Transcranial Doppler Ultrasound for the Assessment of Intracranial Arterial Flow Velocity—Part 1
Examination Technique and Normal Values

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We present the examination technique and normal values of flow velocity from intracranial basal cerebral arteries for a recently developed pulsed Doppler system operating at 2 MHz emitting frequency. Peak systolic, peak diastolic, and mean flow velocity values are analyzed from fast-Fourier transformed (FFT) Doppler spectra at selected depths for 50 presumed normal subjects ranging in age from 22 to 79 years. Interindividual variation is high for peak flow but moderate for mean flow velocity values, which hence are more likely to discriminate normal from abnormal. Flow velocity values within the posterior cerebral artery (PCA) and the basilar artery (BA) are significantly lower than in the anterior cerebral artery (ACA) and the middle cerebral artery (MCA), which is also unique in showing significantly decreasing values with increasing age: calculated mean flow velocities are 47.3 ± 13.6 and 45.3 ± 13.5 cm/sec in the ACA, and 58.4 ± 8.4 and 44.7 ± 11.1 cm/sec in the MCA in patients <40 years and >60 years, respectively, but 34.2 ± 7.8 and 29.9 ± 9.3 (PCA) (patients <40 years and patients >60 years), and 34.9 ± 7.8 and 30.5 ± 12.4 (BA) (patients <40 years and patients >60 years). A new scanning system is introduced, which we suggest will reduce interindividual variations and improve the accurate separation of nearby vessels, which are major causes for the comparatively large standard deviations at present.

KEY WORDS: Transcranial Doppler ultrasound; Pulsed Doppler; Intracranial cerebral arteries; Cerebral blood flow

Although Freund and Kapp [7] described a noninvasive method for examining intracranial arterial pulsations by ultrasound in 1966, and although during the last decade continuous-wave (CW) and pulsed-wave (PW) Doppler techniques (4–10 MHz) have been extensively reported as providing accurate evaluation of extracranial arterial obstructive lesions [3,4,9,11,12,21], the application of noninvasive ultrasound for measurement of intracranial cerebral arterial flow has been impeded, mainly by the properties of bone, which represent an important obstacle to the penetration of ultrasound. Attenuation of the ultrasonic wave near the skull has resulted in weak or barely reproducible reflections, making adequate recordings of blood flow velocities from intracranial arteries impossible.

In 1982 Aaslid et al [2] introduced a high-energy bidirectional pulsed Doppler system operating at lower frequencies (1–2 MHz), which, for the first time, enabled a reliable measurement of flow velocity from distinct cerebral arteries at the base of the skull. This method was suggested to be useful for evaluation of the cerebral circulation in vascular occlusive disease as well as for the detection of vasospasm after subarachnoid hemorrhage [1,8,15,19].

The present study describes the examination technique developed for identification of the intracranial carotid (ICA), middle cerebral (MCA), anterior cerebral (ACA), posterior cerebral (PCA), intracranial vertebral (VA), and basilar arteries (BA). It also includes normal reference values (hitherto unknown) of 50 presumed healthy subjects from different aspects of the fast-Fourier transformed (FFT) Doppler spectra.

Patients, Methods, and Examination Procedure

Patients

Fifty presumed healthy subjects, ranging in age from 22 to 79 years (24 men and 26 women), were studied. Neither their history nor a neurologic examination revealed any signs or symptoms of cerebrovascular disease. In addition, extracranial CW-Doppler ultrasound examination for the evaluation of both carotid and ver-
rebral arteries (Debimetre ultrasonique Delalande) and duplex system studies for visualization of the extracranial carotid system (Diasonis DRF 400) were used to exclude extracranial arterial disease (for details see references 10 and 21). In 16 patients (mean age 67.5 years, age range 55–79 years) four-vessel arteriograms were available for comparison but did not show any definite abnormality.

**Methods**

A microprocessor-controlled directional PW-transcranial (TC) Doppler device operating at 2 MHz was used for studying the basal cerebral arteries (EME, Überlingen). Using a range-gated transducer, measurements were taken from selected areas at depths ranging from 25 to 125 mm at 5 mm steps, with an optimal focus of the ultrasonic beam to a sampling volume of approximately 10 mm in length and 4 mm in diameter at a depth of about 50 mm. The ultrasonic burst length was 10 µsec, pulse repetition frequencies were 6.8–18 kHz, high-pass filter was 100 Hz, and the low-pass filter ranged from 3.4 to 9 kHz. The ultrasonic power emitted varied between 10 and 100 mW/cm².

As the angle between the ultrasonic beam and the direction of the intracranial arteries cannot be determined exactly, estimation of either the Doppler frequency shift (Hz) or the flow velocity (cm/sec) computed by a 64-point FFT spectrum analyzer (EME, Überlingen) is limited. However, optimal recording of the intracranial flow provided an angle between the ultrasonic beam and the axis of the vessel ranging from 0 to 30 degrees with its cosine between 1 and 0.86, which keeps the maximum error reasonably below 15%. The relationship between Doppler shift frequency (Δf) and flow velocity (v) for measurements performed with an ultrasonic instrument operating at 2 MHz is given by the equation:

\[ v = 0.039 \times \Delta f. \]

In this respect the MCA is favorably located when the transducer is placed on the temporal bone, whereas variations of the size and location of the ACA and PCA may result in less reliable data and even difficulties in recording from these vessels. The instantaneous peak velocities in systole and late diastole as well as the averaged mean flow velocity were considered for statistical evaluation from the FFT spectra. Time interval resolution was 25 msec and Doppler signal amplitudes were coded in a grey scale system (dB). Measurements were adjusted to different depths of the sampling volume. All data were recorded on a printer (Hewlett-Packard) and stored on video tape (Sharp).

**Examination Procedure**

Identification and separation of the basal cerebral arteries were performed by determination of flow direction, audio-analysis, depth control of the range-gated Doppler signals, and occasionally by compression tests on the neck arteries. Patients lay comfortably in a supine position in order to prevent fluctuations of cerebral blood flow as a result of hypercapnia or hypocapnia; PCO₂ end-tidal values, measured by use of an Engström aerometer, were kept constant. Moving the probe in small steps in the temporal region, preferably at a depth of 50 or 55 mm, the ultrasonic window had to be determined first. In most subjects selected, the acoustic window could easily be adjusted at a reasonably low signal to noise ratio (recent experience from more than 1500 investigations performed in our laboratory indicate that about 5% of subjects are unable to be examined using the transtemporal approach because of poor ultrasonic bone windows; in contrast, the transorbital and transnuchal pathways were almost always applicable). Identification of the various basal cerebral arteries is then required. The MCA is the easiest to record, at a depth between 30 and 60 mm (Figure 1). The main trunk of the MCA (M1 segment) and proximal branches (M2 segment) reveal a flow directed towards the probe. Distal branches (M3 segment) cannot be as confidently recorded because of their nearly perpendicular axis to the ultrasound beam. Once the MCA is identified, its course can be tracked by small angle movements of the ultrasonic probe until a Doppler signal in the opposite direction and usually of weaker intensity is identified: this signal represents the ACA (between 60 and 75 mm).

Tilting the probe caudally, the C1 segment of the internal carotid artery (ICA) can usually be examined. The C2-C4 segments of the carotid siphon can be evaluated by a transorbital approach in 50–80 mm depths at a reduced ultrasonic power emitted. The ophthalmic artery may be followed from 30 to 50 mm.

Aiming the probe at a posterior position and slightly caudal to that of the MCA, the PCA can usually be recorded at depths between 60 and 80 mm (Figure 2). In the proximal segment (P1) the flow is directed towards the probe like in the MCA. The distal segment (P2) as well as the contralateral PCA-P1 segment show flow in the opposite direction. In contrast to the MCA, the signal is lost when scanning outwards below 50–55 mm.

Compression tests on the ipsilateral common carotid artery (CCA) may answer the question as to whether the PCA is directly supported by the ICA, which can be seen in about 10–30% of cases [16,20]; in this case CCA compression would cause a reduction of flow velocity. However, if the PCA is supplied by the basilar artery CCA compression would result in an increase of
Figure 1. Schematic illustration of the position of the sample volume (A) and flow velocity spectra (B) of the MCA, and the T-junction of the ICA and the ACA for the transcranial approach. Distance between sample volume position and the transducer is indicated (mm of depth) below the symbol demonstrating flow direction: Flow towards the probe (→) is np flow away from the probe is represented by a downward signal. Abbreviations: ICA, internal carotid artery; ACA, anterior cerebral artery; A. opt., ophthalmic artery.
Table 1. Normal Age-Adjusted Calculated Mean ± SD Values of TC-Doppler Flow Velocity within the Basal Cerebral Arteries as Recorded from Selected Reference Points

<table>
<thead>
<tr>
<th>Arteries (depth in mm)</th>
<th>Systolic peak velocity (cm/sec)</th>
<th>Averaged mean velocity (cm/sec)</th>
<th>Diastolic peak velocity (cm/sec)</th>
<th>Age (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA (50 mm)</td>
<td>94.5 ± 13.6</td>
<td>n.s.</td>
<td>58.4 ± 8.4</td>
<td>n.s.</td>
</tr>
<tr>
<td>91.0 ± 16.9</td>
<td>n.s.</td>
<td>57.7 ± 11.5</td>
<td>n.s.</td>
<td>44.3 ± 9.5</td>
</tr>
<tr>
<td>78.1 ± 15.0</td>
<td>*</td>
<td>44.7 ± 11.1</td>
<td>*</td>
<td>31.9 ± 9.1</td>
</tr>
<tr>
<td>ACA (70 mm)</td>
<td>76.4 ± 16.9</td>
<td>n.s.</td>
<td>47.3 ± 13.6</td>
<td>n.s.</td>
</tr>
<tr>
<td>86.4 ± 20.1</td>
<td>n.s.</td>
<td>53.1 ± 10.5</td>
<td>n.s.</td>
<td>41.1 ± 7.4</td>
</tr>
<tr>
<td>73.3 ± 20.3</td>
<td>*</td>
<td>45.3 ± 13.5</td>
<td>*</td>
<td>34.2 ± 8.8</td>
</tr>
<tr>
<td>PCA (60 mm)</td>
<td>53.2 ± 11.3</td>
<td>n.s.</td>
<td>34.2 ± 7.8</td>
<td>n.s.</td>
</tr>
<tr>
<td>60.1 ± 20.6</td>
<td>n.s.</td>
<td>36.6 ± 9.8</td>
<td>n.s.</td>
<td>28.7 ± 7.1</td>
</tr>
<tr>
<td>51.0 ± 11.9</td>
<td>*</td>
<td>29.9 ± 9.3</td>
<td>*</td>
<td>22.0 ± 6.9</td>
</tr>
<tr>
<td>VA/BA (75 mm)</td>
<td>56.3 ± 7.8</td>
<td>n.s.</td>
<td>34.9 ± 7.8</td>
<td>n.s.</td>
</tr>
<tr>
<td>59.5 ± 17.0</td>
<td>n.s.</td>
<td>36.4 ± 11.7</td>
<td>n.s.</td>
<td>29.2 ± 8.4</td>
</tr>
<tr>
<td>50.9 ± 18.7</td>
<td>*</td>
<td>30.5 ± 12.4</td>
<td>*</td>
<td>21.2 ± 9.2</td>
</tr>
</tbody>
</table>

Abbreviations: MCA, middle cerebral artery; ACA, anterior cerebral artery; PCA, posterior cerebral artery; VA, vertebral artery; BA, basilar artery; n.s., not significant.

* p < 0.05

flow velocity if the posterior communicating artery is patent.

Common carotid artery compression maneuvers for the assessment of the anterior communicating artery may similarly cause marked changes of flow direction, velocity patterns, or both in this vessel and the ACA [2]: ipsilateral compression frequently results in an inverse flow while contralateral CCA compression increases the velocity. These tests may be particularly important for evaluation of the collateral capacity in the presence of extracranial obstructive lesions or for identification of the ACA if morphologic variations are present, e.g., aplasia of the A1 segment (<1.0%) or hypoplasia (3-10%) [16,22]. Compression of the CCA should be avoided if mild compression has already introduced significant alterations of the cardiac rhythm. In addition, care should be taken to compress the CCA definitely below the bifurcation at an area free of atheroma as revealed by prior CW-Doppler and/or duplex-system examinations.

The VA and BA can be easily and most consistently recorded from a nuchal position via the posterior bone and/or the foramen magnum. However, separation of these arteries may be limited because of: (1) the variable site of the vertebobasilar junction; (2) anatomical variations in course and length of the BA (approximately 33 mm mean value); and (3) variable distances of the BA to the clivus (<90 mm in about 80% and >100 mm in about 20% of normal subjects) [5,13,22]. In the presence of hypoplasia or aplasia of either of the VAs, separation of the remaining VA from the BA may not be possible at all. For the same reasons, the depth at which the BA can be expected is uncertain. Although signals recorded deeper than 80 mm may be estimated to result from the BA, we occasionally identified the confluence...
Figure 4. Range of normal values as recorded at various depths (indicated in numbers in each column) from the MCA of various age groups for the peak systolic and mean velocities, respectively. Calculated mean values are indicated by the small horizontal bars within each column.

Figure 5. Calculated systolic peak velocity values and standard deviations recorded from presumed normal subjects of two age groups: people younger than 40 years (---) and people older than 60 years (—). Reference depths of recordings are indicated for the MCA, ACA, PCA, and VA/BA. Note the marked difference of calculated values for the MCA in contrast to the other basal cerebral arteries.
located as deep as 90 and 110 mm. With regard to these variations, identification of other bidirectional signals or signals toward the probe is difficult, although one might speculate whether or not they reflect flow in branching vessels of the VA/BA [posterior inferior (PICA) and anterior inferior (AICA) cerebellar arteries] (Figure 2C). Compression tests of extracranial carotid or vertebral arteries—the latter being rather difficult to perform for anatomical reasons—are insignificant for this purpose.

In addition, a pulsatility transmission index (PTI) is introduced for a bilateral comparison of the Doppler spectra recorded. This dimensionless parameter is expressed in percent of the pulsatility indices (PI) of either side [15] as indicated in Table 2:

$$\text{PTI} = \left( \frac{\text{PI ipsilateral}}{\text{PI contralateral}} \right) \times 100.$$  

Statistical evaluations were performed using the Wilcoxon test for nonparametric samples.

Results

Doppler recordings of sufficient intensity to allow reliable estimation of flow velocities within both MCAs, both ACAs, both PCAs, and the VA/BA are obtained in 96%, 82%, 88%, and 100%, respectively. Because subjects with small ultrasonic bone windows were excluded from this study, these figures will be lower in a random population. Table 1 summarizes the analyzed mean values and standard deviations of the systolic and diastolic peak as well as the mean Doppler flow velocities as recorded at selected reference depths where the vessels considered could be identified most consistently. For all three age-groups the values measured from the reference points of the MCA and ACA revealed a highly significant difference (p < 0.001) from those measured within the PCA and VA/BA, which reflects the major difference between the carotid and vertebral arterial systems.

Age-related data from the ACA, PCA, and VA/BA show a slight but nonsignificant increase of all parameters with increasing age (from <40 to 40–60 years) (p < 0.1) and a decrease for the oldest subgroup. In contrast, values of all parameters within the MCA decreased with age.

Whereas in the MCA peak and mean velocities decrease with increasing age, values from the ACA near the anterior communicating artery increase in older subjects (Figure 3). This increase is probably due to mild atherosclerosis within these small vessels even in presumed normal subjects with normal arteriograms (n = 16), and thus should be considered to avoid overestimation of pathologic processes.

Interindividual variation is particularly high for the peak systolic flow velocity as is the range of normal for these values (Figure 4). In contrast, standard deviations of the mean flow velocities are considerably smaller throughout all the different age groups and less variable to the selected depths of recordings.

As shown in Figure 5, consideration of different parameters, recording sites and age-dependence of flow velocity are particularly relevant for the MCA. In contrast to all the other basal cerebral arteries this vessel can be regularly tracked along a comparatively large course at the base of the skull.

No significant difference between flow velocity values recorded from either of bilaterally existing arteries could be established provided insonation was similarly possible from both temporal windows. However, interindividual variations are large, as reflected by the data shown in Table 2.

A recently designed, new pulsed Doppler device, which enables two-dimensional scanning of the basal cerebral arteries and uses a considerably smaller sample volume (4 x 5 mm) was used for some preliminary studies in a few subjects of this report. As shown in Figure 6 this system enables: (1) a stereo assessment of the intracranial recording sites with reference to the individual probe position of the subject examined; (2) demonstration of the topography of the arteries recorded in horizontal, sagittal, and frontal planes; and (3) a sensitive differentiation of nearby vessels even if they show the same flow direction, e.g., distal carotid siphon, proximal MCA, and the posterior communicating artery. In addition, because of the smaller sample volume incorporated, a better delineation can be achieved of small vessels that hitherto could not be recorded reliably, e.g., the posterior communicating and the superior cerebellar arteries.

Discussion

Although extracranial CW- and PW-Doppler ultrasound techniques have been used for the evaluation of both carotid and vertebral arterial systems and have gained acceptance during the last decade [3,4,9,11,12,21], both

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**Table 2.** Calculated Mean and Standard Deviation of Pulsatility Indices from both MCA, ACA, and PCA in all Presumed Normal Subjects Studied

<table>
<thead>
<tr>
<th>Arteries</th>
<th>Pulsatility index</th>
<th>Regression coefficient</th>
<th>U-test</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCA right</td>
<td>0.90 ± 0.24</td>
<td>r = 0.54</td>
<td>n.s.</td>
</tr>
<tr>
<td>MCA left</td>
<td>0.94 ± 0.27</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ACA right</td>
<td>0.78 ± 0.15</td>
<td>r = 0.6</td>
<td>n.s.</td>
</tr>
<tr>
<td>ACA left</td>
<td>0.85 ± 0.17</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PCA right</td>
<td>0.88 ± 0.23</td>
<td>r = 0.74</td>
<td>n.s.</td>
</tr>
<tr>
<td>PCA left</td>
<td>0.88 ± 0.20</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Abbreviations: MCA, middle cerebral artery; ACA, anterior cerebral artery; PCA, posterior cerebral artery; n.s., not significant.

Values are mean ± SD. Pulsatility indices were determined using the following equation: PI = (Vp - Vd)/Vd, where Vp is systolic peak velocity, Vd is diastolic peak velocity, and Vm is averaged mean velocity.
methods are unable to provide similarly reliable information about the state of intracranial cerebral arteries. Transcranial Doppler recordings of flow velocity in the basal cerebral arteries developed by Aaslid et al in 1982 [2] have been reported to be useful for the evaluation of intracranial hemodynamic alterations. However, normal reference values have hitherto not been elaborated, because most of the data available result from restricted samples of healthy young subjects [1,2,8,15].

The results presented from 50 patients in different age classes, who, according to clinical and extracranial ultrasound examination and with respect to their history were supposed not to suffer from cerebrovascular diseases, show a fairly large variation (peak and mean flow velocities, PI and PTI) of most of the parameters analyzed from the Doppler FFT spectra. Whereas intranidividual variations are reasonably small—and hence support the current use of this method for follow-up studies [1,8,18,19]—interindividual peak velocity variations are high, particularly during systole. Thus, this parameter is hardly suitable for a sensitive differentiation between normal and abnormal. This unsuitability is probably due to the large sample volume used so far [17], which prevents definite separation of the vessel considered from smaller neighboring vessels. High peak flow velocities within the latter may therefore be superimposed but hidden in the signals recorded from the artery of major interest. This assumption is further sustained by preliminary observations of multiple superimposed Doppler spectra from various vessels recorded in patients after neurosurgical craniectomy. In addition, asymmetries of flow in the tortuous course of the arteries may result in high frequency, low amplitude signals, hence dominating the spectrum recorded.

In contrast, measurements of the mean flow velocities
are less variable. We therefore suggest this parameter be given preference. We assume that this parameter is less influenced by high flow velocity but low amplitude signals originating from small vessels near the main arteries under consideration, that it reacts less sensitively to minor flow inhomogeneities on the vessel wall, and that it remains less affected by frequently occurring pulse rate differences.

The large variations of normal values in general may be partly due to a matter of selection: values were taken from the same reference points in terms of depths of ultrasound penetration without correction for individual changes in the anatomy of the circle of Willis. However, this procedure seemed justified at present with regard to the major problems of an unknown angle of insonation, the large size of the sample volume, and the inability hitherto to trace the course of recordings. Based on our recent and still limited experience with a new scanning system, we believe that some of these problems will be solved by the smaller size of the sample volume incorporated and the excellent visualization of the areas measured, thus increasing the reproducibility of the method considerably, even if new limitations from a worse signal to noise ratio appear. However, the wide variations of flow velocity values in normal subjects do not restrict the application of this method for evaluation of various types of cerebrovascular diseases, as will be shown in a subsequent contribution in this journal.

Flow velocities measured from the ACA, PCA, and VA/BA are not age-related: whether this is a simple observation or results from inconstant angles, insufficient ability to track these arteries, or interindividual variations in their caliber cannot be answered at present. There is, however, a remarkable tendency toward an increase of values from younger subjects (less than 40 years) to the group between 40 and 60 years, which may be due to elasticity alterations, increase in vasomotor tone, etc. In contrast, decreasing values in subjects older than 60 years have been observed, which are probably due to changes in cerebral autoregulation, dilatative arteriopathy, the development of nonocclusive atherosclerosis, etc. In general, the flow velocity values are significantly smaller in the posterior cerebral circulation supplied by the vertebral system (PCA and BA) than in the ACA and MCA fed by the carotid system. This observation is somewhat surprising although fairly consistent, and differs slightly from what one might have expected in view of measurements of cerebral blood flow and blood volume performed by nuclear methods [6]. Because the nuclear methods examine different aspects of intracranial circulation, we expect further studies to investigate this relationship. The advantages of TC Doppler examination are its noninvasive, easily reproducible approach for the detection of rapid alterations of blood supply within the major cerebral arteries, which is impossible with other techniques available today. Disadvantages include difficulties in insonating patients with small ultrasound bone windows (about 5% of more than 1500 patients admitted for examination to this hospital) resulting in either weak signals or a poor signal to noise ratio. Recordings of the ACA and PCA have a higher dropout ratio (18% and 12%, respectively), which is suspected to be most likely due to the incidence of abnormalities known to exist in the anterior branches of the circle of Willis [14] and/or less suitable transmission conditions from the temporal bone probe position for recordings of these vessels. Both these reasons may also be responsible for the less pronounced variations of Doppler spectrum parameters with different age classes in these vessels, which we believe to be an artifact rather than a simple observation. The preliminary results of this new technical system, which clearly improves examination conditions, are therefore very promising.

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References


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