

Introduction

The SEEG implantation procedures for presurgical evaluation of patients with refractory epilepsy still represent a challenge due to the intrinsic complexity of the method and the number of the depth electrodes required.

In order to stereotactically implant epilepsy depth electrodes, a number of frame-based and frameless (robotic) stereotactic implantation approaches have been taken.

The workflow for standard stereotactic frames includes a significant number of steps to achieve co-registration with the patient and adjusting frame settings (X, Y, Z, ring, arc) for each trajectory of the sequentially implanted electrodes.

The robotic implantation allows a quick repositioning of the tool guide from trajectory to trajectory, but still requires a complex initial procedure for performing the patient co-registration, including the attachment to the patient's head of a frame base and the implantation of bone fiducials (Cardinale et al, 2012a,b).

We are proposing a significantly simplified workflow for the implantation of SEEG depth electrodes using only fiducial markers/anchors and a patient-customized stereotactic fixture built using 3-D laser sintering that incorporates all the planned trajectories into its construction, therefore requiring no adjustments for the sequential implantation of the electrodes. The stereotactic fixture is based on the StarFix™ mTPlatform technology (FHC, Bowdoin, Maine), that has been used in more than 3000 DBS implantation procedures for movement disorders since being FDA cleared and CE marked for human use in 2001.

Methods

Patients with refractory temporal lobe epilepsy referred to pre-surgical evaluation using depth electrodes have been included in this study.

The surgical procedure is performed in two steps, typically spaced two weeks apart. During the first step, small (body: 5mm; thread: 5mm) fiducial markers are attached to the patient's head, as illustrated in figure 1.

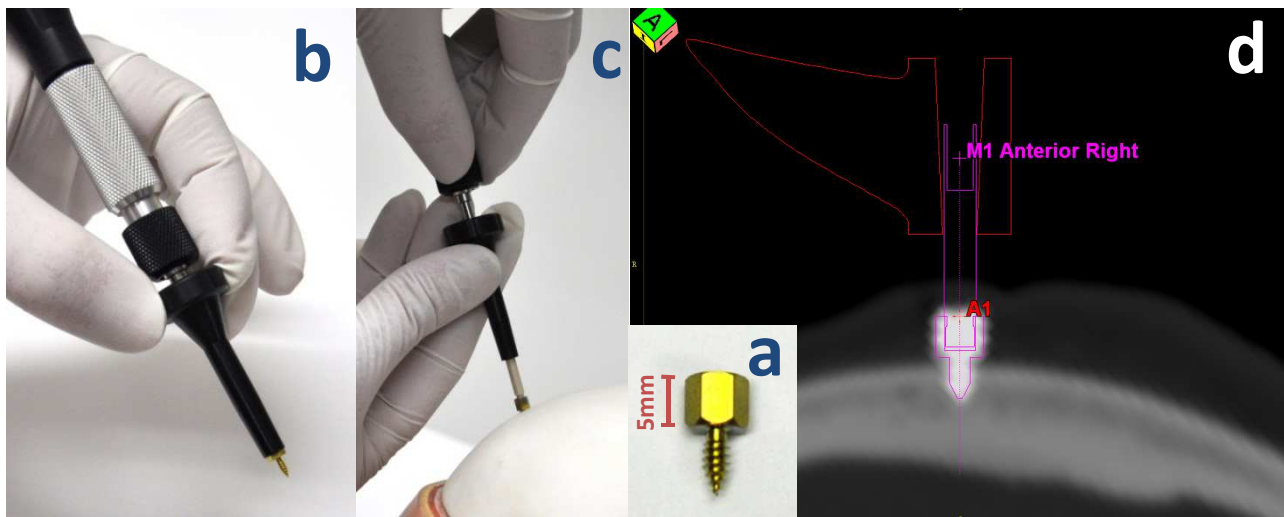


Figure 1. First step of the implantation procedure that requires fiducial markers (a) that also serve as bone anchors to be attached to the patient's skull using a screwdriver (b,c). The anchors are visible on the CT scan (d) and are used for both patient co-registration and as attachment points for the stereotactic fixture,

A CT scan with the fiducial markers in place is performed and co-registered with the prior multi-modal anatomical and functional imaging in the Waypoint Navigator™ (FHC, Bowdoin, Maine) planning software. The fiducials' location and orientation is automatically detected by the planning software.

Trajectories targeting the areas potentially involved in the seizure initiation and propagation according to the working hypothesis are defined in the surgical planning software. Various functional, vascular and other anatomical constraints are taken into consideration when planning the trajectories (Barborica et al, 2012).

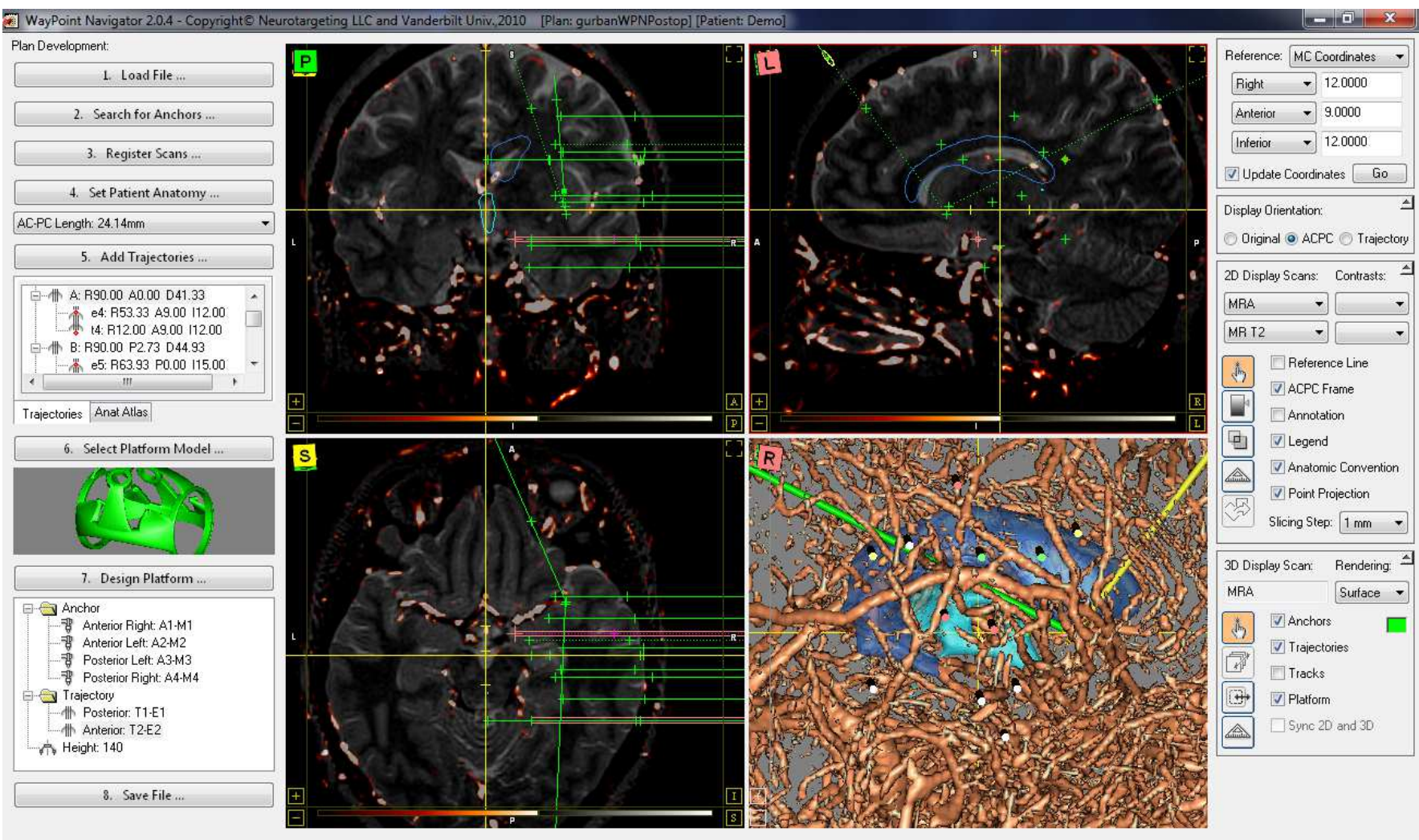


Figure 2. Trajectory planning using the surgical planning software (Waypoint Navigator™, FHC, Maine). The 2-D views display the T2-weighted MR imaging fused with the MR-angiography obtained from contrast-enhanced T1 MRI by applying the Frangi vesselness filter. The 3-D view on the bottom-right panel shows the segmentation and 3-D reconstruction of the vasculature, with trajectories at a safe distance from major intracranial blood vessels.

The anatomical (AC, PC, mid-plane), trajectory and anchor coordinates are used by the planning software to create a digital 3-D stereotactic fixture that incorporates rings for holding the grids that will guide the electrode implant tools, as illustrated in figure 3. The 3-D model is based on a Relational Geometry (Aerohydro, Southwest Harbor, Maine) base model that is automatically morphed to the patient specific 3-D scan coordinates of its elements (anatomy, anchor points, trajectories), specific for each patient. The side rings are aligned with the sagittal plane and centered on the mid-commissure point. They are used for attaching Talairach-style double grids that will be used for orthogonal electrodes. Additional smaller rings are used for smaller grids for the oblique trajectories. The hole spacing on both type of grids is 3mm. Only points defining patient's anatomy (AC, PC, mid-plane) and oblique trajectories have to be entered before building the stereotactic fixture. The orthogonal trajectories can be defined at the later time, in the time interval while the platform is being built.

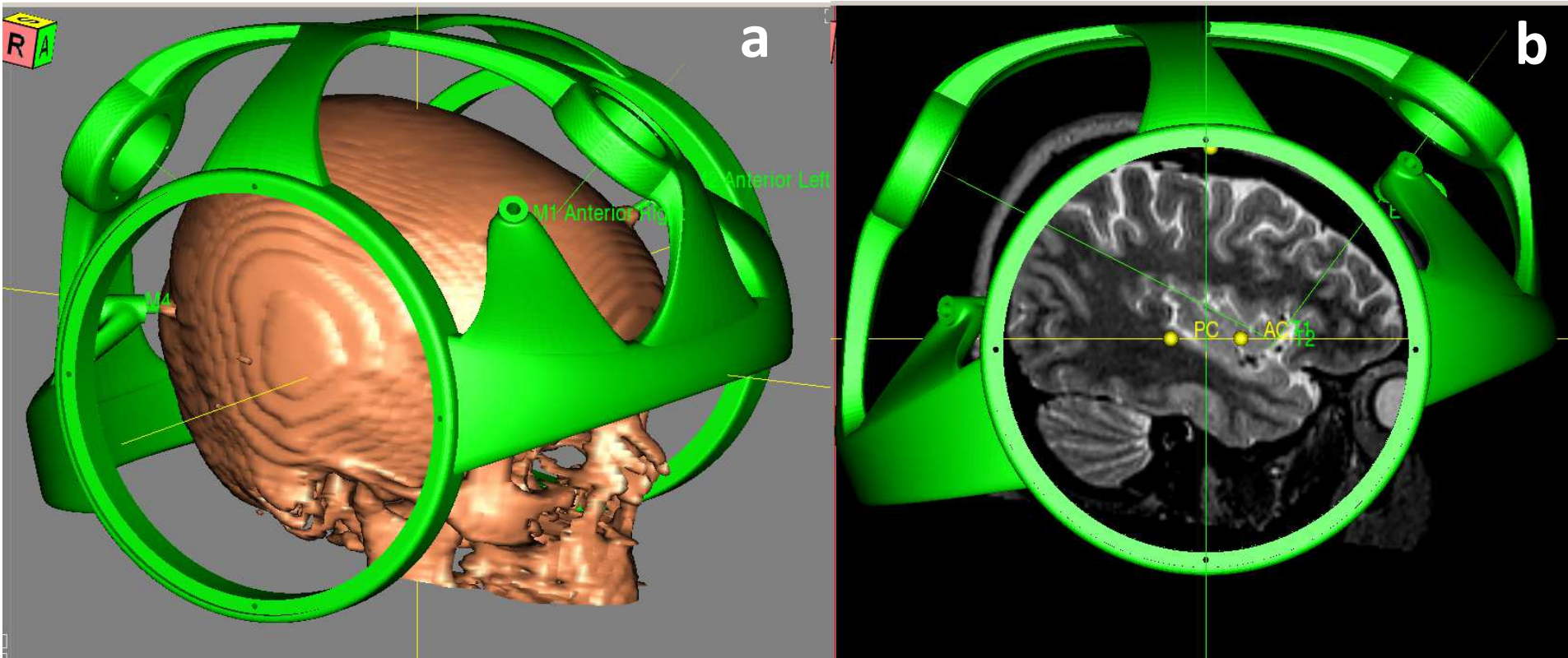


Figure 3. The computer-generated 3-D model of the stereotactic fixture (a) and the illustration (b) of its alignment to the patient's anatomy (para-sagittal, MCP-centered). Double grids having holes spaced 3mm apart are attached to the fixture for transverse orthogonal and oblique trajectories.

The 3-D model files are being sent to the manufacturing facility of FHC, where the plan is verified and the platform built using a rapid prototyping (selective laser sintering) technology (figure 4). After passing quality inspection for targeting accuracy, the fixture is then sent to the hospital, where it is sterilized.

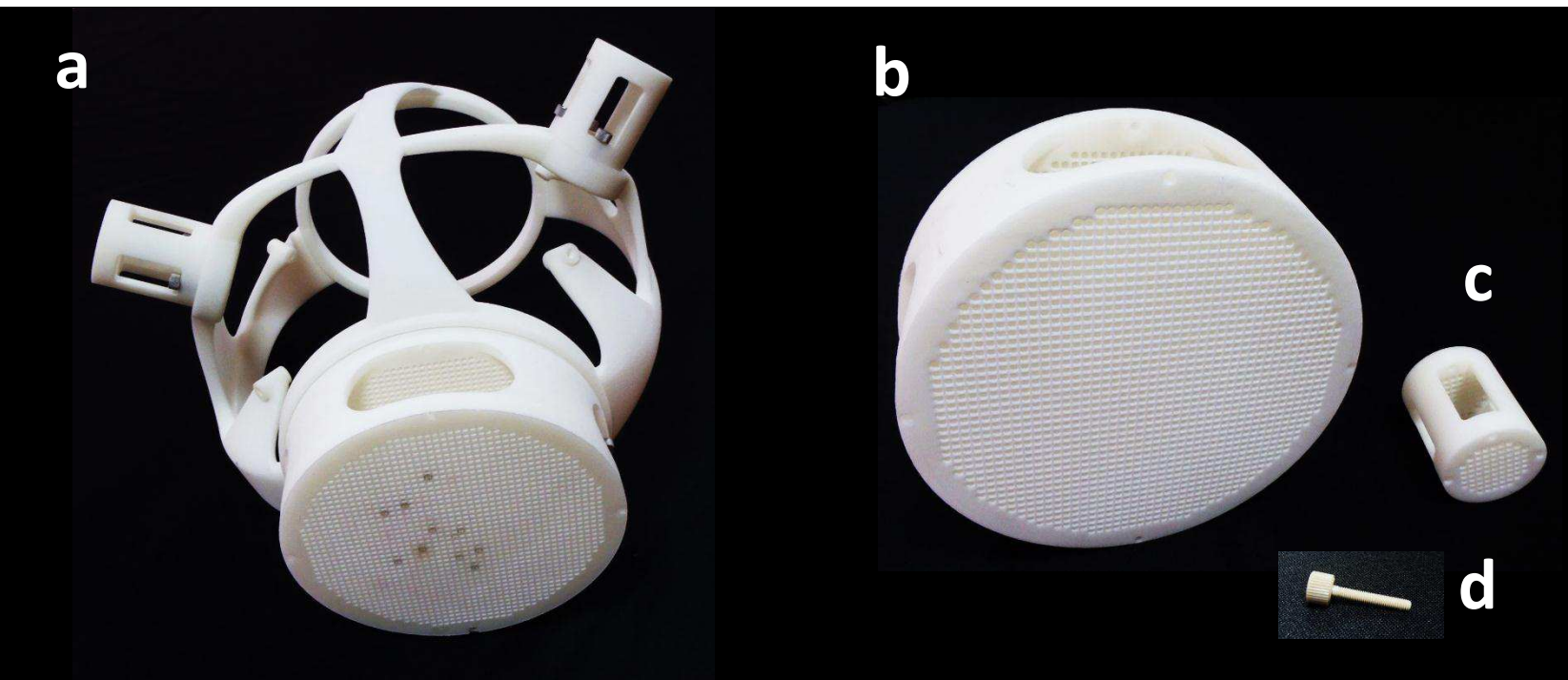


Figure 4. The StarFix stereotactic fixture built by 3-D printing using selective laser sintering, having the double-grids for the orthogonal (b) and oblique (c) trajectories attached with thumbscrews (d).

The day of the surgery, a simple procedure of exposing the previously implanted anchors and using thumbscrews to secure the platform to the patient's head is performed before proceeding with the standard depth electrode implantation (DIXI Microtechniques, Besançon, France) (figure 5). No CT or MRI scan is required the day of the surgery, unlike for traditional frames and robotic arm. The holes to be used during the implantation are marked on the grids. For the oblique trajectories, normally the center hole is used, but parallel adjustments of the trajectories are possible at any time by using one of the other holes in the grid.

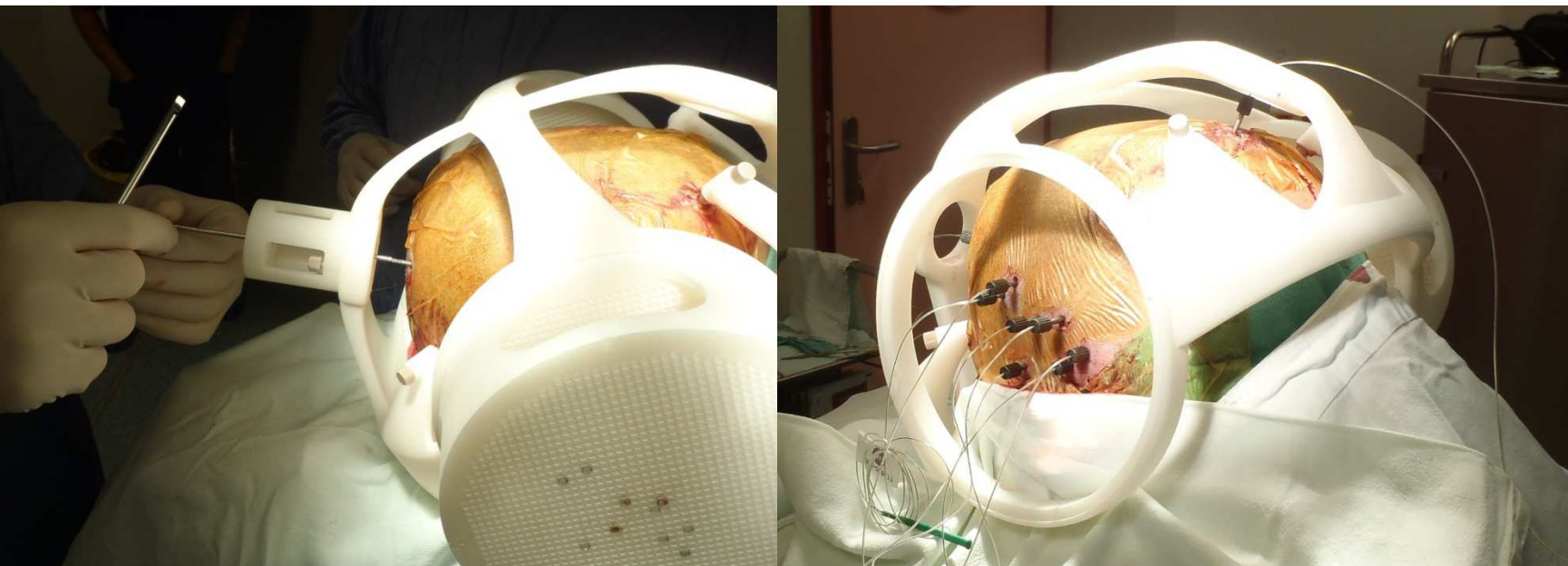


Figure 5. Illustration of the stereotactic fixture attached to the patient's head and of the surgical depth electrode implantation procedure.

Results

We have used the stereotactic fixture for the implantation of a total of $n=32$ depth electrodes in three patients (average $n=10.67$ per patient) with refractory temporal lobe epilepsy. Postoperative CT co-registered with preoperative MR was performed in order to check for the presence of intracerebral hemorrhages and to verify the location of each contact (figure 6). No complications occurred during these procedures.

Each patient had between 10 and 12 electrodes implanted. In the third patient, whose semiology pointed to the involvement of the insula in the seizure propagation, in addition to 8 orthogonal trajectories, we also planned two oblique trajectories targeting the insular cortex, using a parasagittal approach (Robles et al, 2009), as illustrated in the figures 3, 4a, 5, 6b, and 6c. The differences between the planned and actual trajectories at the entry level shown in figure and table 6c demonstrate sub-millimeter accuracy, in average. The duration of the implantation procedure went down to 2 hours and 15 minutes from over 4 hours typically required when using the Leksell frame, not counting the time for mounting the Leksell frame and performing the preoperative CT.

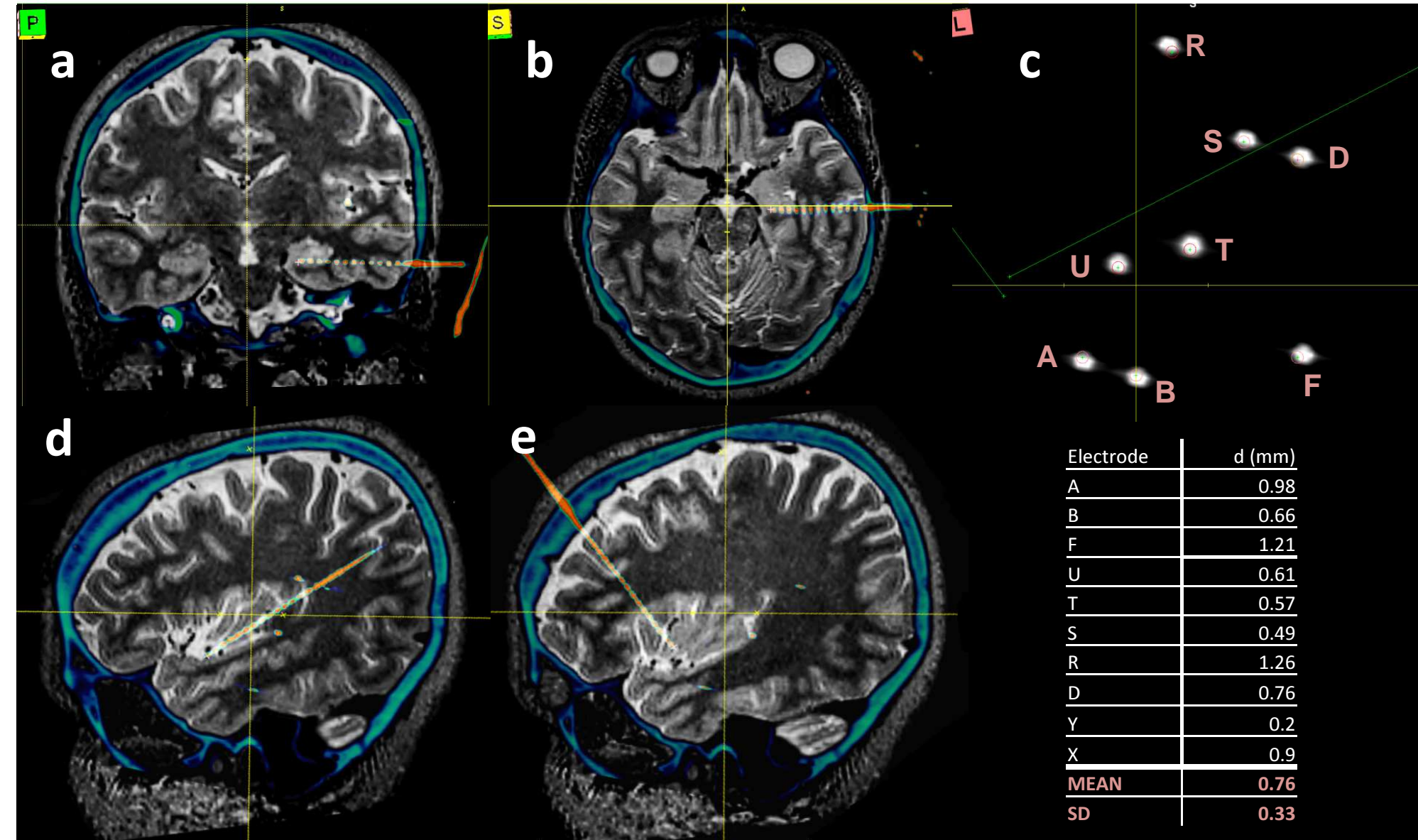


Figure 6. Postoperative CT for patient #3 illustrating the location of the SEEG electrodes (shown using a blue-green-orange color map), overlaid on a T2-weighted MRI (in grayscale); Coronal (a) and axial (b) views of an electrode implanted orthogonally in the hippocampus; (c) A view of all 8 orthogonal planned entry points overlaid with the actual electrode guide screws locations illustrating the deviation from the original trajectories; (d,e) Trajectory-aligned views of an oblique trajectory targeting the posterior long gyri of the insula (d) and the anterior short gyri (e).

Conclusions

The stereotactic fixture significantly simplifies the surgical procedures for SEEG depth electrode implantation while maintaining sub-millimeter accuracy. It presents the following advantages:

- Two-step procedure, with anchor implantation spaced several days apart from the actual surgery, allowing for time to carefully plan the orthogonal trajectories
- Simplicity of operation, fixed device, no adjustable parts – reduces the risk of human error
- Aligned with the patient's anatomy – makes the trajectory planning for standard implantation templates more consistent across patients
- Reduces the procedure time by a factor of two, compared to using standard stereotactic frames that require re-adjusting coordinates, ring and arc from trajectory to trajectory.
- If fiducial anchors are left in place until the end of the presurgical evaluation period, they can be reused for repositioning or adding electrodes without the need to perform another CT for patient co-registration

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