Cerebral AVMs appear within a wide spectrum of clinical manifestations, and their management depends on multiple parameters, such as expected natural course, age of patient, mode of presentation, anatomy of the AVM, hemodynamics of the malformation, and associated aneurysms.1,2

The anatomy of AVMs has been explained in some detail; however, the hemodynamic aspect of these embryologic lesions and its impact on management still remains to be investigated.1,3–10 Cerebral angiography is still the gold standard, providing essential anatomic information; nevertheless, the hemodynamic information concealed in an angiographic series may be inadequate for interpretation.1,5,11–13 TCD ultrasonography, first introduced by Aaslid and colleagues11 in the 1980s, opened up the possibility of noninvasive and easily repeatable examination of blood flow in the intracranial arteries. Feeder arteries of AVMs typically have a higher than normal $V_m$, with increased turbulence, and lower than normal PIs.2,12,14–17 The present study was designed with the ultimate goal of assessing the role of TCD sonog-

Grading and Hemodynamic Follow-Up Study of Arteriovenous Malformations with Transcranial Doppler Ultrasonography

Türker Kiliç, MD, M. Necmettin Pamir, MD, Samantha Budd, PhD, M. Memet Ozek, MD, Canan Erzen, MD

This study presents and tests the clinical validity of a hemodynamic grading system that depends on noninvasive transcranial Doppler ultrasonographic parameters. The suggested transcranial Doppler-based grading system was compared with the Spetzler-Martin anatomic grading for prognosticative validity and clinical dependability. We concluded the following: (1) The pulsatility index was shown to be a more dependable transcranial Doppler parameter in the clinical evaluation of an arteriovenous malformation because of two reasons: preoperative pulsatility index findings inversely correlated with arteriovenous malformation volume, and the pulsatility index returned to normal values before the mean blood flow velocity did. Therefore, hemodynamic arteriovenous malformation grading can be based on the pulsatility index. (2) A transcranial Doppler–based hemodynamic arteriovenous malformation grading system correlated highly with the Spetzler-Martin grading in predicting postoperative neurologic deficits and adverse radiologic findings. (3) The presented grading system may contribute to the standardization and quantification of the hemodynamic changes during multidisciplinary management of arteriovenous malformations. KEY WORDS: Arteriovenous malformations; Grading; Hemodynamics; Transcranial Doppler ultrasonography.

ABBREVIATIONS

AVM, Arteriovenous malformation; TCD, Transcranial Doppler; $V_m$, Mean blood flow velocity; PI, Pulsatility index; CT, Computed tomography; MR, Magnetic resonance; ANOVA, Analysis of variance
raphy in both preoperative and postoperative evaluation of the hemodynamic aspect of AVMs. The study aimed to

1. Investigate characteristic TCD changes in the feeder arteries of AVMs and to indicate the changes in TCD parameters following surgery.
2. Discuss volume-dependent changes in both PI and $V_m$ and to examine possible correlations with subsequent complications.
3. Test clinical reliability of a hemodynamic, TCD-based grading system for AVMs, using data derived from phases 1 and 2. The prognostic validity of the proposed grading system was retrospectively tested by correlations with Spetzler-Martin grading of the same sample of patients in regard to neurologic complications and radiologic findings. Spetzler-Martin grading depends on nidus size [categorized as less than 3 cm (1 point), between 3 and 6 cm (2 points), and more than 6 cm (3 points)], eloquence of adjacent brain tissue [noneloquent, 0 point; eloquent, 1 point], and pattern of venous drainage [deep drainage, 1 point; superficial drainage, 0 point]. So, a Spetzler-Martin grade, which is the sum of the points that an AVM gets according to these three parameters, ranges from 1 to 5.

This study analyzed a homogeneous group of AVMs according to TCD parameters, and in the light of this analysis, hypothesized and tested a hemodynamic grading system for AVMs. Our aim was to convert clinically well-recognized insight on the hemodynamic dimension of AVMs into a methodologically repeatable and statistically dependable grading system that could be used in conjunction with the current anatomic grading systems.

**CLINICAL MATERIAL AND METHODS**

Of a total of 56 patients diagnosed as having a cerebral AVM admitted from January 1991 to September 1997 to Marmara University Department of Neurosurgery, 38 of these patients (the others were treated with gamma knife radiosurgery or embolization or both) who were treated surgically were systematically examined with TCD sonography. Only 18 patients of this group fulfilled the following requirements for inclusion in this study (Table 1): (1) preoperative angiographic demonstration of AVM, (2) TCD examinations performed preoperatively and postoperatively on days 1 and 15 and month 3, (3) postoperatively performed cerebral angiography to diagnose total removal of AVM, and (4) CT and MR imaging studies postoperatively performed in first 12 to 24 h to demonstrate so-called hyperemic complications (cerebral edema with or without intracerebral hematoma). Excluded from the study were (1) patients who had an overt hemorrhage within a 3 month period before surgery, (2) patients previously operated on or later reoperated on (for any reason), and (3) patients having preoperative or postoperative hematocrit values less than 28 g/dl or more than 44 g/dl.

In all TCD investigations, a 2 MHz pulsed TCD device (EME 2000 TCD system, Eden Medizinische Elektronik, Überlingen, Germany) was used. On each TCD examination systolic and diastolic velocities and $V_m$’s and PI values of the AVM-feeding vessels of the circle of Willis and their normal symmetric pairs were recorded. $V_m$ is an absolute value measured by TCD sonography, and defined as centimeters per second, whereas PI is a ratio value, calculated and displayed during TCD examination and defined as (peak systolic velocity – end diastolic velocity)/$V_m$.

The mean age of the 18 patients (10 men, eight women) was 29 years (range, 12 to 54 years) (Table 1). The Spetzler-Martin grading and volume group of each AVM are also shown in Table 1.

Methodologically, this clinical investigation consisted of four phases:

1. Determining natural changes in the PI and $V_m$ values of each individual feeder (25 feeders in 18 AVMs) in the first 3 months after successful surgery.
2. Discerning the effect of AVM volume (i.e., volume of nidus) on both the PI and $V_m$ values of its feeder. According to their nidal volumes, AVMs were classified into three groups, 1, 2, and 3, each including the AVMs having volumes less than 20 ml, between 20 and 40 ml, and more than 40 ml, respectively (Table 1). As determined in the literature, the practical way to measure the volume of an AVM appears to be to multiply the product of three diameters of an AVM by 0.52. This calculation is an approximation of the nidal volume; however, it was practically used to classify the AVMs and to make the volume PI and volume $V_m$ correlations.
3. Formulating a hemodynamic grading system for AVMs from the data obtained during the first two phases. The hypothesized and tested TCD-based hemodynamic grading of AVMs
Table 1: Investigated Patients Distributed According to Spetzler-Martin AVM Grading System, Volume Groups, Complications, and Radiologic Untoward Findings

<table>
<thead>
<tr>
<th>Patient</th>
<th>Sex</th>
<th>Age</th>
<th>Spetzler-Martin Grading</th>
<th>Volume Group* of AVMs</th>
<th>TCD-AVM Grade†</th>
<th>Complications</th>
<th>Radiologic Complications</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>M</td>
<td>12</td>
<td>III</td>
<td>2</td>
<td>II</td>
<td>No</td>
<td>Edema</td>
</tr>
<tr>
<td>2</td>
<td>M</td>
<td>15</td>
<td>IV</td>
<td>3</td>
<td>I</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>F</td>
<td>18</td>
<td>V</td>
<td>3</td>
<td>IV</td>
<td>Permanent, increase in motor weakness</td>
<td>Edema</td>
</tr>
<tr>
<td>4</td>
<td>M</td>
<td>19</td>
<td>IV</td>
<td>2</td>
<td>III</td>
<td>Permanent, speech disturbance</td>
<td>Hematoma and edema</td>
</tr>
<tr>
<td>5</td>
<td>M</td>
<td>20</td>
<td>III</td>
<td>1</td>
<td>IV</td>
<td>No</td>
<td>Hematoma and edema</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>22</td>
<td>III</td>
<td>1</td>
<td>I</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>7</td>
<td>F</td>
<td>23</td>
<td>I</td>
<td>1</td>
<td>II</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>8</td>
<td>M</td>
<td>24</td>
<td>II</td>
<td>1</td>
<td>IV</td>
<td>No</td>
<td>Hematoma and edema</td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>28</td>
<td>I</td>
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<td>II</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>29</td>
<td>III</td>
<td>2</td>
<td>IV</td>
<td>Temporary, motor weakness</td>
<td>Hematoma and edema</td>
</tr>
<tr>
<td>11</td>
<td>M</td>
<td>32</td>
<td>II</td>
<td>1</td>
<td>III</td>
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<td>No</td>
</tr>
<tr>
<td>12</td>
<td>M</td>
<td>34</td>
<td>I</td>
<td>2</td>
<td>I</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>13</td>
<td>F</td>
<td>35</td>
<td>II</td>
<td>2</td>
<td>IV</td>
<td>Temporary, visual field defect</td>
<td>Edema</td>
</tr>
<tr>
<td>14</td>
<td>F</td>
<td>38</td>
<td>III</td>
<td>2</td>
<td>II</td>
<td>Temporary, motor weakness</td>
<td>No</td>
</tr>
<tr>
<td>15</td>
<td>M</td>
<td>38</td>
<td>V</td>
<td>3</td>
<td>IV</td>
<td>Temporary, motor weakness</td>
<td>Hematoma</td>
</tr>
<tr>
<td>16</td>
<td>F</td>
<td>39</td>
<td>IV</td>
<td>3</td>
<td>III</td>
<td>Temporary, motor weakness</td>
<td>Edema</td>
</tr>
<tr>
<td>17</td>
<td>M</td>
<td>42</td>
<td>II</td>
<td>1</td>
<td>II</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>18</td>
<td>F</td>
<td>54</td>
<td>III</td>
<td>1</td>
<td>III</td>
<td>No</td>
<td>Hematoma</td>
</tr>
</tbody>
</table>

*Group 1: AVMs less than 20 ml; group 2: AVMs with volumes between 20 and 40 ml; group 3: AVMs with volumes more than 40 ml. Hemodynamic grading system for AVMs based on TCD parameters.

(TCD-AVM grading, Table 2) depends on preoperative PI values of the AVM feeders. In cases of multiple feeders having AVMs, the feeder revealing the lowest PI value was taken into consideration.

4. Testing the clinical reliability of the proposed grading system by making retrospective correlations with the commonly used anatomic Spetzler-Martin grading in regard to postoperative neurologic complications and radiologic signs of hyperemic complications. Hyperemic complications were defined as (a) a hematoma in the cavity of the resected AVM without mass effect (patients who were reoperated on, including those requiring postoperative reoperation because of intracerebral hematoma having a mass effect, were excluded from the study), (b) edema around the resection area, and (c) both (a) and (b) together. Postoperative CT and MR imaging scans, performed in the first 12 to 24 h after surgery, were evaluated by the same radiologist. Each complication parameter was evaluated on a “yes” or “no” basis (Table 1). In the evaluation of postoperative complications, temporary neurologic deficits, defined as those that disappeared within 3 months after surgery, were also considered (Table 1).
For statistical analysis and display StatView PC software was used. For correlations, one-way ANOVA test was used. P values less than or equal to 0.05 were considered to be statistically significant.

RESULTS

Vm and PI Values in Feeder Arteries of the Circle of Willis and Symmetrically Comparable Normal Arteries

In five patients, multiple AVM-feeding vessels of the circle of Willis were detected by cerebral angiography together with TCD sonography. Three of these patients had two feeding arteries, and in the remaining two patients, three feeders were detected. Thus, a total of 25 AVM-feeding arteries were evaluated.

In preoperative examinations (Fig. 1A, B), Vm values ranged from 68 to 248 cm/s, with PI values varying between 0.32 to 0.84. The Vm values in the comparable normal arteries ranged from 42 to 92 cm/s, and the PI values of normal arteries ranged from 0.56 to 1.20. The statistical difference between the Vm and PI values from feeders and symmetrically comparable normal arteries was found to be significant.

Postoperative day 1 measurements (Fig. 1A, B) revealed a decrease in the Vm values of the feeders, ranging from 62 to 155 cm/s, and an increase in the PI value, 0.52 to 1.30. The difference between postoperative day 1 and day 15 measurements of Vm values was statistically significant, but the difference between the PI values of the same days was not found to be significant. The postoperative day 15 Vm values in the normal arteries ranged from 44 to 90 cm/s; the PI values of normal arteries ranged from 0.58 to 1.30. No statistical difference was apparent between postoperative day 15 Vm and PI measurements of AVM feeders and comparable normal arteries.

Postoperative day 15 measurements (Fig. 1A, B) revealed a further decrease in the Vm values of the feeders, ranging from 44 to 86 cm/s, and a minimal change in the PI value, 0.52 to 1.30. No statistical difference was found between postoperative day 1 and day 15 measurements of Vm values in the normal arteries ranged from 44 to 90 cm/s; the PI values of normal arteries ranged from 0.58 to 1.30. No statistical difference was found between postoperative day 15 Vm and PI measurements of AVM feeders and comparable normal arteries.

Postoperative month 3 measurements (Fig. 1A, B) revealed no major changes in Vm and PI values of the feeders (ranging from 46 to 88 cm/s and 0.56 to 1.30, respectively). No statistical difference was found between postoperative day 15 and month 3 measurements of Vm and PI values. The postoperative month 3 Vm values in the normal arteries ranged from 48 to 86 cm/s, and the PI values of normal arteries ranged from 0.58 to 1.25. No statistical difference was found between postoperative month 15 Vm and PI measurements of AVM feeders and comparable normal arteries.

Correlation of Preoperative Vm and PI of Main Feeders of AVMs with AVM Volumes

Nidal volume is a more important parameter than nidal diameter in assessing the prognosis of AVMs.1,8 To investigate possible volume PI and volume Vm correlations, AVMs were grouped according to their volumes:

**Group 1, AVMs with volumes less than 20 ml**

Eight AVMs had volumes less than 20 ml (the maximum diameters of five cases were calculated to be less than 2 cm, two cases were between 2 to 4 cm, and one case had a maximum diameter of 4.5 cm).

**Group 2, AVMs with volumes between 20 to 40 ml**

Six AVMs had volumes between 20 to 40 ml (maximum diameters of three cases were calculated to be between 2 to 4 cm, and another three cases had maximum diameters between 4 to 6 cm).

**Group 3, AVMs with volumes greater than 40 ml**

Four AVMs had volumes between 20 to 40 ml (maximum diameters of two cases were calculated to be between 4 to 6 cm, and another two cases had maximum diameters greater than 6 cm).
The preoperative average PI and $V_m$ values of each volume group were calculated and correlated with each other. The differences between the preoperative average PI values of groups I and II ($P = 0.013$) and groups II and III ($P = 0.001$) were significant (Fig. 2A). However, although a reversely sloped curve was obtained when the preoperative average $V_m$ values of the three groups were graphically correlated (i.e., an increasing $V_m$ was found with increasing AVM volume), the differences between the preoperative average $V_m$ values of groups I and II and groups II and III were insignificant (Fig. 2B).

**TCD Grading System Proposed for Preoperative Hemodynamic Assessment of AVM Prognosis**

To standardize TCD data, a preoperative grading system was proposed. PI was taken into account as the definitive parameter (Table 2). Quantification was made according to the average PI values of three different volume groups. Patients shown to have an AVM with a feeder having a PI value greater than 0.50 (mean PI of group I, 0.52) were classified as TCD grade I. AVMs having a feeder with a PI value between 0.50 and 0.45 (mean PI of group II, 0.47) were classified as TCD grade II. AVMs with a feeder having a PI value between 0.45 and 0.35 (mean PI value of group III, 0.35) were classified as TCD grade III. AVMs having a feeder with a PI value less than 0.35 were graded as TCD grade IV. In AVMs having multiple feeders, the feeder having the lowest PI value was taken into account.

**Comparison of TCD-AVM Grading System with Spetzler-Martin Grading System in Regard to Postoperative Neurologic Deficits**

In seven of 18 patients, postoperatively initiated or aggravated neurologic deficits were detected (Table 3). Two of these deficits remained 3 months after surgery and were classified as permanent deficits. No patients in TCD grade I experienced any additional neurologic deficits. One patient in TCD grade II revealed a transient deficit; two patients in TCD grade III displayed additional postoperative neurologic deficits: one case was diagnosed to be transient and the other neurologic deficit was permanent. In TCD grade IV, three cases showed transient neurologic deficits, and in one case the neurologic deficit was judged as permanent.

When these seven cases were distributed according to their preoperative $V_m$ findings, AVMs in two patients had $V_m$ values less than 120 cm/s, AVM in one patient had a $V_m$ value of 148 cm/s, AVM in another patient had a $V_m$ value of 182 cm/s, and three patients with new neurologic cases had preoperative $V_m$ values more than 200 cm/s. Both permanent deficits were diagnosed among the patients having preoperative $V_m$ values more than 200 cm/s.
Similar retrospective analysis of the same patient group with the Spetzler-Martin grading revealed a distribution shown in Table 1 and Figure 3.

Comparison of TCD-AVM Grading System with Spetzler-Martin Grading System in Regard to Postoperative Radiologic Untoward Findings

In early postoperative CT and MR imaging examinations, 10 of 18 patients were diagnosed as having a hematoma in the AVM bed (without any signs of anatomic shift) or perilesional edema or hematoma with edema (Table 4). In TCD grade I AVMs, early postoperative CT revealed no hemodynamic complications. In TCD grade II, early postoperative CT revealed a perilesional edema in one case. In TCD grade III, one case occurred in each category of hyperemic CT complication. In TCD grade IV, one patient had hematoma, two patients had perilesional edema, and three patients had both edema and hematoma.

When these 10 cases were distributed according to their preoperative $V_m$ findings, two AVMs had $V_m$ values less than 120 cm/s, one AVM had a $V_m$ value of 152 cm/s, and three cases had preoperative $V_m$ values between 160 and 200 cm/s. Four patients had preoperative $V_m$ values greater than 200 cm/s.

Analysis of the same patient group with the Spetzler-Martin grading revealed a distribution shown in Table 1 and Figure 3.

### Table 3: Hemodynamic (TCD-Based) Grading System for AVMs with Postoperative Neurologic Deficit Correlation

<table>
<thead>
<tr>
<th>TCD-AVM Grade</th>
<th>Total Number of Patients</th>
<th>Patients Having Temporary Complications</th>
<th>Patients Having Permanent Complications</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>5</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>IV</td>
<td>6</td>
<td>3</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Total</td>
<td>18</td>
<td>5</td>
<td>2</td>
<td>7</td>
</tr>
</tbody>
</table>

**DISCUSSION**

**TCD Sonography in Hemodynamic Evaluation of AVMs.**

The unique ability of TCD velocities and pulsatilities to indicate altered cerebral flow and resistance allows several types of hemodynamic assessments of AVMs. Since the pioneering investigations of Lindegaard and colleagues and Hassler in 1986,
collected information about the use of TCD sonography in the clinical management of AVMs has provided a new level of insight on the hemodynamic dimension of AVMs. Our study, by making a correlation of volume PI and volume \( V_m \) complications, aimed to convert this insight into a repeatable and statistically dependable method and, furthermore, to convert this data into a hemodynamic grading system for AVMs (Table 2).

Technically, it is evident that use of TCD sonography in the assessment of AVMs has some serious drawbacks.\(^6,17,18\) Almost all investigators have been convinced that an estimation based on TCD sonography did not constitute an accurate measure of shunt flow, since the arteries feeding the malformation are generally multiple and contribute to the hemodynamic problem to different extents.\(^5,6,9,12,18\) Additionally, changing the insonation angle from one feeder to another in the same or different patients impedes the standardization of the scientific work. Recent data imply that transcranial color-coded duplex sonography allows the exact identification of different feeding arteries, minimizing this technical drawback.\(^20\) However, since this method is noninvasive and can be repeated easily for the evaluation of changes in blood flow after each management step (embolization, surgery, radiosurgery, etc.), in spite of the limiting intrinsic technical properties, TCD sonography can be used as a complementary tool to the direct anatomic and indirect physiologic data derived from cerebral angiography.\(^9,21\)

**PI Is More Dependable TCD Parameter (Than Blood Flow Velocity) in Follow-Up Study of AVMs.**

After Hassler's\(^19\) and Lindegaard and colleagues'\(^12\) pioneering studies, it became well-known that since an AVM carries a large volume of blood at a low resistance, its TCD signals are characterized by an elevated \( V_m \) and a decreased PI (Fig. 1A, B). The TCD data of patients who were treated by serial embolizations (combined with surgery or not) reveal that the high-velocity and low-pulsatility signals of a supply vessel return to normal as the shunt is obliterated.\(^2,21\) However, although Pasqualin and associates,\(^8\) Lindegaard and colleagues,\(^12\) Hassler,\(^19\) and Mast and coworkers\(^18\) previously pointed out that PI and \( V_m \) may have therapeutic and prognostic implications, no study has investigated time-dependent postoperative changes in PI and \( V_m \) and compared them with respect to AVM volume. Regarding time-dependent changes, we concluded that PI returns to normal limits on postoperative day 1, before \( V_m \) does (Fig. 1A, B). Although a decreasing trend in \( V_m \) values was seen on postoperative day 1, normalization was detected later only on postoperative day 15. Surgical manipulation, which was postulated to be the cause of the reversible increase in \( V_m \), due to increased vasospasm in the TCD follow-up study of aneurysmal subarachnoid hemorrhage, might explain the delay in normalization of \( V_m \).\(^21\) PI, which is a mathematical ratio, seems to be less affected by immediate postoperative reversible vasospasm. Therefore, one can conclude that PI is a more dependable parameter to evaluate the physiological success of the operation in early postoperative days.

![Figure 3](image)

**Figure 3** To display the prognostic validity of hemodynamic grading of AVMs with TCD ultrasonography (TCD-AVM grading), the percentage of patients having permanent or temporary neurologic deficit after the operation is shown in comparison with Spetzler-Martin grading. Note that the complication rate increases with the increasing TCD-AVM grade, and TCD-AVM grading parallels Spetzler-Martin grading in predicting the postoperative complications.

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**Table 4**: Hemodynamic (TCD-Based) Grading System for Intracranial AVMs with Postoperative First-Day Radiologic Findings Correlation

<table>
<thead>
<tr>
<th>TCD-AVM Grade</th>
<th>Total Number of Patients</th>
<th>Hematoma</th>
<th>Edema</th>
<th>Edema and Hematoma</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>3</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
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<tr>
<td>II</td>
<td>5</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td>4</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>3</td>
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<tr>
<td>IV</td>
<td>6</td>
<td>1</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>18</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>10</td>
</tr>
</tbody>
</table>
Since anatomic parameters remain the most important factors for determining the operability and surgical risks associated with AVMs, most widely accepted prognosticative grading systems such as Spetzler and Martin,10 Shi and Chen,25 and Luessenhop and Rosa23 are based largely on morphologic criteria. Although, for practical purposes, maximum diameter was widely used to define the “size” of AVM, volume was proposed to be the best measure of AVM size.8 Currently no publication quantitatively clarifies volume PI correlation. In this study, PI values were found to be significantly related to the AVM volume (Fig. 2A). However, a relation between \( V_m \) and AVM volume groups was not found to be statistically significant (Fig. 2B).

**TCD-Based Hemodynamic Grading System of AVMs**

To standardize the clinical data derived from this non-invasive technique, a new TCD grading system (for AVMs) was designed (Table 2), and its prognosticative capability was tested by correlating the results with Spetzler and Martin grading of the same group of patients with respect to postoperative neurologic deficits (Table 3; Fig. 3) and radiologic findings (Table 4; Fig. 4). PI was taken as the primary parameter of the grading system for two reasons: first, it was significantly correlated with the volume of the AVM, as indicated in this study as well as other previous papers, and second, as discussed above, PI was more dependable (than \( V_m \)) in the early postoperative period.

No quantitative study in the literature regards implications of TCD-generated data on the prognosis of AVMs. One report by Pasqualin and associates8 states that a PI value less than 0.5 should be suspected to negatively influence the prognosis, but this criteria was determined arbitrarily without volume PI complication matching. The proposed TCD-AVM grading system is the first attempt to quantify prognostic implications of TCD-derived hemodynamic data. To minimize methodologic drawbacks, the sample group consisted of a homogenous group of patients, and in addition to correlation of this suggested grading system with postoperative neurologic complications and radiologic findings, it was also correlated with Spetzler-Martin grading, which is the most commonly used anatomic grading system for AVMs.

Depending on results of volume-dependent groups, suggestive PI values indicating the range of each TCD-AVM grade were determined (Table 2). The better prognosis PI criteria of greater than 0.5, which were put forward by Pasqualin and associates,8 were determined as the separating numerical value for grades I and II. We found that, in accordance with Pasqualin’s data, no patient having PI > 0.5 (i.e., TCD-AVM grade I) experienced either transient or permanent neurologic deficits.

According to our data we concluded that the newly proposed TCD grading system significantly correlated with the postoperative neurologic deficits (Fig. 3). Furthermore, a significant correlation between the TCD grading system and hemodynamic complications determined on postoperative CT scans was observed (Fig. 4).

In the literature an ongoing debate discusses the validity of the notion of hemodynamic steal in AVMs.26,27 Both clinical data and evidence emerging from pathophysiologic studies suggest that the steal hypothesis should be called into question.18,26,27 The aim of this study was not to add to this discussion but to propose a correlation between a proposed TCD grading system for AVMs and their CT complications, which may or may not be attributed to steal phenomenon.

**TCD-Based Hemodynamic Grading of AVMs Reveals Additional Prognostic Information Complementary to Anatomic Gradings Such as Spetzler and Martin**

Retrospective study of data shows that both the proposed TCD-AVM grading system and the Spetzler-Martin grading system correlate well with
the neurologic and postoperative early radiologic untoward findings. But if the cases are analyzed individually, it can be understood that each of these grading systems, evaluating different aspects of AVMs, can provide prognostic information complementary to each other. A few example cases are stated (Table 1; Figs. 3, 4).

Case 13: This 35 year old female patient, who had a small (less than 3 cm in diameter), superficial AVM located in the calcarine cortex and who should have had a relatively low surgical risk (25%; Fig. 3B) according to Spetzler-Martin grading, eventually suffered from temporary visual field loss. On the other hand, preoperative TCD evaluation of this patient revealed a very low PI value (0.32) (i.e., grade IV associated with a 66% surgical risk; Fig. 3A) in the posterior cerebral artery feeder of this hemodynamically active AVM. In other words, TCD-AVM grading provided hemodynamic data warning of a high risk.

Case 10: Similar to the previous case, TCD-AVM grading was a better predictor of temporary motor weakness and early postoperative radiologic signs of hyperemic complications (Table 1; Figs. 3, 4).

Cases 3, 4, 10, 15, 16: All the patients having TCD-AVM grade III or IV and Spetzler-Martin grade IV or V eventually developed permanent or temporary neurologic complications and radiologic signs of hyperemic complications.

Cases 7, 9, 12, 17: None of the patients having TCD-AVM grade I or II and Spetzler-Martin grade I or II experienced any neurologic or radiologic complications.

Possible Uses of TCD-Based Hemodynamic AVM Grading System

The proposed TCD-AVM hemodynamic grading system may have two possible uses in the current management of AVMs:

1. In the prognostic evaluation phase of AVMs: Each AVM, after its diagnosis is confirmed and anatomically evaluated by cerebral angiography, should undergo TCD examination to obtain hemodynamic data for better prognostication. This study demonstrated that AVMs having higher TCD-AVM grades may have worse prognoses than AVMs in the same morphologic (e.g., Spetzler-Martin) grade. Therefore, complementary use of both grading methodologies possibly will provide a more comprehensive standardizable evaluation and prognostication.

2. In the follow-up study during stepwise embolization therapy (with or without surgery) or after radiosurgery: Serial TCD examination of AVMs can be used to test the physiologic success of the management modality.26,27 Articles on TCD usage in stepwise embolization of AVMs27,28 denoted that “repeated measurements during this treatment modality are easily achieved and noninvasive quantification of hemodynamic changes is possible. TCD may be helpful in the planning of the different steps of embolization.” Chioffi and colleagues21 concluded that TCD sonography was a valuable method for determining physiologic indications regarding timing of surgery after one or more embolizations. In fact, it was demonstrated previously that embolization resulted in hemodynamic changes which were quantitatively similar to those occurring after surgical resection of AVMs.17 Additionally, after radiosurgical treatment of AVMs, the gradual obliteration of the nidus can be hemodynamically monitored by repeated TCD examinations of the related feeders.31 “Staged surgery” was pointed out as another possible indication for TCD examination in the management of AVMs.32 The suggested TCD-AVM grading system may aid quantification of the hemodynamic changes that can be monitored by TCD in the clinical settings stated above. Accordingly, the proposed grading system may contribute to standardization of the language of physiologic changes in AVMs, a language used among neurosurgeons (interventional), neuroradiologists, and radiosurgeons.

CONCLUSIONS

In this study, a TCD-based hemodynamic AVM grading system was proposed and its clinical validity tested in a homogeneous group of patients. PI of the feeder artery was chosen as the primary parameter for the grading system, since it was found to be statistically more dependable in the volume-dependent changes and demonstrated that it returned to normal limits on postoperative day 1. It could be concluded that the proposed hemodynamic grading system correlates well with the Spetzler-Martin grading of the same patient group with respect to postoperative neurologic complications and radiologic untoward findings. When approved by other studies with a larger number of patients, the suggested grading
system may be complementary to the anatomically based grading methodologies. We conclude from this pilot study that the proposed grading system may contribute to the standardization and quantification of the hemodynamic changes during the management of AVMs, which becomes more important in a field that requires multidisciplinary collaboration.

REFERENCES