The Impact of the Reference Imaging Modality, Registration Method and Intraoperative Flat-Panel Computed Tomography on the Accuracy of the ROSA® Stereotactic Robot

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Introduction

Stereotactic surgery makes use of a three-dimensional (3D) coordinate system to locate targets in the brain and perform procedures such as biopsies or the implantation of deep brain stimulation (DBS) electrodes [1]. The accuracy of stereotactic procedures has been extensively studied [2–12]. However, technology is evolving rapidly in terms of both the surgical equipment and imaging techniques. Today, neurosurgeons can realize stereotactic surgery by using either frame-based (FB) or frameless (FL) registration (based on surface recognition). It is known that the imaging and registration modalities have a major influence on the accuracy of stereotactic procedures [13]. The impact of robotic techniques on accuracy in stereotactic surgery is subject to debate, with greater ease of use rather than greater accuracy [3, 12, 14]. ROSA® is a new robotic arm with 6 degrees of freedom. The primary objective of the present study was to determine the accuracy of robotized stereotactic procedures as a func-
tion of the registration technique (FB or FL) and reference imaging used (magnetic resonance imaging, MRI, or computed tomography, CT). The study's secondary objective was to evaluate the impact of the use of intraoperative flat-panel CT (fpCT) on surgical accuracy.

Materials and Methods

Our department uses the ROSA robot (Medtech, Montpellier, France; fig. 1). Our 3T MRI protocol (Signa HDx MRHDx system; General Electric Medical Systems) was as follows: a T1-weighted 3D gradient-echo sequence after gadolinium contrast injection (512 × 512, continuous imaging, 1-mm slice thickness, no gantry) and a 3D high-resolution T2 star-weighted angiography sequence (512 × 512, continuous imaging, 1-mm slice thickness, no gantry). For the implantation of DBS electrodes (using FB robotized stereotactic surgery), we performed a stereotactic CT scan from the base of the frame to the vertex (512 × 512, continuous imaging, 0.625-mm slice thickness, no gantry) on the day of surgery. For stereotactic biopsies (FL robotized stereotaxy), a preoperative FL CT scan was performed (512 × 512, continuous imaging, 0.625-mm slice thickness, no gantry) the day before surgery. We used an O-arm® fpCT system (Medtronic, Minneapolis, Minn., USA) and standard 3D acquisition (512 × 512, 0.8-mm slice thickness, no gantry).

We developed a dedicated phantom device in order to evaluate the overall accuracy of our stereotactic procedures. The phantom was designed so that it could be used with all types of registration and preoperative imaging techniques. The removable container can be filled with water and thus allows the phantom to be imaged in all types of MRI scanners. The face of the phantom is in fact a cavity (wall thickness = 0.25 mm) that can be filled with contrast agent to give a perfect view of this region during the MRI scan. In a CT scan, the phantom is easily viewed because of its radiopacity. Hence, the phantom is perfectly suited to measurements of the overall accuracy of stereotactic procedures. However, given the size of the targets studied here, we could not evaluate accuracy below a distance of 0.3 mm. Using the dedicated phantom developed in-house (fig. 2), we analyzed the target accuracy of the following: (1) FL robotized stereotactic procedures guided by 3T MRI alone or fpCT alone and (2) CT-guided FB robotized stereotactic procedures. We measured the error directly at the target point for 20 planned trajectories. Figure 3 shows the protocol for the phantom study.

We retrospectively evaluated the accuracy of 31 FL and 27 FB robotized stereotactic surgery procedures performed in our department (all of the latter were DBS electrode implantations). The DBS electrode implantation technique has been described elsewhere [15]. Briefly, all preoperative MRI scans were performed under general anesthesia and in the absence of a frame. The Leksell® series G stereotactic frame (Elekta AB, Stockholm, Sweden) was attached to the patient’s head. Stereotactic CT was performed and matched with a preoperative, nonstereotactic MRI data set. The target was located using the robot’s planning software (Rosana®, Medtech) after importing the MRI images into the planning station and reformating them into a plane parallel to the anterior commissure-posterior commissure plane. The patient was placed in the supine position and the fpCT device moved into place. The robot was then moved into place and robotized FB registration was performed. After draping, a 13-mm burr hole was drilled at the entry point indicated by the robot’s laser probe. We installed the ‘Ben’s gun’ (a holder with five parallel channels for micro- or macro-needles) and aligned a guide tube with the central trajectory (without entering the brain tissue). A 3D fpCT scan was performed and the data set was automatically matched with the preoperative imaging data. We used the robot’s planning software to create a new trajectory corresponding to the guide tube’s position in stereotactic space. We then extrapolated the trajectory to the region of interest, measured the possible error in the tube position and corrected the latter through micromovements of the robotic arm. The error measured at this moment is reported in the present study. The procedure concluded with the classical steps in DBS surgery (microrecording and clinical testing).

For stereotactic biopsies, all preoperative imaging data sets (from CT and MRI) were acquired in the absence of a frame or anesthesia a couple of days before surgery. Targets and trajectories were planned (using the robot’s dedicated Rosana software) before the day of surgery. All these operations were performed under general anesthesia. The ROSA robot was moved into place and FL robotized surface registration was performed. The robot was placed. The patient’s head was securely fixed to the robot via a Mayfield headrest. The robotic arm was automatically positioned along the planned trajectory. A 2.5-mm hole was drilled along the axis of the trajectory and a Sedan needle was placed along the trajectory through an appropriate reducer held by the robot’s arm. Staged biopsies were performed in front of and within the target. The total operating time (including patient placement and draping) was less than 1 h.

For 7 patients, robotized biopsies were performed using bone fiducials (n = 3 adults – 1 posterior fossa biopsy and 2 trans cerebel lar brainstem biopsies) or skin fiducials (n = 4 children). The ROSA robot and the fpCT system were moved into place. The fiducials were placed with the patient in the operating position and with his/her head fixed to the robot via a Mayfield headrest. 3D fpCT was performed and used as the reference imaging data set for registration. For surgical planning, the imaging data was automatically matched with preoperative MRI and robotized FL fiducial registration was then performed. The procedure concluded with the same steps as in surface recognition FL biopsy.

The robot is used during stereotactic surgery as an instrument holder (as arcs with frames). Hence, the surgeon manually passes instruments through the reducers (or Ben’s gun). We do not use...
The haptic abilities of the robot to insert probes or electrodes during stereotactic surgeries.

To calculate the accuracy of the stereotactic procedures, we compared the preoperative surgical plan with the trajectory actually achieved by merging the preoperative (planning) CT scan with the intraoperative fpCT data set (which is always acquired during DBS surgery) or the postoperative CT image using Rosana planning software. Given that the microelectrode (in intraoperative fpCT) or the skull hole (in the postoperative CT scan) was easily visible, for a given Z position, we were able to measure the distance in millimeters (X and Y) between the center of the drill hole (A with Xa and Ya coordinates) and the planned trajectory (B with Xb...
and Yb coordinates. The accuracy was then calculated according to the following equation:

For a given Z position, distance \( AB = \sqrt{(X_a - X_b)^2 + (Y_a - Y_b)^2} \)

Figure 4 illustrates the error measurement method for the retrospective study.

For FB surgery (and after having measured and corrected for the error in the position of the robotic arm), we repeated putting fpCT microelectrodes in place and measured the error between the target and the microelectrode according to the above equation. It must be noted that we could objectify the deviation of the microelectrode with regard to the target a few times. In these cases, the microelectrodes were twisted in the part outside the guide’s tube. We did not measure this error, which is not linked to the accuracy of the robot. In these cases we measured the error with regard to the tip of the guide tube.

**Results**

Using the dedicated phantom, the mean accuracy at the target for MRI-guided FL robotized stereotactic procedures was 1.59 mm (min. = 0.5 mm, max. = 3 mm, standard deviation, SD = 0.8). The mean accuracy for CT-guided and fpCT-guided FL and FB robotized stereotactic procedures was always below 0.3 mm (min. = 0.3 mm, max. = 0.3 mm, SD = 0); our phantom was not able to detect errors smaller than this.

In our series, the mean accuracy for FB robotized surgery was 0.81 mm (min. = 0 mm, max. = 1.61 mm, SD = 0.39), the mean accuracy for FL robotized stereotactic procedures was 1.1 mm (min. = 0 mm, max. = 2.17 mm, SD = 0.7) and the mean accuracy for surface recognition FL procedures was 1.22 mm (min. = 0 mm, max. = 2.17 mm, SD = 0.73). Robotized FL fiducial registration had a mean accuracy of 0.7 mm (min. = 0 mm, max. = 1.46 mm, SD = 0.4). Robotized skin fiducial registration had a mean accuracy of 0.94 mm (min. = 0.5 mm, max. = 1.46 mm, SD = 0.4) and bone fiducial registration had a mean accuracy of 0.42 (min. = 0.3 mm, max. = 0.72 mm, SD = 0.2).

We observed a statistically significant difference in accuracy when comparing robotized surgery procedures between the phantom study and clinical study both for the FB (\( p = 8.2e^{-9} \), two-tailed Student’s t test) and the FL study (\( p = 3.6e^{-6} \), two-tailed Student’s t test). We also observed a statistically significant difference in accuracy when comparing robotized surgery procedures based, respectively, on FB registration and FL surface recognition registration (\( p = 0.018 \), two-tailed Student’s t test). In addition, we observed a statistically significant difference in accuracy when comparing robotized surgery procedures based, respectively, on FL surface registration and FL fiducial marker registration (\( p = 0.07 \), two-tailed Mann-Whitney test). There was no statistical difference between FB registration and FL fiducial registration (\( p = 0.503 \), two-tailed Mann-Whitney test).

Additional results are summarized in table 1.

Correction of the position of the robotic arm by using the fpCT data helped to resolve the errors measured during FB robotized surgery after each use (fig. 5). During the present study, correction allowed us to put the central microelectrode in line with the central trajectory in all cases.

Over the 31 targets, diagnostic tissue diagnosis was obtained 30 times (diagnostic yield 96.7%). There was neither mortality nor permanent morbidity related to the stereotactic biopsies; 2 patients (6.45%) presented transient morbidity. These corresponded to an oculomotor palsy (Parinaud’s syndrome) in 1 case (pineal tumor) and
transient deterioration of previous hemiparesis in the second case. Postoperative CT demonstrated a hemorrhage in 3 patients. In 2 cases, a minimal hemorrhage along the trajectory was objectified – these 2 hemorrhages were within 4 mm and clinically asymptomatic. In 1 case, the hemorrhage was within the pineal tumor and may have been responsible for the transient clinical deterioration. For the STN-DBS patients, the mean preoperative L-dopa response was 52.55% and the mean L-dopa response status was 14.25 [4–19]. The mean UPDRS III improvement at 6 months was 75% (mean ‘off med’ score before surgery = 30.8 [13–45], mean score ‘on stim/on med’ = 7.8 [1–17], mean ‘on stim/off med’ score after 6 months = 14.15 [5–26]). There was neither mortality nor morbidity (permanent nor transient) related to the DBS surgeries. There was no hemorrhage in the postoperative CT scan for all the 27 FB stereotactic surgeries.

**Discussion**

The ROSA arm is equipped with a patented registration system that combines high-precision robotic movement with noninvasive, laser-based FL surface registra-
tion. This method enables surgery to be performed without a frame or invasive markers. However, ROSA can be used with all other types of registration (such as FB registration and FL skin/bone fiducial registration). Our protocol made it possible to evaluate the average accuracy and the respective impacts of the imaging protocol, registration technique and mechanical instrumentation on accuracy.

Measuring the Accuracy of Stereotactic Procedures

In our opinion, it is hard for a postoperative CT scanner to point with accuracy to the exact place of the biopsy (air can be close to the exact biopsy site, as well as blood or hypodensity linked to the needle’s trajectory). However, when estimating the accuracy of our FL robotized stereotactic surgery, the center of the skull hole is clearly visible on the postoperative CT scan and can be used to measure the error. This method can introduce errors because it does not evaluate the accuracy over the target and is based on automatic matching (fusion) between the imaging data sets. Nowadays, automatic matching with the help of modern software is very accurate but must be carefully checked before use in order to avoid an error of matching [16]. In our experience, the registration of 2 CT scans with a high-resolution matrix is very accurate. This type of measurement is often performed to check the accuracy of the DBS lead’s position after electrode implantation [17, 18]. Thus, although this measurement method presents an intrinsic error, we consider that it is minimal and that this is the most suitable method for assessing the accuracy of stereotactic surgery a posteriori. We assume that the accuracy measured in this study is very similar to that in line with the target.

How Does Robotized Stereotactic Surgery Help to Improve Accuracy?

Errors in stereotactic surgery are related to imaging factors, the registration technique and the mechanical accuracy of the device used. A CT scanner and MRI are the imaging modalities mostly used in stereotactic surgery. A CT scanner presents a geometric accuracy homogeneous in the entire field of view and accuracy is directly related to the slice thickness and matrix size. The higher the resolution, the better the registration process will be. MRI has excellent contrast resolution but is subject to geometric distortions [20]. The geometric accuracy of MRI is inhomogeneous inside the field of view. The degree of distortion increases with the magnetic field strength. These distortions are most troublesome at interfaces between two different structures (particularly at the air-scalp/skin interface due to a chemical shift and the magnetic susceptibility effect) and with regard to the periphery of the field of view (due to the gradient nonlinearity). In FL procedures, data (3D reconstruction) acquired at the surface of the skin are matched to imaging data of the same surface (at which MRI distortions are major). The distortions for targets within the brain are very small but can be very large for zoned use in FL registration. By mathematical necessity, matching software does not take into account imaging-related distortions [16]. Thus, surface matching is intrinsically error prone when MRI is used as the reference imaging modality. FL procedures with a CT scan as the reference imaging modality are more accurate than FL procedures with MRI as the reference imaging modality because of the absence of intrinsic geometrical imaging errors over the surface of the face. Our study results confirmed that the use of 3T MRI as the reference imaging modality significantly decreases the accuracy of FL stereotactic procedures and robotized FL registration does not change these facts. MRI distortions with regard to the periphery of the field of view can also be a problem during FB registration. With the 3T MRI and the Leksell frame, the robot does not allow the use of MRI as reference imaging because the level of distortion with regard to the fiducial indicator box is too important. Hence, we use a CT scan as the reference imaging modality for all our robotized stereotactic surgery.

The accuracy of FL registration also depends on the ability of the stereotactic device to reproduce an accurate 3D model of the surface of the skin [16]. With the dedicated phantom, there was no difference in accuracy between FB and FL registration when we used a CT scan as the reference imaging modality. However, there was a marked difference in accuracy between our phantom study and our retrospective clinical study. This emphasizes the role of imaging quality, patient motion during imaging and fixation of the head during surgery. The phantom does not move during imaging, and the fact that the skin and face have exactly the same shape during the imaging scan and registration obviously improves the accuracy of the procedure. Similarly, the main advantage of FB surgery is the frame’s ability to minimize head motion during imaging and throughout surgery. These factors mainly explain the lower accuracy observed in the FL robotized stereotactic series. This also explains the absence of statistically different accuracy between robotized FL fiducial registration and FB registration in our retrospective study. The patients were in the same operative position and under general anesthesia when the imaging and registration were realized. FB procedures are subject only to the geometric quality of the image acquired, whereas...
FL procedures also depend on the quality of head reconstruction during surfacing [16, 25].

In our phantom study, CT-guided FL and FB roboticized surgery procedures were both highly accurate. All the targets were within 0.3 mm of the planned site. Hence, the ROSA robot’s FL 3D reconstruction is highly accurate and registration between the two matrices is highly efficient. This may be due to the automatic registration system, which combines precise robotic movements with a noninvasive laser measurement for FL registration. This is an advantage of the ROSA robot compared with other FL stereotactic devices. The accuracy results presented here compare favorably with those reported in the literature for FB stereotactic procedures [11, 14] and are far better than those for FL surgery [4, 12, 25].

Most of the literature data on accuracy concerns phantom studies. The accuracy of the ROSA robot compares favorably with that reported for phantom studies with commercially available frames, i.e. between 1.3 and 1.7 mm with a 1-mm CT scan for targeting [11, 26]. For FB surgery, researchers have reported a mean accuracy of between 1.2 and 1.9 mm and 99.9% of targets within 5 mm [27, 28]. By optimizing the surgical procedure, the accuracy of the ROSA robot was as low as 0.3 mm in our phantom study and 0.8 mm in our retrospective clinical study. For the 57 targets as a whole, the SD was small and the greatest error was 1.6 mm (with the FB robotized procedure). The main difference between the frames and the ROSA robot relates to mechanical accuracy. The robotized arm has a mechanical error of 0.1 mm (data from Medtech). Although we could not measure this mechanical resolution in our department, we can nevertheless state that corrections were always performed as requested. By way of comparison, the Leksell frame plus arc has a mean mechanical accuracy of 0.7 mm [29], which may explain the difference in accuracy for FB robotized procedures between the ROSA robot and the Leksell arc. All commercially available stereotactic frames have an intrinsic mechanical error [11]. The low SD of the robot’s accuracy is also noteworthy. Using the robot, we can systematically reach the target with an error below 1.61 mm (i.e. below the value of 2 mm that is mandatory for satisfactory results in DBS surgery [30]).

The accuracy of the ROSA robot in FL mode compares favorably with FL stereotactic surgery. In a phantom-based study of CT-guided FL stereotactic surgery, Dorward et al. [2] reported a mean error of 1.3 mm with respect to the reference image used for registration and an in vivo postoperative error of 4.8 ± 2 mm. In a phantom study, 1.5T MRI-guided FL stereotactic surgery had a mean accuracy of around 1.6 mm but the SD was high [26]. For FL stereotactic surgery of brainstem lesions, Giese et al. [32] reported an accuracy of 2.8 ± 1.2 mm when using a CT scan as the reference imaging modality and 3.1 ± 1.2 mm when using 1.5T MRI as the reference. These data are confirmed by other studies, reporting a mean error at the target between 1.9 and 3.30 mm (±1.5 mm) [7, 14, 31, 33].

Likewise, the accuracy of the ROSA robot compares favorably with the accuracy of other robotic devices (such as the NeuroMate® and the PathFinder®). In a phantom study, the PathFinder has a mean accuracy of 0.5 mm and almost no deviation [14]. These data are very similar to our present results. In contrast, a phantom-based study of the NeuroMate device reported an accuracy of 1.95 ± 0.45 mm in FL mode (invasive fiducial registration) and 0.86 ± 0.32 mm in FB mode [12]. This difference between two robotic devices may be due to marked improvements in the mechanical accuracy of the robotic arm and in registration techniques. The NeuroMate and ROSA devices were created in the late 1990s and in 2008, respectively.

Impact of Intraoperative fpCT on Accuracy

Intraoperative fpCT is obviously a powerful tool for measuring the registration error during stereotactic surgery. fpCT systems have a high resolution and allow easy viewing of bone, neurosurgical instruments and probe [34]. After correction of the position of the robotized arm, a new fpCT data set was matched with the preoperative planning and always showed the probe just above the planned target. In all these cases, there was no remaining error measurable on the planning software. The remaining stereotactic errors are thus mostly linked to errors in image matching between the MRI and the CT scan [16, 35–38] and, to some extent, a brain shift error when placing the needle or electrode in the brain [39]. Matching between CT and MRI data sets is frequently used in radiosurgery [36, 37] and stereotactic surgery but the potential for residual error must be borne in mind. Thus, in our experience, an intraoperative fpCT scan can greatly improve overall accuracy.

The ROSA robot presents a high level of accuracy. This translates into safe and accurate clinical results as shown by our series, particularly in terms of a very low morbidity. In stereotactic biopsy studies, diagnosis yield accuracy is higher than 90% but permanent morbidity is between 1 and 10%, while in DBS surgery severe adverse effects leading to permanent neurological after effects are mainly due to intracranial hemorrhage, which occurred in 2–4% of cases [44]. Our series compares favor-
ably in terms of morbidity and hemorrhage rate compared with biopsy series [40–43] and DBS surgery series [44, 45].

**Conclusion**

The ROSA stereotactic robot improves the accuracy of stereotactic surgery in three distinct ways, as follows: (1) higher registration quality, (2) lower mechanical error (thanks to the robotized arm) and (3) the planning software’s ability to easily match intraoperative fpCT data sets and thus measure and correct the arm’s position. Robotized FB stereotactic surgery is more accurate than robotized FL stereotactic surgery.

**Disclosure Statement**

The authors have no conflicts of interest to declare.

**References**


