Stereotactic radiosurgery has progressively emerged as both an adjuvant treatment modality for residual tumors and an effective primary treatment of properly selected meningiomas. Radiosurgery is virtually noninvasive, but it does carry a risk of radiation-induced complications. For meningiomas this risk ranges between 3 and 40%, and includes cranial nerve deficits in petroclival and cavernous sinus meningiomas, and motor and visual field deficits in convexity meningiomas. Adverse effects induced by radiation appear to be more frequent in nonbasal meningiomas, and particularly in parasagittal meningiomas. The mechanism underlying this higher incidence remains undetermined. It has been suggested that this higher incidence is due to vasoactive chemicals secreted by the tumors after radiosurgery, but why chemicals produced by a meningioma should vary from site to site is not clear. In fact, one feature of the parasagittal region distinguishes it from others: its venous anatomy. The occlusion of the sagittal sinus and collateral bridging veins has been proposed many times as a causative factor in the development of preoperative edema and it is a well-known cause of postoperative edema and brain infarction. Nevertheless, its role in the development of edema after radiosurgery remains overlooked.

The object of this technical note is to describe our technique of including venographic studies into treatment planning for parasagittal meningiomas treated with CyberKnife SRS. We also detail our optimization procedures, the goal of which is to avoid the uncontrolled irradiation of the often-precarious venous outflow system. These practices, which we have now used in the treatment of 20 patients with parasagittal meningiomas, are described and illustrated in 2 case studies drawn from these 20 patients.

**Methods**

The neuroimaging technique for radiosurgery treatment planning consisted of a thin-section, contrast-enhanced, multiparallel reconstruction-gradient echo volumetric study conducted on a Siemens Magnetom 1.5-T MR imaging system, performed at the following parameters: TR 9.7 ms, TE 4 ms, matrix 200 × 256, flip angle

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**Key Words**

- parasagittal meningioma
- CyberKnife
- radiosurgery
- venous outflow
- brain edema

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**Abbreviations used in this paper:**

- GKS = Gamma Knife surgery
- SRS = stereotactic radiosurgery
- SSS = superior sagittal sinus

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Symptomatic edema is a potential complication of meningioma radiosurgery. Parasagittal meningiomas are at a particular risk for symptomatic edema, suggesting a role for a venous occlusive complication. The authors sought to develop a strategy to optimize CyberKnife stereotactic radiosurgical treatment parameters to reduce the irradiation of the peritumoral venous system. Multislice CT venography with 3D reconstructions was performed and coregistered with thin-section, contrast-enhanced, volumetric MR images. The tumor and critical volumes were contoured on the MR images. Venous anatomical details obtained from the CT venographic study were then exported onto the MR imaging and fused MR imaging-CT study. Target and critical structure volumes and dosimetric parameters obtained with this method were analyzed. The authors found that reducing the irradiation of veins that course along the surface of the meningioma, which may be at risk for radiation-induced occlusion, is feasible in parasagittal meningioma radiosurgery without compromising other treatment parameters including conformality, homogeneity, and target coverage. Long-term follow-up is needed to assess the clinical validity of this treatment strategy. (DOI: 10.3171/2009.8.FOCUS09-157)
12°, effective thickness 0.88 mm, number of excitations 1, orientation sagittal. Multislice CT angiography and 3D volumetric image reconstruction CT venography were added for the treatment planning part of the technique. This examination was performed using a multislice CT scanner (Siemens Sensation 16). A double nonionic contrast medium (300 mg/ml Ultravist; Bayer Schering) was injected. Half of the total dose of 2.0 ml/kg of contrast medium was infused using a pump in the cubital vein at a rate of 0.5 ml/second. A second infusion was performed at a rate of 1.5 ml/second. Image acquisition was performed after a patient-specific delay of 28–37 seconds. The CT protocol was elaborated according to CyberKnife-specific requirements: acquisition 16 × 0.75 mm, Kv 120, mAs 320, rotation time 1 second, pitch 0.45; and reconstruction slice 1 mm, reconstruction increment 1 mm, filter reconstruction B30 (smooth), 512 × 512 matrix. This double-contrast CT venography allowed the contextual visualization of the meningioma and venous structures with different densities (Fig. 1).

The axial source images were transferred to the CyberKnife workstation. Contouring of the tumor and critical volumes (brainstem, optic chiasm, optic nerves, eyes) was performed on the MR images. Venous anatomical details were obtained from the CT venographic study. Simultaneous overlay of these contours on coronal and sagittal reconstructions was performed and completed with a full 3D view.

An inverse planning algorithm using a nonisocentric technique determined the optimal treatment planning program. Some of the methods used include: 1) selection of the size and number of collimators, balancing the necessity of coverage, reduction of the number of radiation beams and monitor units with the necessity of steep dose gradients in specific areas; 2) the addition of tuning structures to reduce uncontrolled dose diffusion; 3) definition of dose constraints and their weights to the target volume and critical structures; and 4) maximization of resolution of dose calculation using the smallest calculation grid and calculation grid expansion to evaluate distant isodose distribution.
The optimal treatment plan was achieved through a procedure of sequential adjustments of collimator size and number, dose constraints and weights, and tuning structures position, size, and number.

**Illustrative Cases**

**Case 1**

This 32-year-old woman presented with a parasagittal meningioma of the middle segment of the SSS, recurring 5 years after a first surgical treatment. The volume of the meningioma was 4.4 cm³ (Fig. 1). The dose to the target was 14 Gy delivered in a single session, prescribed to the 78% isodose line. The Dmax (maximal dose) was 1794 cGy. The coverage of the target was 95.8%, the number of beams was 273, the conformity index 1.24, and the homogeneity index 1.29. Dose to the skin could be limited to < 600 cGy.

The segment of the Trolard vein coursing along the anterior surface of the meningioma was contoured; the volume of this structure was 0.99 cm³. The D1% (dose to 1% of the volume) was 1130 cGy and the D90% was 269 cGy; the V50% (volume irradiated with 50% of the maximal dose) was 0.14 cm³ and the V20% was 0.85 cm³.

A second bridging vein was contoured and dose constraints were assigned. The volume of this vein was 0.12 cm³, the dosimetric parameters were D1% 1325 cGy, D90% 681 cGy, V50% 0.12 cm³, and V20% 0.1 cm³. The SSS was also contoured to obtain dosimetric data. The volume was 4.7 cm³, and the dosimetric parameters were D1% 1256 cGy, D90% 356 cGy, V50% 0.66 cm³, and V20% 4.18 cm³.

The patient was placed supine on the treatment couch and immobilized with a custom-fitted thermoplastic mask. Once the patient’s position was registered, the radiation was delivered. Before and after the completion of treatment the patient received 8 mg of dexamethasone. Cortisone treatment was reduced gradually and discontinued 15 days later. The posttreatment period was clinically uneventful and the MR study obtained 18 months later showed neither tumor progression nor significant perilesional edema development.

**Case 2**

This 42-year-old woman presented with multiple meningiomas, one of which was located at the posterior third of the SSS (Fig. 2). The patient underwent neuroimaging consisting of multiplanar reconstruction gradient echo contrast-enhanced MR imaging and double contrast CT venography according to the modalities described earlier. The volume of the meningioma was 3.5 cm³. The dose to the target was 18 Gy delivered in 2 fractions, equivalent to 13 Gy delivered in a single fraction (biological equivalent dose: 99 Gy for α/β = 2 Gy and 72 Gy for α/β = 3 Gy). The dose was prescribed at the 75% isodose line. The Dmax was 2406 cGy, the coverage of the target was 93.6%, the number of beams was 153, the conformity index 1.35, and the homogeneity index 1.33. Dose to the skin could be limited to < 400 cGy per fraction.

![Fig. 2. Case 2. Magnetic resonance images (A, B, D) and CT angiogram (C) of a patient with a meningioma of the posterior third of the SSS. The isodose line distribution in a 3D reconstruction (A) demonstrates the opportunity to reduce the radiation delivery to a prominent cortical vein, which was confirmed using axial (B), sagittal (C), and coronal (D) views.](image-url)
A large venous collector lying over the meningioma was contoured as critical volumes and dose constraints were established using an inverse planning algorithm. The volume of the structure was 0.7 cm³ and its dosimetric parameters were D1% 1650 cGy, D90% 312 cGy, V50% 0.19 cm³, and V20% 0.49 cm³. The SSS was also contoured; its volume was 3.9 cm³, and its dosimetric parameters were D1% 1320 cGy, D90% 90 cGy, V50% 1.09 cm³, and V20% 0.98 cm³.

Two fractions were delivered 24 hours apart. Before and after the completion of treatment the patient received 8 mg of dexamethasone, tapered over 15 days as described for Case 1. The posttreatment period was uneventful and the MR study obtained 18 months later showed neither tumor progression nor significant perilesional edema.

Discussion

Does Irradiation of the Venous System Increase the Incidence of Postradiosurgery Edema?

Preserving the bridging veins located near the tumor is a recognized caution for surgeons resecting parasagittal meningiomas. In the practice of radiosurgery, however, the role and importance of the venous system, as well as its tolerance to radiation, remain to be clarified. Whether peritumoral edema is attributable to radiation injury to the surrounding parenchyma or to the vasculature has never been sufficiently addressed, but there is 1 point that deserves consideration: there is no correlation between tumor location and risk of pretreatment edema in meningiomas, but the parasagittal localization appears to be associated with a significantly higher probability of edema after radiosurgery.

There are sufficient data to quantify this risk. In a multicenter study reporting management data on 203 patients with parasagittal meningiomas, Kondziolka and colleagues reported a 3- and 5-year actuarial rate of symptomatic edema of 16%. The risk of edema development was not related to tumor margin dose, sex, patient age, history of previous radiation therapy, lower isodoses (< 50%), tumor volume, imaging finding of encephalomalacia, or maximum dose. Recently, in a milestone article, Kondziolka et al. reported the results of a series of 972 patients who underwent GKS. The overall complication rate in this study was 7.7%, but the morbidity rate for meningiomas with parasagittal location was 9.7%.

The association between a higher risk of complications and the parasagittal location of a meningioma is strongly supported by other data. Chang et al. reported their experience in 179 meningiomas treated by GKS. The radiological control rate was 97.1%. Magnetic resonance imaging showed complications after GKS in 35 lesions (25%) among the 140 lesions with follow-up data. Radiation-induced imaging changes were observed mostly in convexity, parasagittal, and falx meningiomas. About 60% of these imaging changes were asymptomatic; the overall rate of symptomatic imaging changes was 9.3%.

The authors analyzed the factors related to peritumoral imaging changes on MR imaging after GKS. In the univariate analysis, tumor location (p < 0.001), maximum tumor dose (p = 0.0002), and tumor margin dose (p = 0.037) were significantly related to imaging changes. However, in the multivariate analysis, only tumor location was significant.

In the series of 76 meningiomas treated with GKS as reported by Singh and collaborators, the only factor related to edema development was the tumor site; edema occurred most frequently in meningiomas of the parasagittal region. No correlation with tumor volume, tumor margin dose, mean or peak dose, or dose received by the surrounding brain tissue was found. The authors concluded that it could be related to the venous outflow in that region, and even though GKS is not known to affect the normal venous sinuses, some effect on a partially occluded sinus, or on the veins draining into the sinus, may be involved.

The somewhat surprising fact that nonbasal meningiomas have a higher rate of complications than basal ones is also confirmed by other groups. Ganz et al. found that edema developed preferentially in nonbasal tumors, especially those around the midline and sagittal sinus and in cases with a marginal tumor dose > 18 Gy. A high incidence of symptomatic posttreatment edema was also reported in patients treated with other devices, such as the Novalis. Very recently, Girvigian et al. reported the development of a similar complication in 7 (23%) of 30 patients treated in multiple fractions, and in 6 (43%) of 14 patients treated with a single fraction. Patil and colleagues reported on 102 supratentorial meningiomas treated with CyberKnife SRS and fractionated radiosurgery. In this study, 9 (29%) of 31 patients with parasagittal meningiomas developed symptomatic edema, and compared with patients with meningiomas in nonmidline supratentorial locations, patients with parasagittal meningiomas were more than 4 times as likely to develop symptomatic edema. Nevertheless, despite substantial evidence of an association between the parasagittal localization and the risk of edema, the role of the venous system remains substantially overlooked.

The frequency of venous occlusive sequelae after radiosurgery is unknown, although it is likely that they occur. Some of the radiographic changes and clinical symptoms nominally ascribed to radiation effects may, at least partially, represent the consequences of venous outflow impairment. This is also true for adverse effects occurring years after treatment, which might not otherwise be easily explained on radiobiological grounds. In addition, it is possible that radiosurgery-induced venous occlusion may account for some of the sequelae observed in the treatment of other conditions. Cavernomas, for example, often are associated with a venous anomaly and have a significantly higher rate of postradiosurgery complications than arteriovenous malformations that are comparable in size and location.

Is a Strategy Aimed at Reducing Irradiation of the Venous System Feasible?

Success in radiosurgery can only be assessed after sufficient time has elapsed since treatment, but treatment-planning parameters, including target coverage, conformity, and homogeneity, can be assessed at the time of treatment.
Reduced irradiation of the venous system in meningioma SRS

treatment. In our patients we added the imaging of the venous system to an MR imaging-based contouring us-
ing the CyberKnife SRS system. The treatment usually involves the use of 100–200 beams of radiation chosen out of a repertoire of more than 1600 possible beam di-
rections. These beams are delivered in a nonisocentric manner via circular collimators of varying size. The ac-
to a large number of nonisocentric beams allows the CyberKnife to deliver a highly conformal and uniform dose with steep dose gradients in selected points. Using inverse planning it is possible to specify dose constraints to critical structures, such as veins, to reduce their ir-
adiation. Also, because head-frame immobilization is not required, hypofractionated or staged treatment can be performed conveniently.

In this technical report we describe the addition of CT venography to the conventional imaging, which al-
lowed the veins surrounding the meningioma to be easily identified and distinguished from the surface of the me-
ingioma (Fig. 1), and dose constraints to be established for each vascular structure. By balancing the different dose constraints to optimize the plan, it is possible to re-
duce the irradiation of the veins while maintaining good coverage of the target lesion, high conformity levels, high homogeneity of the delivered dose, standard dose to the target, and reasonable treatment parameters, including treatment time and number of monitor units.

Disclaimer

The authors report no conflict of interest concerning the mate-
rials or methods used in this study or the findings specified in this paper.

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Neurosurg Focus / Volume 27 / November 2009


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