Intraoperative Stereotactic Frame Registration Using a Three-Dimensional Imaging System with and without Preoperative Computed Tomography for Image Fusion

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Keywords

Frame-based stereotaxy · Deep brain stimulation · O-arm · Image fusion · Intraoperative target localization

Abstract

Background: The O-arm O2 imaging system (OAO2) is an intraoperative cone beam 3D tomogram imaging tool with a wide enough field of view to perform intraoperative fiducial registration with standard stereotactic frames. However, the OAO2 3D images (cone beam CT) provide limited tissue contrast, which may reduce the accuracy of fusion to a preoperative targeting MRI for planning awake deep brain stimulation (DBS) surgeries. Therefore, most users obtain a preoperative CT scan to use as the reference exam for computational fusion with the preoperative targeting MRI and the intraoperative OAO2 cone beam CT. **Objective:** In this study, we retrospectively analyzed the discrepancy between stereotactic coordinates of deep brain targets on MRI derived from intraoperative OAO2 fiducial registration with and without the use of preoperative CT as the reference for image fusion. **Methods:** Preoperative stereotactic CT/MRI and intraoperative OAO2 cone beam CT were retrospectively evaluated for 27 consecutive DBS patients, using two commercial surgical planning software packages (BrainLab Elements and Medtronic Stealth 8). The anterior commissure, posterior commissure, and left subthalamic nucleus were identified on preoperative MRI. Each patient had intraoperative fiducial registration using the OAO2 with a Leksell head-

frame. For each subject, the reference scan for image fusion was set as either the preoperative CT or the preoperative MRI (volumetric T1 with contrast). Computed stereotactic coordinates for each target were then compared. **Results:** For 8 of 27 subjects, a discrepancy greater than 1.0 mm for at least one designated target was observed utilizing the Medtronic Stealth S8 planning station when a preoperative CT scan was not used. An additional 5 (5/27) had a discrepancy greater than 2 mm. The most common discrepancy was in the z axis. No coordinate discrepancies greater than 1 mm were observed utilizing BrainLab Elements. **Conclusions:** Caution is advised in fusing intraoperative OAO2 images directly to preoperative MRI without a preoperative CT as the reference exam for image fusion, as the specific fusion algorithm employed may unpredictably affect targeting accuracy.

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Introduction

Frame-based stereotactic surgery has had a complex workflow due to the requirement to obtain brain imaging in a radiology suite the morning of surgery, following placement of the stereotactic frame. Several strategies have been employed to improve this workflow, including:

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Fig. 1. Illustration of the two different image fusion methods compared in this study: with (left) or without (right) the use of a preoperative CT as the reference exam for image fusion. OAO2, O-arm O2; CT, preoperative CT; MRI, magnetic resonance imaging.

utilization of bone mounted fiducials placed days prior to surgery, to decouple stereotactic imaging from the day of surgery [1], or the use of real-time magnetic resonance imaging (MRI) with a skull-mounted aiming device [2]. While intraoperative computed tomography (CT) imaging [3, 4] can be done, this requires the presence of a CT technologist in the operating room, and existing portable CT scanners typically cannot be used for intraoperative two-dimensional (2D) fluoroscopy, an important tool for many stereotactic surgeries. A recently available mobile three-dimensional (3D) tomographic imaging system, the Medtronic O-arm O2 (OAO2; Medtronic, Dublin, Ireland), allows for both multiplanar 2D fluoroscopy and 3D tomography (“O-arm spin”) with a wide enough field of view to localize stereotactic frame fiducial markers. This device may be operated by an appropriately trained surgeon with a fluoroscopy license, and can greatly simplify the day-of-surgery workflow for frame-based stereotaxy by obviating the need for transport to radiology after frame placement. The 3D tomogram is referred to here as a cone beam CT (CBCT).

However, the technical approach to maximizing the accuracy of fiducial localization using the OAO2 is not well defined. Bone and metal are well visualized with the OAO2 CBCT, allowing accurate computational fusion of

the CBCT with preoperative CT [5–8]. However, its limited soft tissue contrast raises concern about the accuracy of computational fusion of O-arm 3D images with a preoperative MRI. To address this, most surgeons utilizing the OAO2 for intraoperative fiducial localization obtain a preoperative (non-stereotactic) head CT prior to the day of surgery, to serve as the “master reference” exam for image fusion of both the preoperative MRI targeting images, and the intraoperative OAO2 CBCT. This preoperative CT adds additional patient radiation exposure, healthcare costs, and complexity to patients’ preparation prior to surgery.

Methods

Here, we evaluated the necessity of utilizing a preoperative CT as a reference exam for merging intraoperative 3D OAO2 CBCT localization images with preoperative MRI targeting images. We retrospectively analyzed 27 cases of frame-based (Leksell series G) stereotactic placement of deep brain stimulation (DBS) leads, in which all three images sets had been obtained. We calculated the discrepancy in stereotactic coordinates for deep brain targets obtained with, versus without, the use of the preoperative CT (Fig. 1). We tested two contemporary stereotactic surgical planning software packages, Medtronic StealthStation 8 with the Cranial software package (Medtronic) and BrainLab Elements (BrainLab,

Fig. 2. Boxplot of coordinate discrepancies with versus without preoperative CT, compared across the two image fusion/surgical planning software packages. * $p < 0.05$; ** $p < 0.001$ between groups. † Error > 1 mm ($p < 0.001$).

Inc.). To minimize user bias, we utilized the automated fusion algorithms of each software package rather than attempting “manual fusion” to improve accuracy.

All subjects signed preoperative consent allowing retrospective chart review for clinical research. Subject inclusion criteria included placement of DBS leads using frame-based stereotaxy within the past 12 months, availability of all required imaging modalities (preoperative CT, preoperative MRI, intraoperative OAO2, and acceptable OAO2 scan parameters, e.g., < 10 degree gantry angle) for automated fusion processing by each software package. The following MRI sequences were used: T1 3D FSPGR (256×256 matrix), and in cases with alternative scans used to troubleshoot image fusion errors: axial ADNI IR-SPGR (256×256 matrix) 1 mm or T1 3D FSPGR (256×256 matrix) 1.5 mm. The majority of the subjects ($n = 19$) were scanned on GE Discovery MR750 or Signa HDxt at 3 T, 2 subjects had their scans on GE Discovery MR750 at

1.5 T, and 6 subjects had MRI scans on Phillips Achieva at 1.5 T. Preoperative CT were axial (not helical), with 1.25 mm slice thickness.

The anterior and posterior commissures, as well as the left subthalamic nuclei (STN) were selected as midline and lateral targets on preoperative volumetric MRI, respectively. The left STN was defined utilizing consensus AC/PC (anterior commissure/posterior commissure) targeting (AP: -3 mm, lateral: 12 mm, vertical: -4 mm) for each patient [9]. The STN target was included in this analysis so as to have an “off midline” target, as fusion errors arising from “coronal tilt” between image sets may not be detectable with midline targets. Both AC and PC were selected by A.K.C. and verified by J.M.S. Targets did not need to be re-selected when changing the reference exam used for image fusion (i.e., targets remained associated with the MRI imaging that was utilized for planning regardless of fusion algorithm).

Fig. 3. Examples of overt alignment error in the fusion of O-arm spin to volumetric T1 MRI for two patients with a >2 mm discrepancy in at least one coordinate, fused using Stealth Cranial 8 (xx version). Arrows indicate regions where alignment errors are apparent to visual inspection. Patient 1 and 2: **a, d** Axial. **b, e** Coronal. **c, f** Sagittal.

Stereotactic coordinates calculated using preoperative CT as the reference for image fusion, were considered the “gold standard.” Coordinate discrepancies were calculated as the difference between x , y , and z coordinates, when using preoperative CT as the reference for image fusion, versus fusion of the OAO2 CBCT directly with preoperative MRI, without utilizing the preoperative CT. We considered a discrepancy of less than 1 mm in all axes, for both targets, to indicate successful determination of frame-based target coordinates without using preoperative CT. No manual adjustments were made prior to automated image fusion workflow packages (Fig. 1).

Statistical Analysis

All descriptive data are summarized by median and 25th to 75th quartile range unless otherwise specified. Stereotaxic accu-

racy between fusion algorithms, with and without a preoperative CT, was analyzed with Wilcoxon sum test. Resulting values of $p < 0.05$ were considered statistically significant. All statistical analysis was performed in GraphPad Prism 8 (GraphPad Software, San Diego, CA, USA, www.graphpad.com).

Results

Twenty-seven movement disorder subjects met the inclusion criteria. Mean age was 69.4 (range: 54–82) years, 56% were males, and diagnoses were Parkinson disease

(63%), essential tremor (26%), dystonia (7%), chronic pain (4%), and a minority of patients (19%) had prior intracranial hardware at time of surgery. Using the BrainLab Elements automated fusion algorithm, all 27 patients had acceptable stereotaxic accuracy (no coordinate discrepancy >1 mm) without the use of preoperative CT (Fig. 2). In contrast, use of the StealthStation 8 automated fusion algorithm resulted in acceptable stereotaxic accuracy in only 14 out of the 27 subjects without the use of preoperative CT. Eight subjects had a coordinate discrepancy of 1–2 mm and 5 subjects a coordinate discrepancy of at least 2 mm, in at least one coordinate for at least one target (Fig. 3). The discrepancy was usually in the *z* direction. Two manual attempts by independent investigators were unable to improve the stereotaxic accuracy of the MRI to OAO2 fusion. However, selection of an alternative preoperative volumetric MRI sequence reduced coordinate discrepancy in all cases (data not shown, $p < 0.001$), but still did not meet acceptable stereotaxic accuracy. There was no correlation between the StealthStation 8 coordinate discrepancies to MRI scan type, field strength, prior intracranial hardware, surgical date, or diagnosis.

Discussion/Conclusion

Here we studied the accuracy of intraoperative registration of a stereotactic headframe using a CBCT obtained with the OAO2 imaging system. Intraoperative images used for registration of a frame's fiducial markers must be computationally fused to preoperative MRI to provide stereotactic coordinates. We compared several different workflows for use of the CBCT: with versus without the use of preoperative CT as the reference exam for image fusion; and fusion using Stealth Cranial 8 versus Brainlab Elements, two commonly used surgical planning software packages for stereotactic surgery. We show that acceptable (<1 mm) registration accuracy for use of CBCT for stereotactic localization can be achieved without a preoperative CT reference exam, but that accuracy is dependent on the type of surgical planning software used for the registration.

The original version of the O-arm (O-arm 1000) has been used extensively as an adjunct to stereotactic DBS surgery [5, 6, 10–12]. However, reports of its use have largely focused on the intraoperative confirmation of DBS lead location, and have shown that lead locations as determined by CBCT fused to preoperative imaging are similar to those determined by postoperative CT or MRI [5, 6, 10, 11, 13]. In addition, the O-arm 1000 has been

used for stereotactic localization in the setting of bone-mounted fiducials used in conjunction with a “frameless” skull-mounted aiming device, as the field of view of the O-arm 1000 was only adequate for this application [13]. A CBCT with an expanded field of view (OAO2), sufficient for registration of traditional stereotactic frames, has only recently become available for use during DBS cases [14]. Carlson [14] recently reported a retrospective study of portable cone beam registration accuracy and precision compared to preoperative CT registration obtained in 10 patients. This approach is equivalent to our current standard of care approach (Fig. 1) and consistent with our data showing the StealthStation 8 software performed adequately in cases with a preoperative CT as the reference exam for image fusion.

In our practice, implementation of the proposed alternative workflow would result in significant cost savings and a reduction in radiation exposure. The average cost, USD 350, of a non-contrast head CT would equate to an approximate healthcare saving of USD 20,000 for 1 year in our clinical practice. For a routine head CT, the median effective dose is 2.1 mSv, and the corresponding median adjusted lifetime attributable risk of cancer is 0.23 cancers per 1,000 patients (range = 0.03–0.70 cancers per 1,000 patients) [15] compared to 0.66 mSv standard-dose and 0.33 mSv low-dose OAO2 scanning protocols.

Limitations of our study include its retrospective study design and the use of commercial proprietary software packages for which the details of the image fusion algorithms are not publicly known. During MRI acquisition, different scanners or parameters used for scanning different subjects or the same subject at a different time may result in large intensity variations. Thus, it is well appreciated that intensity normalization is an important preprocessing step in brain MRI analysis, which may be a contributing factor to the relative inconsistency of the StealthStation 8 in performing adequate MR-to-OAO2 fusion without a preoperative CT. Of note, numerous factors not evaluated here may contribute to the accuracy and utility of a surgical planning software package for achieving a desired clinical result, and our study only addressed one element of software performance, related to image fusion algorithms.

In summary, the use of OAO2 for intraoperative stereotactic localization in frame-based stereotaxy is an important advance that can substantially simplify day of surgery workflow by obviating patient transport to radiology after frame placement. Due to concerns about the accuracy of image fusion of CBCT to preoperative targeting MRIs, the most conservative technique for intraoperative localiza-

tion still uses a preoperative CT scan as the reference for image fusion. Here, we show that the use of the preoperative CT is necessary for reliable targeting accuracy when utilizing StealthStation 8. However, some image fusion algorithms, such as that utilized in Brainlab elements, appear to be able to adequately fuse the CBCT directly with preoperative MRI, obviating the need for preoperative CT.

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Statement of Ethics

All subjects have given their written informed consent. The study protocol has been approved by the research institute's committee on human research. The authors have no ethical conflicts to disclose.

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Conflict of Interest Statement

The authors have no conflicts of interest to declare.

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Author Contributions

J.M.S., A.K.C., J.S.Y., P.A.S: study design and conduct; data collection, analysis, and interpretation; manuscript drafting, revision, and approval. J.M.S. and P.A.S. take responsibility for the integrity of the data analysis.