Stereotactic Operations Using the O-Arm

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Key Words

Deep brain stimulation · Intraoperative imaging · Region of surgical interest · Stereotactic operation

Abstract

Background: In stereotactic operations, intraoperative imaging is crucial in several stages of the procedure. The aim was to utilize the O-arm intraoperatively for (1) planning the trajectories of stereotactic instruments, (2) calculating the coordinates of the targets, (3) identification of normal intracranial structures, (4) verification of the trajectories of the stereotactic instruments, and (5) visualization of intracranial hematoma. This is the first study using the O-arm for calculations of the target coordinates in frame-based stereotaxy.

Methods: Utilization of the O-arm as a full-scale intraoperative imaging system in stereotactic surgery required a new concept. The concept consists of the O-arm as an intraoperative imaging system and the Leksell stereotactic system with a modified CT coordinate indicator box, with the idea to widen limited imaging volume. The accuracy and feasibility of the concept were studied. **Results:** The use of O-arm imaging was found to be clinically feasible, enabling the achievement of adequate technical accuracy for stereotactic operations with submillimeter errors in the calculation of tar-

get coordinates, and for multiple intraoperative control images when required. **Conclusions:** The O-arm could be used alone, with high accuracy, as an intraoperative imaging system for planning and controlling in stereotactic operations. In addition, it can be used to exclude serious complications, especially intracerebral hematoma.

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Introduction

Perioperative imaging is a crucial part of deep brain stimulation electrode implantation with frame-based stereotactic systems. Most commonly, this concerns bilateral stimulation of the subthalamic nucleus (STN) or the internal segment of the globus pallidus (GPi), which are established treatments for alleviating symptoms of advanced Parkinson's disease in patients not responding sufficiently to medication [1]. In the early days of stereotaxy, ventriculography, with its ability to visualize the anterior and posterior commissures (AC-PC line), which serve as the basis for measurements of relative distances of various cerebral targets, has been used for indirect stereotactic target determination [2]. Although X-ray images, including CT, cannot be used for directly identifying

any brain nuclei, the integration of stereotaxy with CT was an important step in image-guided neurosurgery [3]. Stereotactic CT is spatially accurate and can be utilized, among others, for implantation of deep brain stimulation (DBS) electrodes [4]. The advent of MRI made it possible to directly identify certain deep brain targets without exposing the patient to the potentially harmful ionizing radiation of CT. The disadvantage of MRI is the possibility of distortions due to the inhomogeneous magnetic field causing minor spatial inaccuracy. Electrophysiological microelectrode recording (MER) could be used to verify the final target position [5].

Usually, the stereotactic operation starts in the operating room (OR), where the stereotactic frame is mounted on the skull under local anesthesia. Thereafter, the MRI or CT coordinate indicator box is fixed on the frame, and the patient is transported to the MRI or CT unit to obtain image data for the calculation of the target coordinates. Back in the OR, the DBS electrodes are implanted into the target through burr holes relying on the preoperative imaging data. Due to the leak of cerebrospinal fluid, the resulting brain shift may cause inaccuracy, especially in frameless DBS implantations, such as described by Eljamel et al. [6]. In a recent study, where the real localization of the DBS electrodes was verified by using intraoperative ventriculography, or postoperative MRI and/or CT, CT imaging was estimated to be a satisfactory alternative to ventriculography, whereas MRI was not recommended [7]. The inconvenience caused by intraoperative transport of the patient to the MRI or the CT unit, and the inaccuracy due to brain shift can be avoided by utilizing an OR equipped with a built-in CT scanner, as described by Fiegele and co-workers [8]. To overcome the economic burden caused by building a special CT OR with obvious limitations for other use, we describe here our solution to use a modified O-arm, already routinely used in spinal operations, as a versatile substitute for intraoperative CT scanning. Recently, other centers have published their experiences with the O-arm, especially in DBS cases [9–11]. However, they are using the O-arm only for control images. This study shows how the O-arm can be used for calculations of the target coordinates at the frame-based stereotaxy.

Materials and Methods

The O-Arm

The O-arm (Medtronic Inc., Louisville, Colo., USA) is a CT-like, surgical, mobile 2D/3D X-ray imaging system optimized for spinal and orthopedic surgery. Scanning is based on a flat panel detector and cone-beam technology producing 196 slices in 13 s

in the standard mode and 196 slices in 26 s in the enhanced mode, the latter especially designed for cranial solutions. Pixel size is 0.415×0.415 mm within a slice thickness of 0.833 mm.

The size of the scanned cylindrical 3D volume is 21×16 cm (diameter $\times$ length), i.e. less than required for obtaining a full scan of all nine copper rods situated in a Z-pattern on the lateral and frontal walls of the Leksell CT coordinate indicator box (fig. 1).

Software

FrameLink stereotactic calculation software (Medtronic Inc.) was used for calculating the coordinates of the target at the beginning of the operation. FrameLink was also used for intraoperative control at the end of the operation when the postoperative O-arm 3D dataset was merged with the surgical plan. StealthViz medical image processing software (Medtronic Inc.) was utilized after the patient was scanned with the coordinate indicator box in the O-arm (fig. 2). With StealthViz software, the incomplete scanned dataset of the patient with the coordinate indicator box and the full volume dataset of the CT coordinate indicator box without the patient generically scanned with diagnostic CT in the radiological department could be merged and combined into one single dicom dataset. Both software programs were installed in the StealthStation S7 navigator (Medtronic Inc.) and used in the OR (fig. 3).

Stereotactic System

The G-model Leksell Stereotactic System with the Leksell CT coordination indicator box was used as the stereotactic system (Elekta AB, Stockholm, Sweden). The Leksell Stereotactic System can be used with aluminum (insulated or non-insulated) or carbon fiber posts and the reusable aluminum or titanium fixation screws. To minimize artefacts from the posts and screws, various combinations were tested. As the physical dimensions of the CT coordination indicator box were larger than the scanning volume in the O-arm, some small extra markers of copper were added to the indicator to help the merging of the limited O-arm dataset with the patient to the full generic CT scan of the indicator without the patient.

Surgical Table and Head Fixation System

The patient lay supine on a conventional operating table (Trumpf, TruSystem 7500, Ditzingen, Germany) extended with carbon fiber extension rails (C-Flex AP-vantage OR table adaptor, Allen Medical Systems, Acton, Mass., USA). The Leksell Frame was fixed to the patient's head, avoiding placement of the screws at the level of the AC-PC line, as the aluminum posts and titanium screws caused minor artefacts which could decrease image quality. The frame itself was slid into the sockets of the Leksell Frame Fixation, which was adjusted to the correct position using the C-Flex Polar Head Positioner System (Allen Medical Systems) fixed to the carbon fiber rails.

MER System

The Leadpoint MER system (Alpine Biomed Aps, Skovlunde, Denmark) was used for the verification of the calculated location of the STN. Usually, correct trajectory was verified using a single-microelectrode method, but in cases with inadequate recording of the STN activity or insufficient clinical response during micro- and/or macrostimulation, extra trajectories were measured. In cases with targets other than STN, e.g., ventral intermediate thalamic nucleus and GPi, MER was not applied.

Fig. 1. a The diameter of the scanning volume (210 mm) in the O-arm does not cover all nine rods on the Leksell coordinate indicator box in the axial plane. **b** The length of the cylindrical scanning volume (160 mm) covers the rods in the longitudinal direction. The most posterior rods and parts of the diagonal rods in the side plates are not included in the cylindrical volume as seen in **a**. x = Locations of the extra markers which help to merge the generic CT data set and the patient-specific images.

MRI Analysis

Patients were scanned preoperatively with MRI (GE, Signa HDxt Twinspeed 1.5 T, Waukesha, Wisc., USA) for the preoperative planning and to ensure accurate localization of the anterior and posterior commissures on axial 3D fast spoiled gradient recalled T_1 -weighted images with the contrast agent (repetition time, 7 ms; echo time, 2 ms; flip angle, 10° ; averages, 1; field of view, 300×300 mm; matrix, 256×256 pixels; slice thickness, 1.5 mm; separation, 1.5 mm) and to verify STN anatomically on the axial fast spin echo T_2 -weighted images with the contrast agent (repetition time, 2,800 ms; echo time, 87.6 ms; flip angle, 90° ; averages, 3; field of view, 300×300 mm; matrix, 256×256 pixels; slice thickness, 2.0 mm; separation, 2.0 mm).

CT Scan

The diagnostic CT scanner (Siemens Somatom Sensation 64 with Syngo CT2007S, Siemens AG, Erlangen Germany) was used once to scan a full generic dataset for the CT coordination indicator box without a patient. The scanning parameters were 120 kVp, 380 mAs and $512 \times 512 \times 0.6$ mm within the reconstruction diameter of 271 mm. One dataset was generic for all phantom tests and patient cases.

Patients

At the beginning of the study, the O-arm was validated in a series of 6 patients treated as follows: patient 1, bilateral STN-DBS for advanced Parkinson's disease; patient 2, unilateral GPi-DBS for dystonia; patient 3, unilateral ventral intermediate thalamic nucleus-zona incerta-DBS for multiple sclerosis tremor; patient 4, unilateral thalamotomy for Parkinsonian tremor; and patients 5 and 6, reimplantations of DBS electrodes in 2 cases with previous infection.

After meticulous evaluation of the experiences gathered with these 6 patients, the O-arm was applied routinely in all stereotactic operations.

For further evaluation of the ability of the O-arm to detect intracranial hematoma, 2 additional patients outside the stereotactic series were included: one with an acute spontaneous intracere-

bral hematoma (ICH) and the other with an acute subdural hematoma (SDH).

Phantoms for Accuracy Measurements

Two different phantoms were designed and applied for accuracy assessment; one for the demonstration of spatial accuracy in the scanning volume and one for the determination of the technical accuracy of the concept. In both phantoms, those parts which were to be scanned within the O-arm were made of acrylic plastic (polymethylmethacrylate).

The spatial accuracy phantom included equally distributed acrylic plastic rods in three different levels in known positions. The rods were visualized with the O-arm images and could be used for determination of spatial accuracy in the 3D volume when the positions of the rods were compared to their real positions. Detailed information on the phantom has been published recently [12].

The technical accuracy phantom was designed to be fixed to the Leksell frame and to simulate a real patient with the artificial points of AC, PC and STN as targets. The technical and methodological accuracy of the concept was calculated by running through the whole protocol. This included imaging, planning, calculations of coordinates and placement of the instruments. Quantitative accuracy could be calculated in the X, Y and Z directions since the exact coordinates were known, and qualitative accuracy could be visualized with the phantom.

Results

Surgery with the Present System

In the OR, right after the Leksell stereotactic frame was fixed to the patient's head and the patient was comfortably positioned on the operating table, the O-arm was used to collect a 3D dataset in the enhanced mode for calculation of the target coordinates. After the scanning, the O-arm was moved to its parked position.

Fig. 2. **a** The O-arm is a movable CT-like scanner. **b** With automated positioning, it can be easily placed around the patient to obtain 3D scanning or 2D fluoroscopic images in desired directions, and it can be repeated when necessary. **c** Access to the patient is possible in both the scanning and parked positions.

While the patient was scrubbed and draped, the surgeons and the physicist calculated the target coordinates. The 3D dataset was imported into the StealthViz software of the S7 navigation system. With the StealthViz software, the patient-specific O-arm dataset and the generic CT dataset from the coordinate calculation box without the patient were merged to become one single

dataset (fig. 3). The new dataset was exported into the FrameLink stereotactic calculation software, which was able to recognize all nine rods on the plates and to formulate coordinates inside the brain. In FrameLink, MRI datasets with trajectory plans were then merged to the O-arm dataset. Coordinates of the selected targets were calculated based on the rods in the O-arm images and on

Fig. 3. StealthViz and FrameLink software programs were both needed during the operation to enable calculation of the target coordinates and verification of the final position of the implanted instruments.

anatomical information and plans in the MRIs. This phase, including the 3D scanning and calculation, required approximately 15 min, which was much shorter than the time needed for a visit to the radiological department for MRI or CT.

The surgical operation was done as usual with the O-arm control as needed. The automated positioning system helped to park the gantry of the O-arm away from the surgical area and then to drive it back over the patient's head when 2D or 3D images were needed, so that the control

Fig. 4. In the O-arm image, the rods (grey circles with black centers) of the spatial accuracy phantom were seen in correct positions within 22-mm separations from each other. The grey line grid was laid over the image to check the correctness of the spatial information in the O-arm images. The spatial accuracy could thus be verified throughout in the 3D volume.

images could be taken in seconds. The flat panel detector offered good-quality wide-area 2D images for the control of localization of DBS, MER or thalamotomy electrodes. Image quality was good for intraoperative requirements and ensured exact location of the electrodes.

At the end of the operation, a 3D dataset was scanned. It showed the exact locations of implanted electrodes. The dataset could be merged with the preoperative plan to compare the planned and the real locations of the DBS electrodes.

Radiation Doses

Patients are exposed to ionizing radiation during 2D and 3D O-arm scanning. The 2D fluoroiimages with minor doses are mainly used for a fast check of the instrument trajectory and position in the brain and to verify the optimal position of the O-arm for the 3D scan. Usually, 4–10 fluoroiimages were needed. High-dose 3D scans are required for the planning and calculation of coordinates at the beginning and for the control images at the end of the operation. Calculated radiation doses in the enhanced mode, which is used to achieve better soft tissue contrast, are 5–10 times higher than those in the standard mode.

Accuracy

The spatial accuracy of the images and the technical accuracy of the concept were determined using the two custom-made phantoms.

Spatial accuracy of images could be obtained qualitatively to compare the known structure of the phantom to the locations of the structures on the images as shown in figure 4. Materials in the stereotactic frame could decrease image quality due to artefacts. However, these artefacts did not influence spatial accuracy (fig. 5).

The calculation accuracy of the concept was measured using the technical accuracy phantom with artificial STN targets scanned five times in different positions. From all five datasets, the target coordinates of both STNs, left and right, were calculated as in the patient cases, and the calculated coordinates of the targets were compared to the exact X, Y and Z values (table 1; fig. 6).

Total displacement errors were 0.45 ± 0.07 mm on the left and 0.60 ± 0.16 mm on the right side. In the X, Y and Z directions, displacements were 0.18 ± 0.10 , 0.20 ± 0.08 and 0.30 ± 0.12 mm on the left side and 0.18 ± 0.10 , 0.32 ± 0.10 and 0.38 ± 0.26 mm on the right side, respectively. The technical accuracy of the concept proved to be similar to that of the voxel size of the O-arm images. The voxel size was $0.415 \times 0.415 \times 0.833$ mm.

Intracerebral Hemorrhage

In stereotactic operations, ICH is a risk and can now be excluded after the procedure. To study the application of O-arm imaging for the detection of blood intracranially, 2 patients were scanned as part of their surgery for acute hematoma. One patient had an acute spontaneous ICH and the other an acute SDH. Images showed clear demarcation of the ICH (fig. 7) and the SDH.

Discussion

We hypothesized that the O-arm could be used alone as an intraoperative imaging system during frame-based stereotactic operations. Accuracy tests and clinical patient cases showed our assumptions to be correct. Since the validation in a series of 6 patients, this method is routinely used in stereotactic operations in our hospital.

An intraoperative 3D scanning method, such as the O-arm, could replace the MR and the CT imaging methods required for the coordinate calculations. Typically, MRI scanners utilize smaller head coils to achieve an increased signal-to-noise ratio for better image quality as well as for special imaging methods such as diffusion ten-

Fig. 5. The conventional rods and titanium screws caused larger artefacts on O-arm images (a) than the carbon fiber rods and aluminum screws (b). **b** The carbon fiber rods are invisible and images practically artefact free.

Fig. 6. Qualitatively, a total displacement error of <0.5 mm can be seen mainly in the anterior direction, which falls within the size of the O-arm imaging voxel.

Fig. 7. O-arm image showing intracranial air (black areas in the frontal horns and subdurally) and ICH (white areas). This image was taken from a patient suffering from a spontaneous ICH, about 4 h after bleeding and placement of the ventricle catheter.

sor imaging, which are considered to be useful for DBS patients [13]. The size of the coils prevents scanning patients with stereotactic frames. Therefore, coordinate calculations have to be done with CT or a CT-like method such as the O-arm. Thus, in the future, stereotactic centers using frame-based stereotactic methods and MRI-based coordinate calculation could use the surgical O-arm in the OR as an intraoperative scanning method instead of a CT outside of the OR.

Concept

The present concept proved to be straightforward. It shortened the operation time, since image merging between the generic dataset and the patient-specific dataset could be done as the surgical area was being prepared.

The O-arm is a big scanner and it requires its own floor area at the OR. However, the O-arm is stationary during the whole procedure and does not need to be moved back and forth in the OR. Only the gantry is

Table 1. The technical accuracy of the concept

	Left side							Right side						
	X	\Delta X	Y	\Delta Y	Z	\Delta Z	TOT	X	\Delta X	Y	\Delta Y	Z	\Delta Z	TOT
Exact	112.0		97.0		114.0			88.0		97.0		114.0		
O1	112.0	0.0	96.8	0.2	114.5	0.5	0.54	88.0	0.0	96.6	0.4	114.9	0.9	0.98
O2	112.2	0.2	96.8	0.2	113.9	0.1	0.30	88.2	0.2	96.7	0.3	114.0	0.0	0.36
O3	112.3	0.3	97.4	0.4	113.8	0.2	0.54	88.3	0.3	97.1	0.1	113.5	0.5	0.59
O4	112.3	0.3	97.1	0.1	114.3	0.3	0.44	88.3	0.3	96.6	0.4	114.3	0.3	0.58
O5	111.9	0.1	96.9	0.1	113.6	0.4	0.42	87.9	0.1	96.6	0.4	113.8	0.2	0.46
Average displacement, mm	112.14	0.18	97.00	0.20	114.02	0.30	0.45	88.14	0.18	96.72	0.32	114.10	0.38	0.60
± SD, mm	0.15	0.10	0.20	0.08	0.30	0.12	0.07	0.15	0.10	0.15	0.10	0.40	0.26	0.16

X, Y and Z = Coordinates in the Leksell stereotactic system; $|\Delta X|$, $|\Delta Y|$ and $|\Delta Z|$ = absolute values of the displacement from the exact coordinates; TOT = total displacement calculated by the Pythagorean theorem; Exact = real coordinate values; O1, O2, O3, O4 and O5 = different O-arm datasets; SD = standard deviation.

moved between the parking and scanning positions. The automated positioning system helps to park the gantry of the O-arm away from the surgical area and then to drive it back over the patient's head when 2D or 3D images are needed.

The head fixation system including the Allen carbon fiber extension rails and the C-flex polar head positioning system worked as planned, allowing adjustments for comfortable patient positions. The extension rails and the head positioning system did not limit the positioning of the O-arm so that the patient's head could be placed in the isocenter of the O-arm.

The use of the O-arm did not interfere with our sensitive Leadpoint MER system either.

Accuracy

The concept itself – including merging two datasets to a single one – did not decrease accuracy. The technical accuracy in the X-Y plane was comparable to the pixel size. The X direction was the most accurate as it was determined directly from the pixels. The displacement in the Y direction is slightly less accurate because of inaccuracies in the determination of the rods in the coordinate calculation box in the Y direction. In the Z direction, the differences between calculated and real coordinates were largest, which can be explained by the slice thickness of 0.833 mm which is greater than the pixel size.

Radiation Doses

The Finnish Radiation and Nuclear Safety Authority (Säteilyturvakeskus) has limited the maximum dose lev-

els to 65 mGy (computed tomography dose index) for the brain per one CT scan, and this level was exceeded in some cases. At least two data sets, preoperatively for the planning and postoperatively to ensure location of the DBS electrodes, should be obtained, which causes an overall dose of 130 mGy, if both scans are done with the enhanced mode for ventricle visualization and to rule out hemorrhage. Especially for younger patients undergoing stereotactic biopsy or DBS implantations for epilepsy, obsessive compulsive disorder or dystonia, the dose levels need to be optimized.

Intracerebral Hemorrhage

Stereotactic operations through a burr hole are associated with a minor risk of bleeding [14]. Based on our long-term experience of intraoperative control monitoring, i.e. imaging and MER, we assume that the risk of bleeding exists even if high-quality angiography data are used during planning. Apparently, the risk exists because of the brain shift caused by the cerebrospinal fluid leakage. If bleeding could be detected during operation, it might diminish the possibility of serious intracerebral hemorrhage. Intraoperative O-arm scanning at the end of the operation before closure could show bleeding at the acute phase, even without contrast enhancement.

Benefits of Intraoperative 3D Scanning

More than just controlling the location of implanted electrodes, the O-arm can give unique and valuable information which cannot be achieved without intraoperative 3D scanning. The 3D data can be used to analyze

intraoperative intracranial changes and possible errors in the overall implantation method. Sometimes, postoperative scanning with MRI or CT can give the same information, but not with the same details and spatial accuracy of real intraoperative scanning. Intraoperative data clearly reveal immediate brain shift due to the operation. Amounts and directions of the shifts can be analyzed to study the brain shift around the region of the surgical interest. This can be most valuable in epilepsy DBS cases where the targets, the anterior thalamic nuclei, are below the lateral ventricles and can markedly shift with cerebrospinal fluid leakage. The 3D datasets can be used to check how much the DBS electrodes have moved after the implantation.

Conclusions

The O-arm could be used alone with high accuracy as an intraoperative imaging system for planning and controlling in stereotactic placement of DBS electrodes. The O-arm allowed neurosurgeons to scan the patients as needed in the 2D and 3D mode, to calculate coordinates

of the specific target, to control the positioning of the applied instruments or tools, and to ensure the final position of implanted objects. Thus, neurosurgeons can obtain valuable information on the location of the electrodes intraoperatively.

Even though the diagnostic value of O-arm images is lower than that of real CT or MRI, it can be reliably utilized for visualization of the required objects in the brain, e.g., the lateral and third ventricles, AC-PC line and DBS electrodes. In addition, intraoperative O-arm scanning can be of crucial importance for excluding possible hematoma complication.

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Disclosure Statement

This special study was based purely on clinical interest. None of the authors have any financial interest in the results.

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