Transcranial Color Duplex Sonography in Childhood and Adolescence

Age Dependence of Flow Velocities and Waveform Parameters

M. Schöning, MD; M. Staab, MD; J. Walter; G. Niemann, MD

Background and Purpose: Transcranial color duplex sonographic examinations in children and adolescents without cerebrovascular disease were evaluated retrospectively. Flow velocities and waveform parameters were determined and their side-to-side differences and age dependence analyzed and, finally, compared with analogous data of a previously described group of healthy adults.

Methods: With a 2.0-MHz sector transducer of a computed sonographic system, the anterior, middle, and posterior cerebral arteries were examined in 64 children and adolescents between 1.5 and 17.5 years of age. Angle-corrected systolic peak, end-diastolic maximum, time-averaged, and time-averaged maximum velocities, and the resistance, pulsatility, and spectral broadening indexes were determined in all vessels.

Results: Mean±SD values for time-averaged maximum velocity (and time-averaged velocity) were 92.2±13.0, 79.9±17.7, and 63.9±13.6 (55.3±11.7, 40.4±10.4, and 34.2±9.2) cm/s, respectively, in the middle, anterior, and posterior cerebral arteries in children under 10 years of age; values were 83.2±11.9, 69.4±13.8, and 55.6±10.1 (50.8±9.0, 39.9±10.5, and 33.1±6.3) cm/s, respectively, in children 10 years of age and older. Time-averaged maximum velocity decreased significantly with age in all vessels (P<.001). Although time-averaged velocity did not change significantly during childhood and adolescence, a clear decline occurred from adolescence to adulthood (P<.0001 in the middle and posterior cerebral arteries; P<.01 in the anterior cerebral artery). The spectral broadening index decreased significantly from childhood to adolescence in the anterior and posterior cerebral arteries (P<.0001). The resistance and pulsatility indexes remained stable throughout childhood.

Conclusions: Transcranial color duplex sonography allows angle-corrected measurements of “true” flow velocities in basal cerebral arteries. Additional determination of time-averaged velocity permits more detailed evaluation of flow characteristics for all age groups. The transcranial color duplex technique may provide deeper insights on normal cerebral perfusion and its disorders. (Stroke. 1993;24:1305-1309.)

Key Words • cerebral arteries • child • ultrasonics

Transcranial color duplex sonography (TCCD) has recently been described as a new diagnostic tool for examining basal cerebral arteries in healthy adults.1-4 In comparison to transcranial Doppler sonography (TCD), the color duplex technique provides additional information on brain structures displayed in the B-mode image and depicts the course of the basal cerebral arteries in the color Doppler mode: the sample volume’s exact site can be viewed and flow velocities recorded exactly, because the angle of the vessel’s course to the Doppler beam is clearly visible.

No reports on TCCD in childhood and adolescence exist; thus, we retrospectively analyzed TCCD measurements of children and adolescents in whom there was no evidence of cerebrovascular disease. The aim was to gain preliminary, normal data for clinical application and to make a comparison with transcranial Doppler sonographic studies of the same age group. We investigated age dependence as well as side-to-side differences of flow velocities and waveform indexes of all vessels examined. Finally, we wished to determine whether characteristic, age-related changes in the flow patterns of cerebral arteries would be revealed when comparing our data with analogous data from a previously described group of healthy adults.3,4

Subjects and Methods

Over the past 2 years, we examined with TCCD 182 children and adolescents between 1.5 and 17.5 years of age. In the retrospective analysis of TCCD data, the following patients were excluded: children with any kind of organic brain lesion (eg, brain tumors, meningitis, encephalitis, hydrocephalus, arachnoid cysts, perinatal asphyxia, cerebral palsy, neurodegenerative disease, head trauma, or epilepsy), any type of cerebrovascular disease (eg, stenosis or aneurysm of the intracranial arteries, transient ischemic attack or acute hemiplegia, aneurysm of the vein of Galen, or arteriovenous angioma), and cardiac or hematologic diseases. In 64 cases, no organic disease of the central nervous system or the

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cerebral vessels could be found through TCCD or (when necessary) by other methods (eg, magnetic resonance imaging or computed tomographic scan). These children had functional complaints, such as occasional headache or migraine, vertigo, intermittent vomiting, or syncope, which were the reasons for one or more TCCD examinations. In the examinations considered for this study, these symptoms had already subsided. The neurological status was normal in every case. We thus assume that this group corresponds to a population of healthy children.

In analyzing age dependence of flow velocities and waveform parameters, we divided the cohort into two groups comprising 26 children (13 girls and 13 boys) aged 1.5 to 9.9 (mean±SD 5.2±2.3) years and 38 children (17 girls and 21 boys) aged 10 to 17.5 (mean±SD 12.4±2.2) years. We then compared the data with that from our previous studies of healthy adults3,4 to delineate age dependence more clearly.

A computed sonographic system (Acuson 128, Mountain View, Calif) equipped with a dual-frequency 2.0/2.5-MHz sector scan transducer with an aperture size of 19 mm was used. The technique of examination was identical to that described in previous reports.3,4

In summary, the probe was applied to the preauricular area of the temporal bone, and an optimal acoustic window was found in the B-scan mode. The basal cerebral arteries were depicted in the color Doppler mode (Fig 1). Flow toward the transducer (eg, in the M1 segment of the middle cerebral artery [MCA] and in the P1 segment of the posterior cerebral artery [PCA]) was displayed in red. Flow away from the transducer (eg, in the A1 segment of the anterior cerebral artery [ACA] and in the posterior P2 part of the PCA) was shown in blue. Higher flow velocities were represented by higher intensity of the color signal. The color display was simultaneously superimposed over the B-scan image. In this way, the course of the basal cerebral arteries could be depicted in relation to adjacent cerebral structures.

For TCCD measurements of flow velocities, a pulsed sample volume of 3 mm axial size (lateral size, less than 2 mm) was positioned into the M1, P1, and A1 segments, which had to be displayed at least over a length of 5 to 7 mm in the color Doppler mode. In the MCA, measurements were taken either at the origin of the vessel, where the artery takes a curved course (with a low angle to the Doppler beam), or at a more distal site of the proximal M1 segment, where the vessel runs rather straight (at a 30° to 45° angle to the transducer). In the ACA and PCA, we preferred to take measurements at the origin of the vessels, where the angle to the Doppler beam was low. At slightly more distal parts of these curved vessels, a higher angle of insonation had to be considered. In all cases, the angle between the course of the vessel and the direction of the Doppler beam was determined at the site of the sample volume. There was automatic angle correction of the flow velocities recorded.

The color duplex examination was always initiated with an energy output level of 85 mW/cm² spatial peak time average intensity of the computed sonographic system. Due to insufficient acoustic bone window in some cases, the energy output had to be raised to 405 mW/cm² for reliable registration of Doppler signals. All
### Table 1. Mean Values for Flow Velocities and Waveform Indexes of Basal Cerebral Arteries

<table>
<thead>
<tr>
<th>Vessel/ Age Group</th>
<th>n</th>
<th>Angle (°)</th>
<th>Depth (mm)</th>
<th>Vs (cm/s)</th>
<th>Ved (cm/s)</th>
<th>TAV (cm/s)</th>
<th>TAMX (cm/s)</th>
<th>RI</th>
<th>PI</th>
<th>SBI'</th>
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<tbody>
<tr>
<td>MCA</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
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<tr>
<td>&lt;10 y</td>
<td>52</td>
<td>28.1±15.1</td>
<td>43.0±4.3</td>
<td>142.5±18.9</td>
<td>59.8±11.6</td>
<td>55.3±11.7</td>
<td>93.2±13.0</td>
<td>0.58±0.07</td>
<td>0.90±0.17</td>
<td>0.41±0.08</td>
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<tr>
<td></td>
<td>(0-57)</td>
<td>(33-51)</td>
<td>(106-196)</td>
<td>(36-85)</td>
<td>(30-89)</td>
<td>(69-126)</td>
<td>(39-73)</td>
<td>(51-1.34)</td>
<td>(26-0.68)</td>
<td></td>
</tr>
<tr>
<td>≥10 y</td>
<td>76</td>
<td>27.8±11.6</td>
<td>48.0±4.4</td>
<td>126.9±18.9</td>
<td>58.1±11.6*</td>
<td>50.8±9.0*</td>
<td>85.2±11.9*</td>
<td>0.55±0.06*</td>
<td>0.87±0.17*</td>
<td>0.38±0.07*</td>
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<tr>
<td></td>
<td>(0-54)</td>
<td>(36-56)</td>
<td>(95-181)</td>
<td>(34-101)</td>
<td>(32-70)</td>
<td>(48-108)</td>
<td>(34-65)</td>
<td>(49-1.33)</td>
<td>(25-0.57)</td>
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<tr>
<td>Adults³</td>
<td>96</td>
<td>26.6±14.4</td>
<td>51.8±4.6</td>
<td>107.5±18.0</td>
<td>47.8±8.4</td>
<td>43.0±8.1§</td>
<td>67.0±11.8§</td>
<td>0.55±0.06*</td>
<td>0.90±0.18*</td>
<td>0.36±0.05†</td>
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<td></td>
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<tr>
<td>&lt;10 y</td>
<td>50</td>
<td>13.0±12.2</td>
<td>57.7±5.3</td>
<td>120.0±27.5</td>
<td>52.0±13.0</td>
<td>40.4±10.4</td>
<td>79.9±17.7</td>
<td>0.56±0.08</td>
<td>0.85±0.16</td>
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<td>(0-42)</td>
<td>(47-70)</td>
<td>(49-180)</td>
<td>(31-89)</td>
<td>(9-63)</td>
<td>(29-116)</td>
<td>(36-71)</td>
<td>(48-1.25)</td>
<td>(35-0.70)</td>
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<tr>
<td>≥10 y</td>
<td>76</td>
<td>15.2±12.3</td>
<td>62.6±4.2</td>
<td>106.7±20.5</td>
<td>46.5±10.4†</td>
<td>39.9±10.5*</td>
<td>69.4±13.8†</td>
<td>0.56±0.06*</td>
<td>0.88±0.17*</td>
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<td>(52-71)</td>
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<td>(20-77)</td>
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<td>(39-73)</td>
<td>(51-1.43)</td>
<td>(12-0.73)</td>
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<td>Adults³</td>
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<td>65.4±5.8</td>
<td>91.1±17.1§</td>
<td>39.8±8.3§</td>
<td>36.2±7.5†</td>
<td>58.1±10.3§</td>
<td>0.56±0.07*</td>
<td>0.88±0.19*</td>
<td>0.38±0.10†</td>
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<tr>
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<tr>
<td>&lt;10 y</td>
<td>52</td>
<td>5.2±8.9</td>
<td>57.5±3.7</td>
<td>94.5±18.5</td>
<td>40.6±10.0</td>
<td>34.2±9.2</td>
<td>63.9±13.6</td>
<td>0.57±0.08</td>
<td>0.86±0.23</td>
<td>0.46±0.09</td>
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<tr>
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<td>(0-45)</td>
<td>(49-66)</td>
<td>(58-137)</td>
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<td>(50-180)</td>
<td>(36-87)</td>
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<td>(52-1.78)</td>
<td>(30-0.67)</td>
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<tr>
<td>≥10 y</td>
<td>76</td>
<td>11.0±13.4</td>
<td>60.6±3.8</td>
<td>85.5±12.2†</td>
<td>36.9±8.1*</td>
<td>33.1±6.3*</td>
<td>55.6±10.1†</td>
<td>0.57±0.07*</td>
<td>0.89±0.17*</td>
<td>0.40±0.06§</td>
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<tr>
<td></td>
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<td>(19-60)</td>
<td>(19-52)</td>
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<td>(51-1.41)</td>
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<tr>
<td>Adults³</td>
<td>98</td>
<td>7.5±12.6</td>
<td>63.9±4.1</td>
<td>96.7±13.0</td>
<td>32.6±4.4</td>
<td>28.3±6.5§</td>
<td>45.9±9.6§</td>
<td>0.53±0.05*</td>
<td>0.82±0.13†</td>
<td>0.38±0.08*</td>
</tr>
</tbody>
</table>

All parameters are mean±SD, with range in parentheses. n, Number of vessels investigated; Angle, angle of course of vessel to Doppler beam; Depth, distance of the sample volume to transducer; Vs, peak systolic velocity; Ved, maximum end-diastolic velocity; TAV, time-averaged velocity; TAMX, time-averaged maximum velocity; PI, pulsatility index [(Vs-Ved)/Vs]; RI, resistance index [(Vs-Ved)/TAV]; SBI', modified spectral broadening index (1–TAV/TAMX); MCA, middle cerebral artery; ACA, anterior cerebral artery; PCA, posterior cerebral artery; <10 y, children aged 1.5 to 9.9 years; ≥10 y, subjects aged 10 to 17.5 years; adults, data from previous transcranial color duplex sonography studies on healthy adults aged 20 to 63 years (reproduced with permission of the American Heart Association and the Journal of Neurosurgery).

*Not significant; †P<.01; §P<.001, ‡P<.0001. Data of different age groups were compared statistically with Student’s t test; symbols in line “<10 y” compare data of groups ≥10 y with corresponding data of group <10 y; symbols in line “Adults” compare data of group adults with corresponding data of group ≥10 y.

Vessels were investigated from the corresponding side. Duplex measurements were done only if the registration was stable for at least 5 seconds. Each recording was documented using a video printer.

The following angle-corrected flow velocity measurements were taken: (1) peak systolic velocity (Vs); (2) maximum end-diastolic velocity (Ved); (3) time-averaged maximum velocity (TAMX; ie, the averaged mean of peak flow velocities over a complete cardiac cycle); and (4) time-averaged velocity (TAV; ie, the mean of all frequencies occurring above and below the baseline over at least three complete pulses). We calculated the resistance index according to Proucelsk as $RI = (Vs-Ved)/Vs$ and the pulsatility index according to Gosling and King² as $PI = (Vs-Ved)/TAMX$. In addition, a modified spectral broadening index³ was calculated as $SBI' = 1 – TAV/TAMX$ in analogy to the definition of Douville et al.⁷

Statistical evaluation was done using the SAS programs (SAS Institute Inc, Cary, NC). All parameters and side-to-side differences are indicated as mean±SD. The significance of age-related or side-to-side differences was evaluated with Student’s t test and side-to-side correlation with the Pearson correlation coefficient. The level of statistical significance was set at $P<.01$ for all parameters.

### Results

Color duplex measurements were possible in all MCAs and PCAs and in all but two (presumably hypoplastic) A1 segments of the ACAs. In color Doppler sonography, hypoplasia of the ACA of one side was presumed in six children (Fig 1). In two children, an embryonal type of the PCA could be seen as the P2 part of the PCA emerged directly from the internal carotid artery; a PI part of the PCA could not be detected in these cases.

Mean±SD values of angle-corrected flow velocities and the derived waveform indexes in the MCA, ACA, and PCA in all age groups, as well as age-related differences of corresponding data in different groups, are shown in Table 1.

Side-to-side differences of flow velocities and waveform indexes are listed in Table 2. Maximum side-difference values in MCA, ACA, and PCA were 29 cm/s, 52 cm/s, and 21 cm/s for TAV and 28 cm/s, 64 cm/s, and 31 cm/s for TAMX, respectively. Flow velocities of corresponding arteries correlated well on both sides in the MCA ($r=0.34$, $P<.01$ for Ved and TAV; $r=0.47$, $P<.0001$ for Vs and TAMX) and PCA ($r=0.53$, $P<.0001$ for all flow velocities), whereas there was no significant correlation of flow velocities in the ACA. With one exception (SBI' in the MCA), all waveform indexes showed a significant side-to-side correlation ($r=0.42$, $P<.001$) in all basal cerebral arteries.

### Discussion

To our knowledge, this is the first report on TCCD in childhood and adolescence. In comparison with TCD studies, the angle-corrected MCA flow velocities mea-
sured by TCCD do not differ substantially in the corresponding age groups. In TCCD studies, the optimal site of measurement can be selected under visual control at either the origin of the MCA or more distal sites (under varying angles to the Doppler beam); in TCD studies, the strongest Doppler signal, usually recorded close to the MCA origin, is evaluated. Although both methods may measure flow velocities at different sites of the MCA, similar results are obtained in this way.

In TCD studies, flow velocities were about 10% to 20% lower in the ACA and PCA than in the present TCCD study. The A1 and P1 segments are short and curved. It is likely that flow velocities can be measured more precisely in these vessels by using the small sample volume of the TCCD device rather than the larger TCD sample volume. For reliable registration of Doppler signals, the sample volume must be set beyond the origin of the ACA and PCA, at a distance corresponding to the vessel size, to avoid interference with the MCA or the contralateral PCA, respectively. We assume that flow velocities in ACA and PCA are lower in TCD measurements because they have to be recorded at a rather distal site of the A1 or P1 segment, where the angle of insonation is higher. For clinical purposes, however, the quantitative differences between TCD and TCCD measurements do not seem to be significant.

Besides the commonly recorded flow velocities and waveform parameters, we also determined time-averaged velocity and calculated a modified spectral broadening index in our study. The relation of TAV to TAMX, which is inherent in the term SBI’, shows minor but significant variations in different vessels or age groups: eg, SBI’ was significantly higher in the ACA and PCA than in the MCA (P<.0001), and it declined with age (Table 1). The potential use of TAV and SBI’ for estimating flow volume changes or quantifying stenoses of intracranial vessels has been discussed elsewhere.

Corresponding to the findings of other groups, we observed a marked reduction in Vs and TAMX in all vessels in the period spanning childhood and adolescence. However, TAV remained constant in the ACA and PCA and tended to decrease in the MCA (P=.02). Between adolescence and adulthood, a significant decline of all flow velocities occurred (Table 1 and Fig 2). The age-related decrease of TAMX from childhood to adulthood has also been shown in previous TCD reports.

In the present study as well as in earlier studies, we determined both the resistance and the pulsatility indexes. Both parameters did not vary with age during childhood and adolescence. We found a very high correlation between RI and PI in all basal cerebral arteries, with the Pearson correlation coefficient ranging from 0.90 to 0.94 (P<.0001). To date, there has been no clear evidence on whether either of the two indexes offers diagnostic advantages. By definition, the maximum range of the RI is clearly limited (between 0.0 and 1.0), and its normal range was narrower than that of the PI (Tables 1 and 2) in our studies. On these grounds, we would prefer the RI to the PI.

Unlike in the MCA and PCA, there was no significant correlation of flow velocities in the ACA of both sides. Moreover, the standard deviation of flow velocities proved higher in the ACA than in the MCA or PCA.
(Tables 1 and 2). These findings correspond to the known asymmetry of the anterior part of the circle of Willis.\textsuperscript{13,14} Using color Doppler imaging, we concluded that there were six children with hypoplasia of one A1 segment of the ACA. Duplex sonographic measurements reinforced this view, as the TAMX or TAV side differences were higher than 2 SDs related to mean velocity data (Table 1) in these cases. While in the ACA a side difference of this magnitude may merely be a sign of a normal-variant asymmetric supply, it may be clinically significant in the MCA and PCA.

In conclusion, TCCD sonography is a new diagnostic method that provides not only a color Doppler image of normal or disturbed flow in basal cerebral arteries, but also allows measurements of angle-corrected, “true” flow velocities. With the color Doppler system that we used, the measurement of time-averaged velocity (“the mean of the means”) is possible. This additional parameter (and its derived spectral broadening index) may provide deeper insights on changes in flow characteristics throughout life. We consider TAMX, TAV, RI (or PI), and SBI to be important parameters in the noninvasive assessment of the cerebrovascular circulation and its disorders.

Age-related, normal data are a prerequisite for a new diagnostic method to find clinical acceptance. For TCCD measurements in adults, reference data of all basal cerebral arteries already exist.\textsuperscript{3,4} The data arising from our retrospective study on children and adolescents without cerebral and cerebrovascular disease may serve as preliminary, normal data until a prospective TCCD study of this age group strengthens or elaborates our findings.

References
Transcranial color duplex sonography in childhood and adolescence. Age dependence of flow velocities and waveform parameters. M Schöning, M Staab, J Walter and G Niemann

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