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Intraoperative navigated ultrasound in posterior fossa surgery

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Abstract: High navigation accuracy is a prerequisite for tailored and safe tumor resections. However, in posterior fossa surgery, especially in the semi-sitting position, navigation is often considered to be non-useful due to limited accuracy caused by gravitational effects and brain-shift. To enable navigation in these surgical approaches intraoperative evaluation of accuracy and navigation update strategies are required. Navigated intraoperative ultrasound (iUS) might serve as valuable tool to quantify navigation accuracy and even update navigation to gain higher accuracy. Data of 23 patients (28 lesions) undergoing navigation supported surgery in the posterior fossa with application of navigated iUS including acquisition of a 3D iUS data set were evaluated retrospectively based on intraoperative ratings on accuracy and tumor segmentation based on preoperative magnetic resonance imaging (MRI) and iUS data. In nine cases (eleven lesions) navigation was rated "insufficient" leading to a navigation update by manually outlining the tumor volumes within the iUS data set, whereas in all other cases navigation accuracy was rated "sufficient" with no need for further updates. Tumor volume was comparable between MRI- and iUS-based segmentation. IUS was successfully applied in navigation-supported surgery in the posterior fossa in the semi-sitting position enabling continuous navigation-support throughout surgery by evaluation of navigation accuracy and navigation updates, supporting safe maximum tumor resection.

Keywords: navigation, intraoperative ultrasound, posterior fossa surgery, image-guided surgery

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1 Introduction

Proven its clinical benefits, image-guided surgery has become a routine intrinsic part of many cranial and spinal surgical interventions in neurosurgery [1-4]. Despite its well-known benefits, it has so far not found its way into posterior fossa surgery. Lesion within the cerebellum mostly require resection or at least biopsy for further diagnostics and treatment. Therefore it's essential to choose the best surgical approach with an optimal surgical trajectory to target the lesion while limiting tissue damage [5]. The usefulness of neuronavigation assistance especially in the semi-sitting approach has been doubted due to concerns regarding impaired accuracy by the effects of brain shift caused by loss of cerebrospinal fluid and gravitational effects [5].
Even though overall navigation accuracy can be improved in different ways using sophisticated image fusion techniques and automated patient-to-image-registration approaches, intraparenchymal shifting can only be addressed by the application of intraoperative imaging techniques such as intraoperative magnetic resonance imaging (iMRI) or intraoperative ultrasound (iUS) [6]. While the application of iMRI is limited due to its availability, structural requirements and time consumption [7,8], the application of iUS is easy and fast to use, widely available and cost-effective [9]. In addition, the integration of iUS in neuronavigation systems allows for the acquisition of 3D iUS data sets, that can be used as basis for image-guided surgery or potentially also be used for navigation updates. Therefore, the applicability and usability of iUS in neuronavigation supported posterior fossa surgery is evaluated in this study.

2 Materials and Methods

2.1 Study Cohort

23 patients (male / female: 11 / 12, mean age: 61.51 ± 10.49 years), who consecutively underwent neuronavigation supported microsurgical resection of suspected cerebellar

lesions in a semi-sitting approach between December 2018 and March 2023 were retrospectively analysed.

2.2 Preoperative Planning

All patients underwent preoperative MRI data acquisition allowing for surgical planning as well as computed tomography (CT) imaging the day before surgery with at least seven self-adhesive skin marker attached to the patient's head for registration purposes. After image fusion (Image Fusion, Brainlab, Munich, Germany) the tumor was outlined manually as well as surgically relevant risk structures such as, vascular structures or the brain stem (Smart Brush, Brainlab, Munich, Germany).

2.3 Patient registration

After patient positioning, with the patient's head fixed in a head clamp, and attachment of a reference array, landmark-based registration (Registration, Brainlab, Munich, Germany) was performed using the attached skin-markers enabling image-guided surgery using the Brainlab Navigation System (Curve Navigation, Brainlab, Munich, Germany).

2.4 Intraoperative Ultrasound

After craniotomy and before durotomy navigated iUS imaging (Ultrasound Navigation, Brainlab, Munich, Germany) using a pre-calibrated cranial transducer (N13C5s and BK5000, bk medical, bk medical, Denmark) was performed and a 3D data set was generated by gently sweeping the probe across the accessible dural area in cranio-caudal direction while the MRI based tumor outlines were visualized within the iUS data set.

2.5 Quantification of Accuracy

Navigation accuracy was estimated using different approaches. Intraoperatively, accuracy was evaluated by visually matching MRI-based tumor outlines overlaid on the iUS data set, leading to a decision of "sufficient" or "non-sufficient", followed by manually outlining the lesion based on the iUS data set and continuing surgery based on this. Postoperatively navigation accuracy was evaluated in all cases by comparing MRI- and iUS-based tumor outlines. Object similarity was investigated using the Dice coefficient (DSC) as measure of spatial overlap as well as the Euclidean distance between the geometrical center of gravity (CoG) of the corresponding objects using MeVisLab (MeVis Medical Solutions AG, Bremen, Germany).

Statistical analysis was performed using SPSS 26. Significance level was set to $p < 0.05$.

3 Results

In total, 28 lesions (23 patients) were analysed. Table 1 summarizes tumor volumes segmented within preoperative MRI and intraoperative US data, Dice coefficients, Euclidean distance between corresponding CoGs, as well as the surgical decision on using the iUS data set for navigation update or not. Four patients were excluded from further imaging based analysis as the lesion was not fully covered in iUS data (n=2) or tumor outlines were not clearly identifiable in iUS data (n=2). Manual segmentation of tumor outlines based on preoperative MRI data revealed a mean tumor volume of 10.95 ± 11.04 cm³ (min: 0.01 cm³, max: 30.50 cm³), based on iUS data mean tumor volume was 10.32 ± 10.17 cm³ (min: 0.08 cm³, max: 29.30 cm³).

Patient no.	Tumor volume MRI [cm³]	Tumor volume iUS [cm3]	DSC	Euclidean distance CoG [mm]	iUS navigation update required
1*	29.30	-	-	-	-
2	12.50	13.90	0.30	16.43	yes
3	5.40	5.48	0.85	0.97	-
4	0.09	0.08	0.00	4.88	yes
	8.54	8.60	0.74	6.34	yes
5	4.45	3.76	0.72	3.63	-
	0.01	0.10	0.00	6.22	-
	0.45	0.48	0.04	6.26	-
	2.44	2.27	0.36	6.12	-
6	30.50	26.00	0.00	34.44	yes
7	30.40	28.10	0.65	6.00	-
8	10.00	10.40	0.45	8.85	yes
9*	19.70	-	-	-	-
10	22.10	21.20	0.70	6.17	-
11*	62.50	-	-	-	-
12	21.30	18.90	0.61	8.26	yes
13	2.98	3.64	0.79	1.52	-
14	7.11	7.45	0.63	10.23	-
15	0.43	0.43	0.67	1.24	-
16	29.40	29.30	0.88	1.95	-
17	18.90	15.80	0.32	6.41	yes
18	24.00	17.80	0.39	12.05	yes
	0.60	0.52	0.00	15.97	yes
19	25.10	26.90	0.42	11.93	yes
20*	23.80	-	-	-	-
21	3.23	3.77	0.32	8.19	yes
22	2.33	1.95	0.36	6.03	-
23	0.61	0.77	0.42	3.57	-

Table 1: Tumor object characteristics (*patient excluded from further imaging analysis as the lesion was not fully covered in iUS data or tumor boundaries were not clearly identifiable in iUS data).

Statistical analysis comparing MRI- and iUS-based tumor volumes using the Wilcoxon signed-rank test (no normal distribution given according to Shapiro-Wilk test) revealed no significant differences ($p = 0.354$). The mean Dice coefficient comparing the spatial overlap between MRI- and iUS-based tumor segmentations was 44.25 ± 28.57%, ranging from 0.00 % to 87.56 %. The mean Euclidean distance between the geometrical center of gravity of MRI-based and iUS-based tumor segmentations was 8.07 ± 6.98 mm (min: 0.97 mm, max: 34.44 mm). Navigation was rated "insufficient" in nine cases (eleven lesions) leading to an iUS-based navigation update by manually delineating the tumor in intraoperatively acquired iUS data, see Figure 1.

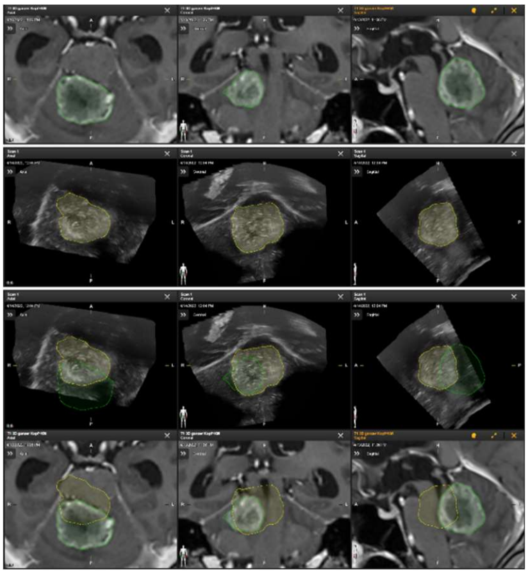

Figure 1: Manual segmentation of tumor outlines based on preoperative MRI data (green) and navigated intraoperative US data (yellow) in axial, coronal and sagittal view (left to right) overlaid on preoperative MRI (row 1, row 4) and iUS data (row 2, row 3) showing the spatial mismatch of preoperative MRI-based tumor outlines and iUS-based tumor outlines leading to an iUS-based navigation update.

4 Discussion and Conclusion

While the application of navigation is well-established in cerebral neurosurgical interventions, already proven its benefits in identifying deep-seated lesions, precisely defining resection margins and assisting in the preservation of functional risk structures, also supporting training and education, its usefulness in posterior fossa surgery in the semi-sitting position is doubted due to inaccuracies caused by gravitational effect and brain-shift. Intraoperative imaging, such as iUS, as often used in cerebral neurosurgery, might serve as one possible tool to identify inaccuracies, but also compensate for those to enable the use of navigation in posterior fossa surgery.

Navigated iUS was in this proof-of-concept study successfully applied in posterior fossa surgery in the semi-sitting position to evaluate navigation accuracy as well as to compensate for navigation inaccuracies by using a 3D iUS data set, visualizing the recent geometrical configuration of the brain, with iUS-based tumor outlines for navigation purposes providing high accuracy at this stage of surgery. Even though the acquisition of high-quality iUS data sets is user-dependent and is especially in the semi-sitting approach challenging due to reduced amount of coupling fluid during iUS acquisition (as no depot can be built up), iUS might serve as valuable, time- and cost-efficient and thereof repeatedly usable tool in neurosurgical procedures in the posterior fossa to enable navigation-support throughout surgery, to quantify accuracy and to update navigation if needed. However, with advances in multimodal image fusion techniques purely iUS-based navigation might be replaced by navigation updates based on rigid or even non-linear MRI – iUS image fusion enabling the continuous use of preoperatively gained information throughout surgery.

Author Statement

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