Continuous monitoring of jugular bulb oxygen saturation as a measure of the shunt flow of cerebral arteriovenous malformations

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Jugular bulb oxygen saturation (SjO₂) was monitored during preoperative embolization procedures in a consecutive series of 15 patients with large supratentorial arteriovenous malformations (AVM's) in order to test the hypothesis that changes in the shunt flow ratio can be continuously evaluated from the SjO₂. A fiberoptic catheter was placed at the dominant jugular bulb. The SjO₂ measured using jugular blood withdrawn before embolization was significantly higher than the SjO₂ measured at the end of the final embolization procedure (mean ± standard deviation 84.1% ± 12.7% vs. 74.2% ± 10.9%, p < 0.001), showing a positive correlation with the AVM volume (r = 0.66, p < 0.001). Continuous monitoring of SjO₂ via the fiberoptic catheter revealed a progressive decrease in association with the embolization procedures. Microsurgical resection of the AVM was performed at 1 to 2 weeks after the final embolization. Cases in which postoperative hemispheric deformation was revealed on computerized tomography demonstrated a higher SjO₂ at the end of embolization compared to that in the remaining cases (81.6% ± 8.6% vs. 67.8% ± 8.4%, p < 0.008). Hemispheric deformation was observed in all cases in which the SjO₂ did not decline to a level below 90% following embolization. The risk of severe hyperemic complications appeared to be greatly diminished when the SjO₂ fell to below 80%. Assuming that the oxygen saturation of the perfusion flow (SjO₂) ranges from 50% to 75%, the ratio of the shunt flow to total flow at an SjO₂ of 90% was estimated to be 0.6 to 0.8 based on the following equation: shunt flow/(perfusion flow + shunt flow) = (SjO₂ − SjO₂)/(arterial oxygen saturation − SjO₂). These results suggest that monitoring the SjO₂ provides real-time information concerning the progress of embolization and helps to determine whether the embolization has progressed sufficiently to avoid postoperative hyperemic complications.

Key Words • arteriovenous malformation • embolization • hyperemia • jugular bulb oxygen saturation

One substantial problem associated with the resection of a large arteriovenous malformation (AVM) is hyperemic complications, such as severe brain swelling and multifocal hemorrhages. It has commonly been inferred that such hyperemic complications result from circulatory breakthrough caused by an abrupt conversion of shunt flow to flow perfusing previously hypoperfused brain tissue, a phenomenon termed "normal perfusion-pressure breakthrough," by Spetzler, et al.

A large AVM volume and the early appearance of large draining veins have been thought to pose an increased risk of hyperemic complications related to a high preoperative shunt flow. In addition, the risk of hyperemic complications is reported to be related to clinical and/or angiographic evidence of steal. These circumstances are indicative of a low preoperative flow perfusing normal brain tissue, which may have caused maximum vasodilation and loss of the normal autoregulatory properties of the blood vessels. One important aspect of predicting hyperemic complications may therefore be the evaluation of the ratio between the shunt flow and the perfusion flow.

Blood flow measurements employing computerized tomography (CT) or single-photon emission CT could provide a measure of the shunt flow ratio: shunt flow/(perfusion flow + shunt flow); however, repeated measurements using these techniques are not feasible in practice. Some authors have recommended blood flow evaluations via transcranial Doppler ultra-
Jugular bulb oxygen saturation and AVM's

sound studies. While there is little doubt concerning the higher risk of hyperemic complications in cases with a very high flow velocity in the feeding artery, interpretation of the data yielded by such a technique is, in general, rather complex due to the varying structure of each AVM. More practical measures of the shunt flow ratio thus need to be developed.

Theoretically, arterial blood flow directly through the shunt does not deliver oxygen to the tissue. The draining veins of the AVM contain highly oxygenated blood, which is evidenced by the intraoperative finding commonly designated as "red veins." The jugular bulb oxygen saturation (SjO₂) has proved to reflect global cerebral hyperemia or ischemia sensitively.

In addition, fiberoptic technology is now available for continuous monitoring of the SjO₂ in a consecutive series of patients with large AVM's in order to estimate the shunt flow ratio. Hyperemic complications can probably be reduced by staged preoperative embolization, as avoiding abrupt changes in the shunt flow ratio. The aims of the present study were to determine whether SjO₂ sensitively reflects changes in the shunt flow ratio during embolization procedures and whether the shunt flow ratio estimated from the SjO₂ can predict hyperemic complications after subsequent microsurgical resection of the AVM.

Clinical Material and Methods

Patient Selection

This series consisted of 15 patients with large AVM's in whom the SjO₂ was measured continuously during planned preoperative embolization. While the maximum diameter of a "large" AVM has been defined variably by different authors (range > 4 to 6 cm), the AVM's included in this study have a maximum diameter of greater than 4 cm. Thirteen patients suffered episodes of hemorrhage. The patients and their families gave informed consent for the procedures described below.

In the present study the AVM volume was calculated as the product of the three angiographic diameters multiplied by 0.52, with a correction for the magnification factor according to the method reported by Fults and Kelly and Pasqualin, et al. According to this method, the AVM's varied in volume from 12 to 91 cc; all were fed by more than two major feeding arteries. The AVM location was classified from neuroradiological as well as intraoperative findings according to the categories of Yaşargil (Table 1).

Emboli Video

We generally considered microsurgical resection as a primary treatment for this group of patients. Due to the large size of the AVM, stereotactic radiosurgery was not considered. The purposes of the preoperative embolization were to reduce the blood flow in the feeding arteries and to avoid sudden changes in the shunt flow during surgical resection. We employed N-butyl-cyanacrylate (NBCA), polyfilament polyethylene threads (diameter 300 µ, length 5 to 10 mm), and/or polyvinyl alcohol (PVA) particles as embolization materials during the study period (1989 to 1991). The embolization procedures were repeated several times, each separated by 1 week and for one to three feeding arteries. No patient was subjected to general anesthesia. A microcatheter was inserted transfemorally into the feeding artery of the AVM. The catheter was connected via a Y-shaped connector to a pressure transducer, and the blood pressure of the feeding arteries was measured before and after each injection of embolization material. The embolization materials were injected via a flow-dependent balloon or Tracker microcatheter, usually until the mean blood pressure of the feeding artery was elevated to approximately 80 mm Hg.

Oxygen Saturation Measurements

A fiberoptic No. 4 French catheter system (Opticath and Oximetrix III system) was employed for continuous measurement of the SjO₂. The tip of the catheter was placed in the jugular bulb at the level between the base of the skull and the top of the C-2 vertebra. The catheter was placed on the dominant side based on findings from CT scans and previously obtained angiograms. The configuration of the venous sinuses was confirmed by retrograde injection of contrast medium through the catheter. The SjO₂ was also measured at the jugular bulb of the contralateral side in five patients. After correct positioning of the catheter had been confirmed radiologically, the system was calibrated in vivo using blood slowly withdrawn from the catheter. The quantitative data analyzed in the present study were those measured using blood withdrawn from the jugular bulb of the dominant side.

TABLE 1

<table>
<thead>
<tr>
<th>Location</th>
<th>No. of Cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>convexity AVM</td>
<td>15</td>
</tr>
<tr>
<td>frontal dorsal</td>
<td>1</td>
</tr>
<tr>
<td>parietal dorsal</td>
<td>2</td>
</tr>
<tr>
<td>parietal paramedian</td>
<td>1</td>
</tr>
<tr>
<td>anterior insular</td>
<td>2</td>
</tr>
<tr>
<td>temporal laterobasal</td>
<td>1</td>
</tr>
<tr>
<td>occipital laterobasal</td>
<td>1</td>
</tr>
<tr>
<td>occipital dorsal</td>
<td>1</td>
</tr>
<tr>
<td>occipital paramedian</td>
<td>1</td>
</tr>
<tr>
<td>central AVM</td>
<td></td>
</tr>
<tr>
<td>amygdalohippocampal</td>
<td>2</td>
</tr>
<tr>
<td>prepyramidal</td>
<td>2</td>
</tr>
<tr>
<td>callofetal</td>
<td>1</td>
</tr>
<tr>
<td>striocapsular</td>
<td>2</td>
</tr>
</tbody>
</table>

* Large arteriovenous malformation (AVM) = maximum diameter > 4 cm.
† Includes one case of multiple convexity AVM's.
‡ Includes one case of an AVM classified in both categories.

* Opticath and Oximetrix III systems manufactured by Abbott Laboratories, Abbott Park, Illinois.
AVM evaluated the flow of 50% blood through the shunt perfusion and monitored the saturation of oxygen using withdrawn arterial blood as well as by pulse oximetry at the finger.

**Shunt Flow Ratio**

The SjO₂ in cases of AVM represents a composite of the oxygen saturation of the shunt flow (SjO₂) and of the perfusion flow (SipO₂). Thus,

\[
SjO₂ = \text{shunt flow} + \text{perfusion flow} = SipO₂ \cdot \text{shunt flow} + SipO₂ \cdot \text{perfusion flow},
\]

Equation 1 can be rearranged as:

\[
\text{perfusion flow} = \frac{\text{shunt flow} (SjO₂ - SipO₂)}{(SjO₂ - SipO₂)}. \tag{2}
\]

The shunt flow ratio can then be rewritten by substituting for Equation 2 as:

\[
\text{shunt flow}/(\text{perfusion flow} + \text{shunt flow}) = \frac{SjO₂ - SipO₂}{(SjO₂ - SipO₂)}. \tag{3}
\]

Since blood flowing directly through the shunt does not deliver oxygen to the tissue, the saturation of this blood flowing through the shunt can be assumed to be the same as the SaO₂. Equation 3 then becomes:

\[
\text{shunt flow}/(\text{perfusion flow} + \text{shunt flow}) = \frac{SjO₂ - SipO₂}{(SaO₂ - SipO₂)} \tag{4}
\]

The SipO₂ can be assumed to be within the range of 50% to 75% when the brain is not globally ischemic (see below). The shunt flow ratio can therefore be evaluated from the SaO₂ and the SjO₂ measurements.

**Results**

It was found that the SjO₂ in patients with a large AVM was very high, exceeding 90% in seven cases in the present study (Table 2). A significant positive correlation existed between the SjO₂ determined from the withdrawn jugular blood before embolization and the AVM volume (p < 0.001, Fig. 1). The relationship between these two variables fits well into a logarithmic approximation. The SjO₂ was significantly greater in patients with AVM's showing clinical and/or angiographic steal than those with no clinical and/or angiographic steal (p < 0.002, unpaired t-test, Table 2). The SaO₂ was approximately 98% in all cases and demonstrated no change during the embolization procedures.

While in many cases the contrast medium flowing through the AVM revealed the transverse sinus of one side predominantly, there was no difference greater than 4% in the SjO₂ between the right and left jugular bulbs insofar as both transverse sinuses were patent. In one case, the AVM drained into the transverse sinus on one side through the vein of Labbé in addition to the sagittal sinus. The SjO₂ was measured at five different sites in this patient as the catheter was withdrawn in a stepwise manner from the confluence to the jugular vein. The SjO₂ was 82% at the confluence and at the middle of the transverse sinus on both sides, 84% at the confluence of the transverse sinus with the vein of Labbé and the sigmoid sinus, 82% at the jugular bulb, and 78% at the jugular vein a little below the top of the C-2 vertebra. Marked differences (in excess of 17%) were observed in the SjO₂ of two patients in whom the transverse sinus on one side was found to be either absent or occluded. The SjO₂ monitored by the fiberoptic catheter system did not deviate more than 5% from the data obtained from withdrawn blood in most instances, insofar as the system was calibrated in vivo at the beginning of the embolization procedure.

The SjO₂ decreased following embolization in association with an increase in the circulation time, the disappearance of early draining veins from the AVM, and evidence of steal on angiography (Fig. 2). Although the embolization was not complete in many cases in the present study because of the large AVM volumes, the SjO₂ determined from blood withdrawn

**Table 2**

<table>
<thead>
<tr>
<th>Classification</th>
<th>No. of Cases</th>
<th>Jugular Bulb Oxygen Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>pre-embolization</td>
<td>15</td>
<td>84.1% ± 12.7%</td>
</tr>
<tr>
<td>clinical &amp;/or angiographic steal</td>
<td>7</td>
<td>93.6% ± 4.4%</td>
</tr>
<tr>
<td>no clinical &amp;/or angiographic steal</td>
<td>8</td>
<td>75.9% ± 11.8%</td>
</tr>
<tr>
<td>postembolization</td>
<td>15</td>
<td>74.2% ± 10.9%</td>
</tr>
<tr>
<td>posthemispheric deformation</td>
<td>7</td>
<td>81.6% ± 8.6%</td>
</tr>
<tr>
<td>no posthemispheric deformation</td>
<td>8</td>
<td>67.8% ± 8.4%</td>
</tr>
</tbody>
</table>

* AVM = arteriovenous malformation. Statistical significance: † = p < 0.002, compared to no clinical and/or angiographic steal (unpaired t-test); ‡ = p < 0.0001, compared to pre-embolization (paired t-test); § = p < 0.008, compared to no postoperative hemispheric deformation (unpaired t-test).

![Graph demonstrating the relationship between the arteriovenous malformation (AVM) and the jugular bulb oxygen saturation. The curve represents a logarithmic approximation (r = 0.66, p < 0.001).](image-url)
Jugular bulb oxygen saturation and AVM's

Fig. 2. Carotid (left) and vertebral (right) angiograms obtained in the case of a 19-year-old woman with a large shunt flow and a total arteriovenous malformation volume of 36 cc before (A) and after (B) final embolization through the pericallosal artery. The intraluminal pressure of the feeding artery (pericallosal artery) rose from 32 to 68 mm Hg. The jugular bulb oxygen saturation was 93% before and 81% after the embolization. ICA = internal carotid artery; SS = straight sinus; VA = vertebral artery.

at the end of the final embolization procedure was significantly lower than that observed before embolization (p < 0.0001, paired t-test, Table 2). Continuous monitoring of SjO2 with a fiberoptic catheter during the embolization procedures revealed a rapid decrease immediately after embolization when NBCA was employed (Fig. 3).

The fall in SjO2 induced by a single injection of NBCA ranged from 2% to 14%. Although the SjO2 did not always decrease markedly following the initial injection, the decline in SjO2 increased as the embolization of the AVM progressed (Fig. 3). A large decrease was generally observed during the final embolization procedure (Table 3). When polyfilament polyethylene threads or PVA particles were employed as embolization material, a gradual decrease in SjO2 was observed as the numbers of injected threads or particles increased (Fig. 4). The SjO2 did not return to the original level within a period of observation ranging up to 2 hours, insofar as an appropriate amount of embolization material was injected. Headache, nausea, drowsiness, and/or neurological deficits were observed in three patients in whom the SjO2 was originally above 90%, then reduced by 12% to 22% following a single session of preoperative embolization. These complications disappeared within 1 week.

Severe complications were not encountered after microsurgical resection of the AVM's in the present series, owing presumably to the staged preoperative embolization. Midline shift and/or ventricular asymmetry caused by either brain edema or swelling was, however, demonstrated on postoperative CT scans in seven cases. With one exception, such hemispheric deformation was observed in all cases with an AVM volume of greater than 30 cc. Small intracerebral hemorrhages with or without intraventricular hemorrhage were noted in three of these cases. There was no significant difference in AVM volume between the cases asso-

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**Table 3**

Representative examples of sequential changes in feeding artery pressure and jugular bulb oxygen saturation before and after embolization procedures*

<table>
<thead>
<tr>
<th>Procedure No.</th>
<th>Feeding Artery</th>
<th>Feeding Artery Pressure (mm Hg)</th>
<th>Jugular Bulb Oxygen Saturation (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
<td>After</td>
<td>Before</td>
</tr>
<tr>
<td>1</td>
<td>Lt middle cerebral artery, anterior temporal artery</td>
<td>45</td>
<td>82</td>
</tr>
<tr>
<td>2</td>
<td>Lt posterior cerebral artery, posterior temporal artery</td>
<td>26</td>
<td>92</td>
</tr>
<tr>
<td>3</td>
<td>Lt middle cerebral artery, posterior temporal artery</td>
<td>80</td>
<td>89</td>
</tr>
</tbody>
</table>

* Measurements recorded in a 42-year-old man with a temporal lobarbasal and amygdalohippocampal arteriovenous malformation (volume 74 cc) embolized with N-butyl-cyanocrylate and polyfilament polyethylene threads. The patient suffered a headache for 3 days after embolization.

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J. Neurosurg. / Volume 80 / May, 1994

829
blood, from was associated with postoperative hemispheric deformation and the remaining cases (mean = standard deviation 49.6 ± 28.3 cc and 24.7 ± 28.7 cc, respectively). After embolization in the former group of patients, the SjO₂ was significantly greater than that in the latter (p < 0.008, unpaired t-test, Table 2). All cases in which the SjO₂ was not reduced by embolization to a level below 90% demonstrated hemispheric deformation on postoperative CT scans. In contrast, most cases in which the SjO₂ declined to below 80% following embolization revealed no hemispheric deformation. There were two exceptions in which hemispheric deformation was observed despite the SjO₂ being reduced to 80% or less by embolization; these cases revealed very high SjO₂ values (90% or more) before embolization. The clinical symptoms observed in association with hemispheric deformation in these cases were mild.

Discussion

Technical Considerations

The present study showed that the SjO₂ was very high in patients with large AVM’s. The SjO₂ levels were related to the AVM volume and steal phenomena. As the embolization procedures progressed, the SjO₂ declined in association with an increase in the circulation time, the disappearance of early draining veins, and evidence of angiographic steal. In addition to the data from repeated measurements using withdrawn jugular blood, continuous monitoring of SjO₂ using a fiberoptic catheter demonstrated a progressive decrease in SjO₂ in association with the embolization procedures.

These findings support the hypothesis that higher levels of SjO₂ reflect a larger shunt flow through AVM’s. In cases in which the transverse sinus on each side was patent, the difference in SjO₂ between the right and left jugular bulbs was not greater than 4%, suggesting that the possible range of overestimation caused by the SjO₂ being measured only at the dominant jugular bulb is not very large (see below). It should be borne in mind, however, that when the AVM drains into the infratentorial sinuses on one side, the SjO₂ measurement would overestimate the ratio of the shunt flow to the total flow perfusing both hemispheres. In cases in which the transverse sinus on one side is either occluded or absent, the SjO₂ measured at the jugular bulb of the other side naturally reflects the ratio of the shunt flow to the total flow, since both flows drain into the same transverse sinus. Thus, measurements of the SjO₂ using blood withdrawn from the dominant jugular bulb appear to provide a reasonable estimate of the shunt flow ratio in most cases. In addition, continuous monitoring of the SjO₂ using a fiberoptic catheter yields real-time information regarding changes in shunt flow.

Since the SjO₂ at the confluence and the jugular bulb did not differ, it does not seem necessary to place the catheter at the intracranial sinuses. Significant contamination with extracerebral blood did apparently occur, however, when the SjO₂ was measured from the jugular vein below the level of the C-2 vertebra. Bauer, et al., reported that the SjO₂ at the jugular vein ranged from 77% to 89% in a series of seven patients with large AVM’s. These values are comparable to those found in the present study if the difference in the SjO₂ between the jugular vein and the jugular bulb is taken into account.

Estimation of the Shunt Flow Ratio

Jugular bulb oxygen saturation normally varies from 60% to 75% and decreases to approximately 50% before the brain becomes globally ischemic. In patients with AVM’s, the perfusion flow may be reduced due to steal, and more oxygen will be taken up by the brain tissue under the limited flow, so that the SjO₂ may be lowered. Batjer, et al., reported an augmented vasodilatory reactivity in hypoperfused territories adjacent to high-flow AVM’s. This finding suggests that the vessels in the hypoperfused territories are still capable of dilating with further increases in metabolic demand, supporting the notion that the SjO₂ in such cases lies somewhere between 50% and 75% unless the brain is globally ischemic.

Based on these values and Equation 4, the shunt flow ratio can be estimated from the observed SjO₂ together with the SaO₂ (Fig. 5). For example, an SjO₂ of 90% suggests that the shunt flow ratio is within the range between 0.6 and 0.8. The possible range of overestimation, assuming a 4% error in SjO₂ (see above), is less than 0.2 at this level. Such a range of overestimation may be balanced by the possible underestimation arising from the assumption for the range of SjO₂, since the SjO₂ is probably not as high as 75% due to steal in cases with a large shunt flow. It should be borne in
Jugular bulb oxygen saturation and AVM’s

**Prediction of Hyperemic Complications**

Pasqualin, *et al.*, 28 reported that AVM’s with volumes greater than 20 cc are associated with significantly higher rates of postoperative hyperemic complications. In the present study, hemispheric deformity was observed only in cases with a much larger AVM volume, due presumably to preoperative embolization.

Quantification of the shunt flow ratio has significant clinical implications for the timing of surgical resection of AVM’s, since a large shunt flow appears to be the most important variable for predicting postoperative hyperemic complications.14,17,28,34 While several variables have been found to predict hyperemic complications, most are related to a large shunt flow ratio. An alteration in the range of autoregulation in hypoperfused territories represents another theoretical basis of normal perfusion-pressure breakthrough.24 Batjer, *et al.*, 2 demonstrated that AVM’s complicated by normal perfusion-pressure breakthrough are characterized by an augmented vasodilatory reactivity in the chronically hypoperfused territories adjacent to AVM’s. The location of the AVM28 and the presence of deep and/or long feeding arteries24,28,32 have also been reported to contribute to hyperemic complications. While these variables should also be evaluated carefully, a staged preoperative reduction in the shunt flow ratio is essential for preventing postoperative hyperemic complications.

The present data suggest that there is a high risk of postoperative hyperemic complications when the SjO2 is not reduced to below 90% by embolization. Hyperemia may also be responsible for the symptoms observed following a sudden and large decrease in the SjO2 by embolization from a level above 90%. When an SjO2 below 80% is achieved by embolization, the risk of fulminant hyperemic complication appears to be greatly reduced. In some of the cases with an SjO2 greater than 90% before embolization, postoperative hemispheric deformation was observed even though the SjO2 declined preoperatively to below 80%. It may be that a partial recovery of shunt flow occurs before surgery in such cases. Nevertheless, the observed clinical symptoms of postoperative hyperemia were mild in all cases in which the SjO2 was reduced to 80% or less. Continuous monitoring of SjO2 thus appears to help in determining whether the embolization has progressed sufficiently to avoid severe complications.

**Clinical Value of SjO2 Monitoring**

Angiographic analysis provides information concerning the shunt flow of only the vascular system visualized. The overall shunt flow is difficult to evaluate continuously by standard angiographic analysis. Monitoring of SjO2 appears to represent the most practical means for estimating changes in the shunt flow ratio in association with radiological and surgical management of large AVM’s. If postoperative hyperemia is the result of unregulated conversion of a large shunt flow to perfusion flow due to an alteration in the range of autoregulation,3 the SjO2 may be elevated when it occurs. While no such observation was made in the present study, the SjO2 may provide real-time infor-
rangement regarding the development of hyperemic complications if monitored intra- and postoperatively using a fiberoptic catheter. It is not yet certain what percentage of hyperemic complications is related to the pathophysiology designated as normal perfusion-pressure breakthrough. Monitoring of $\text{SO}_2$ in a larger series of patients would help to clarify its role in hyperemic complications in general.

Acknowledgments

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Y. Katayama, et al.
Jugular bulb oxygen saturation and AVM's


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