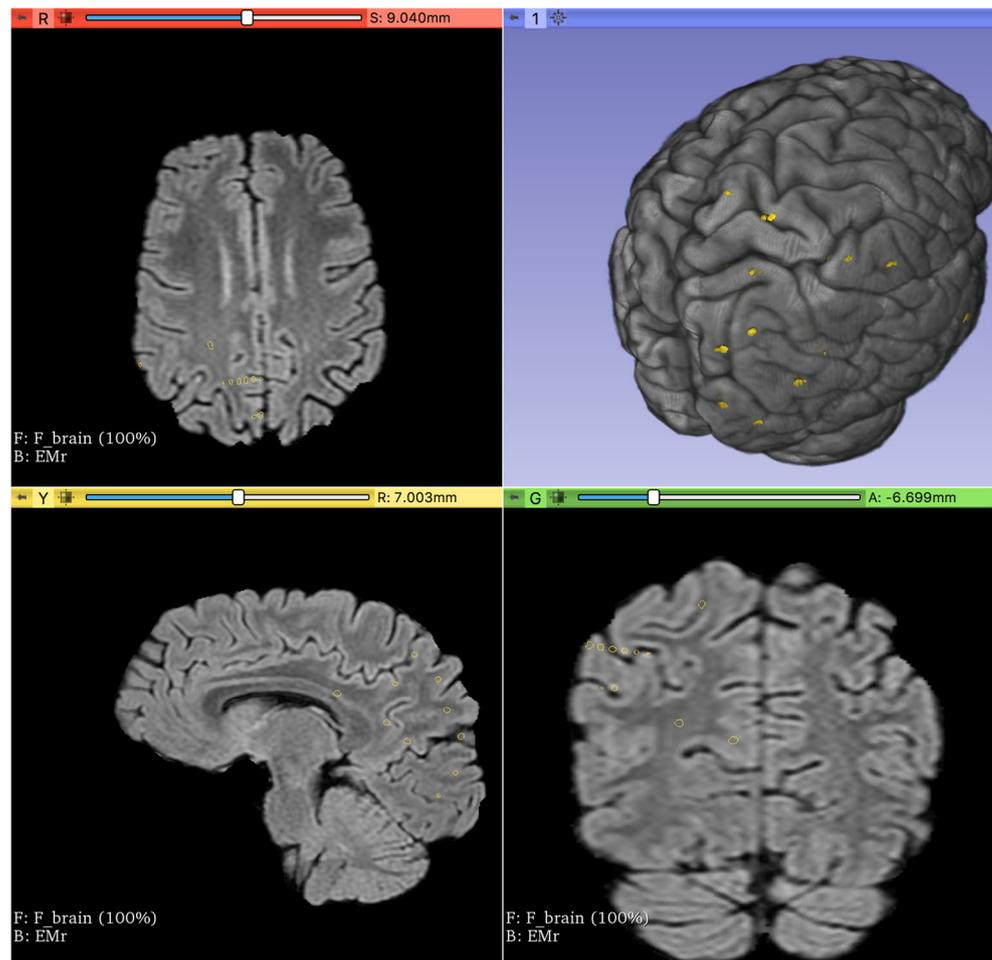
Fig. 3 Preoperative planning on 3DSlicer platform using the volume-rendering tool, slice visibility, and background foreground layer mixture

of the cortex [3]. Even some DICOM viewers as OsiriX may achieve satisfactory skull striping using volume rendering, sculpt, rotate, and move tools [4]. Mert et al. use diffusion tensor imaging mask to perform brain extraction from T1 sequence and subsequently use these images on commercially available neuronavigation software [5]. Some neuronavigation systems as StealthStation S8 (Medtronic) provide a semiautomatic tool for brain and tumor 3D segmentation which may be used in multimodal tumor or epilepsy surgery [6].

We present a method of brain extraction using free software which could be applied for preplanning and produce DICOM sets for all available neuronavigation platforms. Free software as 3DSlicer and FSL improved dramatically the quality of 3D reconstruction [7, 8]. We use a Flair sequence for cortical reconstructions because suppression of the cerebrospinal fluid signal permits a sharp delineation of the cerebral cortex. Postprocessing of T1 with contrast enhancement provides vascular reconstructions. We obtain comparable results of brain surface reconstruction using FSL from 1.5- and 3-T imaging.

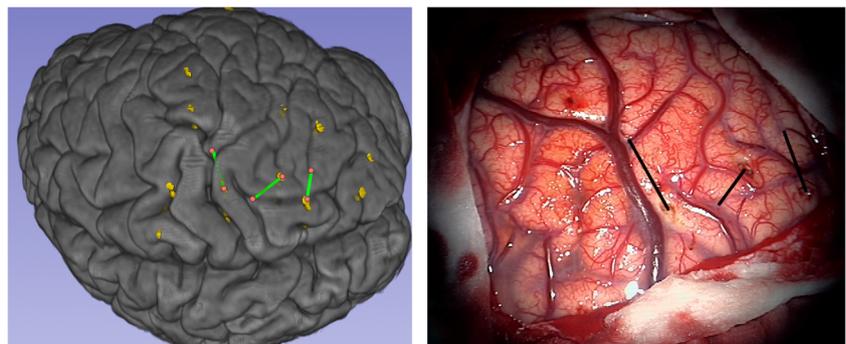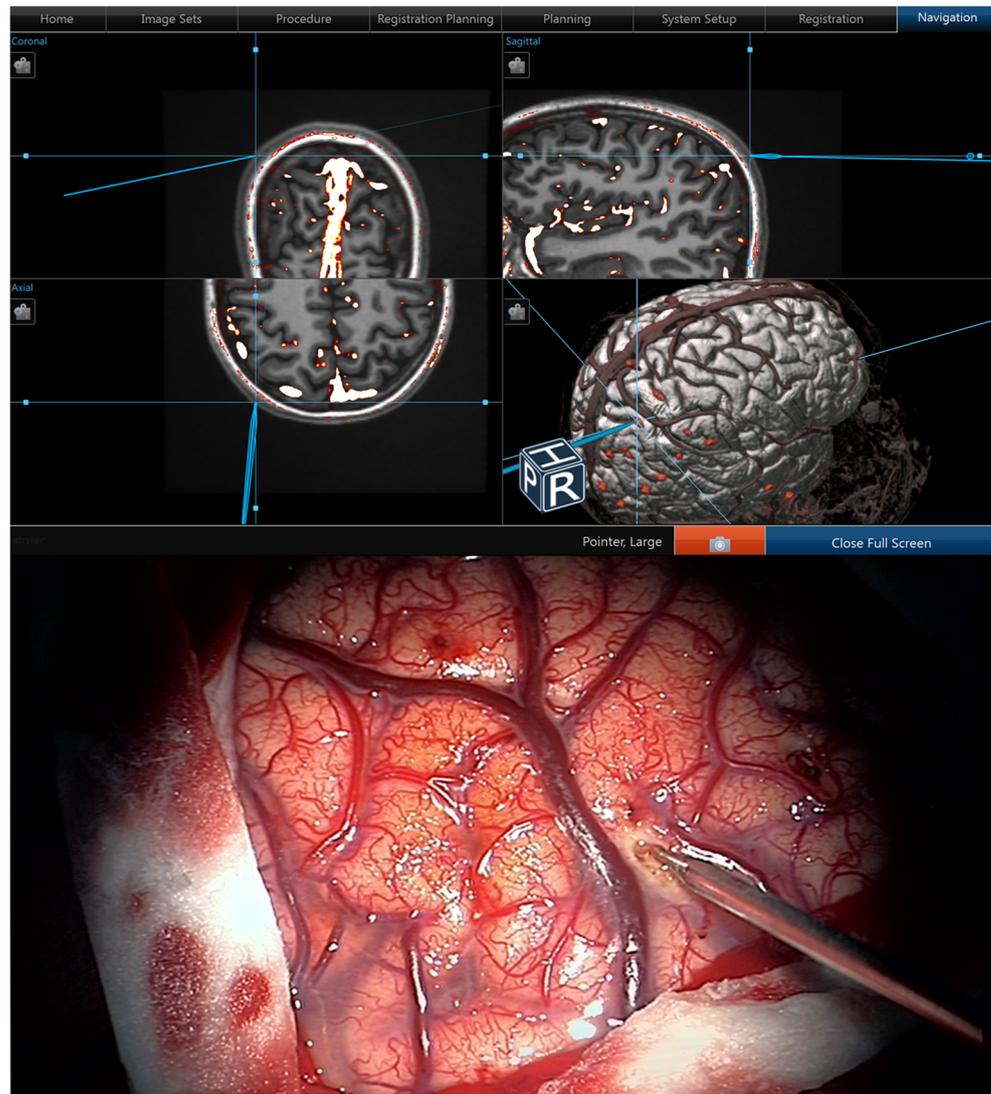**Fig. 4** Accuracy of 3D SEEG reconstruction

Fig. 5 Accuracy of 3D neuronavigation

However, 3-T MRI may detect subtle lesions in some MRI-negative patients. Our study presents a simple technical recipe for 3D neuronavigation which may be applied in different brain surgeries using 1.5-T or 3-T MRI. Other more complicated and time-consuming solutions are possible as the use of FreeSurfer software for cortical and white matter extraction [1]. However, FreeSurfer can be applied only for T1 without contrast. StealthViz software implemented in Medtronic neuronavigation provides a brain extraction tool which reconstructions are faster but seems to be with worse spatial resolution compared to the results of FSL and needs manual adjustments [6].

3D SEEG electrodes reconstructions

SEEG may provide a piece of important information about the localization of the epileptogenic zone. In the past, visualization of SEEG electrodes in the intracranial space was schematic and based on the AC-PC grid of Talairach. Introduction of CT, MRI, and different software for DICOM post-processing reveals new opportunities for visualization of the SEEG results. Nowell et al. proposed the use of homemade software for multimodal imaging and electrode reconstructions [9]. Narizzano et al. developed an open-source 3DSlicer extension which discriminates between the white and gray matter location of contacts [10]. We propose the use of free software and a simple pipeline for SEEG electrode reconstruction. Evaluation of our post-processing technique reveals satisfactory accuracy (0.8 mm) and precision (1.5 mm). We have to mention that the simplest way of SEEG electrode presentation is to perform post-implantation MRI and to look for the electrodes' artifacts. However, the artifacts of the different contacts of one electrode are difficult to be distinguished from each other and 3D cortical image is significantly perturbed.

The accuracy of 3D neuronavigation in epilepsy surgery

The mean accuracy of 3D neuronavigation in our series was 2.68 mm. We use the real entry points of the electrodes visible on the brain surface as fiducials for evaluation of the accuracy and precision of neuronavigation. This error may be explained with co-registration imperfections and brain shift. Brain shift may vary from 2 to 4 mm parallel to gravity and from 4 to 7 mm on the gravity but can reach in many cases more than 1 cm making neuronavigation hazardous [11, 12]. 3D neuronavigation did not compensate the brain shift but is useful for the identification of the magnitude and direction of the shift. 3D brain surface presentation remains applicable even after a cerebrospinal fluid loss and tissue resection because of the presence of unaffected entry point-cortico-vascular relationships. Application of 3D cortical reconstruction can help neurosurgeons in defining the superficial borders of the resection according to the preoperative plan on the cortical surface even in cases of important brain shift [11]. However, we have to mention that these software packages are not certified for medical use and may be only a complementary tool in our decision making. The brain surface reconstruction performed by FSL and 3DSlicer was compared with the real brain relief. Three-dimensional neuronavigation was always checked with 2D neuronavigation without post-processing.

On the other hand, 3D imaging and neuronavigation may not replace intraoperative mapping and monitoring in asleep or awake conditions for primary motor, sensory, and language cortex preservation. The combination of 3D neuronavigation, 3D tractography, and intraoperative neurophysiological tools seems optimal for safe and effective epilepsy surgery.

The utility of 3D neuronavigation in SEEG-guided epilepsy surgery

Epilepsy surgery is mainly cortical surgery and frequently deals with eloquent areas. Typical epileptogenic lesions as focal cortical dysplasia or glioneuronal tumors often affect small parts of gyri or sulci. Cortical reconstructions are particularly helpful when operating on limited cortical epileptogenic lesions. Multimodal imaging and especially invasive EEG investigations may be implemented in the definition of the epileptogenic zone which resection is presumed to be sufficient to achieve seizure control [13]. 3D visualization of invasive EEG exploration helps EEG interpretation, surgical planning, and intraoperative cortical navigation. Despite these facts, the application of 3D neuronavigation in the current epilepsy surgery practice remains limited because of the restricted availability of 3D neuronavigation and the lack of knowledge about its advantages.

Our study did not explore the value of 3D neuronavigation in epilepsy surgery comparing data before and after the introduction of 3D neuronavigation in our practice because there are important biases as a learning curve in the beginning and more complicated MRI-negative cases in the last years. However, the logical next step after the introduction of 2D neuronavigation in the routine epilepsy surgery practice will be the implementation of 3D neuronavigation and augmented reality methods displaying EEG, PET, SPECT, and other preoperative data on the cortical surface during the operation.

Conclusions

3D neuronavigation for SEEG-guided epilepsy surgery is possible and a reliable method even with navigation system without a brain extraction tool using free software for post-processing of common MRI sequences.

Compliance with ethical standards

All procedures performed in studies involving human participants were in accordance with the ethical standards of the University Hospital "Saint Ivan Rilski" and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards.

For this type of study formal consent is not required.

Conflict of interest The authors declare that they have no conflict of interest.

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