Image-guided microradiosurgery for skull base tumors: advantages of using gadolinium-enhanced constructive interference in steady-state imaging

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• Gamma Knife surgery (GKS) is image-guided surgery for brain tumors. Precise tumor visualization is needed in dose planning to control tumor progression. The surrounding vital structures must also be clearly defined to allow the preservation of their function. A special magnetic resonance (MR) imaging sequence was chosen for use with GKS to treat skull base and suprasellar tumors.

Gadolinium-enhanced 0.5-mm constructive interference in steady-state (CISS) slices were obtained in skull base and suprasellar tumors. Each structure that was adjacent to the tumor could be visualized more clearly by using this imaging technique because the tumor became transparent even though there was no change in the appearance of the surrounding structures after injection of Gd. Use of this technique in acoustic tumors allowed the seventh and eighth cranial nerves to be visualized in the cisternal and intrameatal portions; both of which were distinguishable from the tumor. Suprasellar tumor could be distinguished from the adjacent optic pathway. The use of Gd-enhanced CISS imaging allowed for optimal dose planning with high conformity in every tumor. Achieving this high conformity allowed the preservation of adjacent structures and their functions.

Establishing optimal dose planning in brain tumors is very important to overcome the problem of producing new neurological deficits in patients who may already be suffering disease-related deficits. The use of this special CISS MR imaging sequence may help accomplish this goal.

KEY WORDS • Gamma Knife surgery • constructive interference in steady-state imaging • radiosurgery • skull base tumor

Although microsurgery is a standard treatment for skull base tumors, total tumor removal is often difficult. Induction of general anesthesia is always risky in elderly patients, and there is the attendant risk of causing new morbidity in the patient even when microsurgery is performed by a highly skilled surgeon. In recent years, radiosurgery has drawn attention as an effective treatment for skull base tumors. In some cases, GKS has been chosen as the first treatment option, depending on the type of tumor and the condition or preference of the patient. As with any surgical procedure, it is critically important to understand the anatomical relationship between the lesion to be treated and the delicate surrounding structures.

Stereotactic radiosurgery such as GKS must be performed with great care. Clear visualization of the anatomical locations of particularly highly radiosensitive structures such as auditory nerve, facial nerve, and brainstem is essential. Dose planning should be done so that the tumor is conformally and selectively irradiated and the surrounding vital structures are spared. Recently, advances in dose planning have been made because of the development of more sophisticated MR imaging technology. Very significant is the development of a 3D heavily T2-weighted thin-slice CISS MR imaging technique, which provides sharp
Images and Methods

Three types of MR imaging sequences were obtained for dose planning when treating patients with skull base tumors. First, CISS images were obtained at a slice thickness of 0.5 mm and a repetition time of 9.04 msec, an echo time of 4.52 msec, an average of 2, a flip angle of 70°, slice oversampling at 10%, phase oversampling at 0%, and 80 slices per slab. Acquisition time was 6.4 minutes. The second sequences were Gd-enhanced CISS images. After the administration of Gd, imaging was performed under the same conditions as the first set. The third sequences obtained were Gd-enhanced, modified time-of-flight axial 1-mm images. This is an original image of MR angiography and very similar to T₁-weighted images. This sequence allows bone structures to be visualized three-dimensionally, which makes understanding their relationships to the tumors much easier. Thin-slice contrast-enhanced CT bone window images were also added.

In total, 400 to 500 images were obtained during each acquisition session. The images were then exported to the GammaPlan (Elekta Instruments AB, Stockholm, Sweden) workstation, and treatment planning was performed. A large isocenter was positioned at the center of the tumor, and small isocenters were positioned near vital structures in an attempt to make a steep dose fall off. Essentially, the entire tumor was covered conformally and selectively at the 50% isodose line. We purposely demonstrated the 80% isodose line to homogenize the intratumoral dose distribution as much as possible. The margin dose setting varied based on the pathological composition of the tumor and its volume; the prescription dose was typically 12 Gy at the 50% isodose line.

Illustrative Cases

Case 1

This 67-year-old woman presented with visual field disturbance and blurred vision. Magnetic resonance imaging revealed a tumor at the postoptic chiasm. The patient was being treated for breast cancer, and we determined that this new tumor had metastasized to the brain. The tumor was in an uncommon location. The maximal diameter of the tumor was approximately 20 mm, and it significantly compressed the optic tracts. The size of the tumor made it well-suited for GKS. Without the benefit of the CISS MR imaging technique for dose planning, we might have chosen to treat the patient with stereotactic radiotherapy because of concern about the radiation effects on the normal optic apparatus.

The headframe was attached with the anterior part downward so that it became parallel to the optic nerve. We found that adequate visualization of the anatomical relationship of the tumor and optic nerve was impossible using normal Gd-enhanced T₁-weighted imaging; however, Gd-enhanced CISS imaging demonstrated an intensely translucent tumor and highlighted the optic apparatus. Based on this imaging sequence we were able to deliver radiation only to the tumor, leaving the optic nerve undamaged. We were able to homogenize the intratumoral dose distribution, thereby promoting tumor shrinkage (Fig. 1).

Case 2

This 65-year-old woman presented with the onset of right-sided hearing loss. Magnetic resonance imaging revealed a right-sided cerebellopontine lesion, which was determined to be an acoustic tumor (Koo, Stage 4). The patient’s primary concern was for preservation of auditory and facial function, so GKS was chosen as the first treatment option. The tumor involved the brainstem, and visualization of facial and auditory nerves was impossible using MR imaging alone. Likewise, CISS imaging did not provide sufficient distinction between the tumor and the surrounding structures. Gadolinium-enhanced CISS imaging demonstrated an intensely translucent tumor and highlighted the facial and auditory nerves, making it possible to delineate them for treatment planning. We were able to perform GKS on the tumor only, while sparing the nerves, at a dose of 11 Gy to the 50% isodose line. We were able to homogenize the intratumoral dose distribution and shrink the tumor (Fig. 2).

Case 3

This 33-year-old woman presented with transient left facial hemiparesis. Magnetic resonance imaging demonstrated a 25-mm tumor in the middle fossa, which expanded into the internal acoustic meatus via the facial notch. The tumor was determined to be a facial neuroma as it was located mainly in the geniculate ganglion fossa. Because the patient was young, we recommended tumor
resection by microsurgery, however, she chose to undergo GKS because of her concerns about nerve injury and ensuing facial palsy.

Gadolinium-enhanced CISS images and bone window thin-slice axial CT scans were obtained and fused. The images perfectly demonstrated the facial and acoustic nerves as well as the cochlea and semicircular canal. We could clearly visualize the border between the internal middle fossa tumor and temporal lobe. Based on the dose planning images, we conformally and selectively covered...
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the tumor to the 50% isodose line and spared the surrounding vital structures, including the cranial nerves and cochlear. Gamma Knife surgery was performed at a dose of 12 Gy to the 50% isodose line (Fig. 3). As in the other cases, we aimed at tumor shrinkage by making the intratumoral dose distribution homogeneous.

Case 4

This 55-year-old man presented with left-sided facial numbness. Magnetic resonance imaging demonstrated a large multicystic tumor in the left cerebellopontine angle. The tumor was so large that it compressed the brainstem. Initially, microsurgical removal was considered to be the best treatment option; however, preoperative evaluation strongly suggested that this lesion was an acoustic tumor. The patient was referred to our institute for further examination. We placed a special boxlike frame on the patient's head, which was designed for GKS dose planning. This boxlike frame allows us to process neuroimages directly into GammaPlan. To verify the locations of all cranial nerves as possible, Gd-enhanced CISS imaging was performed to visualize and delineate each cranial nerve. The abducens, facial, and acoustic nerves could be well delineated; however, delineation of the trigeminal nerve became impossible as it neared the tumor. Based on these findings, all trigeminal schwannoma was strongly suspected and this determination was proved correct intraoperatively (Fig. 4).

Case 5

This 73-year-old woman was being treated for acromegaly by an endocrinologist. Magnetic resonance imaging was performed, but the tumor was difficult to identify. As in Case 4, we placed a special boxlike frame on the patient's head, obtained the images, and exported them directly into GammaPlan; we then ran the treatment simulation.

We found that Gd-enhanced CISS imaging is effective in verifying the locations of the anatomical structures of the intracavernous sinus. Clear visualization of the oculomotor nerve (which runs from the preoptic cistern in the lateral wall of the cavernous sinus), the abducens nerve (which runs from the preoptic cistern through the inner and outer plexuses of the Dorell canal, passes posteriorly to the internal carotid artery, and reaches the lateral wall of the cavernous sinus), and the first and second divisions of the trigeminal nerve (which extend to the lateral wall of cavernous sinus from Meckel cave) became possible. The 3D images created almost instantaneously by GammaPlan are very beneficial for treatment planning for cavernous sinus tumors (Fig. 5).1,4,5,6,11,12

Discussion

Advantages and Limitations of CISS Imaging

We have found the use of CISS imaging very effective in allowing visualization of structures in the cerebrospinal fluid such as the cisterns and the ventricular system.2,5,9,11,13 Thin-slice images in particular provide clear delineation of the anatomical structures in all dimensions—axial, coronal, and sagittal—in GammaPlan. Tumor visualization by using this technique alone is impossible when the tumor is located in the cerebellar tissue. If tumor involves the brainstem or cerebellum, as it did in the patient in Case 5, the boundary with the petrous bone is ill-defined. In this situation, we routinely also obtain CT bone window scans and export them into GammaPlan.
to create fused images that allow very clear visualization. These fused images, however, are an ineffective dose planning tool if any positional distortion exists on the MRI images. The Gd-enhanced CISS imaging sequence provides the clearest visualization of the boundary between the tumor and the surrounding structures, which cannot be visualized well using the plain CISS sequence. On the other hand, the Gd-enhanced CISS sequence is less effective in allowing determination of how much tumor-free space exists at the fundus of the internal acoustic meatus.

Fig. 4. Case 4. Preoperative 3D images, lateral view, obtained using a GammaPlan simulation revealing a left trigeminal schwannoma. The images were obtained framelessly.

Fig. 5. Case 5. Preoperative 3D images, suprasellar view, obtained using a GammaPlan simulation, visualizing the cranial nerves in the right cavernous sinus.
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Therefore, CT bone window scans fused with Gd-enhanced CISS images is the more useful modality.5

Benefit of Preoperative Simulation Using Gd-Enhanced CISS Images

We regularly make treatment decisions in outpatient settings. At present, treatment indications are evaluated subjectively based on a surgeon’s experience. For difficult cases, we routinely run a treatment simulation using GammaPlan. These types of difficult cases include pituitary tumors that are very close to the optic nerve, cavernous sinus tumors, and skull base tumors such as the one described in the patient in Case 4. At our institute, we have two Gamma Knife planning stations. Images transferred from the MR unit to the first GammaPlan workstation are imported to a second workstation in the consultation room, where we show the treatment simulation to patients and families and explain the potential results, effects, and complications. Because patients are given a precise explanation of the treatment they will undergo accompanied by the 3D images, their understanding and level of comfort increases substantially.

Application of Gd-Enhanced CISS Imaging in the Future

Gadolinium-enhanced CISS imaging can be used to demonstrate structures in the cavernous sinus because the sinus is filled with blood, allowing clear visualization not just of the tumor but also important structures such as cranial nerves.7 Using this imaging protocol has allowed us to spare these important structures from the radiation field, and thus we can anticipate fewer postoperative complications. Similarly, GammaPlan simulation as part of the preoperative evaluation is very useful. GammaPlan is currently being used in a treatment trial for patients with internal carotid artery aneurysms, especially those with an aneurysm neck at the C2-3 segment. Traditional examinations have not yielded sufficient information about the microanatomical nature of internal carotid artery aneurysms.1,3,6,12 Gadolinium-enhanced CISS imaging visualizes the dural ring that separates the cavernous sinus and intracranial space. Currently, we are trying to distinguish the proximal ring and distal ring as part of the preoperative evaluation.

Conclusions

Gamma Knife surgery is a very precise treatment, and the more MR imaging techniques improve the more improvement we can expect in GKS results. Now, the use of Gd-enhanced CISS imaging enables us to use dose planning more effectively and provides the opportunity to practice preserving nerve function. We believe that because of its simplicity and accuracy, GammaPlan simulation may be useful for preoperative planning in microsurgery as well. We will continue our efforts to achieve better treatment outcomes for our patients.

References


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