STEREOTACTIC radiosurgery has become a well-accepted treatment for intracranial arteriovenous malformations (AVMs), particularly those located in surgically inaccessible regions, critical brain areas, or in patients who are poor surgical candidates. A number of reports suggest that stereotactic, focused radiosurgery using heavy particles (protons or helium ions), cobalt (gamma knife) and x-radiation (linear accelerator) can obliterate AVMs with a high success rate and low complication rate. However, this treatment method has limitations, including a decreased rate of obliteration and higher risk of radiation-induced complications for larger AVMs, as well as the potential for intracranial hemorrhage during the latency period, before complete obliteration occurs. Furthermore, some neurosurgeons have found it more difficult to operate on AVMs after stereotactic radiosurgery has been performed, due to radiation-induced changes within and surrounding the AVM. We report our results in 33 patients who underwent microsurgical resection of AVMs 1 to 11 years after radiosurgical treatment.

Clinical Material and Methods

Patient Population

Between 1980 and 1995, approximately 750 patients with intracranial AVMs were treated in our multimodality AVM program. Of these 750 patients, 500 received stereotactic radiosurgery, 150 underwent embolization, and 180 had microsurgical resection of their AVM. Many patients underwent more than one procedure. From 1990 to 1994, 33 patients underwent microsurgical AVM resection 1 to 11 years after radiosurgical treatment, 31 for incomplete AVM obliteration and two for radiation necrosis. These patients had a mean age of 30.4 years, with a range of 7 to 64 years. There were 13 males and 20 females in this study. The patients were graded clinically using the scale of Drake and colleagues before all treatments; 2) after radiosurgery; 3) after embolization and radiosurgery but before microsurgery; and 4) after all treatments including microsurgical resection. Final clinical outcome was largely related to the pretreatment grade. Radiosurgery several years prior to open microsurgery may prove to be a useful adjunct in treating unusually large and complex AVMs.

Key Words • arteriovenous malformation • stereotactic radiosurgery • embolization

Surgical resection of large incompletely treated intracranial arteriovenous malformations following stereotactic radiosurgery

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Although radiosurgery is effective in obliterating small arteriovenous malformations (AVMs), it has a lower success rate for thrombosing larger AVMs. The authors surgically resected AVMs from 33 patients ranging in age from 7 to 64 years (mean 30.4 years) 1 to 11 years after radiosurgery. Initial AVM volumes were 0.8 to 117 cm³ (mean 21.6 cm³), and doses ranged from 4.6 to 45 GyE (mean 21.2 GyE). Of 27 AVMs in eloquent or critical areas, 10 were located in language, motor, sensory, or visual cortex, 11 in the basal ganglia/thalamus, one each in the brainstem, hypothalamus, and cerebellum, and three in the corpus callosum. Venous drainage was deep in 13, superficial in 12, or both in eight lesions. Spetzler–Martin grades were II in one, III in 12, IV in 16, and V in four patients. Eight patients experienced rebleeding after radiosurgery but prior to surgery. Three patients developed radiation necrosis and 25 underwent endovascular embolization prior to surgery.

At surgery the AVMs were found to be markedly less vascular, partially thrombosed, and more easily resected, compared to those seen in patients who had not undergone radiosurgery. Pathological investigation showed endothelial proliferation with hyaline and calcium in vessel walls. There was partial or complete thrombosis of some AVM vessels and evidence of vessel and brain necrosis in many cases. Complete resection was achieved in 28 patients and partial resection in five. Clinical outcome was excellent or good in 31 cases, and two patients died of rebleeding from residual AVM. Four patients’ conditions worsened following microsurgical resection. Final clinical outcome was largely related to the pretreatment grade. Radiosurgery several years prior to open microsurgery may prove to be a useful adjunct in treating unusually large and complex AVMs.

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work and live independently); poor (having a severe neurological deficit and dependent on family or nursing help); or dead. At initial presentation, 23 of the patients were graded excellent and 10 good, with no patients graded poor.

Twenty patients (61%) presented with one or more clinical hemorrhages (Table 1). Two (6%) presented only with progressive neurological deficits, four (12%) with medically intractable seizures, six (18%) with severe headaches, and one (3%) with an incidental finding during a magnetic resonance (MR) evaluation for an aneurysm. Of the 20 patients who presented with hemorrhages, four also had progressive neurological deficits, five had seizures, and six had chronic recurrent headaches. Overall, 12 patients (36%) had chronic, severe headaches (seven unresponsive to analgesic medications).

Twenty-seven patients had AVMs located in eloquent or critical areas, whereas six AVMs were located in noneloquent areas. Specifically, four of the AVMs were in the frontal, six in the temporal, and three in the parietal lobes, 11 in the basal ganglia/thalamus, one in the temporoparietal lobes, two in the parietooccipital lobes, one in the brainstem, one in the hypothalamic region, one in the cerebellum, and three in the corpus callosum.

The size of the AVMs was measured from MR images in the coronal, axial, and sagittal views. The AVMs were then grouped according to their largest diameter. Two patients in the study had AVMs of 1 to 2 cm, 11 had 2- to 3-cm AVMs, 13 had 3- to 4-cm AVMs, four had 4- to 5-cm AVMs, and three had AVMs of greater than 5 cm. Venous drainage was noted as superficial, deep, or both. In this study, 12 of the patients had superficial, 13 had deep, and eight had both superficial and deep drainage (Table 2).

Assessment of AVM size, eloquent location to brain area, and venous drainage allowed the determination of the Spetzler–Martin grade. There was no patient with a Grade I AVM. One patient had a Grade II, 12 had Grade III, 16 had Grade IV, and four had Grade V AVMs (Figs. 1–4 and Table 2).

**Surgical Treatment**

All patients were treated with stereotactic radiosurgery prior to microsurgical resection. Some were treated with more than one type of radiosurgery. Twenty-two of the patients received helium–ion radiation, four received proton radiation, two were treated by means of the gamma knife, two were treated using the linear accelerator system, two received both helium–ion and gamma knife treatments, and one received both linear accelerator and gamma knife radiosurgical therapy (Table 2). The doses of radiation used ranged from 4.6 to 45 GyE, with a mean of 21.2 GyE (Fig. 5). The volume of tissue irradiated ranged from 800 to 117,800 mm³, with a mean of 21,600 mm³. All patients were treated on an outpatient basis. Clinical follow-up review was performed at least every 6 months following treatment, and the patient’s neurological status was recorded as unchanged, better, or worse than before radiation treatment. The number of patients suffering rebleeding from their AVMs and the number and type of complications were also recorded. Because radiation
causes gradual obliteration of the AVM over the course of 1 to 3 years, during which the patient is still subject to rebleeding. Hemorrhages following radiosurgery were considered separately from radiation complications. Whenever possible, MR images were obtained at 6-month intervals and cerebral angiograms at 12-month intervals to document the percentage of AVM obliteration and to follow any radiological complications.

Embolization of the AVMs with N-butyl cyanoacrylate or polyvinyl alcohol was performed in 25 of the 33 patients. Nine of the patients underwent embolization prior to any radiosurgical treatment, nine received embolization treatments after radiosurgery, seven underwent embolization both before and after radiation, and eight patients received no embolization treatments. Ten of the 25 patients underwent one embolization session, three had two sessions, five had three sessions, five had four sessions, and two patients had six or more sessions.

Microsurgical resection of the AVM was performed on all patients after their radiosurgery and embolization treatments. Resection was performed at the following times after radiosurgery: 1 year (one patient), 2 years (seven patients), 3 years (nine patients), 4 years (six patients), 5 years (two patients), 6 years (one patient), 7 years (one patient), 8 years (two patients), 9 years (two patients), and 11 years (two patients). There were a total of 45 operations performed in the 33 patients (Table 3). In 22 patients surgical resection was performed in a single stage, whereas 10 required two stages and one patient required three stages. Surgical stages were spaced 1 to 4 weeks apart. In 24 surgeries the approach to the AVM was transcortical, in nine the approach was via the transsylvian fissure, in nine the approach was interhemispheric, and in three surgeries the approach was suboccipital. The use of a Cosman-Roberts-Wells stereotactic ring was necessary in nine cases where precise AVM localization was required for deep-seated lesions. Other perioperative adjuncts included intraoperative ultrasonography (one case), intrao-
Resection of large AVMs following radiosurgery

Fig. 3. Angiographic and magnetic resonance (MR) studies obtained in a 34-year-old man presenting with seizures secondary to a large left frontoparietal arteriovenous malformation (AVM) extending to the basal ganglia. Left: Anteroposterior view showing filling of the AVM from branches of the middle cerebral artery. The patient was treated with 35 GyE to 7500 mm³. Center: Gadolinium-enhanced T₁-weighted MR image, axial view, showing radiation necrosis that led to development of expressive aphasia and mild right hemiparesis 23 months posttreatment. There was no change in the angiographic appearance of the AVM 36 months after radiosurgery. The patient underwent resection of the radiation necrosis and AVM with resolution of his symptoms. Right: Anteroposterior anterior circulation view after surgery demonstrating complete AVM resection.

Radiosurgical Treatment

Of the 33 patients, 25 did not bleed from the time of radiosurgery to the time of microsurgical resection, whereas eight patients suffered an intercurrent hemorrhage from their AVM. Six patients (18%) suffered one rebleed, three of which led to worsened neurological status (two transient and one permanent). The radiation dose administered to these patients was 15, 17, 18, 20, 28, and 45 GyE. One patient suffered two rebleeds after receiving a radiation dose of 15 GyE and another suffered three rebleeds after a radiation dose of 28 GyE. Neither patient suffered any permanent change in neurological status. Four patients (12%) had complications directly related to radiosurgery, although three subsequently improved following either steroid treatment or surgical resection of

Pathological Review

All AVMs resected were submitted for pathological review. The neuropathology team evaluated each specimen without knowledge of radiation dosage, volume treated, location of the AVM, or clinical status of the patient. Each AVM was evaluated for the following radiation-induced changes: endothelial proliferation, hyaline and calcium in AVM vessel walls, partial or complete thrombosis of AVM vessels, and necrosis of vessels and adjacent brain tissue. Finally, a semiquantitative scale (mild, moderate, or severe) was used to classify the extent of radiation-induced change.

Results

Radiosurgical Treatment

Of the 33 patients, 25 did not bleed from the time of radiosurgery to the time of microsurgical resection, whereas eight patients suffered an intercurrent hemorrhage from their AVM. Six patients (18%) suffered one rebleed, three of which led to worsened neurological status (two transient and one permanent). The radiation dose administered to these patients was 15, 17, 18, 20, 28, and 45 GyE. One patient suffered two rebleeds after receiving a radiation dose of 15 GyE and another suffered three rebleeds after a radiation dose of 28 GyE. Neither patient suffered any permanent change in neurological status. Four patients (12%) had complications directly related to radiosurgery, although three subsequently improved following either steroid treatment or surgical resection of

Fig. 4. Magnetic resonance (MR) and angiographic studies showing a deep right temporooccipital arteriovenous malformation (AVM) in a 34-year-old man. A: Axial T₂-weighted MR image showing extent of AVM. The patient was treated with 15 GyE to 47,500 mm³. B and C: Anteroposterior and lateral views obtained 2 years after radiosurgery showing AVM filling from branches of the middle cerebral artery with no significant reduction in AVM size. The patient subsequently underwent four staged embolizations (resulting in 70% obliteration) and then microsurgical resection. D: Lateral view following surgical resection showing complete AVM obliteration.

Fig. 5. Scatterplot showing dose in GyE versus volume in mm³ of the 33 arteriovenous malformations (AVMs) in our series. Note that most AVMs were treated with radiation doses of between 15 and 25 GyE.
radiation necrosis. One of these patients developed a right hemiparesis with white matter edema seen on MR imaging 8 months after 15 GyE delivered to 18,000 mm$^3$ via gamma knife treatment (the patient had been treated 4 years earlier with 20 GyE to 21,000 mm$^3$ via linear accelerator radiosurgery). Two other patients suffered severe radiation necrosis following linear accelerator radiosurgery (25 GyE to 24,000 mm$^3$) or helium–ion radiosurgery (35 GyE to 7500 mm$^3$) and developed hemiparesis, expressive aphasia, and memory impairment. The fourth patient developed a permanent right visual field deficit from radiation necrosis after treatment with 25 GyE of radiation.

When the percent of AVM obliteration following radiosurgery was assessed, 13 patients had no obliteration, 13 had 10% to 50%, five had 80% to 95%, and two had 100% obliteration but radiation necrosis. Twenty-nine (88%) of the 33 patients were clinically unchanged after radiosurgery treatment, whereas four were worse, two of them permanently.

**Embolization Treatment**

The percent of AVM volume obliterated with each embolization session as measured by postembolization angiograms ranged from 10% to 60% with a mean reduction of 29%. The total percent of AVM volume obliterated in all sessions of embolization for each patient ranged from 15% to 90% with a mean reduction of 56%. Of the 25 patients undergoing embolization therapy, two experienced permanent neurological worsening, one from intraparenchymal hemorrhage and one from ischemia. Five additional patients suffered transient neurological worsening, one from an infarct, one from subarachnoid hemorrhage, and three from ischemia, all of whom ultimately improved. Four patients had minor nonneurological complications, including catheters glued in the AVM (three) and pulmonary emboli from embolization glue (one). When clinical outcome was considered, 23 of the 25 patients were clinically unchanged 2 weeks postembolization, whereas two were worse.

**Microsurgical Treatment**

At surgery we found the AVMs to be partially thrombosed, markedly less vascular, and more easily resected than expected, even in nonembolized areas, than if the patient had not received radiosurgery. Blood loss was minimal and the radiosurgery usually transformed difficult AVMs into relatively easily resectable ones. Despite the persistent angiographic filling of the AVM, much of the small-vessel component was obliterated by the radiosurgery. Additionally, some patients had partial volume reduction in their AVM from radiosurgically induced thrombosis, allowing resection of smaller, residual patent AVMs. In 28 (85%) of the 33 cases, complete surgical resection was achieved and confirmed by angiographic follow-up evaluation. In the remaining five cases a partial resection had been deliberately planned. Six patients suffered transient neurological deficits post surgery, including aphasia, facial droop, anomia, hemiparesis, and seizures. Four patients experienced permanent neurological deficits post surgery, including hemiparesis, sensory deficits, dysarthria, and facial droop. Four patients suffered other postoperative complications such as deep venous thrombosis, pulmonary emboli, and aspiration pneumonia, al-
though no patient had any permanent deficits. From a clinical standpoint, 4 months after surgery 23 of the patients were neurologically unchanged, six were better, and four were worse.

Pathological Findings

The AVMs were submitted for pathological review in all cases. Compared with AVMs that had not received radiation, the majority of the AVMs in this study showed evidence of endothelial proliferation, hyaline and calcium deposits in vascular walls, partial or complete thrombosis of vessels, and necrosis of AVM vessels as well as adjacent brain tissue. These changes likely accounted for the ease of resection of these AVMs compared to our experience with nonradiosurgically treated AVMs. Specifically, 27 of the 33 AVMs showed significant radiation-induced changes in some or all of the AVM vessels. There was a significant correlation ($r = 0.624; p < 0.01$) between the extent of radiation-induced changes and the dose of radiation received (Fig. 6). There was no absolute radiation dose threshold below which radiation-induced changes were absent. However, all but one patient receiving radiation doses greater than 20 GyE developed moderate-to-severe radiation-induced vascular changes, and the three patients treated with greater than 30 GyE all had severe radiation-induced changes. Hyaline was noted in the walls of 18 AVMs, and calcium deposits were seen in the walls of 10 specimens. Thrombosis of AVM vessels was common, with 24 specimens showing complete thrombosis of some vessels and nine specimens demonstrating partial thrombosis, but not complete obliteration of any vessels.

Clinical Outcome

The clinical follow-up period after final surgical resection ranged from 12 to 84 months. Seizures were improved in three (33%) of nine patients and cured in four (44%), headaches resolved in seven (70%) of ten patients, and improved in two (20%). Progressive neurological deficits improved in two (33%) of six patients, three patients developed new seizures that were controlled with anticonvulsant drugs, and five patients had new neurological deficits or worsening of their preoperative deficits. After all multimodality treatments, the outcome was excellent in 21 patients and good in 10 patients, with two patients dying secondary to hemorrhage from residual AVM. The outcome of patients classified by Spetzler–Martin grade revealed that outcome worsened as the grade increased: Grade II resulted in an excellent outcome (one patient); Grade III, excellent (11 patients) and good (one patient); Grade IV, excellent (seven patients), good (one patient), and dead (one patient); and Grade V, good (three patients) and dead (one patient) (Table 5). From a neurological standpoint, 22 of the 33 patients were clinically unchanged, six were neurologically improved, and five were neurologically worse.

Discussion

In the past 10 years stereotactic radiosurgery has been established as a successful treatment for certain intracranial AVMs, particularly for small- or moderate-sized AVMs located in critical brain regions. A number of clinical series using either heavy-charged particles (protons and helium ions) or photons (gamma knife or linear accelerator) have demonstrated that AVMs less than 3 cm in diameter treated with 20 to 25 GyE have a 3-year obliteration rate of 80% to 95%, with a low complication rate (2.5%–4.5% permanent neurological deficits, 2.5%–4.5% transient deficits).7,11,12,22,26,27,35,39 However, various limitations of stereotactic focused radiosurgery have become apparent after analyzing the results in treating larger AVMs and some complex moderate-sized lesions. These AVMs have a much lower obliteration rate, even af-

### Table 4

<table>
<thead>
<tr>
<th>Finding</th>
<th>No. of Cases</th>
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<tr>
<td>endothelial proliferation</td>
<td>27</td>
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<tr>
<td>hyaline in AVM vessel walls</td>
<td>18</td>
</tr>
<tr>
<td>calcium in AVM vessel walls</td>
<td>10</td>
</tr>
<tr>
<td>partial thrombosis of some AVM vessels</td>
<td>9</td>
</tr>
<tr>
<td>complete thrombosis of some AVM vessels</td>
<td>24</td>
</tr>
<tr>
<td>necrosis of vessels</td>
<td>15</td>
</tr>
<tr>
<td>necrosis of brain</td>
<td>11</td>
</tr>
</tbody>
</table>

* AVM = arteriovenous malformation.

### Table 5

<table>
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<th>Variable</th>
<th>Outcome</th>
<th>Neurological Status</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Excellent</td>
<td>Good</td>
</tr>
<tr>
<td>before radiosurgery</td>
<td>21</td>
<td>12</td>
</tr>
<tr>
<td>after radiosurgery</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>after embolization</td>
<td>21</td>
<td>11</td>
</tr>
<tr>
<td>after microsurgery</td>
<td>21</td>
<td>10</td>
</tr>
<tr>
<td>after radiosurgery, embolization, &amp; microsurgery</td>
<td>21</td>
<td>10</td>
</tr>
</tbody>
</table>

* All four patients worsened from radiation necrosis (three) or edema (one), with three patients improving after steroid treatment (one) or surgical resection (two) of the radiation necrosis.
ter 3 years (33%–58%) and a higher complication rate (20%–30%) at treatment doses of 15 to 20 GyE.7,11,12,21,25,27,35,39 Higher obliteration rates can be achieved with these larger AVMs using higher treatment doses (25–45 GyE) but the risk of radiation-induced neurological deficit (transient and permanent) is even greater (approximately 50%).11,19,35 The risks associated with conventional microsurgery or embolization plus microsurgery for treating these large AVMs in critical brain regions are also considerable.3,8,10,16,20,21,33,34 These AVMs continue to represent a challenge for successful treatment.

Our current series includes 31 patients in whom radiosurgery failed to obliterate the AVM after 1 to 11 years. The reasons for incomplete obliteration included too low a dose, too large a volume, incomplete or inaccurate stereotactic targeting, and most likely, other idiosyncratic intrinsic properties of particular AVMs. We have also observed that basal ganglia and thalamic AVMs seem to have a higher resistance to cure via stereotactic radiosurgery compared with AVMs in other locations. There were a total of 11 AVM bleeds over 139 patient-years following radiosurgical treatment, corresponding to an annual rebleed rate of 8%. Because the number of patients in the study is small and they were selected for nonobliteration, it is not known whether our findings represents an increase in the natural history for AVM bleeds (3%–4%/year) as has been suggested by other authors.5,8,13,14,31 A 1.6% to 7.4% annual rebleed rate for AVMs following radiosurgery has been reported previously.7,12,39 Our hemorrhage data in these patients do not support the hypothesis of a protective effect of radiosurgery for incompletely obliterated AVMs (unpublished data).4,7,19,37

Three patients (9%) in our series developed delayed radiation necrosis after treatment with 25 GyE to 24,000 mm³, 25 GyE to 18,000 mm³, and 35 GyE to 7500 mm³, respectively. All three patients had worsening in their neurological status, and two improved after surgical resection of the radiation necrosis. This rate of radionecrosis is similar to that seen in other large series.7,11,27,35,39 Another patient developed radiation edema after receiving 15 GyE to 18,000 mm³ via gamma knife radiosurgery following 20 GyE to 21,000 mm³ via previous linear accelerator radiosurgery. This patient recovered after receiving steroid therapy. Symptomatic radiation-induced necrosis and edema are rare when doses of less than 25 GyE are used17,24,25,28,35 and this was confirmed in our series.

The benefits of radiosurgery as a preoperative adjunct became apparent in our patients. In some patients partial AVM thrombosis significantly reduced the volume of residual AVM that required surgical resection. More important, at surgery the irradiated (but patent) AVMs were found to be much less vascular, even in nonembolized areas compared to AVMs not previously irradiated. This is contrary to other surgeons’ impressions that prior radiosurgery makes microsurgical resection more difficult. We observed that the radiosurgically treated AVM vessels were easier to coagulate with a bipolar cautery unit, facilitating quicker and safer resection with less blood loss. Although preoperative angiograms often demonstrated significant residual AVM, the observations at surgery suggested that prior radiosurgery obliterated the small-vessel component of the AVM not visible on the angiogram. Our success in completely obliterating several previously irradiated AVMs with embolization alone also suggests that prior radiosurgery may thrombose a small vessel component leaving larger arteriovenous fistulous portions of the AVM.29,36

Our overall clinical results following radiosurgery, embolization, and microsurgery are encouraging. Seizures were improved in three (33%) of nine patients and cured in four (44%), with three (10%) of 30 patients developing new seizures that were controlled by anticonvulsant drugs. Similar results have been reported in other radiosurgical or microsurgical series treating smaller and less complex AVMs.1,4,18,26,30 Headaches resolved in seven (70%) of 10 patients and improved in two patients (20%) in our series. These results are also similar to previous radiosurgery reports.18,26,35 Progressive neurological deficits were the presenting symptoms in a total of six patients, and in all six the deficit either stabilized or improved. These deficits included visual changes, memory difficulties, aphasias, and dysarthrias. It is important to consider the cumulative risks of all treatment modalities used when analyzing their benefits and risks for a particular patient. Before radiosurgical treatment in our series, 21 patients were in excellent condition and 12 were in good condition as defined by the scale of Drake and colleagues.9,10 Following multimodality therapy, 21 patients were rated as excellent, 10 were good, and two were dead. Twenty-two of the 33 patients were clinically unchanged, six were better clinically, and five had worsened with multimodality treatment. Worsening of the clinical condition was due to rebleeding in two patients, embolization complications in one, and embolization and microsurgical complications in two patients.

The Spetzler–Martin classification for AVMs33 predicted the clinical outcome of patients in our series. The majority of our patients had AVMs of Spetzler–Martin Grade III (12 patients), Grade IV (16 patients), or Grade V (four patients). Eleven of the Grade III patients (92%) had an excellent final outcome, confirming the good prognosis for these patients following surgical treatment alone.3,9,10,15,16,20,34 The results of the multimodality therapy in our Grade IV and V patients are also encouraging. Of the Grade IV patients, 15 (93%) had successful results, with excellent results in nine (56%) and good results in six (37%). One Grade IV patient died (6%). Of the four Grade V patients, three (75%) showed good results and one (25%) died. Other surgeons experienced with AVMs have demonstrated similar late results in Grade IV and V AVM patients using combinations of embolization and microsurgery.15,16 In our experience prior radiosurgery decreases the surgical morbidity and improves the clinical outcome compared with preoperative embolization alone. Of note is the fact that in our series there were no poor results. Patients either did well (excellent or good) or died. The two deaths were related to bleeding from residual AVMs, confirming that any remaining AVM poses a risk to the patient.

There are few previous histopathological reports of irradiated AVMs.18,35 Pathological examination of AVMs in our series verified intraoperative visualizations of small AVM vessel thrombosis. We found evidence of endothelial proliferation, hyaline and calcium deposits in AVM vascular walls, partial or complete thrombosis of some
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AVM vessels, as well as necrosis of AVM vessels and adjacent brain tissue. These pathological changes likely caused decreased vascularity of the AVM and made surgical resection easier. We also found a correlation between treatment dose and the extent of pathological changes involving AVM vessels. Patients receiving doses of more than 20 GyE at radiosurgery developed more radiation-induced vascular changes compared to those patients receiving less than 20 GyE; all patients receiving greater than 30 GyE had severe radiation-induced vascular changes.

Patients in whom AVMs have not been obliterated completely 3 years after radiosurgical treatment have several options available to them. One choice is no further treatment, although our previous data and other reports suggest that these patients are not protected from future hemorrhage (unpublished data). Furthermore, we have never observed an AVM that is incompletely obliterated at 3 years posttreatment achieve complete obliteration without further treatment. Another option for such patients would be a second course of stereotactic radiosurgery. We, as well as others, have used this option in selected patients. The disadvantages of such an approach are the second latency period of 1 to 3 years before obliteration occurs, the possibility that a second radiosurgical treatment still may not obliterate the AVM, and the risk of radiation-induced injury that may be higher with a second radiosurgical treatment. One strategy we have used in certain patients is to embolize portions of the unobliterated AVM to reduce the volume requiring a second radiosurgical treatment. Investigation of the long-term outcome will be required to determine the overall efficacy of repeat radiosurgery or embolization plus repeat radiosurgery for AVM patients. The approach taken in our current series of 33 patients was to use microsurgery or embolization plus microsurgery following incomplete obliteration of the AVM after radiosurgery alone. We found this approach to be quite valuable in treating some of the AVMs, particularly when patients rebled from residual lesions and there was more urgency to cure the AVM, rather than waiting for a second radiosurgical treatment to mature. In certain cases stereotactic radiosurgery prior to microsurgical resection can transform large, complex AVMs into lesions that can be resected with a high rate of success and a low rate of complication. A future strategy for treating such AVMs might be the use of combined embolization and radiosurgery to treat portions of large AVMs located in the deep and eloquent areas of the brain, with planning for microsurgical resection of the more superficial and easier components several years later.

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