Technical Report

Stereotactic and Functional Neurosurgery

Stereotact Funct Neurosurg 2019;97:303–312
DOI: 10.1159/000504945

Received: September 11, 2019
Accepted after revision: November 21, 2019
Published online: January 21, 2020

Utilization of the Intraoperative Mobile AIRO® CT Scanner in Stereotactic Surgery: Workflow and Effectiveness

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Keywords

Intraoperative imaging · AIRO® · Stereotactic surgery · Biopsy · Intraoperative CT

Abstract

Background: In frame-based stereotactic surgery, intraoperative imaging is crucial. It generally follows a workflow including preoperative MRI and intraoperative frame-based CT. The intraoperative transport of the anesthetized and intubated patient to and from the CT unit can be time-consuming and cumbersome. Here, we report the first 50 patients who underwent stereotactic biopsies using the mobile AIRO® intraoperative CT (iCT) scanner. ***Methods:*** A conventional stereotactic frame was mounted to the AIRO® carbon table via carbon adapter. 0°gantry thin-slice iCT was performed. The imaging data were transferred to a conventional stereotaxy working unit. After fusion of the preoperative MRI and AIRO® iCT, the stereotactic system was built based on the iCT, and trajectories were calculated accordingly. ***Results:*** The frame-based stereotactic iCT was easy to implement and successfully accomplished in all patients. The MRI/iCT image fusion was feasible in all of the studies. A conclusive histological result was obtained in 46 of the 50 cases included. There was no bleeding complication. Net surgery time was reduced by 38 min, on average. ***Conclusion:*** We conclude that the AIRO® system is a safe, easy-to-use, and sufficiently accurate iCT for CT frame-based stereotactic biopsy planning that results in a considerable reduction of surgery time. In the future, it remains to be evaluated if the accuracy rates and intraoperative workflow will permit its application in deep brain stimulation and other functional procedures as well.

Introduction

In any stereotactic procedure, perioperative imaging is indispensable. Correct calculation of the target structure and construction of a safe trajectory rely on spatially accurate pre- and intraoperative scans, as well as proper image fusions.

Often, stereotactic trajectory planning is based on a CT scan, due to higher spatial accuracy and less distortions when compared to MRI. The CT scan is usually merged with preoperative imaging data that provide better visualization of the target region, such as MRI or PET sequences. Frame-based stereotactic procedures generally begin with the mounting of the stereotactic frame onto the patient's head in local or generalized anesthesia. The patient is then transported to the CT unit to obtain image

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data sets for the generation of stereotactic coordinates. After this, the patient is transported back to the OR. Here, only after merging the CT scans with prior generated MRI data, creating the stereotactic system, calculating target and trajectory, and adjusting the stereotactic instruments, does the actual surgery begin.

The transport to and from the CT unit can be inconvenient for the awake patient and can put the intubated patient at transport-associated risks. For the staff, the transport is time-consuming and cumbersome. An OR-inbuilt CT might avoid the transport-associated risks and inconveniences for patient and staff and reduce the gross surgery time. Intraoperative imaging solutions have been described before, both for CT and for MRI [1–6]. The first report of a CT-scanner build into an OR was as early as 1980 at the University of Pittsburgh [1]. However, a fully intraoperative CT suite is not easily realizable, since a dual room solution with major building work is generally required. Therefore, a smaller mobile intraoperative CT (iCT) that fits into an existing OR suite and is not committed to any OR but available to multiple ORs and used only on demand was implemented.

With recent advances of integrating high-quality intraoperative imaging modalities into the neurosurgical OR, the compelling advantages of these so called “hybrid-solutions” have become evident. Those include: an increase in efficacy by integrating planning and documentation into the surgical procedure itself; time saving and reduction of involved personnel by introducing interfaces that can be operated by the neurosurgeons themselves; and the possibility of generating control images at any time during the procedure to update the current patient anatomy. The practical experience of using these hybrid solutions has been reported extensively for cranial tumor surgery, endovascular treatments, and spinal instrumentations [7–9]. The authors believe hybrid OR solutions hold enormous potential for functional and stereotactic procedures as well. However, their usage in this sector of neurosurgery has hardly been depicted yet.

The successful introduction of iCT for frameless navigated biopsies has been reported recently [10]. As concerns frame-based planning, there have been some attempts of integrating the O-arm® (Medtronic Inc., Luisville, CO, USA) into functional procedures [11–13]. However, the O-arm does not offer full Hounsfield soft tissue imaging or application of contrast medium. Therefore, the O-arm is not suitable for stereotactic biopsies based on O-arm imaging alone [11–13]. To the authors knowledge, this is the first report of implementing a mobile iCT scanner in a hybrid OR setting for frame-based stereotactic biopsies.

Here, we report the first 50 cases of frame-based stereotactic biopsies using the AIRO® (Brainlab, Feldkirchen, Germany) mobile iCT. The aim of the study was to evaluate technical feasibility, accuracy, and usefulness of the AIRO® mobile iCT concept in stereotaxy.

Methods

The AIRO® iCT

The AIRO® (Brainlab AG, Feldkirchen, Germany) is a mobile 32-slice CT scanner, whose gantry can be translated to different OR suites and rotated as required. Its rather small footprint of 1.5 m^2 allows it to be housed into an existing OR suite, without the requirement for reconstructive modifications. It offers a considerably large gantry opening of 107 cm. Thus, a stereotactic frame including plates for fiducials/a CT indicator box and mounting can easily be accommodated. It allows a scan volume of up to 100 × 50 cm.

The gantry itself is relatively narrow with an outer diameter of 38 cm, containing the X-ray tube, the scan detector array, a high-voltage generator, the air cooling system, and a buit-in battery pack. There are several predetermined scan programs to choose from and currently three reconstruction kernels: soft, standard, and sharp. The AIRO® is operated by a detachable handheld touch panel, which can be transferred outside the OR suite. Surgery and scans are both performed on the same mobile radiolucent carbon table (Trumpf TruSystem 7500, Trumpf Inc., Farmington, CT, USA) that is connected to the AIRO®. The carbon table can be rotated and adjusted again by a handheld electrical control. A change of patient position or transfer to a different table is not required throughout the procedure.

Presurgical Phantom Studies

Up to the time point of the start of this study, the AIRO® iCT was solely used in spinal applications. Therefore, to confine suitable scanning parameters and also to ensure technical feasibility and spatial accuracy, phantom studies were conducted in a prepatient setting first. A conventional stereotactic phantom containing CT and MRI opaque particles was used (courtesy of Brainlab AG; Fig. 1). First, the mounting of the phantom-bearing stereotactic frame to the carbon table was performed. Table adjustments were tested that would fit the stereotactic installation comfortably through the gantry while securing the phantom to remain in the exact isocenter of the detector. Test scans were performed to define the most suitable radiation hardness and kernel to detect fiducials on the maximum number of scan slices in order to generate an accurate stereotactic transformation. Scan parameters and the field of scan were confined to reduce exposure dose remaining safely under the maximum dose allowance for head CT scans of 900 μSv. After the stereotactic transformation was successful, the phantom was taken to the MRI and an MRI/iCT fusion was tested using a conventional software for stereotactic planning (Inomed; inomed Medizintechnik GmbH, Emmendingen, Germany; Fig. 1). Subsequently, phantom biopsies were performed to substantiate the precise and reproducible accuracy of stereotactic planning on iCT ba-

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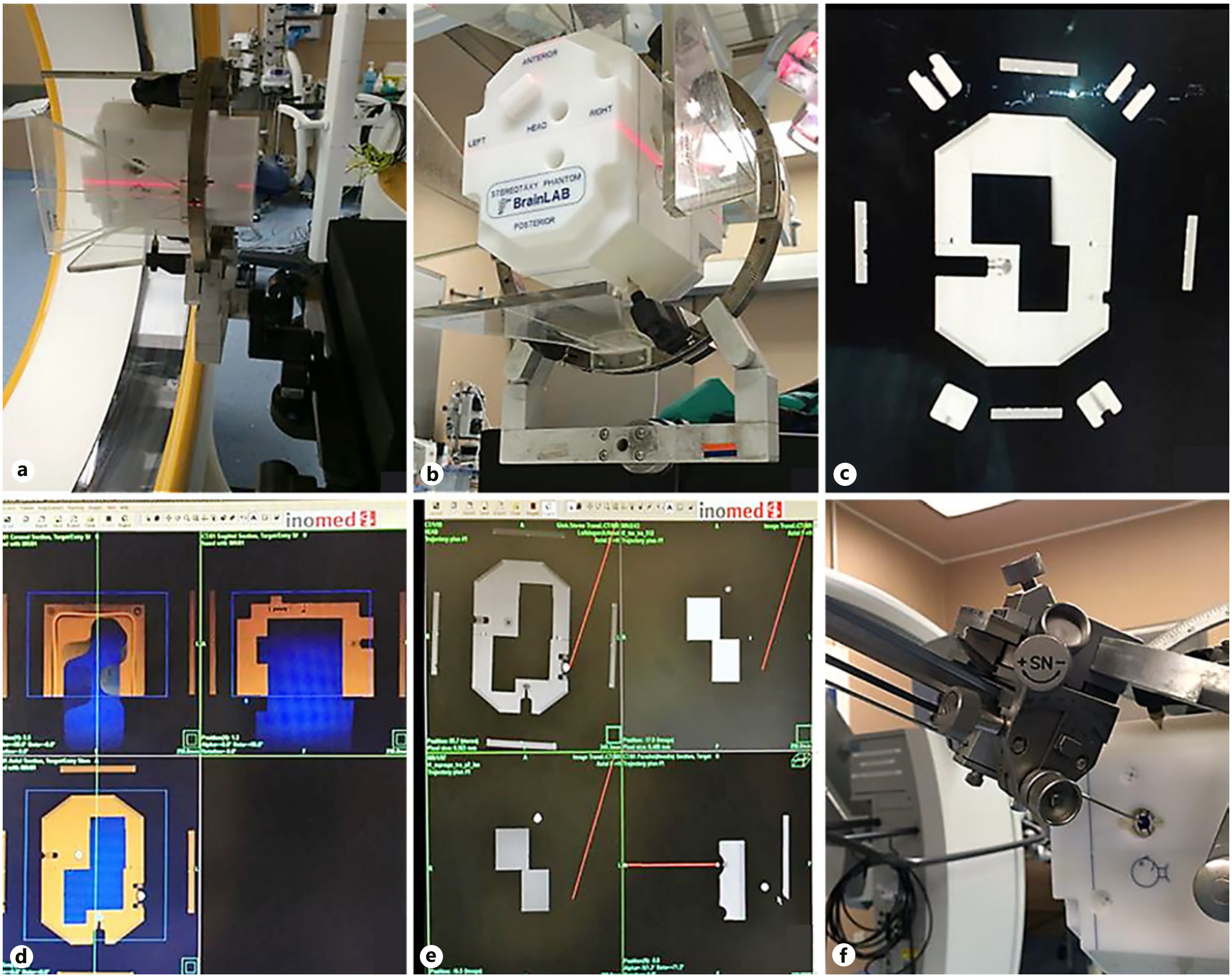

Fig. 1. Phantom studies using the mobile AIRO® iCT in stereotaxy. **a** Phantom mounting in conventional frame. **b** Phanotom scan. **c** Phantom AIRO® iCT scan. **d** AIRO® iCT/MRI fusion. **e** Trajectory planning on fused images. **f** Phantom biopsy based on AIRO® iCT planning displaying precise target accuracy.

sis (Fig. 1). The established protocol for iCT stereotaxy was transferred to a real patient setting only after assured evidence of fiducial detection, correct transformation, precise image merge, and reliable conversion of stereotactic coordinates.

Workflow

AIRO® iCT Setup

While the patient is being intubated in the anesthesia room, the AIRO® iCT is transferred into the OR suite by single person electric transport and warmed up as described before [14].

Positioning

At the beginning of the surgery, the patient is positioned supine on the carbon table parallel to the AIRO® iCT (Fig. 2). The head is fixed in a conventional stereotactic ring, which is locked into a conventional ring holder. The ring holder is then connected to the carbon Mayfield mounting by a toothed wheel translation. For the Riechert-Mundinger stereotactic system, the standard carbon Mayfield mounting does not fit the translation of the ring holder. Therefore, an additional translation adapter had to be designed, which is now also available commercially (through Trumpf Inc.). Fiducial-bearing plates (or a respective stereotactic frame) are mounted to the ring for generation of coordinate planes. For orientation of entry, CT-dense markers can be attached to the head, if required (Fig. 2b).

Scan

To perform the scan, the table is rotated 90° to be orthogonal to the iCT gantry (Fig. 2b). The head is then adjusted to the isocenter of the scanner in the 0° gantry position (Fig. 2c) with the

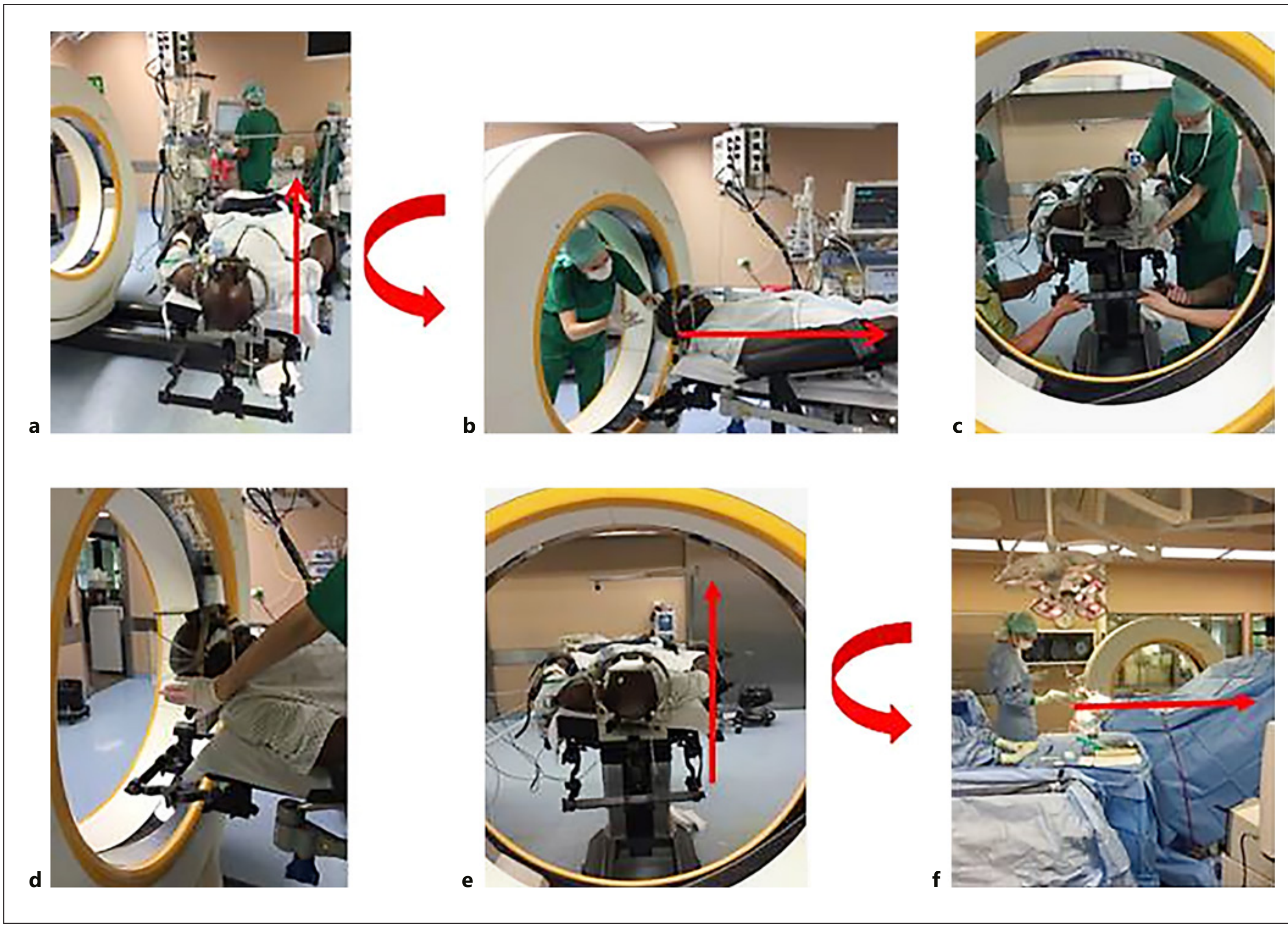

Fig. 2. Workflow using the mobile AIRO® iCT in stereotaxy. **a** Initial positioning of the patient on a carbon table parallel to the AIRO® iCT scanner. **b** Turning the carbon table on the socket. **c** Allocating the frame in the isocenter of the gantry by relocating table position and various joints of the mounting. **d** Aligning fiducials with laser makers. **e** Performing the scan. **f** Turning the table back 90°after the scan and proceeding with biopsy surgery.

aid of laser markers, by shifting the table electrically and relocating various joints on the carbon Mayfield mounting manually (Fig. 2d). The field of scan is being narrowed down and the respective scan parameters are chosen. The scan is initiated by the handheld panel.

Data Processing and Target Planning

The iCT image data are transferred digitally in a dicom format to a conventional stereotactic workstation (Fig. 3). We use inomed software (IPS 4.0, inomed Medizintechnik). The iCT is stereotactically transformed and then fused with preexisting MRI data sets (and/or PET scan data), which were generated one or several days prior. The subsequent steps are conformable to any conventional stereotaxy planning, including definition of target and entry, generation of coordinates, and reverse kinematics translation to generate adjustments on the respective stereotactic arch (Fig. 3). To proceed with the biopsy, the table is rotated back by 90°, and surgery is performed as in any other stereotactic procedure (Fig. 2f). (Biopsy through the gantry, abstaining from another turn of the table, is also possible, but might be less comfortable for the surgeon.)

Study of the Intervention

Patient characteristics, lesion characteristics, complication rates, histological results, and mean surgical times were analyzed in the 50 patients receiving AIRO® iCT stereotactic biopsies, and then compared with a retrospective group of 50 stereotactic biopsies that were performed directly prior to the implementation of the AIRO®-based stereotaxy, using a conventional CT. All biopsies in the AIRO® iCT group and the conventional CT group were performed by the same two operating surgeons.

Measures

The main two objectives for assessing the impact of the intervention were to determine biopsy accuracy rates and gross surgery times.

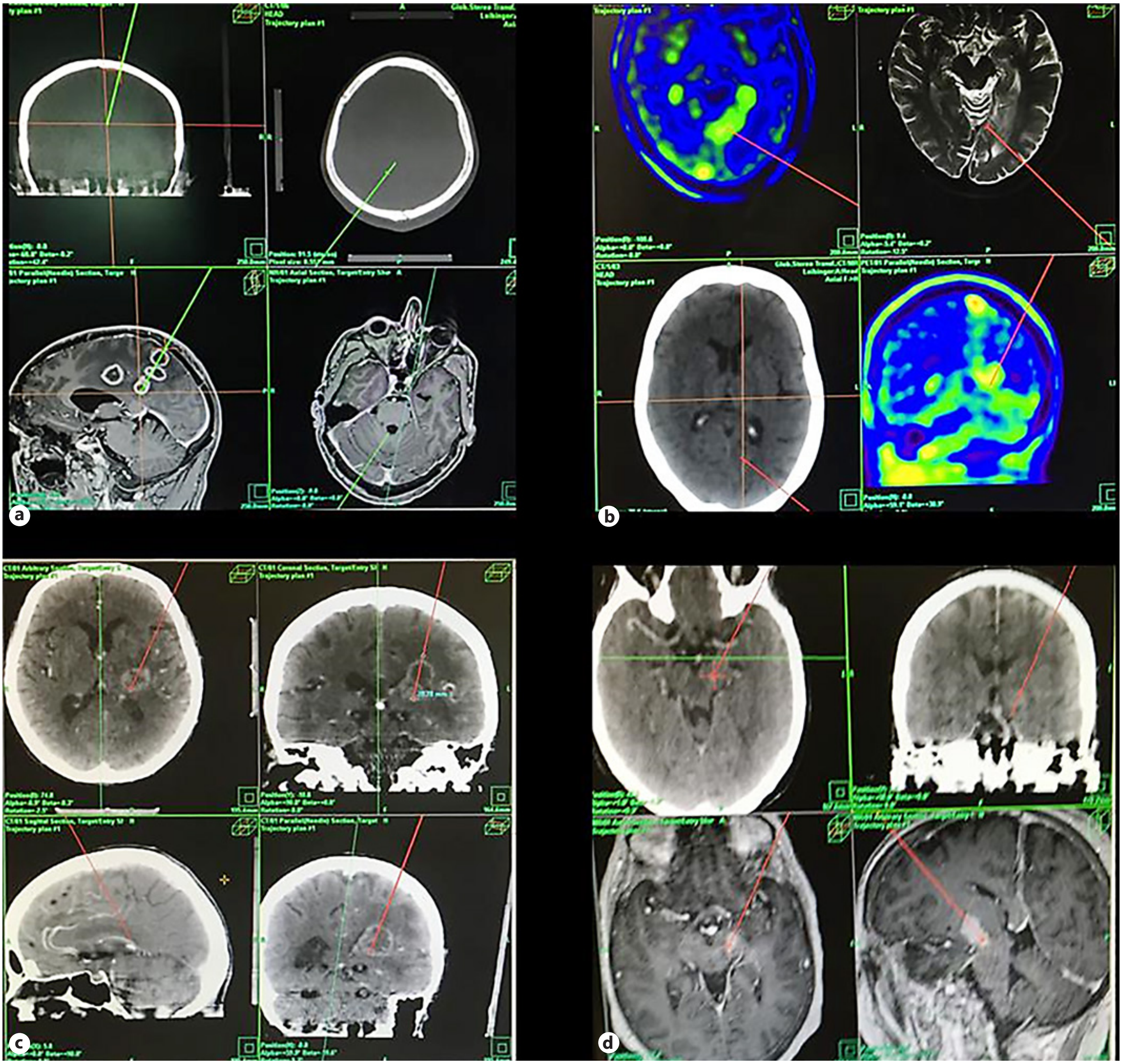

Fig. 3. Building a stereotactic system based on AIRO® iCT data and fusing the iCT with preexisting imaging data. **a** iCT fused with MRI T1 MPRAGE. CT fusion initially based on bony landmarks only. **b** iCT fused with MRI T2 and PET. Better software resolution of AIRO® iCT after software updates. **c** No fusion with preexisting data. Biopsy planning based solely on AIRO® iCT (postvenous phase + arterial phase). **d** iCT with arterial phase fused with MRI T1 MPRAGE.

Accuracy was estimated by percentage of conclusive histological results compared to a patient cohort of biopsies taken without iCT. Safety was measured by percentage of postoperative bleeding complications compared to a patient cohort of biopsies taken without iCT. Changes over time were assessed by plotting surgery times chronologically over the sequence of biopsies taken to register a learning curve. Gross surgery times were measured from the beginning of positioning the patient in the OR until complete removal of the stereotactic frame from the head of the patient after surgery. Again, gross surgery times of a cohort of 50 stereotactic biopsies taken using the mobile iCT and of a cohort of 50 stereotactic biopsies taken without using the mobile iCT were compared.

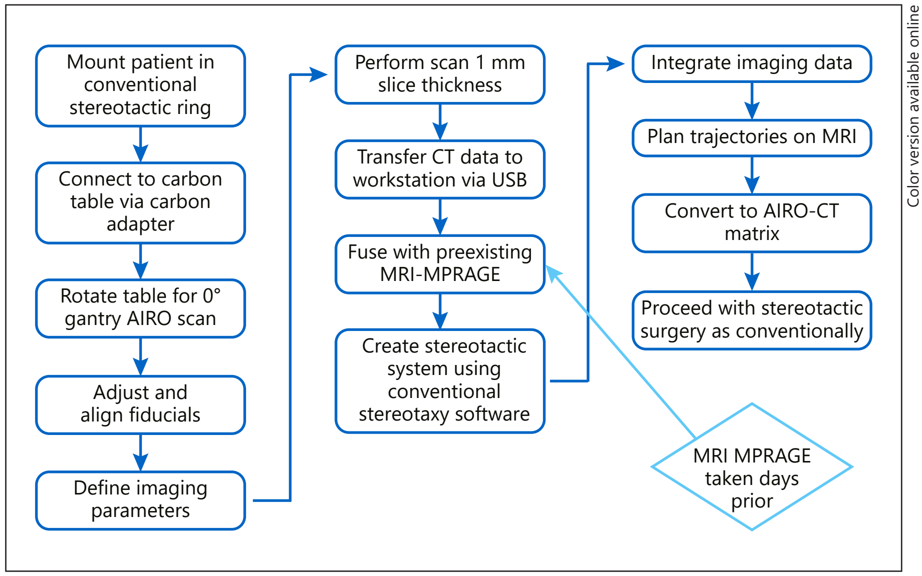

Fig. 4. Flowchart depicting AIRO® iCT workflow for stereotactic biopsy.

Analysis

For comparison of histological success rates, complication rates, and surgery times, the respective means of the study and control cohort were compared using simple Student's *t* tests. For estimation of workflow optimization, the respective contributing staff (i.e., surgeons, anesthetists, and nursing staff) were interviewed. However, no standardized questionnaire was applied.

Ethical Considerations

After the AIRO® iCT had been approved for all cranial applications including contrast-based studies, no additional ethics approval for stereotactic procedures was sought. Patient consent to intraoperative cranial CT and contrast administration was obtained in every case.

Results

Intraoperative Applicability and Workflow

Execution of a frame-based AIRO® iCT for stereotaxy with the given mounting was possible in all patients, including obese patients and patients with spine deformities in the cervicothoracic region. The AIRO® iCT workflow for stereotaxy is depicted in Figure 2 and summarized in Figure 4.

Scan Modalities

The established scan parameters were: AIRO® iCT program (radiation hardness) "stereotaxy head," effective dose rate: 120 kV; AIRO® iCT kernel: "standard," scan length: 32 cm, radiation dose 300 mA, dose index volume: 45 mGy, dose length: 730 mGy cm. With this program, a sufficient soft tissue resolution displaying the borders of the ventricles and sulci was established. For contrast medium-supported iCT, iodine-containing contrast medium Ultravist (Iopromide; Bayer Bayer Pharma AG, Berlin, Germany) was injected after calculation of the respective doses according to the weight of the patient. For postvenous contrast iCT, the scan was initiated 180 s after i.v. contrast injection. For iCT arterial phase, contrast was administered with an injection flow rate of 4 mL/s. The scan was performed 30 s after initiation of injection. A smart prep was not feasible/is not yet established. An example of an AIRO® iCT arterial phase is depicted in Figure 3c.

Accuracy of Biopsies Taken

Phantom studies confirmed a correct image fusion with the AIRO® iCT as well as fiducial detection with the chosen scan modalities. Phantom iCT biopsies revealed straightforward trajectory calculation and correct strike of target.

In our patient series, we observed no serious complications, such as relevant intracerebral bleeding or infection (Table 1). However, minimal traces of blood (volume <0.5 mL) in the control CT were detected in both the iCT and the conventional CT group in up to 30% of the cases. However, these minor bleedings on control CT were always clinically unapparent in both groups and thus considered negligible. Patient characteristics and lesion sizes in the AIRO® iCT group were comparable to those in the control group in which a conventional CT scan was trans-

Table 1. Summary of patient characteristics comparing a series of 20 AIRO® iCT-based stereotaxes with conventional stereotaxes

	AIRO® iCT	Conventional CT
Histology		
Lymphoma	12	14
GBM	9	12
Astro III	7	5
Astro II	0	2
Metastasis	3	2
Multiple sclerosis/ autoimmune encephalitis	4	3
Bacterial abscess	3	5
Tuberculosis	2	0
Toxoplasmosis	2	1
Stroke	2	1
Medulloblastoma	2	0
Neuroepithelial tumor	0	1
PML	0	1
No clear result	4	3
Bleeding complications	0	0
Age range, years	26–80	22–83
Mean age, years	60±17	61±20
Male:female	12:8	11:9
Size range, mm	7×9–55×68	5×8–52×72
Mean size	18±13×30±22	21±14×28±18
Contrast +	35	32
Contrast –	15	18
PET +	21	17
PET–	15	15
No PET performed	14	18
Surgery time, min	114±16	152±21

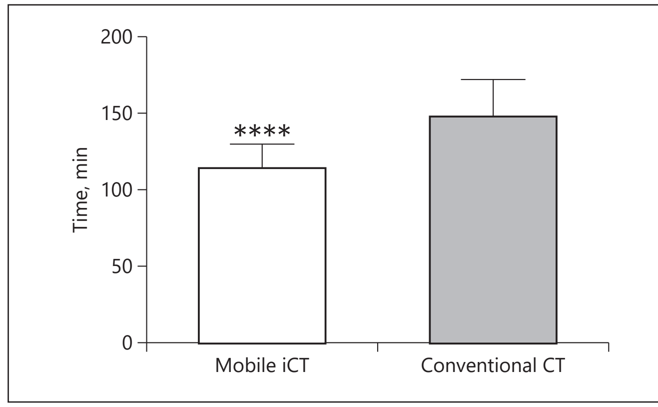

Fig. 5. Comparison between surgery times of stereotaxy with AIRO® iCT vs. conventional stereotaxy with CT transport (114 ± 16 vs. 152 ± 22 min, **** $p < 0.0001$).

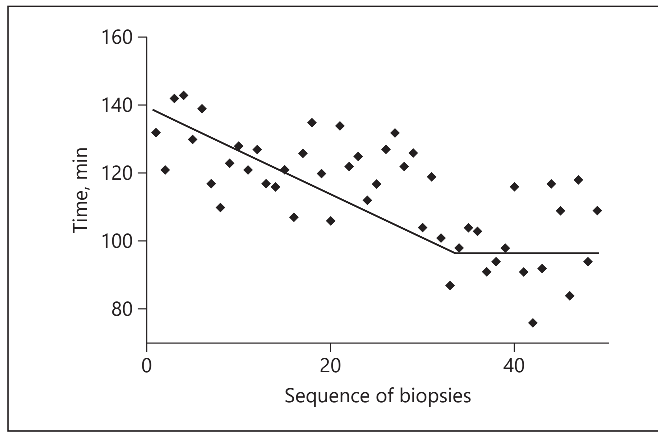

Fig. 6. Learning curve. Reduction of surgery times over the number of biopsies with growing experience in using the mobile iCT. After >30 biopsies, the learning curve levels out.

formed (Table 1). A repeat iCT scan due to failure of transformation or MRI/ iCT fusion or insufficient image quality was not required in any of the cases. Forty-six iCT biopsies revealed a conclusive pathology. Those are depicted in Table 1. Of the 4 biopsies lacking conclusive pathologies, 2 were repeated using frameless navigated biopsy (Varioguide®; Brainlab, Feldkirchen, Germany), again without a clear result. One of these 2 patients was later diagnosed with multiple sclerosis based on CSF findings. The third patient received revision through open surgery with a diagnosis of pilocytic astrocytoma. In the fourth biopsy without result, repeated MR imaging was suggestive of stroke. Rates of inconclusive stereotaxes were similar in both groups. There was no need for a repeat biopsy due, e.g., to insufficient material.

Time Saving

Average biopsy time, as measured from the beginning of positioning the patient to removal of the stereotactic ring after biopsy, was 114 ± 16 min for the 50 biopsies analyzed. Compared to the 50 consecutive conventional stereotaxy cases that were performed in the months directly before AIRO® iCT biopsies with average time consumption of 152 ± 21 min, the AIRO® iCT stereotactic biopsy resulted in a mean time saving of 38 min, $p < 0.0001$ (see also Fig. 5). There was a sequential decrease in total surgery times over the series, indicating a learning curve with respect to patient positioning and iCT handling (see Fig. 6), with a plateau effect after approximately 35 surgeries.

Staff Feedback

As concerns the personal appreciation of the involved personnel, all staff perceived the introduction of the iCT into stereotactic procedures as a major simplification and load relief. As regards economization of personal, one anesthesia nurse (the one previously responsible for accompanying the intensive care transport to the radiology department) could be spared during surgery and deployed otherwise.

The radiological technologists of the CT unit appreciated the time they saved not having to transfer the fully equipped and intubated patient and not having to equip and dissipate the CT table for the head mounting. Surgeons and anesthesiologists saved considerable time as well and perceived the novel workflow as more comfortable.

Discussion

Summary

Here, we report our first experience using the mobile AIRO® iCT in stereotactic procedures. Our principle novel findings are as follows: (1) the AIRO® iCT has been fully integrated into the stereotaxy workflow in the OR; (2) use of the AIRO® iCT provides a high accuracy as demonstrated in phantom studies; (3) use of the AIRO® iCT optimizes the stereotaxy workflow with a clinically meaningful reduction of OR time.

Interpretation

In all frame-based stereotactic procedures, an imaging modality (generally a cranial CT scan) has to be performed intraoperatively with the patient's head already mounted in a stereotactic frame in order to generate an image-based coordinate system for stereotaxy planning. This previously required a (generally anesthesia-accompanied) transport to a CT unit. The intraoperative patient transport is always time-consuming and cumbersome both for the patient and for the surgical and anesthesiological teams. In most neurosurgical departments, the radiology department is located in a different building or at least on a different floor from the OR suites. Intubated patients can be put at certain transport-associated risks, since the patient has to be repositioned at least twice on different tables and be taken on and off ventilation systems. Awake patients often feel stressed and uncomfortable with the frame on during the transport to the CT unit. Considerable waiting times may occur. The use of an iCT avoids transport and repositioning of the patient and may thus shorten surgery times.

The AIRO® iCT has been designed both for cranial and spinal intraoperative use. Initially, however, the AIRO® iCT was mainly used in spinal navigated instrumentation. This application has previously been evaluated by our group [14]. The AIRO® iCT is, however, also licensed and suitable for cranial CT scans, prompting us to test its applicability in stereotactic procedures as well. After all, the AIRO® iCT features a considerably large gantry of 107 cm, which can easily accommodate the mounting and frame used for stereotactic CTs.

Evolution of the Procedure

Starting off with software designed for detection of bony structures in the spine, cranial CT protocols had to be established during the time of our study. Several software updates resulting in continuous improvements in cranial image quality were put into effect in the AIRO® iCT. Initially, standard radiation protocols of the AIRO® iCT did not allow sufficient soft tissue resolution with kernels and radiation hardness still designed for the detection of bony landmarks. In addition, during the time of our first cranial CT scans, the AIRO® iCT was not yet licensed for the application of contrast medium. Therefore, initially, a fusion with preexisting imaging data (MRI and/or PET) was indispensable in every case. With a recent change of license, the administration of contrast medium has become possible, allowing us to restrain from preoperative MRI data in sufficiently contrast-enhancing lesions. Also, the possibility of arterial phase contrast imaging improves the safety with biopsies in highly vascularized surroundings by direct visualization of the vessels in the master series, avoiding possible MRI/iCT fusion inaccuracies.

Safety and Accuracy

Our data confirm the adequacy of AIRO® iCT-based imaging for stereotactic transformations and trajectory planning. The fact that there were no relevant bleeding complications in our series and that >90% of the AIRO® iCT-based biopsies revealed a conclusive pathological diagnosis confirmed safety and sufficient precision of AIRO® iCT-based stereotactic planning. From that, it can be inferred that the quality of biopsies taken using the AIRO® iCT-based planning is comparable to the conventional off-suite CT-based planning.

Impact on Healthcare

The most clinically relevant finding of this study is the significant reduction of total surgery time using the mobile iCT. The benefits of shorter surgery times are well known, starting from lower infection rates [15–17] to economic advantages. There was a sequential decrease in total surgery times over the series, indicating a learning curve with respect to patient positioning and iCT handling. The intraoperative workflow starting with positioning the patient in the respective carbon mounting and adjusting the frame in the isocenter of the gantry, then choosing the right scan parameters, administering contrast medium, transferring the iCT data to a stereotaxy work station, and integrating the iCT data into stereotactic planning was adopted with a steep learning curve.

Another advantage of using the AIRO® iCT is the possibility to take a second, postbiopsy scan in the OR. This second scan can serve to either exclude an early postbiopsy hemorrhage, or confirm the correct target, if an air bubble or small metal ball has been placed in the target region. This marker-containing postoperative scan can then be overlaid and compared with the initial target planning scan.

Limitations and Future Directions

In principle, it is also possible to use the AIRO® iCT planning for deep brain stimulation (DBS). Yet, as patients undergoing DBS usually suffer from movement disorders like tremor or dystonia and as DBS generally is an awake procedure with long surgery times, it is of utmost importance that the awake patient lies comfortably and safely fixed to the mounting. The current construct used in our clinic that connects the carbon Mayfield mounting to the frame holder via a small carbon adapter is rather wobbly, and the mounting does not allow sufficient degrees of freedom to completely remove tension from the neck of the patient. A more rigid construct with more angles of motion is desirable for use in DBS.

Comparison with Other iCT Solutions

The AIRO® iCT has several advantages over other possible solutions for intraoperative CT scans in stereotaxy. As compared to the O-arm® (Medtronic Inc., Luisville, CO, USA), the AIRO® iCT allows full Hounsfield soft tissue imaging with high-contrast tissue interfaces as well as contrast medium application and a larger field of scan. The O-arm® has been used in stereotactic procedures with good fusion accuracy [11–13]. However, the O-arm has been exclusively used in DBS trajectory planning and not in stereotactic biopsies. As compared to the AIRO® iCT, the O-arm does not provide any soft tissue resolution. Consequently, contrast-supported images and visualization of vessels are not possible. Thus, stereotactic biopsies which are done without MRI-CT fusion and which depend on postvenous contrast CT scans are not feasible with the O-arm®. As compared to an OR-inbuilt CT, no dual room solution is necessary using the mobile iCT scanner. With the cohesive imaging and patient positioning solution, the AIRO® iCT is operated by gantry translation rather than by translation of the gantry table.

Conclusion

The AIRO® iCT is suitable and safe for use in stereotactic biopsies, either alone with application of contrast medium or after fusion with preexisting MRI data. The accuracy of trajectory planning with the AIRO® iCT is comparable to any other off-suite CT scanner. The use of the mobile iCT in stereotaxy results in a considerable shortening of total surgery times.

Statement of Ethics

The authors have no ethical conflicts to disclose.

Disclosure Statement

The authors have nothing to disclose.

Funding Sources

No funding was involved to conduct this study.

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