Vascular complications after radiosurgery for meningiomas

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During the past 25 years, radiosurgery has evolved as a primary treatment modality for certain meningiomas when resection would be associated with high patient morbidity. In addition, radiosurgery is now routinely used as an adjunctive therapy for residual or recurrent meningiomas after surgical removal. In this review the authors summarize the vascular complications that occur after radiosurgery for meningiomas as well as experimental study data that give insight into the pathogenesis of this complication. These data may be useful when discussing with patients the risk/benefit ratio of choosing among conservative management, radiosurgery, and surgery.

Key Words • vascular complication • hemorrhage • occlusion • meningioma • radiosurgery

Most meningiomas are histopathologically benign lesions, and yet their rate of recurrence increases if complete resection is not achieved. Despite advances in the surgical approaches and techniques for removing these lesions, complete removal of parasellar, cavernous, orbital, and petroclival meningiomas and those near the major venous sinuses remains difficult and is associated with high morbidity. In reporting on the outcome of the aggressive removal of cavernous sinus meningiomas in 41 patients, DeMonte and colleagues noted permanent worsening of cranial nerve deficits in 15%, new cranial deficits in 17%, and cerebral ischemia in 7% of patients and a mortality rate of 7%. As a result, stereotactic radiosurgery has emerged as the primary or adjuvant treatment modality in certain cases. In most reported series authors have used GKS as a therapeutic procedure. It is important to note that as the Gamma Knife prescription dose is delivered to the 50% isodose line, the intratumoral maximum dose reaches twice the prescription dose. Four-year actuarial tumor control of up to 92% has been reported.

The rate of complications has ranged from 3 to 40% in different series. Most complications occur within 2 years of treatment and commonly include cranial nerve palsies in petroclival and cavernous sinus meningiomas, hemiparesis in convexity lesions, and hemianopia in occipital lobe meningiomas. Vascular complications following radiosurgery seem to be rare and can be classified as occlusion of vessels or hemorrhage. In this review article we summarize the reported cerebrovascular complications following radiosurgery for meningiomas as well as the experimental study data related to the histopathological findings of the cerebral vasculature after applying radiation.

Vascular Complications after Radiosurgery for Meningiomas

The vascular type of complications are rare among those reported after radiosurgery for meningiomas and can be categorized as hemorrhage or occlusion of vessels leading to ischemia. In 2000 Roche and colleagues reported the first vascular complication from radiosurgery for meningioma. In their study 92 patients with cavernous sinus meningiomas underwent GKS. One patient, a 32-year-old woman, presented with a transient contralateral central facial palsy 14 months after the radiosurgery treatment date. The prescription dose to the tumor margin was 18 Gy to the 50% isodose line. The estimated dose delivered to the intracavernous carotid artery was 36 Gy. Doppler ultrasonography and MR imaging results showed occlusion of the intracavernous ICA.

Stafford and associates reported on their results in 190 patients with 206 meningiomas that had been treated using GKS; 77% of the lesions involved the cranial base.
Internal carotid artery stenosis occurred in two patients (1%) with cavernous sinus meningiomas. One patient presented 60 months after the radiosurgical treatment date with ischemic symptoms contralateral to the meningioma. A 50% stenosis of the cavernous segment of the ICA was seen. Another patient experienced cerebral infarction 35 months after radiosurgery, and total occlusion of the cavernous ICA was discovered. The calculated radiation dose to the affected arteries exceeded 25 Gy. Both patients suffered permanent cerebroischemic deficits.

In reporting on their experience with GKS for cavernous sinus meningiomas (49 lesions), Pollock and Stafford described one patient (2%) with an ischemic stroke causing hemiparesis and aphasia, which had occurred 39 months after treatment. The cavernous segment of the ICA was occluded on MR angiography at the time of the stroke. The exact dose delivered to the affected artery is unknown; however, the mean dose to the tumor margin was 15.9 Gy, and the mean maximum radiation dose was 32.4 Gy.

Kwon and associates reported on the incidence of intratumoral bleeding after GKS among a series of 173 meningiomas. Four patients suffered intratumoral hemorrhage. Two patients with tentorial meningiomas experienced intracystic hemorrhage occurring 1 and 5 years after treatment. Both received 20 Gy radiation as the prescription dose, with an intratumoral maximum of up to 40 Gy. In another case, a patient with a temporal meningioma treated with 18 Gy, intratumoral bleeding was found 2 years after treatment. Last, a patient with a cavernous petroclival lesion presented with progressive third and sixth cranial nerve palsies and was found to have intratumoral bleeding 8 years after GKS. The overall incidence of intratumoral bleeding was 2.3%. On histological examination in three cases, no specific findings correlated with postradiosurgical changes; therefore, radiosurgery itself could not be shown to be a significant factor in the development of intratumoral bleeding.

Sanno and associates reported on the case of a patient with a frontoparietal parasagittal meningioma that had undergone a sarcomatous change. The patient presented with hemiparesis and aphasia 4 years after GKS. Computed tomography results showed intratumoral and peritumoral hemorrhage. The prescription dose was 30 Gy radiation. Last, Kim and colleagues reported on a patient harboring a tentorial meningioma who had presented with hemiparesis and a visual defect 3 years after treatment with GKS (prescription dose 15 Gy). She was found to have peritumoral hemorrhage on CT scanning.

The literature on vascular complications following radiosurgery is summarized in Table 1.

### Experimental Study Data

**Vasculopathy After Fractionated Radiotherapy**

The effect of radiation on cerebral vasculature has been reviewed. Authors of numerous reports have implicated radiation in the development of cerebrovascular injury including arterial stenosis/occlusion, necrosis, moyamoya disease, atherosclerosis, hemodynamic changes, and stroke. Experience with fractionated radiotherapy has shown that after administering radiation, the cerebral vasculature structure and function undergo distinct acute, intermediate, and late changes. Capillaries seem to be the most sensitive component of the vasculature and typically undergo pinocytosis and hypertrophic changes that correlate with endothelial proliferation and luminal narrowing. The component most radiosensitive to early injury is the endothelial cell. Ultrastructural study data have shown that, after a single dose of 20 Gy radiation, early changes occur in the capillary extracellular basement membrane and rough endoplasmic reticulum associated with cellular swelling. Platelet-fibrin thrombi develop a few days later. These pathological changes lead to increased permeability, which is responsible for severe cerebral edema after applying radiotherapy to the brain.

When aortic endothelial cells are exposed to ionizing radiation in vitro, within hours there is a change in endothelial cell F-actin distribution, cell retraction, and a dose-dependent increase in transendothelial flux of low-molecular-weight solutes and albumin. These changes are accompanied by increased secretion of growth factors and chemoattractants as well as alterations in eicosanoid synthesis. After irradiation, surviving endothelial cells undergo cytoplasmic hypertrophy and giant cell formation with increased cellular adhesiveness for neutrophils. Last, the endothelial cells promote intercellular platelet deposition. Taken together, these changes ultimately lead to luminal narrowing and vessel occlusion.

### Table 1

**Literature review of studies on vascular complications after GKS**

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Vascular Complication</th>
<th>Time Delay (mos)</th>
<th>Radiation Dose (Gy)</th>
<th>Tumor Location</th>
<th>Clinical Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roche et al., 2000</td>
<td>ICA occlusion</td>
<td>14</td>
<td>36†</td>
<td>cavernous sinus</td>
<td>temporary central facial palsy</td>
</tr>
<tr>
<td>Stafford et al., 2001</td>
<td>50% ICA stenosis</td>
<td>60</td>
<td>&gt;25</td>
<td>cavernous sinus</td>
<td>permanent cerebroischemic deficit</td>
</tr>
<tr>
<td></td>
<td>complete ICA occlusion</td>
<td>35</td>
<td>&gt;25</td>
<td>cavernous sinus</td>
<td>permanent cerebroischemic deficit</td>
</tr>
<tr>
<td>Kwon, 2002</td>
<td>intracystic hemorrhage</td>
<td>12</td>
<td>20</td>
<td>tentorium</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>intracystic hemorrhage</td>
<td>60</td>
<td>20</td>
<td>tentorium</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>intratumoral bleeding</td>
<td>24</td>
<td>18</td>
<td>temporal</td>
<td>—</td>
</tr>
<tr>
<td></td>
<td>intratumoral bleeding</td>
<td>96</td>
<td>17</td>
<td>cavernous petroclival</td>
<td>CN III &amp; VI progressive palsy</td>
</tr>
<tr>
<td>Kim et al., 2004</td>
<td>peritumoral hemorrhage</td>
<td>36</td>
<td>15</td>
<td>tentorium</td>
<td>hemiparesis, visual defect</td>
</tr>
<tr>
<td>Sanno et al., 2004</td>
<td>intratumoral bleeding</td>
<td>48</td>
<td>30</td>
<td>frontoparietal</td>
<td>hemiparesis, aphasia</td>
</tr>
<tr>
<td>Pollock et al., 2005</td>
<td>ICA occlusion</td>
<td>39</td>
<td>12–20</td>
<td>cavernous sinus</td>
<td>hemiparesis, aphasia</td>
</tr>
</tbody>
</table>

* CN = cranial nerve.
† Calculated dose to ICA; 18 Gy to tumor margin.
Authors of various experimental studies who have focused on the effects of radiation on cerebral vasculature have provided insight into the pathogenesis of vascular changes following radiotherapy. Arteries of the circle of Willis are examples of large muscular arteries. These vessels are less frequently injured than small or medium-sized arteries; however, the pathological consequences of the postradiation lesions may result in vessel rupture, stenosis, or occlusion.7 Rupture of these vessels can occur early due to wall necrosis. Delayed lesions are frequently fibrous intimal plaques that can narrow or occlude the lumen. This intimal fibrosis is either concentric or eccentric, causing significant reduction in the vessel diameter. The intimal cell may show slight atypia. The next most frequent type of lesion is a transmural healed necrosis. In this scenario, the vessel wall is replaced by fibrosis, and organized thrombi are frequent. The least common lesion to the arteries is similar to intimal fibrosis except that foam cells form part or all of the intimal plaque. Radiation vasculopathy seems to be dose and time dependent.34

Vasculopathy After Radiosurgery

Similar to the effects after fractioned radiotherapy, high doses of gamma radiation (100–300 Gy) to the cat basilar artery cause endothelial degeneration, desquamation with medial hyalinization, and necrosis.22 Omary and colleagues24 irradiated the frontoparietal cortex in rats by using the Gamma Knife at a single dose of 120 Gy. Four weeks later, MR spectroscopy and gadopentetate dimeglumine–enhanced T1-weighted MR imaging were performed. Results of histological analysis showed extensive proliferation of capillaries associated with a moderate degree of astrocytosis. Gadopentetate dimeglumine–enhanced T1-weighted MR imaging showed statistically significant signal intensity changes suggesting blood–brain barrier disruption; however, no reproducible metabolic derangements of ischemia or necrosis were detected by MR spectroscopy. These results suggest that blood–brain barrier disruption occurs in the early delayed phase of radiation injury; yet ischemia and necrosis have not occurred at this latency period.

Kamiryo and colleagues11 observed that the ACA was occluded after a single radiation dose of 100 Gy to the rat brain 20 months after GKS, causing cerebral infarction (Fig. 1). They observed arterial wall thickening with fibrosis, splitting of the internal elastic membrane, luminal organized thrombus, and migration of smooth-muscle cells into the thrombus. Endothelial injury seemed to be the initiating factor. In small arteries various changes occurred, including fibrosis and thrombosis, thickening of the smooth-muscle layer, lymphocytic infiltration, thickening of the vessel wall with fibrinous thrombosis, and leakage of fibrin into the surrounding tissue. Size-, dose-, and time-dependent effects on the cerebral vasculature were observed after administering radiation (25–100 Gy). Capillaries showed early hyalinization, arterioles revealed muscular thickening, small arteries had thrombus formation, and muscular arteries showed arterial wall fibrosis as

![Fig. 1. Photomicrographs depicting the pathological features of the ACA 20 months after radiosurgery. a: Occlusion of the ACA with fibrosis of the wall and intraluminal thrombus. b: Disrupted internal elastic lamina (arrowheads). c: Thickening of the arterial wall with collagen fibers. d: Smooth-muscle cells (arrowheads) in the thrombus and fibrosis in the arterial wall. Bar = 100 μm. (Reprinted with permission from Kamiryo et al: Acta Neurochir (Wien) 138: 983–991, 1996.)](image-url)
well as thrombosis. The authors concluded that thrombosis caused by vascular damage is one of the mechanisms of artery occlusion and that gamma radiation causes damage to endothelial cells directly or indirectly.

In another study, Kamiryo and colleagues\(^\text{10}\) irradiated the parietal cortex of adult rats with GKS at different dosages. At 4 months postirradiation (75 Gy), they observed thickening of arteriolar walls by subintimal accumulation of fibrin and hyaline substance causing narrowing or occlusion of the lumen of capillaries and arterioles. Last, in another study involving Gamma Knife irradiation of the rat parietal cortex, Kamiryo and associates\(^\text{12}\) observed that delayed necrosis induced by gamma radiation is preceded by distinct microvascular changes such as capillary basement membrane thickening, suggesting a vascular mechanism for radiation necrosis.

Stereotactic radiosurgery has thus been shown to be an effective treatment for cerebral AVMs. The histopathological effects of radiosurgery are most prominent in abnormal vessels within the AVM and include early endothelial damage, intimal thickening, cellular degeneration, and vessel obliteration with hyalinization.\(^\text{10}\) Most likely, the radiation response mechanisms mediating vessel wall changes in AVMs are similar to those involved in normal arteries.

The literature regarding the pathophysiological processes of radiosurgery is sparse. To date, there have been no experimental studies elucidating the mechanism underlying intratumoral bleeding associated with radiosurgery. Spontaneous bleeding occurs in 1.3 to 2.4% of meningiomas.\(^\text{19}\) Kim and colleagues\(^\text{14}\) have theorized that thrombosis, edema, vessel erosion, and rapid tumor growth lead to tumor infarction. As tumor infarction progresses, the intratumoral pressure increases and rupture of the peritumoral vessel eventually occurs. Further studies are needed to demonstrate these results. Experimental studies regarding the vascular changes following radiosurgery are summarized in Table 2.

### TABLE 2

<table>
<thead>
<tr>
<th>Authors &amp; Year</th>
<th>Radiation Dose (Gy)</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nilsson et al., 1978(^\text{†})</td>
<td>100–300</td>
<td>endothelial degeneration</td>
</tr>
<tr>
<td>Omary et al., 1995</td>
<td>120</td>
<td>BBB disruption, no ischemic necrosis at 4 wks</td>
</tr>
<tr>
<td>Kamiryo et al., 1996(^\text{§})</td>
<td>100</td>
<td>occlusion of ACA at 20 mos</td>
</tr>
<tr>
<td>Kamiryo et al., 1996(^\text{‡})</td>
<td>50–120</td>
<td>time and dose-dependent changes</td>
</tr>
<tr>
<td>Kamiryo et al., 2001</td>
<td>75</td>
<td>capillary basement membrane thickening</td>
</tr>
</tbody>
</table>

* Abbreviation: BBB = blood–brain barrier.
† Study performed in the cat; all other studies performed in the rat.
‡ Reference 11.
§ Reference 10.
Vascular complications after radiosurgery for meningiomas

radiosurgical risk of vascular complications may in fact compare quite favorably to the surgical risk.

References


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