Intraoperative Computed Tomography and Awake Craniotomy: A Useful and Safe Combination in Brain Surgery

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■ BACKGROUND: **Awake surgery is an effective technique to improve safety in surgical resection of lesions involving eloquent areas of the brain. Intraoperative imaging guidance and neuronavigation are widely applied in neurosurgical procedures. However, data on the application of intraoperative imaging to awake craniotomies are limited. We report our experience with intraoperative computed tomography (i-CT) during awake surgery, focusing on technical feasibility and effectiveness.**

■ METHODS AND RESULTS: **Four patients with a lesion located in an eloquent area of the brain—1 with a cavernous hemangioma, 1 with a high-grade glioma, and 2 with a low-grade glioma (LGG)—underwent awake surgery with neuronavigation guidance. In all patients, i-CT was used to evaluate the completeness of resection or the extent of residual tumor. Intraoperative ultrasound was also used during microsurgery to verify the presence of residual tumor. The use of i-CT us allowed to obtain updated images for neuronavigation and to correct for brain shift.**

■ CONCLUSIONS: **i-CT in awake surgery is reliable and effective. It does not significantly affect the duration of surgery and does not add stress for the patient. The possibility to correct for brain shift also in awake patients can increase the precision and accuracy of surgery, particularly in cases of LGG, avoiding the resection of normal white matter or tumor remnants in noneloquent areas.**

INTRODUCTION

Over the last few years, intraoperative imaging, coupled with neuronavigation and brain mapping, has been used to increase patient safety and expand the extent of lesion resection. In particular, intraoperative computed tomography (i-CT) has been used to treat various pathologies, including vascular and neoplastic ones.[1-4] Awake surgery is typically used to reduce surgery-related neurologic deficits in patients harboring tumors in eloquent brain areas.

Extremely limited data are available on the use of intraoperative imaging during awake surgery. Motomura et al.[5] reported their experience on combined intraoperative magnetic resonance imaging (i-MRI) and awake craniotomy during glioma surgery. However, a literature review revealed no published studies on the concurrent use of i-CT, intraoperative ultrasound (i-US), and awake craniotomy.

We report on 4 patients with brain lesions—2 with low-grade glioma (LGG), 1 with high-grade glioma (HGG), and 1 with cavernous hemangioma—affecting eloquent areas who underwent awake surgery assisted by neuronavigation, cortical-subcortical electrical stimulation, i-US, and i-CT, highlighting the potential benefits of such a combination. We also discuss the feasibility, safety, and effectiveness of i-CT in fully awake patients.

ILLUSTRATIVE CASES

Case 1

A 42-year-old man was admitted to hospital following a generalized tonic-clonic seizure. Neurologic evaluation did not reveal sensorimotor deficits. MRI indicated a left insular LGG (**Figures 1**

Key words
- Awake surgery
- Cavernous hemangioma
- Intraoperative computed tomography
- Intraoperative ultrasound
- Neuromonitoring
- Neuronavigation glioma

Abbreviations and Acronyms
CT: Computed tomography
FLAIR: Fluid-attenuated inversion recovery
HGG: High-grade glioma
i-CT: Intraoperative computed tomography
i-MRI: Intraoperative magnetic resonance imaging
i-US: Intraoperative ultrasound
LGG: Low-grade glioma
MRC: Medical Research Council
MRI: Magnetic resonance imaging
WHO: World Health Organization

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Citation: World Neurosurg. (2018) 119:e159-e166.
https://doi.org/10.1016/j.wneu.2018.07.078

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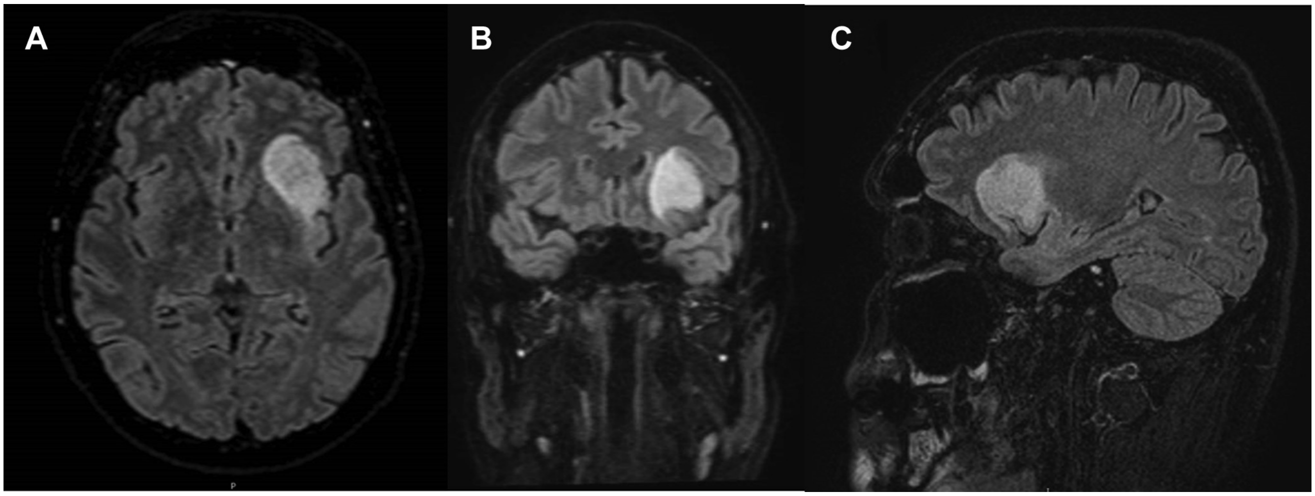

Figure 1. Case 1. Preoperative axial (**A**), coronal (**B**), and sagittal (**C**) T2 fluid-attenuated inversion recovery magnetic resonance imaging sequences showing a left insular low-grade glioma.

and 2). Tumor volume measured on 3D volumetric fluid-attenuated inversion recovery (FLAIR) MRI sequences was 67.3 cm^3. A preoperative CT scan performed after positioning but before craniotomy showed a homogeneously hypodense nonenhancing lesion, clearly distinguishable from the normal white matter.

After a left front-temporal awake craniotomy, before opening of the dura, navigated i-US images outlining the tumor and its extension were obtained. Microsurgical tumor resection was then performed. Frozen sections analysis revealed a World Health Organization (WHO) grade II astrocytoma. When resection was deemed complete, i-US revealed a probable small tumor remnant in the posteromedial part of the surgical field. i-CT (1.25-mm-thick axial slices with 512 ×512 image resolution) confirmed the i-US findings, showing a small hypodense area. Preoperative and intraoperative CT scans were merged and compared using a

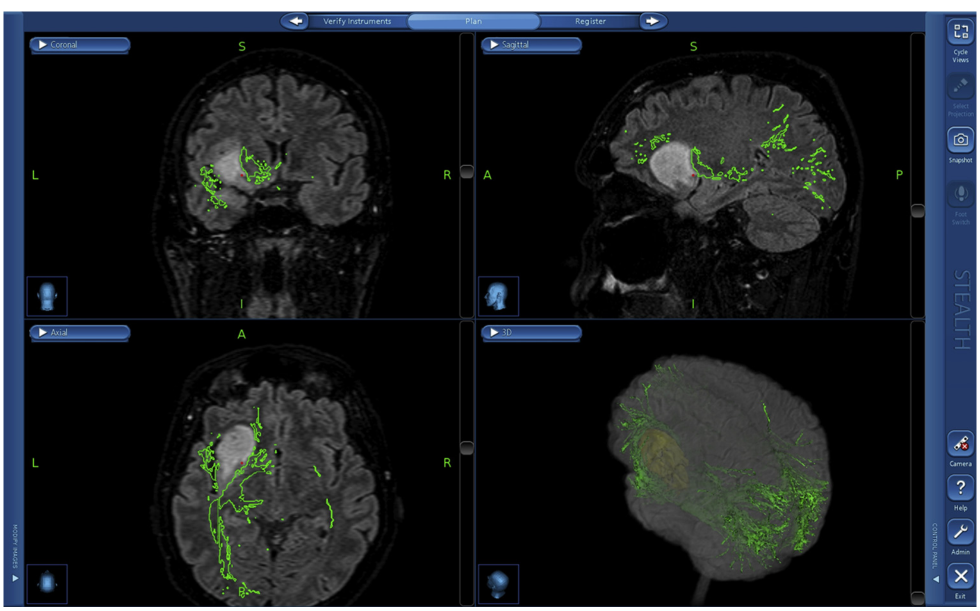

Figure 2. Case 1. Preoperative magnetic resonance imaging with tractography showing the relationship of the low-grade glioma with the inferior fronto-occipital fascicle and the frontal branch of the arcuate fascicle.

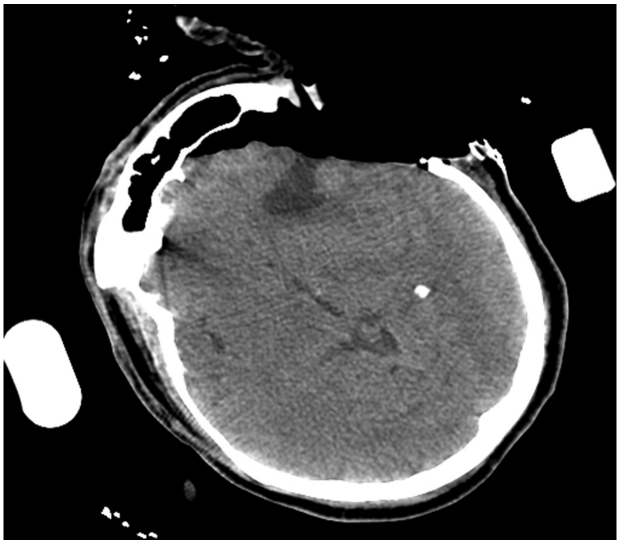

Figure 3. Case 1. Intraoperative computed tomography scan showing subtotal tumor removal.

navigation system (StealthStation S7; Medtronic, Minneapolis, Minnesota, USA). A further comparison was made with preoperative MRI used for patient registration. Shifting of the brain surrounding surgical cavity was documented and corrected, as new images were uploaded onto the navigation system and used for real-time neuronavigation and accurate tumor localization (Figure 3). Subcortical electrical stimulation of the area in which residual tumor was located elicited several deficits in language functions, including mistakes in counting (dyscalculia followed by acalculia), naming (semantic paraphasia), and visuospatial recognition became evident, and surgery was stopped.

Final histopathologic examination confirmed diffuse WHO grade II astrocytoma; the Ki-67 index was <2%. The postoperative course was uneventful, without new neurologic deficits. No further seizures were recorded. Postoperative MRI, performed within 48 hours, confirmed the presence of a small tumor remnant in the area where resection had been stopped because of language impairment following subcortical electrical stimulation (Figure 4). Volumetric evaluation of the residual tumor nodule (4.9 cm^3) showed an overall extent of resection of 92.7%. Diffusion tensor imaging sequences showed that the tumor remnant was very close to the stem of the inferior fronto-occipital fascicle and the frontal branch of the arcuate fasciculus (Figure 5).

Case 2

A 54-year-old woman was admitted with an LGG (Figure 6). She reported recurrent seizures, likely caused by a right fronto-opercular lesion initially diagnosed 15 years earlier. Since then, she had undergone regular neurologic and radiologic evaluations.

Neurologic evaluation revealed only mild weakness of the left upper limb (a Medical Research Council [MRC] score of 4/5). Functional MRI demonstrated a bilateral activation during naming and word generation tests. Tumor volume, measured on 3D volumetric FLAIR MRI sequences, was 48.7 cm^3. A CT scan performed in the operating theatre before craniotomy depicted a hypodense nonenhancing area in the right fronto-opercular region.

A right front-temporal awake craniotomy was performed, and microsurgical total tumor excision was carried out, assisted by neuronavigation, i-CT, i-US, and brain mapping. Once i-US—guided resection was deemed complete, i-CT was performed, which confirmed complete resection of the hypodense pathological area (extent of resection, 100%). Final histopathological examination confirmed a diffuse WHO grade II astrocytoma, with gemistocytic elements and a Ki-67 index of <5%.

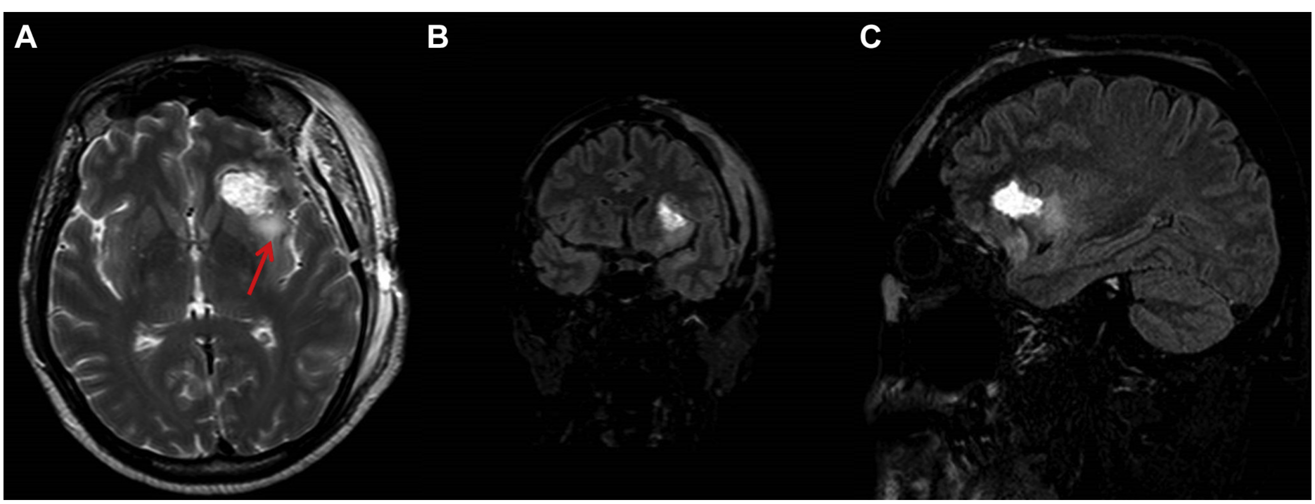

Figure 4. Case 1. Postoperative T2-weighted axial (**A**), T2—fluid-attenuated inversion recovery coronal (**B**), and sagittal (**C**) magnetic resonance imaging sequences showing a tumor remnant (*red arrow*) in the posterior area of the surgical field.

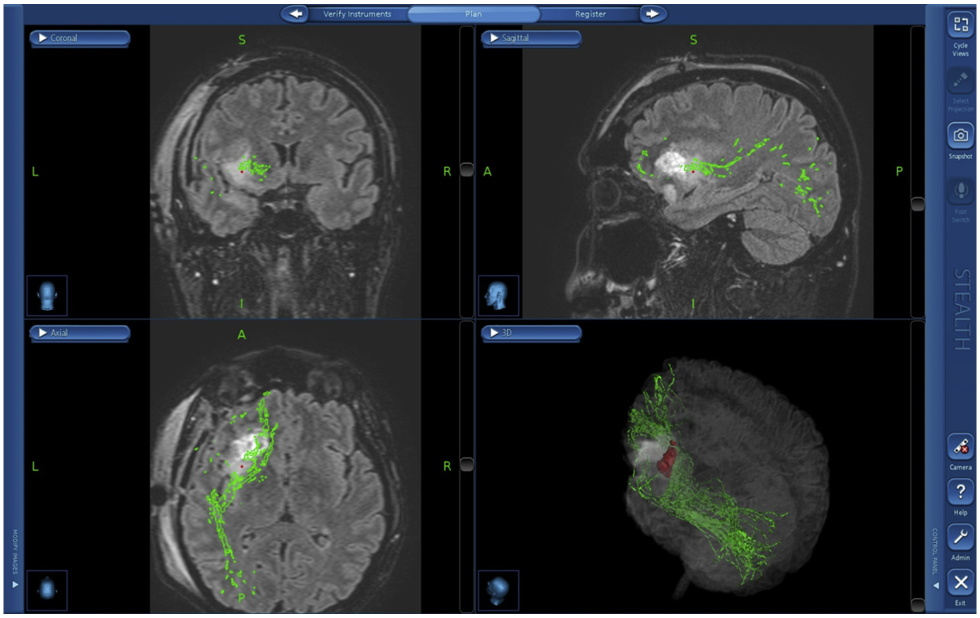

Figure 5. Case 1. Postoperative diffusion tensor imaging with tractography showing the tumor remnant (*red area*) relationship with the inferior fronto-occipital fascicle and the frontal branch of the arcuate fascicle.

After surgery, a moderate left upper limb hyposthenia, MRC grade 4/5, was present. Neurologic worsening was related to vascular spasm of small perforating branches coming from the sylvian artery, which were anatomically preserved but manipulated during resection maneuvers. All deficits demonstrated improvement starting on the third postoperative day, and complete neurologic recovery was achieved within 3 months after surgery. Postoperative volumetric MRI documented complete tumor resection, also showing small areas with restricted diffusion signal, demonstrating the vascular nature of the deficit (Figure 7).

Case 3

A 38-year-old man was admitted to the Emergency Department with sudden onset of tinnitus and aphasia. After self-resolution, his symptoms reappeared 1 hour later. Brain CT scan revealed a hyperdense area in the right temporal lobe with perilesional edema, in keeping with a cavernous hemangioma with recent bleeding. The patient was then transferred to the Neurosurgery Department. Neurologic evaluation did not reveal any abnormalities. MRI confirmed the presence of a cavernous hemangioma (Figure 8). The lesion volume measured on postcontrast T1-weighted MRI sequences was 28.4 cm^2. The patient did not undergo a preoperative CT scan in the operative theatre, because a volumetric CT scan for comparison with intraoperative images had been performed before admission.

A right temporal awake craniotomy was performed, and the vascular malformation was totally resected with the aid of neuronavigation, brain mapping and i-US. i-CT confirmed lesion removal and the absence of early complications. A subtle anomic aphasia was present during the postoperative course, but no other neurologic deficits were revealed. Postoperative MRI confirmed the i-CT findings, demonstrating a 100% extent of resection (Figure 9). No hypoxic or ischemic areas were found. The mild

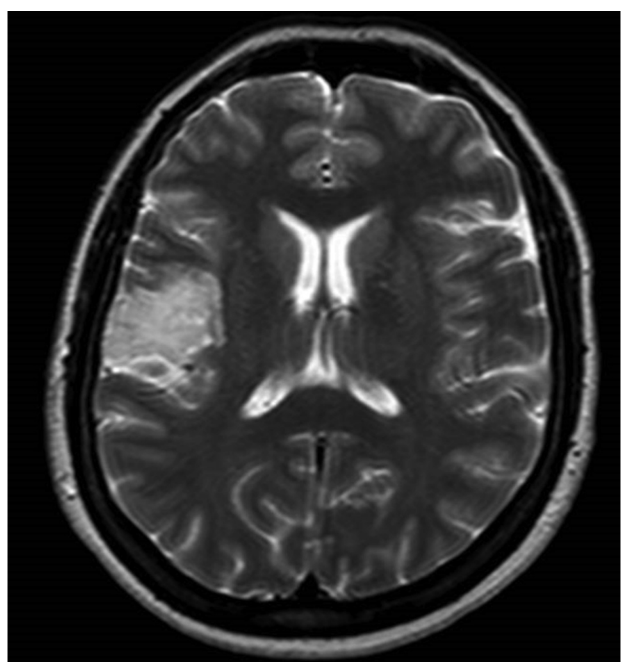

Figure 6. Case 2. Preoperative T2-weighted magnetic resonance imaging sequence (axial view) showing a right fronto-opercular low-grade glioma.

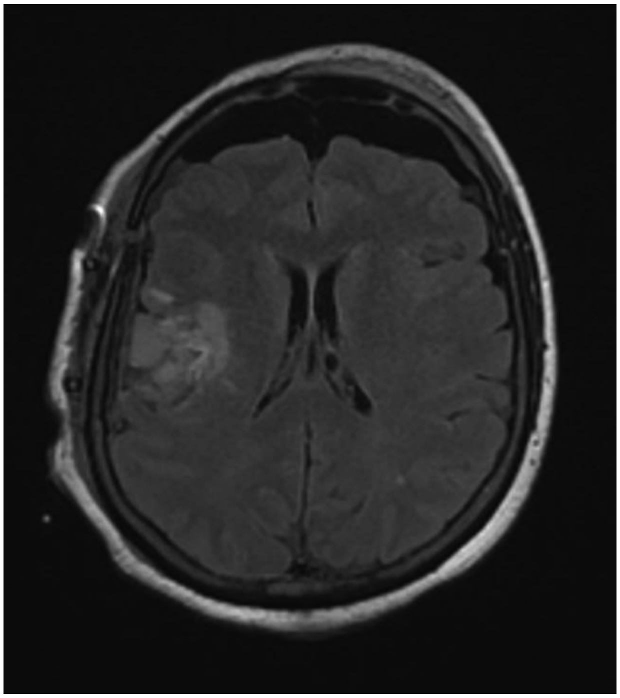

Figure 7. Case 2. Postoperative T2–fluid-attenuated inversion recovery magnetic resonance imaging sequence (axial view) showing the area of tumor resection and effects of surgical manipulation on white matter.

aphasia was interpreted by a neuropsychologist as a psychological reaction to the surgical stress. It resolved by 6 months after surgery.

Case 4

A 60-year-old woman was admitted to the Emergency Department because of a focal seizure followed by a Jacksonian seizure. Brain CT scan and MRI revealed a multilobulated lesion involving the left Rolandic region and a separate nodule located in the left fronto-opercular region (**Figure 10**). Neurologic examination revealed a right upper and lower limb hyposthenia (MRC grade 4+/5), right-side hypoesthesia, right bicipital and tricipital hyperreflexia, and positive Romberg sign. The lesion volume measured on post-contrast T1-weighted MRI sequences, was 34.2 cm^2. A CT scan performed before craniotomy confirmed the presence of the Rolandic multilobulated enhancing lesion (**Figure 11**).

A left parietal awake craniotomy was performed, and microsurgical total tumor excision was carried out, assisted by neuronavigation, i-CT, i-US, and brain mapping. i-US was performed during resection to progressively verify the extent of resection. A continuous use of neuromonitoring ensured the safety of resection; the presence of voluntary movements of right limbs was verified during surgical resection. i-CT with and without iodinate contrast confirmed complete resection of the enhancing tumor (**Figure 12**). The extent of resection as evaluated on postoperative volumetric MRI was 100%.

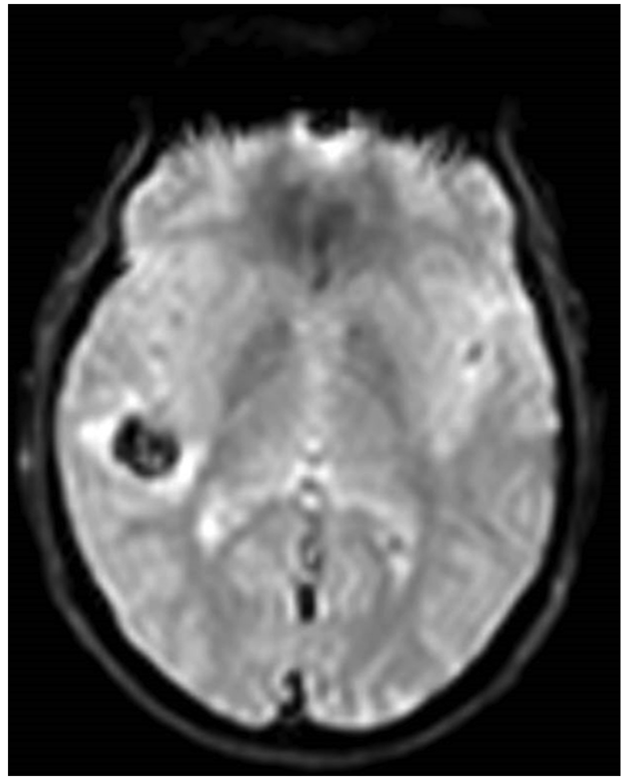

Figure 8. Case 3. Preoperative gradient echo magnetic resonance imaging sequence (axial view) showing a right temporal hemangioma.

The patient experienced postoperative right-sided neglect due to surgical manipulation of the parietal lobe. Histological examination revealed an HGG.

DISCUSSION

Gliomas account for 24.7% of all primary brain tumors and 74.6% of all primary malignant brain tumors.[6] A low frequency of presentation is reported for cavernous malformations, accounting for only 5%–10% of cerebrovascular alterations. These malformations may cause seizures and neurologic deficits due to bleeding and mass effect. Although 75% are located superficially, in some cases eloquent areas or important fiber tracts may be involved.[7-11]

Excision is the goal for both LLGs and cavernous malformations. Neuronavigation based on T1-weighted, T2-weighted, FLAIR, and diffusion tensor imaging MRI sequences helps surgeons localize the tumor position in relation to brain areas and white matter fibers. However, owing to possible errors of neuronavigation accuracy associated with brain shift (secondary to cerebrospinal fluid outflow and entrance of air into the skull), adjuvant techniques are needed.[12]

Although intraoperative MRI is a possible option, even in cases of both LGG and cavernous malformations,[13,14] the technical complexity, high costs related to an MRI-compatible operating

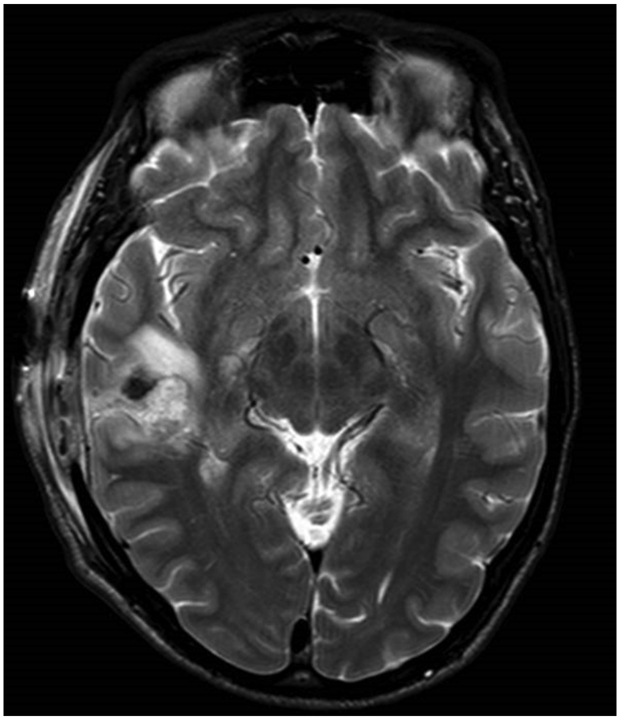

Figure 9. Case 3. Postoperative T2-weighted magnetic resonance imaging sequence (axial view) showing the area of hemangioma resection and blood clot in the surgical cavity.

Figure 10. Case 4. Operating theatre during awake craniotomy aided by intraoperative computed tomography scan.

theatre, and the extra time needed for the technique itself (scan time ranges from approximately 20 to 36 minutes, plus patient positioning time)[5] have significantly reduced its use in many neurosurgical centers.

i-US is an easier technique to perform, and several studies have verified its accuracy in localizing the tumor and guiding the surgeon.[15,16] It provides real-time imaging to examine the brain during surgery. i-US is useful to correct for brain shift and help the surgeon evaluate the extent of tumor resection. However, should a tumor remnant be suspected, localization in the surgical field by i-US alone is not always straightforward, particularly when dealing with small remnants. Moreover, the use of intracavitary i-US probes does not aid localization in all cases.[17] Indeed, beyond the aforementioned technical challenges as well as US imaging features, it also should be considered that most surgeons are much more familiar with MRI- or CT-based neuronavigation.

Video

Video available at WORLDNEUROSURGERY.org

To further improve neuronavigation accuracy and overcome the well-known limitations secondary to the brain shift phenomenon affecting the preoperative imaging-based navigation, the use of i-CT is becoming a reality. Hosoda et al.[1] and Barbagallo et al.[2] have demonstrated the effectiveness of i-CT both in performing real-time evaluation of tumor resection and ruling out early intraoperative complications.[1,2]

The combination of i-US and i-CT, even in surgery for LGGs, is a feasible option for assessing the extent of resection. We have reported on the use of cottonoids, with their radiopaque line, as markers placed under i-US guidance to determine the depth of the resection cavity or to examine for tumor remnants. i-CT provides real-time, updated navigation to check whether the intended extent of resection has been achieved by merging preoperative MRI and i-CT used for navigation (**Figures 1—5**).[2]

However, combined i-US and i-CT—guided surgery, although done in real time, does not prevent language deficits when dealing with lesions in eloquent areas. In these cases, because of its accuracy, brain mapping during awake craniotomy remains necessary to localize and quantify the proximity to eloquent areas.[18]

Even during awake surgery, the surgeon might need to check the extent of tumor resection or localize tumor remnants. I-CT can be helpful in such cases (**Video 1**).

Indeed, in our experience, after removing the tumor using preoperative MRI-based navigation and i-US, when we either felt that all pathological tissue had been resected or decided to halt resection because of intraoperative neurologic deficits induced by electrical stimulation, we performed i-CT (**Video 1**) to check the extent of resection. The intraoperative imaging protocol used in this series of awake patients is the same as described by Barbagallo et al.[2] in a study of the technical feasibility, safety, and effectiveness of i-CT in asleep patients with an HGG. As described above, we used a small-bore portable scanner (CereTom; NeuroLogica, Danvers, Massachusetts, USA) in 3 of 4 cases, and a portable scanner with a large bore (BodyTom; NeuroLogica) in 1 case (**Figure 10**).

Using the new i-CT images for updated navigation, it is also possible to refine tumor resection if residual tumor tissue is seen and subcortical stimulation confirms that it can be safely removed. Draping of the surgical field must be appropriate and suitable for both awake craniotomy and i-CT. Before surgery, patients are informed that i-CT will be performed during the procedure and that i-CT should take between 8 and 12 minutes, depending on whether a basal scan or a contrast-enhanced scan is obtained. In

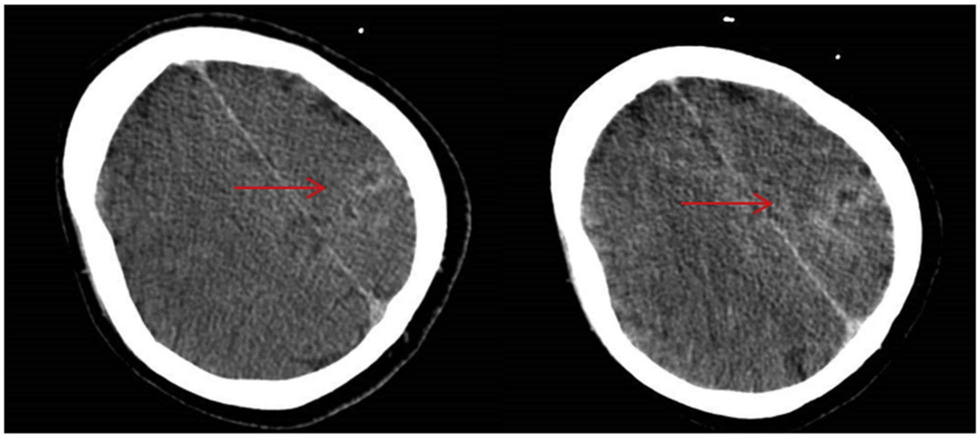

Figure 11. Case 4. Preoperative post-contrast computed tomography scan performed before craniotomy showing the presence of a left Rolandic multilobulated enhancing lesion (*red arrows*).

the cases reported here, the average time for i-CT was slightly longer (14 minutes), because we did not change the table inclination and did not use the Trendelenburg position during the scan, to minimize patient discomfort. Indeed, patients remained fully conscious during the entire surgical procedure, including i-CT (**Video 1**).

In these 4 patients who underwent awake craniotomy, i-CT was useful to better visualize the extent of the residual tumor intentionally left behind (case 1), to confirm the radical resection of intra-axial lesions or to rule out early hemorrhagic complications (cases 2 and 3). In cases of tumors infiltrating eloquent areas (such as in case 1), when electrical stimulation generates neurologic deficits, resection is usually stopped. In such cases, residual tumor may be inadvertently left behind even in noneloquent areas, and i-CT can precisely localize and quantify the residual tumor, avoiding remnants in noneloquent areas.

Moreover, i-CT does not require dedicated equipment other than a radiolucent skull clamp in the surgical theatre, and it can be easily performed without moving the patient from the surgical position. This reduces the risk of surgical field contamination without a significant impact on the duration of surgery.

CONCLUSIONS

Here we report the first experience on the use of i-CT during awake surgery. i-CT combined with i-US, neuronavigation, and

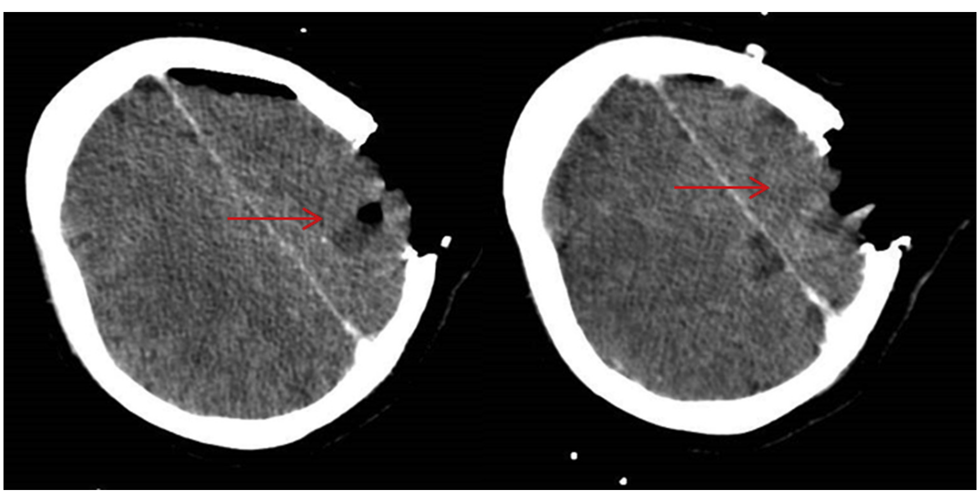

Figure 12. Case 4. Intraoperative computed tomography scan showing complete resection of the enhancing tumor (*red arrows*).

brain mapping during awake craniotomy is a useful, safe and effective tool allowing real-time navigation and updated evaluation of the extent of tumor resection, as well as exclusion of early complications.

ACKNOWLEDGMENTS

We thank the Scientific Bureau of the University of Catania for language support.

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Received 11 March 2018; accepted 9 July 2018

Citation: World Neurosurg. (2018) 119:e159-e166.
https://doi.org/10.1016/j.wneu.2018.07.078

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