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Cerebral Arteriovenous Malformations: The Value of Radiologic Parameters in Predicting Response to Radiosurgery

Jean François Meder, Catherine Oppenheim, Jerry Blustajn, François Nataf, Louis Merienne, Dimitri Lefkoupolos, Alex Laurent, Jean-Jacques Merland, Michel Schlienger, and Daniel Fredy

PURPOSE: To define the morphological patterns of cerebral arteriovenous malformations (AVMs) that influence their response to radiosurgery at 2 years. METHODS: We retrospectively reviewed the yearly MR and angiographic follow-up studies in 102 patients who had radiosurgical treatment for cerebral AVMs between 1990 and 1992. Parameters studied were maximum length and volume of the nidus, position relative to the midline, anatomic structures involved, sectional anatomic location (depth within the brain tissue), angioarchitecture, and Spetzler and Martin grading. Statistical analysis determined their influence on treatment results at 2 years. RESULTS: Parameters that correlated with obliteration at 2 years were maximum length less than 25 mm, small volume, sectional location deep within brain tissue, and plexiform angioarchitecture. Ventricular and paraventricular locations correlated with nonobliteration at 2 years. CONCLUSION: This study highlights the role of two new morphological parameters in predicting the efficiency of radiosurgery in the treatment of cerebral AVMs: depth within the parenchyma and angioarchitecture. It also emphasizes the usefulness of sectional imaging in the work-up before radiosurgery.

Stereotactic radiosurgery uses convergent beam irradiation techniques to deliver a high dose of radiation to a sharply delineated target. The three types of radiation sources used in the treatment of cerebral arteriovenous malformations (AVMs) are gamma rays generated by cobalt-60, charged particle beams produced by a cyclotron, and X-rays produced by a linear accelerator (1–4). Regardless of the radiation technique used, the obliteration rate of cerebral AVMs at 2 years after stereotactic radiosurgery varies from 60% to 85% (5–14). The differences observed in response to stereotactic radiosurgery among cerebral AVMs can be explained by the influence of either technical or morphological factors. The technical factors that have been considered are radiation dose delivered to the target (5, 11, 14–20), target delineation, and number of isocenters (13, 21, 22). Cerebral AVM size is the only morphological factor shown to influence response to stereotactic radiosurgery. It is generally agreed that the obliteration rate of cerebral AVMs after stereotactic radiosurgery decreases as AVM size increases (6, 10, 11, 18, 22).

In light of our experience, cerebral AVM size does not appear to be the only parameter to influence response to stereotactic radiosurgery. We therefore undertook a retrospective study of imaging examinations in an attempt to identify other morphological parameters capable of in-

TABLE 1: Characteristics of the studied population

Factor	No. of Cases	%
Sex		
Female	42	41.0
Male	60	58.8
Neurologic symptoms		
Prior intracranial hemorrhage	68	66.0
Seizures	21	20.5
Progressive neurologic deficit	2	1.9
Headache	17	16.6
Prior treatment	50	49.0
Subtotal resection	8	7.8
Embolization	42	41.2
Resection and embolization	4	3.8
Radiosurgery	0	0

fluencing the response of cerebral AVMs to stereotactic radiosurgery.

Materials and Methods

Population

One hundred twenty-nine patients with cerebral AVMs were treated by radiosurgery between January 1990 and June 1992. All patients were asked to undergo yearly angiographic follow-up studies. Only those patients whose angiographic follow-up findings allowed a determination of treatment results within 24 ± 6 months after radiosurgery were included in this study. Twenty-seven patients were excluded for the following reasons: eight patients had no angiographic follow-up (one patient died of myocardial infarction, one patient refused follow-up, six patients were lost to follow-up); nine patients showed obliteration of their malformation on follow-up angiography performed more than 30 months after stereotactic radiosurgery with no previous follow-up; 10 patients showed persistent cerebral AVMs on follow-up angiography performed less than 18 months after stereotactic radiosurgery without further follow-up. The definitive study group included 102 patients. The mean age of patients at the time of treatment was 33 years (range, 6 to 68 years; SD, 14.7). Clinical characteristics and prior treatment are listed in Table 1.

Pretherapeutic Radiologic Work-up

All patients underwent a radiologic work-up that included magnetic resonance (MR) imaging and conventional angiography performed under stereotactic conditions. The angiographic technique was systematically performed as follows: head positioned via the stereotactic Talairach frame; films obtained in the anteroposterior and lateral views as well as offset views, allowing for stereotactic viewing; distance of 4.5 m between X-ray source and film, resulting in a constant and reproducible magnification factor of 1.045; and exposure rate of two films per second. Optimal target location and delineation were always based on angiographic data. In five cases, super-

selective injection was used to improve definition of the angioarchitecture of the AVMs.

Radiosurgery

The irradiation technique was identical in all cases. Patients were irradiated in the Betti armchair (16, 23) with head position obtained by the Talairach stereotactic frame. Fifteen-megavolt X-ray minibeams from a Saturn 43 Linac were used along with eight additional collimators (6 to 20 mm). A dose of 25 Gy was delivered at the periphery of the nidus, delineated on the pretherapeutic angiogram. This dose corresponds to the 60% to 70% peripheral isodose range. In 60 cases, the nidus could be covered by one isocenter; in 26 cases, by two isocenters; in seven cases, by three isocenters; and in nine cases, by four or more isocenters. Nidus shapes were spheroid in 29 cases, elliptical in 51 cases, and irregular or complex in 22 cases.

Angiographic Follow-up

In our follow-up protocol, angiography was scheduled on a yearly basis. The average number of follow-up angiographic studies per patient was 2.3. The first follow-up included all angiograms obtained at 12 ± 6 months (mean, 12 months; SD, 2.4); the second follow-up included all angiograms obtained at 24 ± 6 months (mean, 25 months; SD, 2.5).

Studied Parameters

Pretherapeutic radiologic work-ups were reviewed retrospectively by two radiologists who evaluated seven parameters.

Maximum Cerebral AVM Length.—This corresponds to the greatest length of the nidus measured on one of the orthogonal views of the stereotactic angiogram. The mean maximal nidus length was 24 mm (SD, 10.1); the median was 22 mm (minimum, 9 mm; maximum, 55 mm). To generate data comparable to those used in most radiosurgical studies, the size categories chosen for analysis were less than 25 mm and 25 mm or greater.

Cerebral AVM Volume.—This was determined by a method described previously (21). The mean volume was 3.8 cm^3 (SD, 3.8); the median was 2.8 cm^3 (minimum, 0.3 cm^3; maximum, 19.9 cm^3). Volumes were divided into four groups: 0 to 1 cm^3, 1 to 4 cm^3, 4 to 10 cm^3, and more than 10 cm^3.

Cerebral AVM Position Relative to the Midline.—Cerebral AVMs were considered as either hemispheric or midline; the former corresponded to those located in a cerebral or cerebellar hemisphere (n = 95), the latter to those located either completely or for the most part within a midline structure, such as the corpus callosum, brain stem, or vermis (n = 7).

Anatomic Structures Involved.—These were determined from stereotactic angiographic and MR data. Nine groups were defined depending on whether the AVM com-
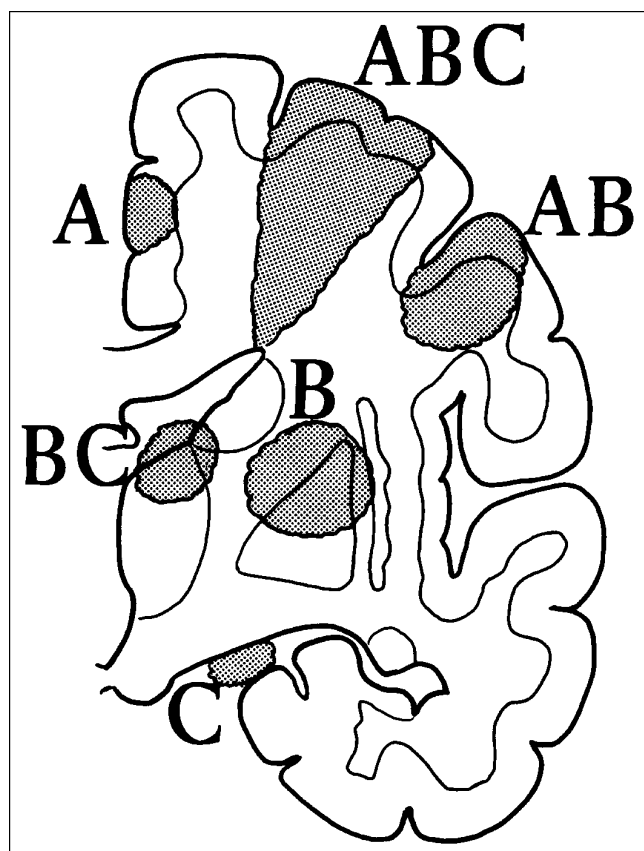
Fig 1. Cross-sectional anatomy of a cerebral AVM. Schematic representation of the classification of the nidus according to its location within brain tissue.

pletely or primarily involved the following regions: frontal lobe (n = 23); parietal lobe (n = 12); occipital lobe (n = 9); temporal lobe (n = 21); insular lobe (n = 3); corpus callosum (n = 3); basal ganglia, including the caudate nucleus, lenticular nucleus, thalamus, and internal capsule (n = 21); posterior fossa, including the cerebellum and brain stem (n = 7); and extraparenchymal sites, including the ventricles and cisternae (n = 3).

Sectional Anatomic Location.—This defines the AVM location in terms of depth within the brain tissue but does not take into consideration the supratentorial, infratentorial, or lobar situation. Six types have been defined on angiograms and MR images (Fig 1): type A, nidus located in the cortex (n = 32); type B, nidus located deep within brain tissue, including the white matter, basal ganglia, and brain stem (n = 20); type C, nidus located in the ventricles or cisternae (n = 3); type AB, nidus located in the corticosubcortical region (n = 32); type BC, nidus located deeply, with ventricular or cisternal involvement (n = 13); and type ABC, nidus involved in all the above regions (n = 2).

Angioarchitecture.—This was determined from the stereotactic angiographic data as well as from the superselective injection, when available. On the basis of the Yasargil terminology (24) and Houdart classification (25), two types of angioarchitecture were defined: the plexiform type, representing a simple network of compact or loose arteriolovenular shunts (Fig 2) with a relatively homogeneous morphology (n = 89), and the nonplexiform type (n = 13), including all nidi with evidence of a direct arteriovenous fistula or unique intranidal draining vein (Fig 3).

Spetzler and Martin Grading.—The Spetzler and Martin grading system was used to classify all cerebral AVMs according to size, neurologic eloquence of adjacent brain, and venous drainage pattern (26). Fourteen cerebral AVMs were graded 1, 37 were graded 2, 38 were graded 3, and 13 were graded 4.

Statistical Analysis

Single Variable Analysis.—This analysis was carried out in two steps. The first step explored the influence of each of the previously described parameters on treatment response. This was achieved by searching for each parameter within the obliterated group (group 1) and the nonobliterated group (group 2) and by performing a χ^2 test. For each of the seven parameters studied, we determined the number of cerebral AVMs that underwent rapid obliteration (group 1A) and those that underwent slow obliteration (group 1B).

Multivariate Analysis

Multivariate analysis, which is a correspondence analysis based on the χ^2 distance (27), was performed to determine whether the variables studied were linked to one another.

Results

Radiosurgical Outcome

Only complete angiographic obliteration as defined by Lindquist and Steiner (28) ("normal circulation time, absence of former nidus vessels, disappearance or normalization of draining veins") was considered the desired end result of radiosurgical treatment. Whenever one of the above criteria was not fulfilled, the cerebral AVM was considered not obliterated. Depending on the observed angiographic results, patients were categorized into two groups as follows.

Group 1 (Obliteration, n = 68).—Group 1A (early obliteration, n = 43): obliteration of AVM confirmed at the first angiographic follow-up; group 1B (delayed obliteration, n = 18): persistent AVM seen at the first follow-up with obliteration seen at the second follow-up; 1C (n = 7): obliteration seen at the second follow-up; no first follow-up.

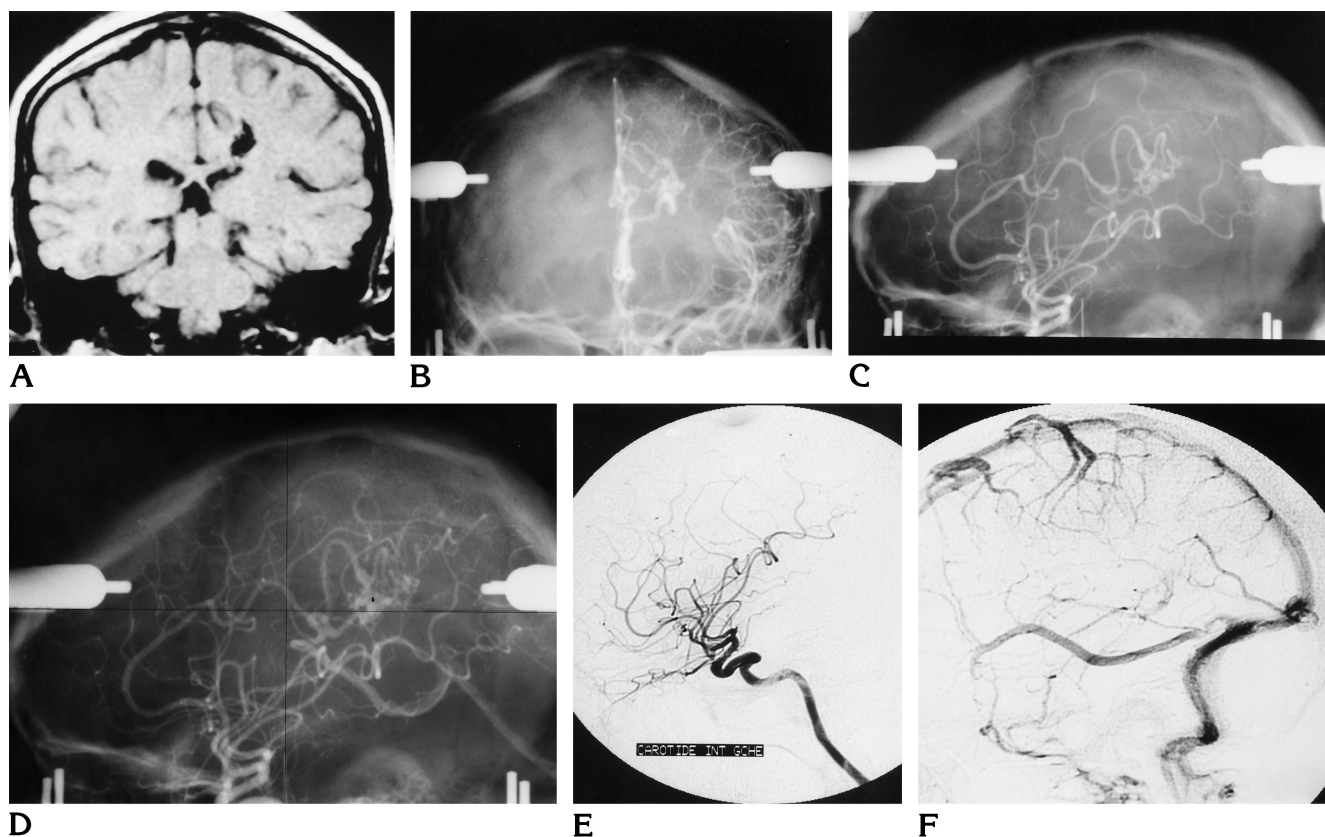*Group 2 (Nonobliteration, n = 34).*—Persis-

Fig 2. Type B plexiform cerebral AVM with rapid obliteration after treatment, revealed by intracerebral hemorrhage in a 26-year-old pregnant woman.

A, Pretherapeutic frontal T1-weighted MR image (600/25/1 [repetition time/echo time/excitations]) shows type B nidus located deep within the brain parenchyma.

B, Pretherapeutic stereotactic left carotid artery angiogram in frontal projection.

C, Pretherapeutic stereotactic left internal carotid artery angiogram in lateral projection shows plexiform nidus supplied essentially by the cerebral anterior artery.

D, Pretherapeutic stereotactic left internal carotid angiogram shows cerebral AVM drainage into the internal cerebral vein via the lateral atrial vein.

E, Left carotid angiogram in lateral projection, arterial phase, 14 months after therapy.

F, Posttherapeutic angiogram, venous phase, 14 months after therapy shows complete obliteration of the nidus. Deep venous system fills normally.

tent AVM seen at the second follow-up or at angiography performed later.

Single Variable Analysis

Maximal Length (Table 2).—The response to radiosurgery was greater in the group of cerebral AVMs whose maximal length was less than 25 mm ($\chi^2 = 8.2$, $P < .005$, degrees of freedom [df] = 1).

Volume (Table 3).—The obliteration rate increased as AVM volume decreased ($\chi^2 = 9.41$, $P < .003$, $df = 3$) (Fig 4).

Position Relative to the Midline (Table 4).— Cerebral AVM position relative to the midline

did not seem to have any influence on response to treatment ($\chi^2 = 0.3$, not significant [NS], $df = 1$).

Anatomic Structures Involved.—Table 5 shows the absence of a statistically significant relationship between response to radiosurgery and anatomic structures involved.

Sectional Anatomic Location.—The obliteration rate of type B cerebral AVMs was statistically higher than the rest of the cerebral AVM population ($\chi^2 = 4.9$, $P < .003$, $df = 1$). Conversely, none of the type C (Fig 5) or type ABC AVMs were obliterated. Owing to the small sample size of these two groups, the χ^2 test could not be applied. The obliteration rates of type A
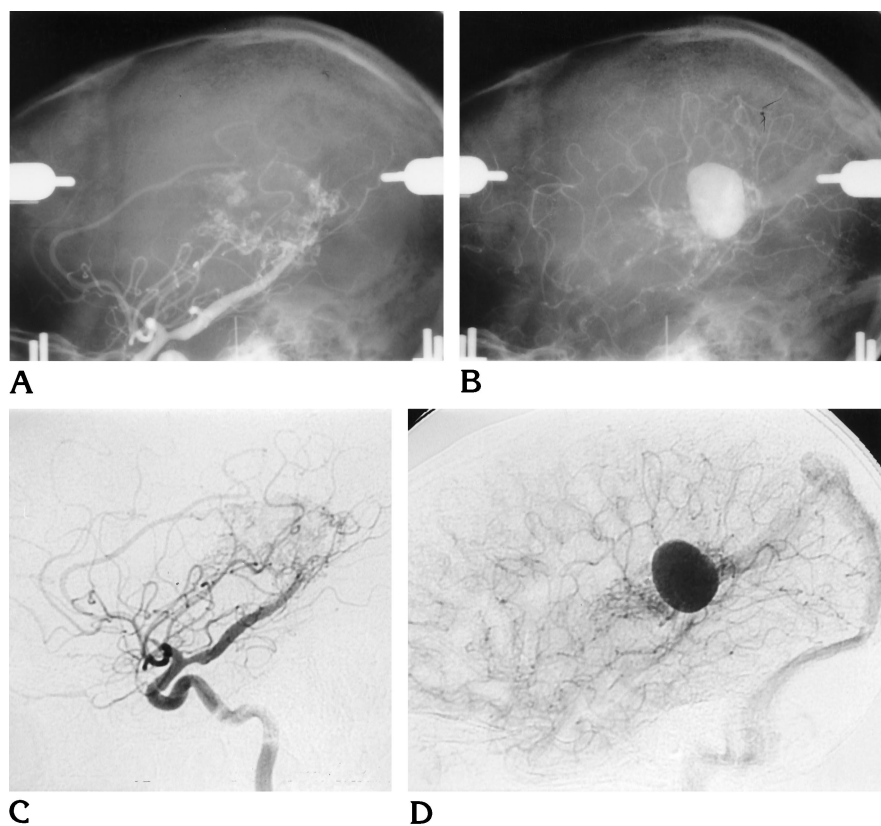
A

B

C

D

Fig 3. Nonplexiform cerebral AVM, not obliterated after treatment, revealed by an intracranial hemorrhage in a 26-year-old man.

A, Left carotid artery stereotactic angiogram, arterial phase.

B, Left carotid artery stereotactic angiogram, capillary phase, shows nidus is formed by several arteriolar feeding vessels converging upon a dilated vein of Galen. Note the presence of a falcine sinus.

C, Left carotid artery angiogram, arterial phase, 27 months after treatment.

D, Left carotid artery angiogram, capillary phase, 27 months after treatment, shows AVM is unchanged.

TABLE 2: Response to radiosurgery according to maximal length of cerebral AVM

Length of Cerebral AVMs	Number of Obliterated Cerebral AVMs	No. of Nonobliterated Cerebral AVMs
<25 mm	48 (33 rapid, 9 slow)	14
≥25 mm	20 (10 rapid, 9 slow)	20

TABLE 3: Response to radiosurgery according to volume of cerebral AVM

Volume of Cerebral AVMs, cm³	No. of Obliterated Cerebral AVMs	No. of Nonobliterated Cerebral AVMs
≤1	15 (10 rapid, 4 slow)	4
1–4	34 (23 rapid, 8 slow)	11
4–10	17 (10 rapid, 4 slow)	14
>10	2 (2 slow)	5

($\chi^2 = 1.1$, NS, $df = 1$), AB ($\chi^2 = 0.1$, NS, $df = 1$), and BC ($\chi^2 = 1.2$, NS, $df = 1$) did not differ statistically from the rest of the population.

Among the 18 type B cerebral AVMs that were completely obliterated, 15 were obliterated early, at the first angiographic follow-up (12 ± 6 months), while the remaining three were not obliterated at the first follow-up but were obliterated at the second follow-up (24 ± 6 months). None of the other groups showed such a tendency toward early obliteration.

Angioarchitecture (Table 6).—The obliteration rate of the nonplexiform cerebral AVMs was statistically smaller than that of the rest of the population ($\chi^2 = 23.3$, $P < .0001$, $df = 1$).

Spetzler and Martin Grading.—The obliteration rates of cerebral AVMs in relation to their grades are given in Table 7. Statistical analysis showed no significant difference between the obliteration rates of the AVMs graded 1, 2, and 3 and that of the general population. AVMs graded 4 showed a significantly lower obliteration rate.

Multivariate Analysis.—No qualitative link was found between any of the previous variables except for maximal length, volume, and the Spetzler grade. We therefore calculated the coefficient of correlation between maximal length and volume and found a positive correlation of $\rho = 0.72$. For precise quantitative analysis, the average volumes of each subgroup are indicated in Tables 6, 7, and 8.
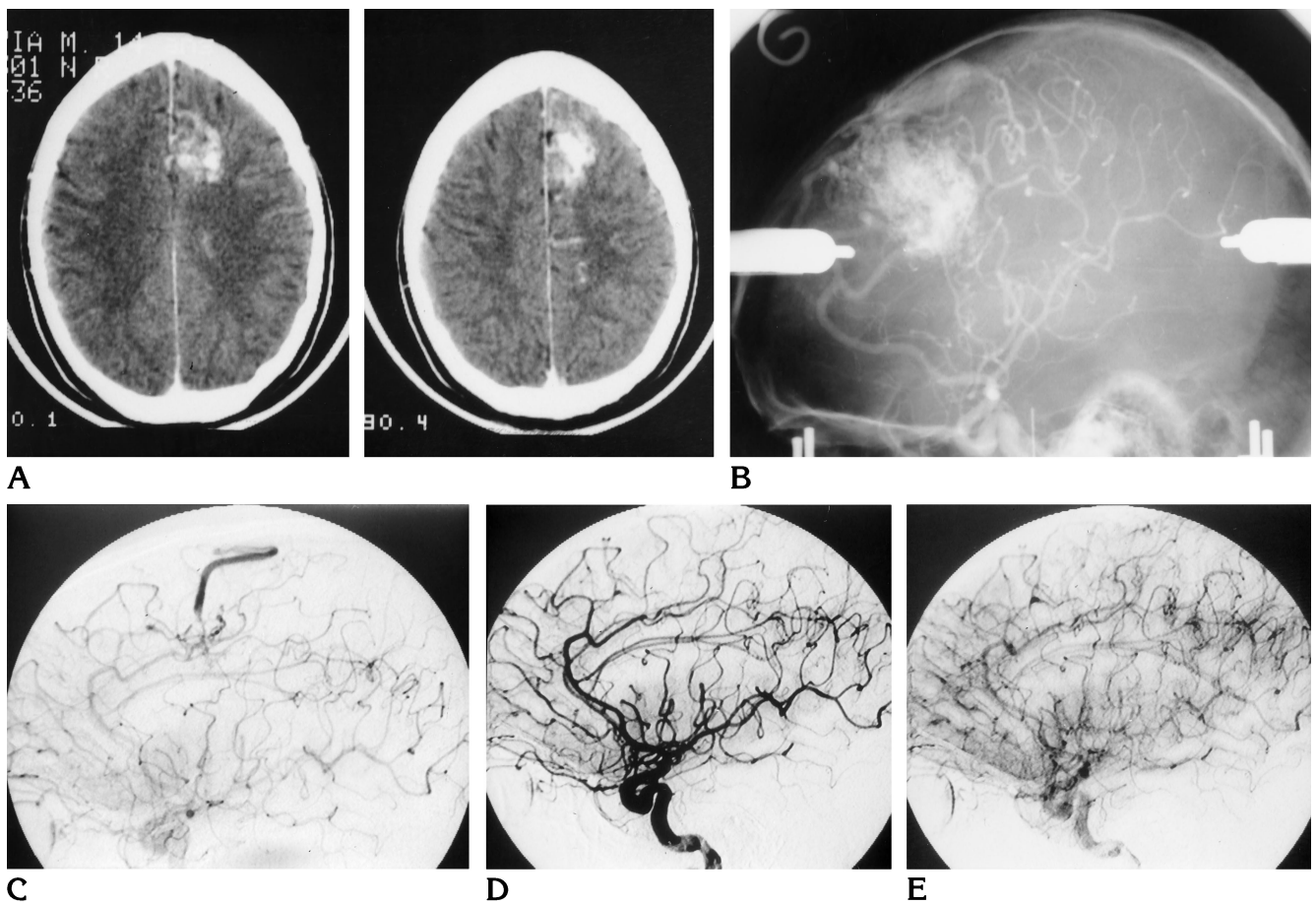
Fig 4. Type AB cerebral AVM with delayed obliteration after treatment, revealed by seizures in a 14-year-old boy.

A, Contrast-enhanced CT scans, before treatment, show the corticosubcortical nidus.

B, Pretherapeutic stereotactic left internal carotid artery angiogram, lateral projection, shows large nidus (44 mm) supplied by the left anterior and the left middle cerebral arteries.

C, Angiogram in lateral projection 24 months after therapy shows persistence of an early draining vein and a slight opacification of the nidus.

D, Angiogram in lateral projection, arterial phase, 31 months after therapy shows branches of the pericallosal artery are narrowed.

E, 31-month posttherapeutic angiogram, capillary phase, shows complete obliteration of the AVM.

TABLE 4: Response to radiosurgery according to location relative to the midline

Location of Cerebral AVMs	No. of Obliterated Cerebral AVMs	No. of Nonobliterated Cerebral AVMs
Midline	4 (3 rapid, 0 slow)	3
Hemispheric	64 (40 rapid, 18 slow)	31

TABLE 5: Response to radiosurgery according to location of cerebral AVM

Topography	No. of Obliterated Cerebral AVMs	No. of Nonobliterated Cerebral AVMs	χ^2 Test ($df = 1$)
Frontal lobe	14 (8 rapid, 3 slow)	9	0.44*
Parietal lobe	8 (6 rapid, 1 slow)	4	0.05*
Occipital lobe	6 (8 rapid, 6 slow)	3	.0001*
Temporal lobe	14 (2 rapid, 1 slow)	7	.0001*
Insular lobe	3 (2 rapid, 1 slow)	0	Nonvalid
Corpus callosum	1 (1 rapid)	2	Nonvalid
Basal ganglia	16 (10 rapid, 3 slow)	5	0.3*
Posterior fossa	6 (4 rapid, 1 slow)	1	1.2*
Extraparenchymal site	0	3	Nonvalid

* Not significant.

Discussion

Since its application in the early 1970s, stereotactic radiosurgery has proved to be efficacious in the treatment of cerebral AVMs in different respects. Cerebral AVMs respond to relatively low doses of radiation after a single session of radiosurgery. Progressive sclerosis of the malformative vessels leads to gradual he-
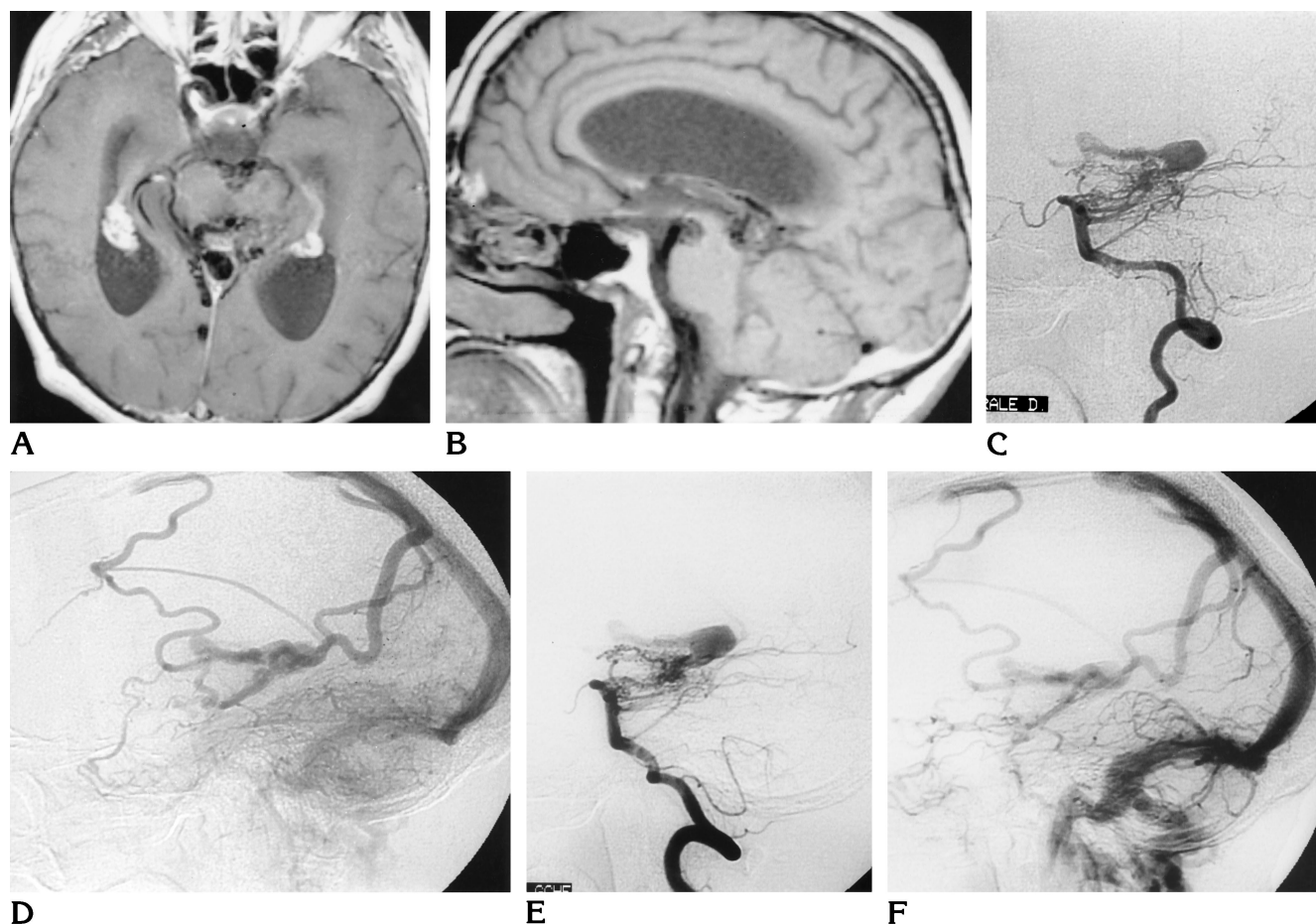
Fig 5. Type C cerebral AVM not obliterated after treatment, revealed by an intracranial hemorrhage in a 42-year-old man.

A, Pretherapeutic axial contrast-enhanced T1-weighted spin-echo MR image (600/20/1).

B, Pretherapeutic sagittal T1-weighted MR image (600/20/1) shows nidus located in the perimesencephalic cisterna.

C, Right vertebral artery angiogram before treatment, arterial phase.

D, Right vertebral artery angiogram before treatment, venous phase, shows nonplexiform cisternal nidus supplied by choroidal arteries.

E, Left vertebral artery angiogram, 49 months after treatment, arterial phase.

F, Left vertebral artery angiogram, 49 months after treatment, venous phase, shows AVM is unchanged.

modynamic changes, thereby allowing the adaptation to new circulatory conditions. The obliteration rate of cerebral AVMs is relatively high in comparison with the low rate of cerebral complications due to radiosurgery (14, 17, 29). "Rapid" obliteration is possible, observed before the 12th month after stereotactic radiosurgery in 29% to 52% of the cases reported in the literature (6, 8, 11, 17, 30, 31). Nevertheless, between 15% and 40% of cerebral AVMs remain nonobliterated 2 years after radiosurgery. It is therefore important to distinguish cerebral AVMs that will obliterate from those that seem to resist stereotactic radiosurgery. Moreover, as long as complete obliteration is not obtained, the risk of hemorrhage remains unchanged (13, 17, 32). This emphasizes the importance of selecting cerebral AVMs that will respond to stereotactic radiosurgery within a "reasonable" amount of time.

Increasing interest has recently developed in the search for prognostic factors concerning the efficacy of radiosurgery on cerebral AVMs. Apart from technical factors, size is the most widely studied morphological criterion. Most authors agree that small cerebral AVMs have a greater chance of obliteration than large ones. While this is usually the case, we have observed, as have others (6, 8, 27, 33), that certain large cerebral AVMs respond to radiosurgery while other small ones remain unchanged several years after treatment. These observations led us to search for other morphological parameters, directly observable by imaging

TABLE 6: Response to radiosurgery according to angioarchitecture

Angioarchitecture of the Nidus	No. (Average Volume, cm^3) of Obliterated Cerebral AVMs	No. (Average Volume, cm^3) of Nonobliterated Cerebral AVMs
Plexiform	67 (3.1) 42 rapid, 18 slow)	22 (5)
Nonplexiform	1 (3.7) (1 rapid, 0 slow)	12 (5.7)

TABLE 7: Response to radiosurgery according to Spetzler and Martin grading system

Grade	No. (Average Volume, cm^3) of Obliterated Cerebral AVMs	No. (Average Volume, cm^3) of Nonobliterated Cerebral AVMs	χ^2 test ($df = 1$)
1	12 (2.9)	8 (0.7)	2.6*
2	25 (4.5)	12 (2.3)	0.02*
3	26 (2.8)	12 (3.85)	0.08*
4	5 (9.9)	8 (9.8)	5.3, $P = .002$

* Not significant.

TABLE 8: Response to radiosurgery according to sectional topography

Topog-raphy	No. (Average Volume, cm^3) of Obliterated Cerebral AVMs	No. (Average Volume, cm^3) of Nonobliterated Cerebral AVMs	Mean Volume, cm^3
A	24 (2.1) (14 rapid, 7 slow)	8 (2.1)	2.1
AB	20 (5.6) (10 rapid, 7 slow)	12 (7.2)	6.2
B	18 (2.3) (15 rapid, 3 slow)	2 (1.2)	2.2
BC	6 (1.5) (4 rapid, 1 slow)	7 (4.7)	3.2
C	0	3 (7.6)	7.6
ABC	0	2 (10.3)	10.3

techniques, that may be linked to treatment efficacy.

Series Analysis

The 129 patients of this study were part of a consecutive group that underwent treatment under identical conditions. Apart from the nine patients lost to follow-up, 19 others, whose follow-up data were insufficient for establishing status of the cerebral AVM 2 years after stereotactic radiosurgery, were excluded to render the series as homogeneous as possible. The studied population consisted of 102 patients who underwent regular angiographic follow-up studies. As opposed to the conditions in other large published series (10), in our series, cerebral AVMs were not preselected on the basis of MR data, since all patients treated by radiosurgery were asked to undergo yearly angiographic follow-up. Thanks to the homogeneity of the treatment protocol (22) and the regularity of follow-up angiography, this series constitutes a solid data base for studying morphological parameters.

The clinical profile of our series is similar to that of other series reported in the literature. The only characteristic that differs is the large number of AVMs embolized before stereotactic radiosurgery. In our study group, 41% of the patients had at least one previous endovascular treatment, while only 9% and 21% of the patients in the Friedman et al (29) and Lundsford et al (10) studies, respectively, underwent such treatment.

Size

While few authors report no difference in outcome after stereotactic radiosurgery between small and large cerebral AVMs (30), most authors agree that the obliteration rate of cerebral AVMs is inversely correlated to their volume (4, 8, 10, 11, 29). The same relationship has been observed with regard to maximum nidus length (6, 15, 16). Our results are in agreement with these findings. Moreover, we found a strong positive correlation between maximal length and volume of the nidus, which explains why these two variables seem equally valuable in predicting obliteration rate. This is of importance in clinical practice because maximal length can be measured easily from stereotactic angiograms while volume measurement requires workstations with dedicated software (21). Previous studies have shown, however, that volume is a discriminating factor for predicting response to stereotactic radiosurgery at 1 year but not at 2 years (8, 29). Some authors also report nearly equal obliteration rates for lesions of medium size or greater (8, 14). These observations, in addition to the fact that certain voluminous cerebral AVMs are angiographically cured at 2 years after stereotactic radiosurgery while other small ones persist, suggest that size/volume alone cannot explain the response of cerebral AVMs to stereotactic radiosurgery (14, 34).

Topography

Few studies have focused on the influence of cerebral AVM location on the response rate after

stereotactic radiosurgery. Kemeny et al (31) found a relationship between the proximity of the AVM to the midline and obliteration rate. They observed better results in patients with laterally located AVMs than in those with midline location. In our study, no difference in response to stereotactic radiosurgery was found between medial and lateral AVMs. Yamamoto et al (30) suggested that infratentorial and brain stem AVMs may have a lower obliteration rate than supratentorial ones. According to Duma et al (33), AVMs located in the midbrain have the same obliteration rates as those of similar size in other brain locations. Six of the seven infratentorial AVMs in our study group were angiographically cured at 2 years, indicating that infratentorial AVMs have an obliteration rate similar to those in other brain locations. To analyze topographical influence on obliteration rate, nine groups were defined according to the anatomic structures involved on angiographic and MR findings. No relationship was found between lobar distribution of the AVMs and the obliteration rate. A tendency toward obliteration was observed, however, for the deeply located AVMs involving the basal ganglia and the thalamus. Yamamoto et al (30) reported complete obliteration in six of the seven thalamic AVMs in their study. This original finding led us to classify the AVMs according to their depth within the brain. For surgical purposes, this type of classification has been proposed by Yasargil (24). When applied to radiosurgically treated cerebral AVMs, it appears that deeply located AVMs tend to obliterate at 2 years. Before considering that the depth within the brain tissue was directly linked to the high rate of obliteration, the average volume of each class had to be considered. Qualitative multivariate statistical analysis showed no relationship between sectional anatomic location of the nidus and any other parameter. This independence is particularly clear with regard to nidus volume. While the average volume of the mixed forms of nidi (types AB, BC, and ABC) was greater than that of the pure forms (types A, B, and C), the average volume of types A, B, and C was identical. Therefore, the difference observed in obliteration rates between types A, B, and C was not due to a volume bias.

The respective obliteration rates for AVMs located on the convexity and those located deep within the brain tissue have not been established previously: we have shown that, for a given volume, type B cerebral AVMs have a greater chance of obliteration at 2 years than do superficial ones. Moreover, because of the difference in response to radiosurgery between types B and BC AVMs, one should distinguish AVMs completely surrounded by brain tissue (type B) from those located deeply with ventricular involvement (type BC).

Furthermore, our results indicate that type B cerebral AVMs obliterate faster than others. This emphasizes the importance of sectional anatomic location, since patients with deep cerebral AVMs (type B) seem to be protected against hemorrhage earlier.

We have found no explanation in the literature for this difference in response. Pollock et al (35) advanced the concept of "radiobiological resistance" as a potential factor associated with failed radiosurgery. In accordance with this hypothesis, the difference in response to stereotactic radiosurgery between deep and superficial cerebral AVMs may be related to a difference in local environment. Since type B AVMs are surrounded by densely packed areas of brain tissue, they may have a different radiosensibility than AVMs located in areas in contact with cerebrospinal fluid. While this hypothesis is appealing, there is no evidence to support it. Tew et al (36) suggested that the small feeding vessels of deep structures, such as internal capsulae, were more radiosensitive than cortical vessels. This statement is interesting but concerns normal blood vessels. Its application to malformed vessels remains speculative.

Angioarchitecture

In the absence of superselective injection for the majority of patients, a precise definition of nidus angioarchitecture is impossible. To be observer independent, we chose a simple classification, taking into account both Houdart (25) and Yasargil's (24) criteria. As a result, a great number of plexiform nidi were found in our series. This is probably due to the fact that a great number of malformations were partially embolized before stereotactic radiosurgery. The high-flow compartments within these nidi may have been occluded as a consequence of the flow dependency of the catheters used for embolization. Furthermore, a number of high-flow fistulas probably went undetected because of the global angiographic technique used. According to the strict criteria used, only those malformations with an indisputable zone of high-flow

were included in the nonplexiform group, resulting in an underestimation of this group. Our results show a highly significant difference in obliteration rate between the plexiform and nonplexiform groups. While plexiform cerebral AVMs tend to obliterate, only one of the 13 AVMs classified as nonplexiform was obliterated at 2 years. These data emphasize the interest of superselective catheterization in preradiosurgical work-up. The difference in response observed cannot be explained by variations in volume or location. First, mean volumes were similar between the two groups. Second, although the precise hemodynamic characteristics of the AVMs could not be defined by means of our angiographic technique, there seems to be no correlation between cross-sectional anatomic location and angioarchitecture, since we found as many nonplexiform AVMs in the type B location as in neighboring locations. Our results are in agreement with the findings of Petereit et al (37), who demonstrated a negative correlation between flow velocity and response to stereotactic radiosurgery by using semiquantitative measurements of blood flow with phase-contrast MR imaging in 14 cases. The nine slow-flow ($<$ 60 cm/s) or intermediate-flow (60 to 100 cm/s) AVMs showed partial or complete nidus obliteration at the 10-month follow-up angiographic study, whereas only three of the five fast-flow AVMs ($>$ 100 cm/s) showed obliteration. These authors suggested that flow velocity has a prognostic value. Many authors recommend the use of combined treatments, embolization and radiosurgery, for the management of cerebral AVMs (38–40). Since the volumetric limitation is the major restraint of radiosurgery, it is usually admitted that prior embolization is considered helpful only when the nidus volume can be reduced (40, 41). In cases of cerebral AVMs with mixed high- and slow-flow compartments, we believe that intravascular embolization will be particularly useful not only for reducing the volume of the AVM but also for eradicating the high-flow compartment upon which radiosurgery seems less efficient. The utility of this hemodynamic reduction before radiosurgery must be confirmed by a dedicated study.

Spetzler and Martin Grading System

We chose to analyze the influence of this grading system because it is the most widely used in neurosurgical practice and, therefore, as stated by Spetzler and Martin "may be applied to lesions treated either by radiation therapy or by embolization for the purpose of comparing the results of these techniques with those of surgical excision" (26). In addition, some authors have demonstrated its predictive value in combined treatments, including radiosurgery (42). The only significant result we found was that grade 4 cerebral AVMs tended to respond poorly to radiosurgery. This poor result is likely to be due to large volume, since grade 4 cerebral AVMs had a much larger volume than the others. Therefore, the Spetzler and Martin grading system in itself has no value for predicting response to radiosurgery.

Conclusion

Two morphological parameters should be taken into account before deciding on a treatment approach for cerebral AVMs: the depth of the AVM and its angioarchitecture. Patients with AVMs located deep within the brain tissue (type B) seem to be ideal candidates for radiosurgery, since the chances of complete and rapid obliteration are particularly high. This highlights the importance of determining the sectional anatomic location of the AVM during the pretherapeutic work-up by means of cross-sectional imaging. For patients with AVMs of nonplexiform angioarchitecture, the option of combined management should be discussed, as radiosurgery seems to be less efficient. Because it seems advisable to analyze the angioarchitecture, more frequent use of selective catheterization, as suggested by Pollock (35), as part of pretherapeutic evaluation, would be judicious.

A grading system specifically adapted to radiosurgery based on size, topographical, angioarchitectural, and hemodynamic parameters should be established to select candidates for radiosurgery and to compare the results of the different radiosurgical series.

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