The application of ultrasound in the management of cerebral arteriovenous malformation

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Abstract: Ultrasound is used in the diagnosis, treatment and follow-up of cerebral arteriovenous malformation (AVM). Several parameters including flow velocity, flow volume, resistance index, pulsatility index, vasomotor reactivity and their influencing factors are reviewed. The applications of ultrasound in the preoperative evaluation, intraoperative monitor and postoperative follow-up of AVM, are summarized. Although some limits exist, ultrasound can provide more reliable information about AVM, if lesions are classified according to their characteristics, compared in different conditions between preoperation and postoperation, feeding and non-feeding side, patients and healthy adults, and if ultrasound method is combined with other examinations and different developed ultrasound techniques. With the appearance and development of new ultrasound technique, its application will be wider in management of AVM.

Keywords: arteriovenous malformation; ultrasound

1 Introduction

Cerebral arteriovenous malformation (AVM) is a common vascular disease in neurosurgery. Although the technique and devices have developed since the first description of AVM, the operation of large AVM is still a challenge for neurosurgeons. Ultrasound is most commonly used for the localization and characterization of intracranial and spinal masses. After reviewing literatures about ultrasound and cerebral AVM, we summarized the usage of ultrasound in the diagnosis, treatment and follow-up of the AVM.

2 Parameters

Several parameters used in ultrasound are helpful in the diagnosis and treatment of the AVM, which include peak systolic velocity (PSV), end-diastolic velocity (EDV), mean flow velocity (MV), resistance index (RI), pulsatility index (PI), flow rate (flow volume), cerebral circulation time, and

vasomotor reactivity. Hemodynamic parameters of basal arteries have been reported in the literatures on healthy adults.

2.1 Flow velocity The MV in a vessel with laminar flow represents the mean value of all the velocity components in the parabolic velocity profile. It is proportional to the flow rate and inversely proportional to the vessel cross-sectional area. As one of the most widely used techniques in AVM, transcranial Doppler (TCD) could record the PSV, EDV and MV of vessels.

In 1987, Grolimund *et al.*^[1] reported flow velocities in a group of 535 patients with normal neurologic status and no localized increases in intracranial or extracranial Doppler velocities. The mean velocity of middle cerebral artery (MCA) was 57.3 ± 14.8 cm/s; anterior cerebral artery (ACA), 49.2 ± 15.1 cm/s; posterior cerebral artery (PCA), 37.2 ± 10.4 cm/s; internal carotid artery (ICA), 36.3 ± 8.6 cm/s. Reutern *et al.*^[2] summarized several reports and calculated the mean values of PSV, EDV and MV were 89, 42 and 60 cm/s in MCA; 73, 34 and 50 cm/s in ACA; 55, 27 and 37 cm/s in PCA; 57, 28 and 35 cm/s in terminal segment of vertebral artery (VA) and basilar artery (BA). Mast *et al.*^[3] recorded the PSV and MV were 104 ± 14 , 67 ± 7 cm/s in MCA; 76 ± 17 , 47 ± 14 cm/s in ACA; 60 ± 13 , 44 ± 11 cm/s in PCA; 56 ± 13 , 39 ± 9 cm/s in BA/VA. Nagasawa *et al.*^[4] detected velocity of posterior circulation

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vessels, and results were 25.7 cm/s in PCA, 28.3 cm/s in BA, 18.5 cm/s in VA. Schöning *et al.*^[5] reported that mean $\pm$ SD values were 45.9 $\pm$ 9.6, 45.5 $\pm$ 10.8, and 39.2 $\pm$ 10.6 cm/s for time-averaged maximum velocity, and 28.3 $\pm$ 6.5, 30.6 $\pm$ 7.2, and 24.7 $\pm$ 8.4 cm/s for time-averaged velocity in the PCA, BA and VA, respectively. Tsuchiya *et al.*^[6] reported that corrected mean velocity of the horizontal MCA was 86 $\pm$ 17 cm/s.

2.2 Flow rate/flow volume Schmidt *et al.*^[7] reported the mean flow rate of ICA was 277 $\pm$ 25 mL/min (239-338 mL/min). Zheng *et al.*^[8] recorded the flow rate of extracranial segment of ICA was 268.10 $\pm$ 29.50 mL/min by the use of angle-independent dual-beam flow ultrasound technology. By the use of TCD, Manchola *et al.*^[9] reported that the flow volumes of MCA, ACA and PCA were 254 $\pm$ 13, 136 $\pm$ 14, and 79 $\pm$ 8 mL/min on the non-supplying side of AVMs, and 552 $\pm$ 47, 369 $\pm$ 70 and 484 $\pm$ 67 mL/min on the supplying side. Nagasawa *et al.*^[4] calculated the flow volumes of PCA and VA were 60 and 10 mL/min, respectively. Schöning *et al.*^[10] reported the mean $\pm$ SD values of flow volumes in ICA and VA were 265 $\pm$ 62 and 85 $\pm$ 33 mL/min on either side, respectively.

2.3 Resistance index and pulsatility index RI is introduced to Doppler sonography as a means of characterizing the peripheral resistance in the cerebral circulation. This index describes the ratio of the PSV to EDV. It has been generally accepted that RI is between 0.55 and 0.75 for the normal carotid artery. In arteries that supply high-resistance musculo-cutaneous beds, RI is greater than 0.75. And the arteries that supply the brain and those supplying the parenchymatous organs (e.g. the thyroid artery) have an RI less than 0.75. RI as an angle-independent parameter for vascular resistance [(Vmax-Vmin)/Vmax] in the downstream region is calculated from the spectral waveforms of the Doppler samples, while PI is calculated by the use of formula [(Vmax-Vmin)/Vmean]

Mast *et al.*^[3] reported in healthy adults the values of PI in MCA, ACA, PCA and BA/VA were 0.8 $\pm$ 0.2, 0.8 $\pm$ 0.2, 0.9 $\pm$ 0.2, 0.8 $\pm$ 0.2, respectively. Wang *et al.*^[11] found that there was significant difference in RI between lesion vessel and normal artery (0.34 $\pm$ 0.08 vs 0.60 $\pm$ 0.05), but there was no significant difference in PSV (82.6 $\pm$ 26.7 cm/s vs 73.7 $\pm$ 14.3 cm/s). They emphasized that the value of RI was important in the judgment of vessels and took the RI greater than 0.45 as the normal criterion.

All indices are not just the function of flow resistance but also influenced by vascular compliance and therefore are

age-dependent, which will be discussed later.

2.4 Vasomotor reactivity Hyperventilation or increased in-hale CO₂ concentration was applied to assess the reactivity of vessels. Carbon dioxide reactivity was calculated as percentage mean blood flow velocity change per mmHg of CO₂ change. In patients with repeated examinations, special care was taken to obtain the Doppler measurements with the same ventilation rate because flow depended strongly on PaCO₂.

2.5 Cerebral circulation time Schreiber *et al.*^[12] used echo-contrast “bolus tracking” by ultrasound to study cerebral haemodynamics. Global cerebral circulation time (CCT) was measured by extracranial Doppler as the time difference of contrast bolus arrival between the internal carotid artery and internal jugular vein. A total of 64 healthy volunteers and 9 patients with an angiographically diagnosed AVM were studied. CCT in volunteers and patients was calculated as the time interval between the points of 10% rise (CCT1) and 90% rise (CCT3) of the total intensity increase and between the turning points (CCT2) of the resulting time-intensity curves. In the volunteer group, CCT1 was 5.4 $\pm$ 1.8 s, CCT2 7 $\pm$ 1.3 s and CCT3 7.5 $\pm$ 1.8 s. CCT results in the AVM group were 2.8 $\pm$ 2.5, 3.0 $\pm$ 1.3 and 4.5 $\pm$ 2.1 s, respectively, and differed significantly from the controls. They confirmed a significant shortening of CCT in patients with cerebral AVM by ultrasound.

3 Factors that may affect ultrasound parameters

There are limits of devices and methods, for example, correcting the angle of insonation using transcranial color-coded sonography may enable estimation of blood flow velocities closer to the “true” values than those derived using conventional transcranial Doppler^[13]. Several factors may affect the parameters of ultrasound including age, sex, lesion, subarachnoid haemorrhage (SAH), hydrocephalus, increased intracranial pressure (ICP) and so on.

3.1 Age and sex The influence of age and sex has been noted in literatures. But the results of these studies are occasionally contradictory.

Schebesch *et al.*^[14] used an angle-independent Doppler system to measure flow velocity of 77 healthy persons. They found that the blood flow volume in the ICA decreased significantly with age. No side-to-side effects as well as no gender-related differences could be observed. There was no influence of hemoglobin, hematocrit and blood pressure in this

healthy population.

Torbey *et al.*^[15] found that MVs of MCA and ICA were lower in older patients (median 76 vs 114 cm/s; 76 vs 126 cm/s, respectively). The decline in flow volume with age may be associated with certain changes in the cerebrovascular hemodynamics such as decreased cerebral blood flow or metabolic demands, vessel-size changes, and lower cardiac output. Zheng *et al.*^[8] found that there were no significant difference in sex (female, 269.8±33.5 mL/min vs male, 265.7±23.7) in the blood flow volume of extracranial ICA, but significant difference in age. The blood flow volume was 281.3±22.8 mL/min in the group of younger than 35 years old, and 260.0±33.0 mL/min in the group of older than 35.

Dividing the subjects into age groups, Grolimund *et al.*^[11] found a significant decrease in MV in all arteries with increasing age. The mean difference between the oldest (> 70 years) and the youngest (< 30 years) age groups was 33%. Scheel *et al.*^[16] also found that flow velocities decreased significantly during ageing, and there were no significant side-to-side differences in flow velocities and flow volumes in any of the extracranial arteries. Due to a pronounced decrease in EDV, the RI decreased in ICA and VA during ageing.

However, Krejza *et al.*^[17] found that statistically significant differences between the sexes existed for the age group 20–40 years, so they took two mean normal reference values into account: 125 cm/s for women and 113 cm/s for men. Schöning *et al.*^[10] reported the mean values of flow volumes in ICA and VA, and there were no variation in age or sex. There were no significant variations between sides or days in cerebral artery blood velocities and PIs^[18].

Martin *et al.*^[19] reported that MV and EDV decreased significantly with age in all vessels, and PSV decreased significantly except in PCA. Blood velocities were higher in women except in the group of older than 60 years old. Velocities showed the least interhemispheric asymmetry in the middle cerebral artery and the greatest asymmetry in the posterior cerebral artery. RIs and PIs increased significantly with age in all vessels.

3.2 AVMs Due to low-resistance direct connections between the arterial and venous systems over AVM, the flow in the feeding vessels is increased in most cases and the pulsatility of the flow is reduced. A low RI value is also seen in cases where flow resistance is decreased with arteriovenous shunts. Side-to-side differences were significantly higher in patients

with AVMs than in those without a malformation.

In 1986, Lindegaard *et al.*^[20] had recorded blood flow velocities in basal cerebral arteries noninvasively in 28 patients with AVMs. In normal arteries remote from the AVM, flow velocities ranged from 44 to 94 cm/s (median 65 cm/s) with PIs from 0.65 to 1.10 (median 0.87). This is consistent with the findings in normal individuals. Arteries feeding the AVMs were identified by the high flow velocities (ranging from 75 to 237 cm/s, median 124 cm/s). The PIs ranged from 0.22 to 0.74 (median 0.48). The difference of these results from findings in normal remote arteries was highly significant. Uggowitz *et al.*^[21] had found that assessment of PSVs and RIs resulted in a higher (mean, 191.1 cm/s) and a lower (mean, 45.7%) value, respectively, in the feeding arteries as compared with the contralateral arteries (mean, 101.8 cm/s and 55.6%, respectively). Mast *et al.*^[3] concluded that by the use of TCD, sensitivity was high for medium-sized and large AVMs, but more than 50% of small AVMs were missed.

By angle-independent ultrasound, Rothoerl *et al.*^[22] examined flow volumes in the ICA of AVMs. All patients showed pre-operatively elevation on the side harboring the pathological lesion compared with normal values evaluated in 50 volunteers. The contralateral ICA showed volume flow values within the normal limit. After surgical resection of the malformation, normal values could be measured in all patients. Zheng *et al.*^[8] reported the similar results.

Murayama *et al.*^[23] reported that MV of vein was 39.0±22.5 cm/s before and 21.2±14.6 cm/s after the operation.

Diehl *et al.*^[24] reported a pathological increase in blood flow velocity (57.6%) and a decrease in vasomotor reactivity (72.7%) were frequently found in AVM feeding arteries. Vasomotor reactivity was also reduced in several nonfeeding arteries both ipsilateral (53.3%) and contralateral (30.8%) to the AVM.

Massaro *et al.*^[25] found that compared with nonfeeders, feeding arteries exhibited higher MV (68±5 vs 31±3 cm/s) and lower PI (0.64±0.03 vs 0.88±0.04); Carbon dioxide reactivity was (0.2±0.2)%/mm Hg in feeders and (2.1±0.2)%/mm Hg in nonfeeders, with no significant difference between arteries.

Hyperventilation tests indicate that flow through an AVM is independent of CO₂ variations, which can be used to enhance the diagnostic value of TCD investigation. De Salles *et al.*^[26] had assessed AVMs hemodynamics based on the

response of AVM feeding arteries to hypocapnia. Hyperventilation induced a significant decrease in MV and an increase in the PI. Carbon dioxide reactivity was 0.92 ± 1.12 for feeding vessels and 2.59 ± 1.78 for nonfeeding vessels. Hyperventilation induced significantly more hemodynamic changes in control and nonfeeding MCA than in feeding vessels. So it may be helpful of impaired CO_2 reactivity to identify AVM feeding vessels.

3.3 Other factors Blood flow velocity in a major cerebral artery can increase not only because of narrowing of its lumen but also because of hyperemia. Increased ICP, hydrocephalus, SAH, blood pressure and so on may affect the parameters of ultrasound.

Jindal *et al.*^[27] found that fall in PIs correlated well with decrease in ventricle size. Independent of the type of intracranial pathology, a strong correlation between PI and ICP was demonstrated. Therefore, PI may be of guiding value in the invasive ICP placement decision in the neurointensive care patient^[28].

Patients with SAH but no pathologic angiogram showed an incidence of 55.6% pathologically increased velocities in the basal cerebral arteries. There is a direct correlation between the increase in velocity and the amount of CT-visualized cisternal blood^[15].

If autoregulation is intact, cerebral blood flow remains constant within a wide range of mean arterial blood pressures. Under these conditions, changes in mean blood pressure should influence TCD measurements to only a minor degree.

4 Clinical applications

In clinical, ultrasound is important in the diagnosis of middle and large AVMs, location of nidus, identification of vessels, modification of drift in navigation operation, and identification of complete resection. Intraoperative sonography is becoming increasingly important in neurosurgery. AVMs are recognized as multiple vessels lying side by side that display chaotic, multidirectional blood flow without intervening brain tissue in the scale imaging.

4.1 Preoperation Cerebral angiography is considered the gold standard for making the diagnosis, but this method is invasive and less convenient than ultrasound.

As discussed above, ultrasound is a useful tool to evaluate the hemodynamic parameters of AVM before the operation. Zhuang *et al.*^[29] reported that transcranial power Doppler

image had detected 23 cases of AVM, which size and location were well correlated to the results obtained by cerebral angiography.

4.2 Intraoperation Intraoperative ultrasonographic examination during the surgical treatment of AVMs is a non-invasive, useful, and simple diagnostic tool in the detection of the components and accompanying parts of the lesion. It is a valuable adjunct in the localization and excision of the AVM and has been used in AVM surgery.

The value of intraoperative real-time ultrasound during surgery of AVMs has been investigated by many researchers^[11,30-36]. The niduses of AVM are localized and defined precisely by ultrasound due to their dichromatic flow pattern. The appearance of AVMs can be divided into two parts, a hyperechogenic thrombotic part and a hypoechoic perfused part in the sonography. The feeding and draining vessels are distinguished from normal ones morphologically and hemodynamically. Intraoperative real-time ultrasound allows accurate localization and navigation of the cerebral AVMs, provides valuable information during surgery, and helps determine the degree of removal of the cerebral AVM. However, complete removal of the AVM, determined by sonography should be confirmed by angiography.

The assessment of PI and RI is helpful to the judgment of supplying vessels and whether the nidus was totally removed. Dempsey *et al.*^[37] measured RI of vessels around the nidus to distinguish feeding arteries from en passant and normal vessels. The mean pre-resection RI of vessels feeding the AVM was 0.34 ± 0.01 . The postresection RI was 0.62 ± 0.04 . The postresection scan identified a nidus with persistent low RI flow. Comparison of pre-resection and postresection RI accurately indicated the completeness of resection. Yu *et al.*^[30] measured the RI to differentiate the feeding arteries and draining veins. The mean RI of AVMs' feeding arteries was 0.36 before and 0.62 after removal of AVM. They suggested that further evaluations should be taken to exclude the remnants of AVM whether the RI was less than 0.5 after the presumed totally resection.

With so-called "burst-refill" technique, Wang *et al.*^[38] successfully identified the vascular anatomy of malformation lesions in multi-planes. They concluded that by applying ultrasound contrast-specific imaging combined with intraoperation ultrasound, the real-time perfusion of microbubbles and its perfusion pattern followed "artery-tissue-

vein procedures” can be observed. Their results made the judgments of supplying arteries and draining veins more reliable.

Ultrasound can be used to adjust the brain shift during the operation, which is a problem of neuronavigation. Mathiesen *et al.*^[39] have reported an intraoperative imaging and navigation system which used navigation on intraoperatively acquired three-dimensional ultrasound data, as well as preoperatively acquired magnetic resonance imaging scans and magnetic resonance angiograms (MRA). Angiographic reconstructions of three-dimensional images were obtained before and after resection. Intraoperative ultrasound corresponded well to the intraoperative findings and allowed confirmation of feeding vessels in surrounding gyri and rapid identification of the perinidal dissection planes, regardless of brain shift.

Akdemir *et al.*^[40] used neuronavigation and intraoperative microvascular Doppler sonography to identify afferent and efferent vessels and control the totality of the surgical resection of AVMs, which was a safe, effective, and reliable method for identifying the afferent and efferent vessels and for confirming the complete resection.

4.3 Postoperation Ultrasound is also used in the follow-up of the AVMs. Tyagi *et al.*^[41] evaluated blood flow velocities in the basal cerebral arteries in 41 patients with supratentorial AVMs, using a transcranial Doppler instrument. On follow-up study at 3 months, blood flow velocity in feeding cerebral artery was found to be increased in 47 percent of patients who were embolized, but remained normal in all the patients who underwent surgery, which were found markedly decreased in both the groups at 24 h after intervention. Ultrasound investigations were also used to measure the haemodynamic changes before and after AVM super-selective embolization operation^[42,43].

5 Limitations

There are some limitations in the application of ultrasound in the managements of cerebral AVMs. Unlike the value of blood pressure, no universal accepted normal ranges of these parameters are established. As showed above, many factors may influence the true values of ultrasound parameters. And in healthy adults, values of parameters varied according to different researches. Uggowitz *et al.*^[21] discussed that since a complete evaluation of the complex blood sup-

ply and drainage of AVMs was unrealistic with ultrasound, a confident morphologic evaluation of the involved vessels along with the establishment of cut-off values of PSV, RI, or side-to-side differences was highly questionable. It is more reasonable that differences between bilateral vessels might be better criteria for diagnosis and monitor than absolute values.

The size and location of AVMs have influences on the detection of ultrasound. Smaller AVMs have lower flow volume, so they are less likely be detected by the preoperative ultrasound sonography. Mathiesen *et al.*^[39] argued that the spatial resolution of ultrasound depended on flow volume and flow speed. Arteries with a flow velocity of greater than 5 cm/s or diameter of greater than 0.5 mm seem to be detectable, whereas cerebral angiograms depict vessels down to a diameter of 0.1 or 0.2 mm. Adequate acoustic windows are necessary for the preoperative sonography, so the lesion locating in the posterior fossa is unable to be detected.

One of the primary applications of ultrasound in AVMs is to confirm the total resection of lesions in the operating room without angiography. However, it is possible that in some lesions, regions of low-velocity blood flow or areas with very small vessels (i.e., much smaller than 0.6 mm in diameter) will be missed with ultrasound. Hence, abnormalities such as venous angiomas on cryptic AVMs with low velocity blood flow or thrombosed vessels may not be discernible in sonography. So the postoperative ultrasound findings should be confirmed by angiography.

There are some problems in different techniques of ultrasound. Both the angle-dependent TCD and the examiner technical skills make the measurements less reproducible. New angle-independent techniques, such as angle-independent dual-beam flow ultrasound technology^[8], and ultrasound contrast-specific imaging^[38] have been used with more reliable depiction of the entire arterial blood supply and the venous drainage of cerebral AVMs.

Hölscher *et al.*^[44] found that intraoperative ultrasound using the phase inversion harmonic imaging (PIHI) technique was sensitive to the nonlinear acoustic response of tissue, and especially to ultrasound contrast agent microbubbles PIHI enabled intraoperative visualization and morphological assessment of neurovascular pathologies. In combination with an ultrasound contrast agent, the flow dynamics of these lesions can be displayed in real-time.

As some authors^[45,46] suggested, transcranial color-coded duplex sonography (TCCD) should not be used as a screening method for cerebral AVMs, but should be used as a valuable noninvasive method for the diagnosis and long-term follow-up of intracranial AVMs. Baumgartner *et al.*^[47] concluded that as one of noninvasive or minimally invasive techniques for the study of the intracranial circulation, TCCD was relatively inexpensive and permitted bedside examination and improved the accuracy and reliability of conventional transcranial Doppler studies. The main limitation of TCCD is the ultrasonic windows. They restrict the area of insonation to the major cerebral arteries and the proximal part of its branches, lower the spatial resolution, and may prevent transtemporal insonation.

The identification of vessels on the basis of their color on the images provides information only about the position of a vessel in the sonography and the direction of blood flow relative to the scan head. There are multiple tortuous feeding arteries and draining veins or arterialization of veins which can not be distinguished on the basis of color alone. Hence, the distinction between feeding arteries and draining veins still depends on the surgeon's understanding of the patient's vascular anatomy that showed in the preoperative angiography.

6 Summary

Ultrasound is used in the preoperative evaluation, intraoperative monitor and postoperative follow-up of cerebral AVMs. As no normal values of the parameters in ultrasound are established by now, we suggest that classification, comparison and combination should be noted in the application of ultrasound in cerebral AVMs.

According to the size and location of AVM, classification is helpful in determining the application of ultrasound, for the ultrasound is less sensitive in small one and unable to detect the lesion in the posterior fossa. Comparison of parameters before and after operation, on feeding and non-feeding side, in patients and healthy adults, can provide dynamic and more reliable information about AVMs. Combination should be emphasized, including combination with other examinations and different ultrasound techniques, to get comprehensive information of the lesion.

Although some limits exist, ultrasound provides hemodynamic and real-time information that can not, or at least

inconveniently, be provided by MRA and angiography. With the development of ultrasound technique, its application will be wider and more reliable in the managements of cerebral AVMs.

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超声技术在脑动静脉畸形中的应用

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摘要: 超声技术常应用于脑动静脉畸形诊断、治疗以及随访。本文回顾了用超声技术测量脑血管血流速度、流量、脉搏指数、阻力指数、血管反应性等指标以及其相关影响因素, 总结了超声技术在脑动静脉畸形的术前评估、术中监测以及术后随访中的应用。尽管超声技术目前不能作为脑动静脉畸形的筛选手段, 但是, 如果根据脑动静脉畸形病变特性分组选择检查方法, 对比患者在手术前、后, 供血侧与非供血侧以及患者与健康人群之间的检查结果, 配合其它检查手段以及不同的超声成像技术, 超声技术则能提供更为可靠的诊断信息。随着新的超声技术的出现和发展, 超声在动静脉畸形方面的应用会更加广泛。

关键词: 动静脉畸形; 超声