*Archives of Disease in Childhood,* 1988, **63,** 606–611

# Age dependence of flow velocities in basal cerebral arteries

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SUMMARY Flow velocities in the basal cerebral arteries were studied by transcranial Doppler sonography. A longitudinal study was undertaken on 25 healthy newborn babies during the first 20 days of life, and a cross sectional study was performed on 112 healthy children between 1 day and 18 years of age. A rapid linear increase of flow velocities was found within the first 20 days with higher velocities in neonates of higher birth weight and gestational age. Maximal values were recorded at the age of 5 to 6 years. After that the velocities decreased linearly to 70% of their maximum at the age of 18 years. Reference values were derived from the data considering age and birth weight. The increasing flow velocities probably reflect the increasing cerebral blood flow during the first years of life. Our results also support the hypothesis of a decrease in cerebrovascular resistance during infancy. With the technique of transcranial Doppler sonography and the introduced reference values normal and abnormal intracranial flow velocities can now be assessed by non-invasive methods in all paediatric age groups.

Since the report by Bada *et al*[1] many Doppler sonographic studies have been undertaken to evaluate cerebral blood flow in neonates at risk for perinatal brain injury.[2] Because of technical difficulties the recording of flow velocities in the intracranial arteries by Doppler sonography has been restricted to neonates and young infants. The new technique of transcranial Doppler sonography combines a low emitting frequency with the pulsed Doppler technique,[3] and by this method flow velocities in the basal cerebral arteries now can be determined at any age. So far this has been done systematically only in adults.[4]

In childhood the thinner bones facilitate the penetration of ultrasound through the skull. For that reason the registration of signals by transcranial Doppler sonography is easier than in adults. The examination technique, however, must be adapted to the size of the child's head. The changing intracranial haemodynamics during infancy and childhood require age dependent reference values in order to distinguish physiological and pathological flow velocities in the basal cerebral arteries.

## Subjects and methods

Twenty five healthy preterm and term neonates with a mean (SD) birth weight of 2248 (776) g (range 1170–4150 g) and a postconceptional age of 35·6 (3·0) weeks (range 28–41 weeks) were examined by transcranial Doppler sonography in a longitudinal study on days 1, 2, 3, 4, 7, 10, 15, 20, 25 of age. Systolic, mean, and diastolic arterial blood pressure and heart rate were measured simultaneously (Dinamap 847). In a cross sectional study, 112 healthy children between 1 day and 18 years of age were examined by transcranial Doppler sonography. Cerebral sonography (ATL Mark 100) was performed in all children under 1 year and showed no disease.

Doppler recordings were made with an EME TC 2–64 system with a pulsed 2 MHz Doppler probe and an integrated Fast Fourier real time frequency analyser (sliding average technique, 64 frequency points, 132 spectral lines). The system requires no calibration because of digitalised signal processing. Frequency to blood flow velocity conversions are assuming an insonation angle of zero.

The examination technique for children over 1 year old was the same as for adults.[3 4] Middle cerebral artery, internal carotid artery, anterior cerebral artery, posterior cerebral artery with its precommunicating (P1) and postcommunicating (P2) part and basilar artery were recorded.

In children under 1 year old middle cerebral, anterior cerebral, and internal carotid artery were recorded. The position of the Doppler probe for registration of the middle cerebral artery was the same as in older children. The internal carotid artery was recorded with the Doppler probe on the anterior fontanelle directing the ultrasonic beam to the angle of the lower jaw. The extracranial part of the internal carotid artery (flow towards the probe) was identified beside the jugular vein (flow away from the probe). In following the extracranial part of the internal carotid artery by reducing the depth of the sample volume the intracranial part of the internal carotid artery was found. The postcommunicating part of the anterior cerebral artery was recorded with a probe position high frontally in the midline directing the ultrasonic beam caudally and slightly backwards. Probe position, depth of the sample volume, direction of flow and, in some older children, compression tests were used for vessel identification.[3 4]

Systolic peak flow velocity, mean flow velocity (time–mean of the maximum velocity envelope curve[3]) and end diastolic peak flow velocity were recorded. The pulsatility index (PI) was calculated according to the formula PI=(S–D)/S, where S and D are systolic and end diastolic peak flow velocity.

Children under 1 year old were asleep, those over 1 year were awake during Doppler sonography. All children were studied in a horizontal position with the head in the midline. Only constant recordings of at least 15 seconds duration were analysed.

Mean reference values were calculated for flow velocities in middle cerebral, internal carotid, and anterior cerebral artery. Mean reference values for the first 20 days of life for different birth weights were derived from the data of the longitudinal study. Linear relations between flow velocities on day 1 and birth weight were found. The derived equations were used to calculate weight dependent values of each flow velocity for the first day of life. From the linear relations between flow velocities and age the mean daily increase of each flow velocity was calculated and added to the weight dependent velocities of the first day of life. Mean reference values of flow velocities from 0–18 years were derived from the cross sectional study by an equation of non-linear parameters.[5]

The study was approved by the hospital ethical committee.

## Results

In total 337 Doppler studies were carried out. Altogether 1347 vessels were insonated resulting in recordings of 4041 flow velocities. Depending on age and head size the basal cerebral arteries were found at different distances from the Doppler probe (table 1). Bilateral examination of corresponding arteries showed variation of flow velocities between 2% and 8% intraindividually.

During the first 20 days of life all flow velocities increased linearly. The average daily increase of systolic peak flow velocity, mean flow velocity, and end diastolic peak flow velocity was about 1·5, 0·8, and 0·4 cm/second, respectively with no significant difference for various birth weights (table 2). On average the pulsatility indices increased slightly from 0·69 to 0·72 within this time. The mean values of systolic, mean, and end diastolic arterial blood pressure of all children increased significantly from 54/43/32 mm Hg on day 1 to 75/57/44 mm Hg on day 20.

Beyond the 3rd week of life flow velocities increased less quickly. Maximal velocities, which were about three to four times as high as those of the first days of life, were found at an age of 5–6 years. After that flow velocities decreased to about 70% of the maximal velocities by the age of 18 years. On average the pulsatility indices decreased from 0·70

Table 1 *Age dependent distances between Doppler probe and cerebral arteries (mm)*

| *Age* | *Middle cerebral artery* | *Internal carotid artery* | *Anterior cerebral artery* | *Posterior cerebral artery* | | *Basilar artery* |
|---|---|---|---|---|---|---|
| | | | | *P1** | *P2†* | |
| 0–3 months | 25 | 55–65‡ | 25–30§ | — | — | — |
| >3–12 months | 30 | 60–70‡ | 30§ | — | — | — |
| >1–3 years | 30–45 | 40–50 | 55–65 | 55 | 50–55 | 50–60‖ |
| >3–6 years | 40–45 | 45–55 | 60–65 | 55–60 | 50–60 | 55–70‖ |
| >6–10 years | 45–50 | 50–55 | 60–70 | 60–70 | 55–65 | 55–75‖ |
| >10–18 years | 45–50 | 55 | 65–75 | 60–70 | 60–65 | 60–80‖ |

*Precommunicating part of the posterior cerebral artery.
†Postcommunicating part of the posterior cerebral artery.
‡Insonation of the vessel through the anterior fontanelle.
§Insonation of the vessel from high frontally.
‖Insonation through the occipital foramen.
The other vessels were insonated through the temporal bone.

Table 2 *Mean (SD) flow velocities in basal cerebral arteries (in cm/second) of a longitudinal study of normal preterm and term neonates (n=25)*

| | *Day 1* | *Day 5* | *Day 10* | *Day 15* | *Day 20* |
|---|---|---|---|---|---|
| **Middle cerebral artery:** | | | | | |
| Systolic peak flow velocity | 42 (10) | 54 (10) | 61 (13) | 64 (10) | 70 (13) |
| Mean flow velocity* | 22 (6) | 26 (6) | 30 (6) | 32 (6) | 37 (7) |
| End diastolic peak flow velocity | 13 (4) | 15 (4) | 16 (3) | 17 (5) | 19 (6) |
| **Internal carotid artery:** | | | | | |
| Systolic peak flow velocity | 35 (6) | 44 (10) | 51 (8) | 52 (8) | 62 (8) |
| Mean flow velocity* | 18 (5) | 22 (6) | 27 (5) | 28 (4) | 33 (5) |
| End diastolic peak flow velocity | 11 (4) | 12 (3) | 14 (3) | 14 (3) | 16 (3) |
| **Anterior cerebral artery:** | | | | | |
| Systolic peak flow velocity | 32 (7) | 42 (7) | 44 (8) | 52 (7) | 57 (7) |
| Mean flow velocity* | 17 (5) | 21 (6) | 23 (5) | 27 (5) | 31 (3) |
| End diastolic peak flow velocity | 11 (5) | 13 (3) | 13 (3) | 16 (5) | 16 (2) |

*Mean flow velocity=time–mean of the maximal velocity envelope curve.

Table 3 *Mean (SD) flow velocities in basal cerebral arteries (in cm/second) in a cross sectional study of healthy children (n=112)*

| *Age* | *n* | *Middle cerebral artery* | *Internal carotid artery* | *Anterior cerebral artery* | *Posterior cerebral artery* | | *Basilar artery* |
|---|---|---|---|---|---|---|---|
| | | | | | *P1** | *P2†* | |
| **Systolic peak flow velocity:** | | | | | | | |
| 0–10 days | 18 | 46 (10) | 47 (9) | 35 (8) | — | — | — |
| 11–90 days | 14 | 75 (15) | 77 (19) | 58 (15) | — | — | — |
| 3–11·9 months | 13 | 114 (20) | 104 (12) | 77 (15) | — | — | — |
| 1–2·9 years | 9 | 124 (10) | 118 (24) | 81 (19) | 67 (18) | 69 (9) | 71 (6) |
| 3–5·9 years | 18 | 147 (17) | 144 (19) | 104 (22) | 84 (20) | 81 (16) | 88 (9) |
| 6–9·9 years | 20 | 143 (13) | 140 (14) | 100 (20) | 82 (11) | 75 (10) | 85 (17) |
| 10–18 years | 20 | 129 (17) | 125 (18) | 92 (19) | 75 (16) | 66 (10) | 68 (11) |
| **Mean flow velocity‡:** | | | | | | | |
| 0–10 days | 18 | 24 (7) | 25 (6) | 19 (6) | — | — | — |
| 11–90 days | 14 | 42 (10) | 43 (12) | 33 (11) | — | — | — |
| 3–11·9 months | 13 | 74 (14) | 67 (10) | 50 (11) | — | — | — |
| 1–2·9 years | 9 | 85 (10) | 81 (8) | 55 (13) | 50 (17) | 50 (12) | 51 (6) |
| 3–5·9 years | 18 | 94 (10) | 93 (9) | 71 (15) | 56 (13) | 48 (11) | 58 (6) |
| 6–9·9 years | 20 | 97 (9) | 93 (9) | 65 (13) | 57 (9) | 51 (9) | 58 (9) |
| 10–18 years | 20 | 81 (11) | 79 (12) | 56 (14) | 50 (10) | 45 (9) | 46 (8) |
| **End diastolic peak flow velocity:** | | | | | | | |
| 0–10 days | 18 | 12 (7) | 12 (6) | 10 (6) | — | — | — |
| 11–90 days | 14 | 24 (8) | 24 (8) | 19 (9) | — | — | — |
| 3–11·9 months | 13 | 46 (9) | 40 (8) | 33 (7) | — | — | — |
| 1–2·9 years | 9 | 65 (11) | 58 (5) | 40 (11) | 36 (13) | 35 (7) | 35 (6) |
| 3–5·9 years | 18 | 65 (9) | 66 (8) | 48 (9) | 40 (12) | 35 (9) | 41 (5) |
| 6–9·9 years | 20 | 72 (9) | 68 (10) | 51 (10) | 42 (7) | 38 (7) | 44 (8) |
| 10–18 years | 20 | 60 (8) | 59 (9) | 46 (11) | 39 (8) | 33 (7) | 36 (7) |

*Precommunicating part of posterior cerebral artery.
†Postcommunicating part of posterior cerebral artery.
‡Mean flow velocity=time–mean of the maximal velocity envelope curve.

to 0·55 during the first year of life and remained nearly unchanged beyond infancy. At all ages the flow velocities decreased in the sequence: middle cerebral artery, internal carotid artery, anterior cerebral artery, basilar artery, posterior cerebral artery (table 3). Mean reference values of flow velocities in the middle cerebral, internal carotid, and anterior cerebral artery were derived from the data as described above (figs 1 and 2). Velocities not differing more than 30% from these

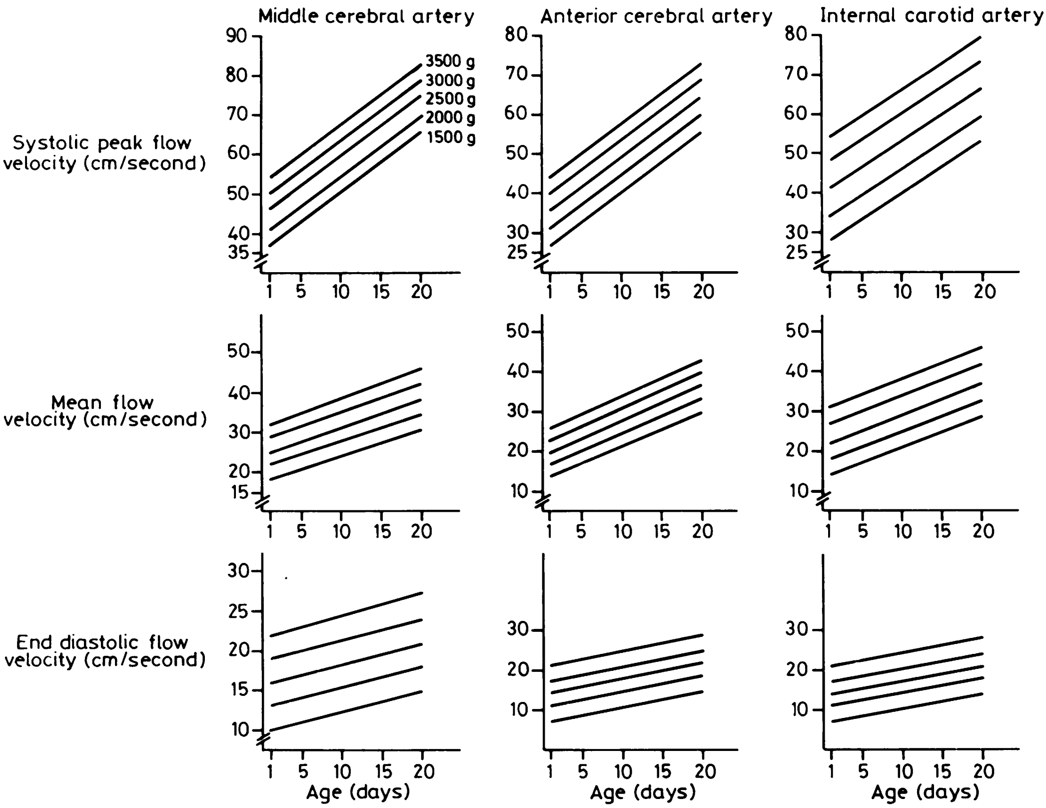


Fig 1 *Mean reference values of flow velocities in basal cerebral arteries from 1–20 days of age for different birth weights.*

values were considered as being within the reference range.

## Discussion

For the first time we present flow velocities and pulsatility indices in the basal cerebral arteries recorded by transcranial Doppler sonography in healthy children of 0–18 years of age. Our results are comparable with recordings obtained by other Doppler techniques.[6 7] Spectral mean flow velocities of 10·5 cm/second in the anterior cerebral artery and of 10 cm/second in the internal carotid artery were found in a population with comparable gestational age and a mean postnatal age of 5 days.[6] In the same study the end diastolic peak flow velocities in the anterior cerebral and internal carotid artery were 10·8 and 9·5 cm/second respectively.[6] In children 10–18 years old we recorded flow velocities, which were 15–30% higher than those of adults.[3 4]

Owing to the strong dependence on age and birth weight, Doppler sonography of many more children would be required to determine 'exact' normal values. The mean reference values presented here, however, indicate the flow velocities to be expected for different ages and birth weights. The derived reference ranges prove useful in detecting abnormal flow conditions.

Newborn babies with higher birth weights might be expected to have a less rapid increase of flow velocities after birth. Our data do not support this assumption. For calculating reference values we therefore supposed a weight independent increase of flow velocities during the first 3 weeks of life. The justification for this approach is given by the good correspondence between the recorded data and the calculated reference values (tables 2 and 3 and figs 1 and 2).

Principles and techniques of transcranial Doppler sonography have been discussed elsewhere.[3 4] The absolute value of the Doppler shift depends on the cosine of the angle between ultrasonic beam and insonated vessel. In transcranial Doppler sonography angles of insonation well below 30 degrees are

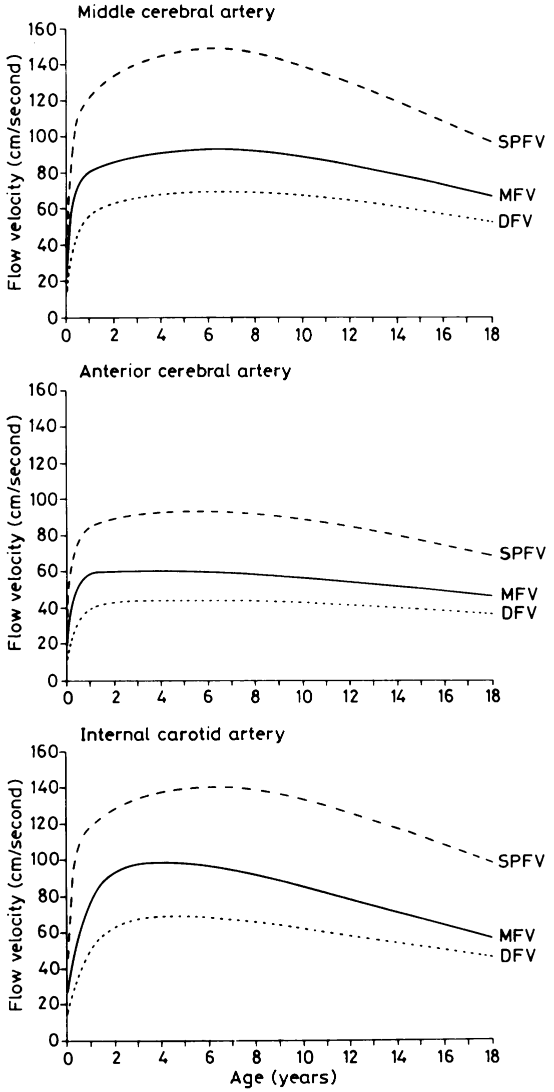


Fig 2 *Mean reference values of flow velocities in (a) middle cerebral artery, (b) internal carotid artery, and (c) anterior cerebral artery from 0 to 18 years of age. SPFV=systolic peak flow velocity; MFV=mean flow velocity (time–mean of the maximal velocity envelope curve); and DFV=end diastolic peak flow velocity.*

used. The cosine of 30 degrees is 0·87. That is why the recorded flow velocities deviate less than 13% from the true velocities.

The flow volume through a vessel is the product of the spectral mean flow velocity and the cross sectional area of the vessel. The former is about half of the time mean of the maximum velocity envelope curve.[8] As the individual cross sectional area of the basal cerebral arteries cannot be determined exactly the individual flow volume through the basal cerebral arteries cannot be calculated quantitatively by any Doppler sonographic method. Cerebral blood flow (in ml/100 g brain weight/minute), however, is proportional to the quotient: blood flow velocity x cross sectional area of basal cerebral arteries divided by brain weight.

We will not discuss in detail the adaption of human cerebral haemodynamics to birth and early extrauterine life. Vasoactivity of the major intracranial arteries and of the cerebral arterioles are supposed to have an important influence on flow velocities and pulsatility indices during this time.[9–11]

The cross sectional area of the basal cerebral arteries in young adults is three times higher than that of newborn babies.[12 13] The adult values are reached at the age of 6 years. The brain weight trebles during the first 6 years of life.[14] From this relatively constant ratio of the cross sectional area of the basal cerebral arteries and brain weight one can derive a proportionality between cerebral blood flow and blood flow velocities during the first 6 years of life. The recorded velocities increase three to four fold during this time, which is comparable with the wide range of values for cerebral blood flow.[6 15 16] Similarly we see the higher flow velocities of term neonates compared with premature babies as a sign of a higher cerebral blood flow.

The capillary density in the brain doubles during the first year of life,[17] and the histological structure of the basal cerebral arteries changes.[18] These alterations cause a decrease in cerebrovascular resistance during infancy. The pulsatility index to some extent indicates the vascular resistance.[19 20] The decrease in pulsatility index of the basal cerebral arteries during infancy may reflect the decrease of cerebrovascular resistance.

So far Doppler sonography of intracranial arteries has been used mostly in neonates. With the aid of transcranial Doppler sonography it can be extended to older children with problems such as bacterial meningitis (severe forms with extremely increased flow velocities due to vessel narrowing); acute hemiplegia; migraine (reduced or increased flow velocities on the affected side depending on the underlying pathology and stage of the disease); increased intracranial pressure (decreased flow velocities); cerebral death (reverberating flow pattern), etc. Our data and reference values help to distinguish normal and abnormal intracranial flow conditions in all paediatric age groups. The already developed continuous recording facilities will allow closer monitoring of cerebral haemodynamics in children receiving intensive care.

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Accepted 21 December 1987