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Doppler diagnosis of intracranial artery occlusive disorders

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SUMMARY Pulsed wave 2 MHz Doppler with accoustical focusing was used to obtain blood flow velocity recordings through the intact cranium in 11 patients with occlusive disease of major intracranial arteries. Increased blood flow velocities were recorded from stenoses of the carotid siphon and of the middle cerebral, anterior cerebral and basilar arteries. A clear, inverse relationship existed between angiographical residual lumen diameter and flow velocity. The Kendall rank correlation coefficient (Tau) was $-0{\cdot}89$ ($p = 0{\cdot}0001$). Transcranial Doppler is a useful means for evaluating patients with this disorder.

Extracranial carotid artery disease is responsible for a high proportion of transient and permanent cerebral ischaemic events. Doppler flow velocity recordings from carotid arteries in the neck are widely used to identify atherosclerotic lesions of the extracranial carotid arteries.[1-3]

The clinical importance of intracranial artery stenosis has come into focus more recently.[4-13] Special Doppler techniques taking advantage of natural foramina of the cranium or of relatively thin areas of the temporal squama, are required to investigate these lesions noninvasively. For relatively low frequency ultrasound (1 to 2 MHz), the attenuation in bone and thick layers of soft tissue is considerably less than for the ultrasound frequencies in the range 4 to 10 MHz which are commonly used for recordings from extracranial arteries. Doppler-shifted signals hence can be recorded from the carotid siphon[14] and from the basal cerebral arteries in adults.[15-17] Investigation using noninvasive Transcranial Doppler (TCD) is being employed clinically to evaluate cerebral vasospasm after subarachnoid haemorrhage and to assess intracranial haemodynamic patterns in patients with extracranial carotid artery disease.[16 17] The method also seems capable of detecting occlusive disorders of the major brain arteries. The present report concerns the use of TCD for the noninvasive diagnosis of intracranial artery occlusive disorders.

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Material and methods

Patients

A total of 71 patients with clinical symptoms suggestive of cerebrovascular disease were investigated with TCD and angiography. Ten of these patients had angiographically well demarcated stenoses involving intracranial arteries varying in length from about 3 to about 10 mm. Cervical or ocular bruits were absent. One of these patients also had an extracranial carotid stenosis of 55%, and underwent carotid endarterectomy (table, No. 1). One patient had a totally occluded internal carotid contralateral to the carotid siphon stenosis (table, No. 2). Eight patients had no extracranial carotid stenosis.

Angiographically, 21 of the other 61 patients had one normal extracranial internal carotid artery and no collateral flow in the circle of Willis. The TCD findings in these 21 angiographically normal hemispheres provided the reference values with which the TCD recordings from intracranial artery stenoses were compared. The TCD investigations and angiography were performed and interpreted independently.

The present study also included one patient in whom a middle cerebral artery total occlusion was disclosed at necropsy (table, No. 11).

Doppler recordings

Pulsed wave range-gated directional 2 MHz Doppler instruments with accoustical focusing and real-time spectrum analysis were used. The emitted radiofrequency energy was selectible within the range 10 to 100 mW/cm^2 (Laboratory prototype and production model TC2-64, Eden Medizinische Elektronik GmbH, D-7770 Überlingen/Federal Republic of Germany). The instrumentation principle and the procedure using an "ultrasonic window" in the temporal region for recordings from the middle, anterior and posterior cerebral arteries (MCA, ACA and PCA) has been described previously.[15-17]

Table *Summary of findings in patients with intracranial artery stenosis*

Patients No.	*Angiography findings*			*Transcranial Doppler findings*	
	Artery involved	*Stenosis (per cent)*	*Residual lumen diameter (mm)*	*Stenosis flow velocity (cm/s)*	*Doppler audio signal*
1	MCA	78	0·8	250	Very coarse
1*	MCA	74	0·9	232	Very coarse
2	Siph. Prox.	66	1·7	132	Very coarse
3	Basilar a.	55	1·9	122	Coarse
4	MCA	55	1·5	136	Tonal 450 Hz
5	Siph. Dist.	55	2·0	110	Smooth
6	MCA	55	1·4	142	Coarse
7	Siph. Prox.	60	2·2	100	Smooth
8	MCA	60	1·4	160	Very coarse
9	Siph. Prox.	50	2·3	88	Coarse
10	MCA	50	1·8	108	Coarse
,,	ACA	60	1·5	128	Coarse
11	MCA	†	—	—	—
Flow velocity in angiographically normal arteries:				Range: 35–80	Smooth

MCA and *ACA*: Middle and anterior cerebral arteries.
Siph.: Carotid siphon, *Prox.* and *Dist.*: Proximal (extradural) and distal (intradural) segments.
Doppler audio signal: Quality of the Doppler audio signal not apparent from the flow velocity (mean spectrum outline) value.
*Repeated investigations 3 months after carotid endarterectomy, same side.
†No angiography. Total MCA occlusion disclosed from autopsy.

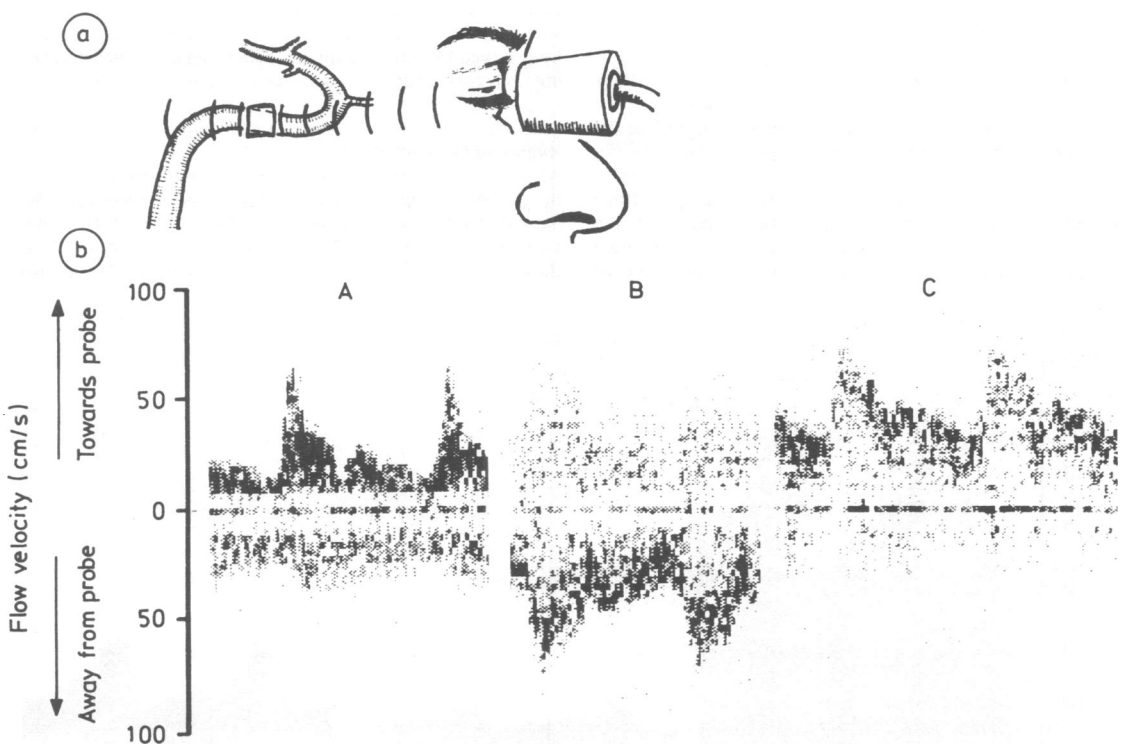

Fig 1 *(a) Recording from the carotid siphon using the transorbital approach. The transducer is placed over the closed eyelids and steadied against the orbital rim. The carotid siphon is located behind the apex of the orbital cavity. (b) Transorbital recordings in normal individual. Flow velocity spectrum recorded from the ophthalmic artery (A) has a markedly pulsatile spectrum outline (sampling depth 55 mm). Compare with recordings from the distal carotid siphon segment (B), (shown below the zero line to indicate flow direction away from the probe) and from the proximal portion of the carotid siphon (C). Sampling depth was 70 mm for recordings b and c.*

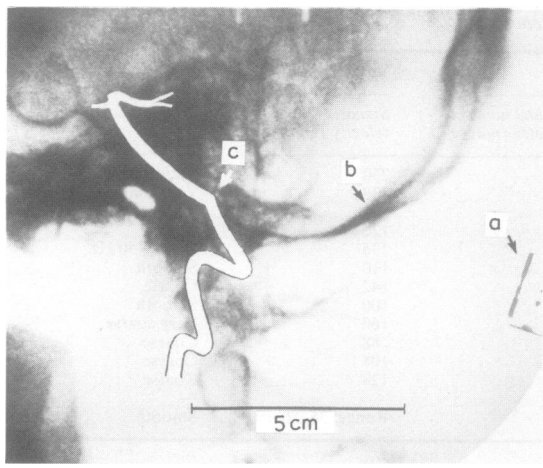

Fig 2 *Radiograph taken during recording from the basilar artery in a brawny subject. A 5 cm marker is shown for comparison. Note distance between transducer surface (a arrow) and the posterior rim of the occipital foramen (b arrow). Vertebral and basilar arteries are drawn in. Sampling area using a range-gate setting of 7 cm is located at c arrow.*

A transorbital approach was preferred for recordings from the carotid siphon. The transducer was placed over the closed eyelids and steadied against the orbital rim, while the ultrasound beam was directed at the apex of the orbit (fig 1a). At depth settings of about 5 cm two distinct types of Doppler signals were obtained representing the ophthalmic artery and the carotid artery siphon. Recordings from the proximal and distal carotid siphon segments were obtained as the depth setting was gradually increased. These vessel segments have flow directions toward and away from the probe respectively, as can be seen from the directional Doppler display (fig 1b). The "ultrasonic window" appears to be the superior orbital fissure or the optic canal.

Since the ultrasound beam traverses the eyebulb when the carotid siphon is investigated transorbitally, low radiofrequency output settings (25 mW/cm^2 or less) were used.

For recordings from the basilar artery, the probe was placed suboccipitally, midway between the mastoid process and the midline. One vertebral artery was first identified, and the intracranial course could be tracked to the vertebrobasilar junction where the signal from the contralateral vertebral artery was recognised. Radiographs taken during these recordings confirmed that this landmark was located at sampling distances of from 5 to 7 cm from the transducer, varying with the stature of the subject (fig 2). The ultrasonic window usually seemed to be the occipital foramen. Using a paramedian approach, it also often seemed possible to insonate the basilar artery through the thin paramedian areas of the occipital squama. A midline probe position seemed to increase the sampling distance.

The time-mean of the velocity spectrum outline was determined from the frozen spectral display. All figures represent the average of ten consecutive cardiac cycles. Although the exact angle of incidence between the vessel and the ultrasound beam was not known, the three different approaches used served to minimise the incidence angle for each recording. No correction for incidence angle was introduced.[1 18]

Angiographic assessment

All angiographical films were first reviewed subjectively by the neuroradiologist. The films considered as showing a demarcated stenosis involving one or more of the intracranial arteries were then evaluated as follows: The outer edges of the contrast-filled vessel lumen was marked with two pencil

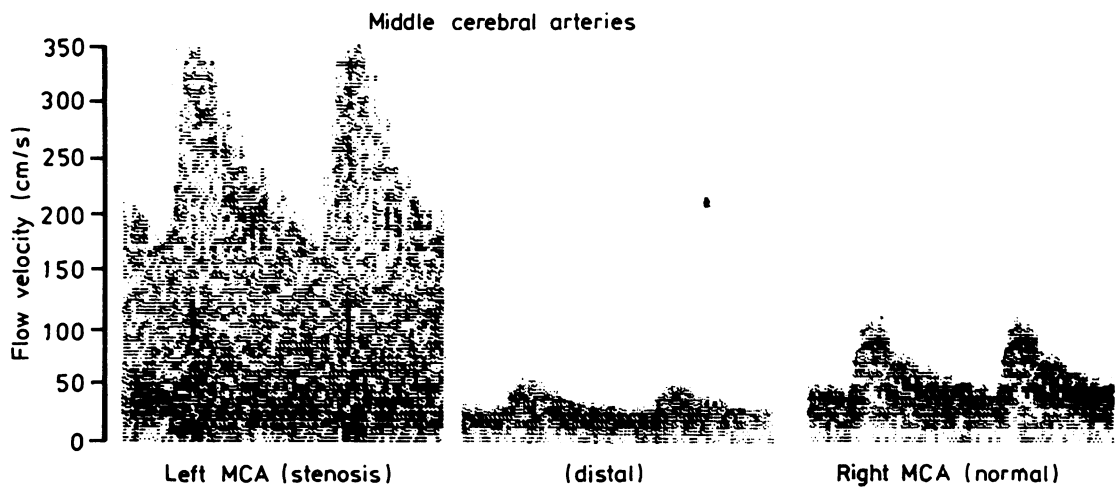

Fig 3 *Recordings from patient No. 1 (table). Flow velocity in stenosis 250 cm/s, sampling depth 50 mm. Flow velocity in distal left MCA was low, 32 cm/s (sampling depth 30 mm), This velocity spectrum outline shows reduced pulsatility, illustrating a throttling effect of the MCA stenosis. Compare with recording from the angiographically normal right MCA. Angiographic findings in fig 4a.*

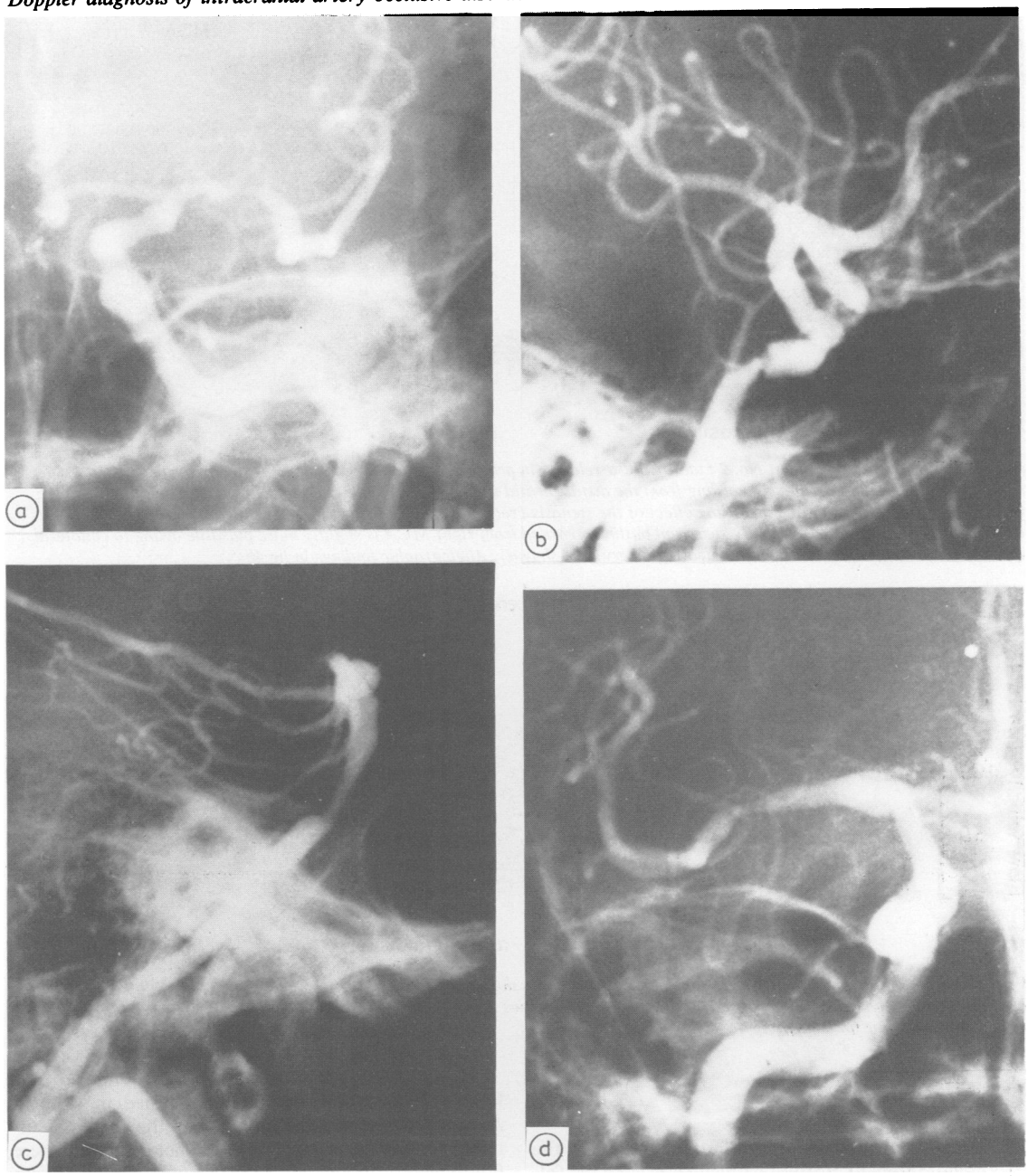

Fig 4 *Angiographic findings in patient Nos. 1 to 4 (see table). Corresponding Doppler recordings are shown in fig 3 (No. 1), fig 5 (No. 2), fig 6 (No. 3) and fig 8 (No. 4).*

dots on the original films. A reticle marked to 0·1 mm was laid over the film, and the distance between the nearest edges of the pencil dots measured using a 4× magnifier. The residual lumen diameter was measured at the site of stenosis and corrected for angiographic magnification. This diameter was also compared to the diameter of the adjacent vessel segment appearing as normal, and the result was expressed as percentage diameter stenosis. Measurements of intracranial arteries in more than one projection were not usually possible.

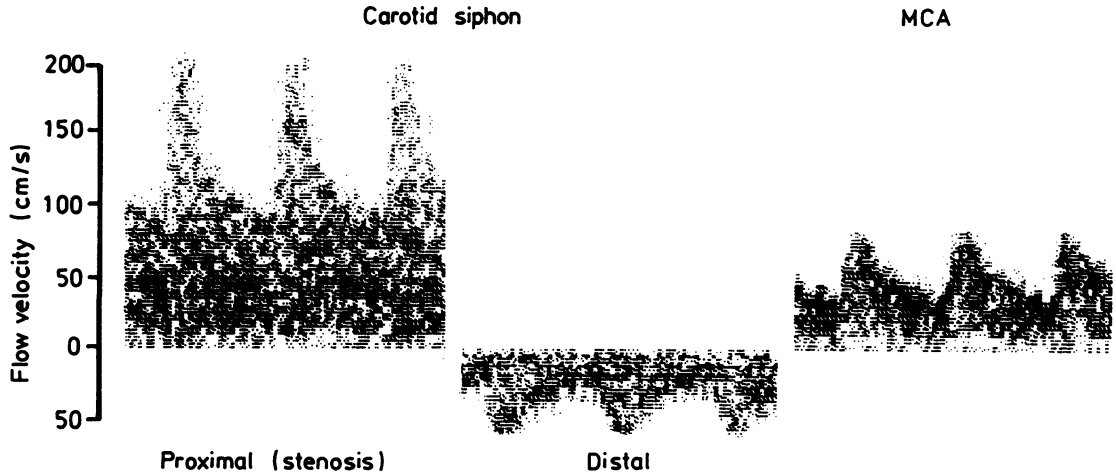

Fig 5 *Recordings from patient No. 2 (table). Flow velocity in proximal carotid siphon segment stenosis was 132 cm/s, sampling depth setting: 85 mm. Recording from the distal carotid siphon segment shows a reduced pulsatility of the velocity spectrum outline, reflecting the throttling effect of the stenosis (recording shown below the zero line to indicate flow direction away from the transducer). Velocity spectrum outline recorded from right MCA is slightly more pulsatile owing to collateral inflow from the right posterior communicating artery (not shown). Angiographic findings in fig 4b.*

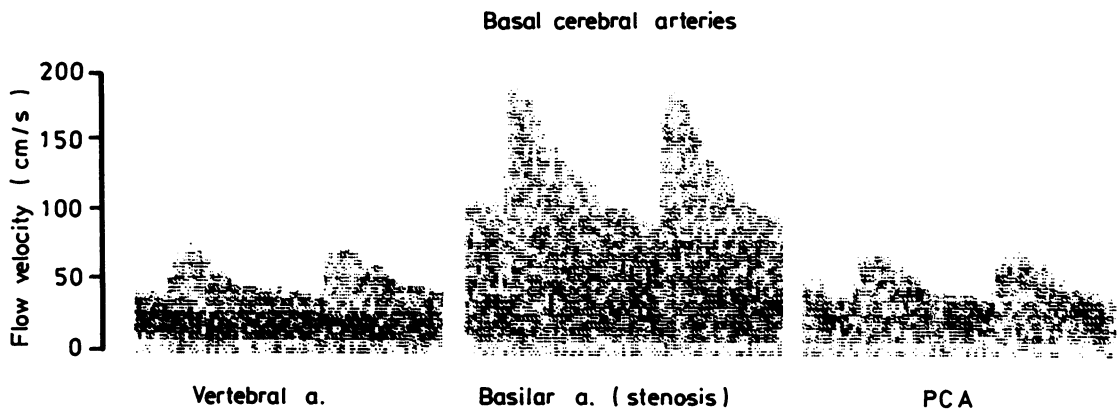

Fig 6 *Recordings from patient No. 3 (table). Flow velocity in the stenosis was 122 cm/s (sampling depth: 80 mm), which was about four times the vertebral artery flow velocity. Flow velocities in the posterior cerebral artery (PCA) show no throttling effect. Angiographic findings in fig 4c.*

Results

The TCD recordings from intracranial arteries in the 21 angiographically normal hemispheres gave the following findings. Middle cerebral artery (MCA) flow velocity ranged from 38 to 82 cm/s, median 54 cm/s. Flow velocity in the ICA siphon was from 32 to 68 cm/s, median 44 cm/s. The basilar artery recordings showed flow velocities ranging from 34 to 66 cm/s, median 48 cm/s. Recordings from the anterior cerebral artery were obtained in 18 hemispheres. These flow velocities ranged from 30 to 74, median 46 cm/s. Angiography revealed hypoplasia of the proximal anterior cerebral artery in two of the hemispheres where flow velocity in this vessel was not recorded. From these findings, flow velocities of from 35 to 80 cm/s were accepted as representing the expected range in angiographically normal intracranial arteries in a population at risk.

Artery stenoses presented as confined artery segments showing clearly elevated flow velocity levels. The probe position and the depth setting corre-

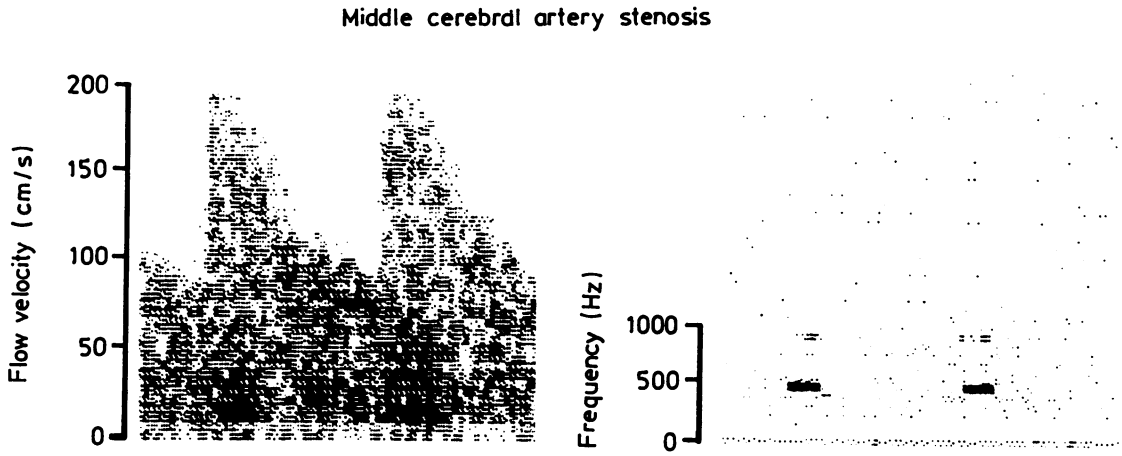

Fig 7 *Spectral displays of flow velocities and systolic musical murmur in patient No. 4 (table). Systolic peak velocity: 194 cm/s, time mean: 136 cm/s (left). The pure tone quality of the murmur is evidenced by a high intensity frequency band at 450 Hz (right). This frequency should not be mistaken as representing Doppler-shift frequencies. Angiographic findings in fig 4d.*

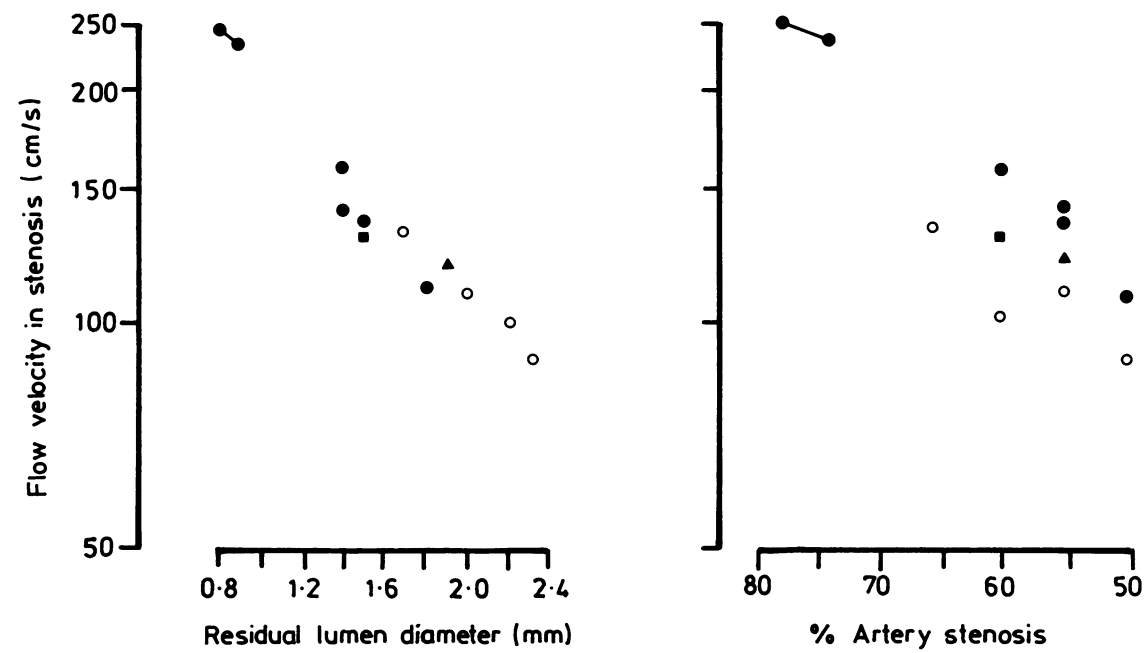

Fig 8 *Correlation between stenosis velocity and residual lumen diameter (left) showed an inverse relationship, Tau = −0·89 (p = 0·0001). The correlation between flow velocity and stenosis percentage (right) was Tau = 0·59 (p = 0·0108). Drawn line connects two different observation pairs in Patient (table, No. 1). Vessels: ● = Middle cerebral, ■ = Anterior cerebral, ▲ = Basilar artery, ○ = Carotid siphon. Logarithmic flow velocity scale.*

sponded well with the anatomical location of stenoses seen from angiography. Recordings from stenoses were characteristically different from recordings from angiographically normal vessels (figs 3, 4, 5, and 6). Damping of the pulsatile velocity spectrum outline in recordings from more distal vessel segments was seen when the stenosis exceeded 60% diameter reduction (figs 3 and 5).

The Doppler audio signal recorded from normal cerebral arteries had a smooth and breezy character. In most recordings from stenoses, low-frequency broad-band noise, indicating disturbed flow and ves-

sel wall flutter, was present throughout the cardiac cycle. Originally applied to Doppler recordings from extracranial carotid stenoses, the term "gruffy" aptly describes the coarse character of these Doppler audio signals.[19] A musical murmur with pure tone quality was noted in one patient (table, No. 4). This murmur had a fundamental frequency of 450 Hz in systole (fig 7), and its point of maximum intensity seemed to be 5 or 10 mm downstream to the site where the highest flow velocities were recorded. Systolic flow velocity in this stenosis was 194 cm/s, which corresponds to a Doppler-shift frequency of about 5 KHz using 2 MHz emitted ultrasound.

The table summarises findings in the 11 patients. An inverse relationship existed between flow velocity in the stenosis and the residual lumen diameter, the Kendall rank correlation coefficient, Tau, being $-0{\cdot}89$ ($p = 0{\cdot}0001$) (fig 8). The relationship between flow velocity and stenosis percentage was Tau $= 0{\cdot}59$ ($p = 0{\cdot}0108$). In correlating between stenosis percentage and residual lumen diameter, Tau was $-0{\cdot}50$ ($p = 0{\cdot}0328$). The carotid siphon is normally wider than the middle cerebral artery diameter, which therefore has a smaller residual lumen for any given stenosis percentage.

No MCA velocity signal was found on the left side in one patient admitted the day after an acute right hemiplegia. Recordings from the left anterior and posterior cerebral arteries were nevertheless obtained, confirming the patency of the "ultrasonic window". A total MCA occlusion was hence predicted. CT scans indicated an acute infarction of the left MCA territory. The clinical condition did not warrant an angiography. This patient died two days later, necropsy findings revealing total occlusion of the proximal MCA.

Discussion

Methodological considerations

Recordings from intracranial artery stenosis resembled those from extracranial carotid stenoses.[1 2 3 19] In intracranial arteries, blood flow velocities above normal levels also prevail in Willisian collateral channels.[17] It is therefore important to ascertain the identity of the vessel from which a recording is being obtained. The depth resolution capability of range-gated pulsed Doppler devices is advantageous in this respect. Brief and carefully executed test-occlusions of the carotid arteries in the neck further confirm vessel identity.[17]

Flow velocities in intracranial arteries show a wide normal range which probably parallels individual vessel calibre variation.[15–17 20] The diameter of the carotid siphon normally exceeds the MCA diameter.[20] For any given stenosis percentage the MCA stenosis therefore also has the smaller residual lumen. Being able to identify each vessel investigated means that anatomical considerations can be incorporated when the findings are being interpreted. Furthermore, collateral flow in the circle of Willis and damped flow velocity outlines in distal vessels can be demonstrated.[17] Such findings illustrate the haemodynamic effect of a stenosis. In a previous study, we demonstrated damping of the pulsatile velocity spectrum outline in the middle cerebral artery due to the haemodynamic throttling effect of ipsilateral extracranial carotid stenosis with more than 75% lumen area reduction.[17] Atherosclerotic arterial stenosis does not develop axisymmetrically.[3] The present findings of a distal throttling effect with intracranial artery stenoses of more than 60% diameter reduction therefore seem to be in accordance with previous observations. The clinical value of haemodynamic information like this can be just as significant as a stenosis being graded in terms of stenosis percentage or residual lumen diameter.

Musical murmurs from cerebral arteries probably occur under special local flow conditions associated with high flow velocity levels. This subject has recently been reviewed by Aaslid and Nornes.[21] Anatomical structures vibrating within the ultrasound beam cause phase-shifts in the reflected echoes, and thus modulate the received signal. This vibration frequency is obtained through demodulation and spectrum analysis in the same way as the Doppler-shifted spectrum is extracted; however, it should not be mistaken as representing Doppler-shift frequencies. The present findings indicate that musical murmurs are not specific to the underlying pathological process. There nevertheless seems to be a positive correlation between the fundamental frequency and the coexisting blood flow velocity.[21]

Hypoplastic or missing MCA is extremely rare. When the MCA velocity signal is absent in the expected location, a total MCA occlusion can therefore be suspected. To exclude technical error, however, it is essential that a suitable "ultrasonic window" has been located. Recordings from other intracranial vessels should be obtainable using the very same probe position. One also has to be aware of the possibility that an expansive mass may dislocate the course of the proximal MCA. Such large expansive lesions will nevertheless be revealed by CT.

Clinical implications

Reduced MCA perfusion pressure is the basic requirement for maximal efficacy of bypass procedures.[22] The development of a pressure gradient secondary to an arterial narrowing reflects the loss of

energy. In artery stenosis most of this loss occurs because the potential energy transmitted by means of pressure is converted into kinetic energy, most of which is again irretrievably spent generating poststenotic disturbed flow.[23] Kinetic energy is a square power function of velocity. Blood flow velocity in stenoses therefore has considerable clinical relevance.

We consider the present series as too small to warrant conclusions concerning sensitivity and specificity; however, TCD investigation seems to be a promising and clinically feasible method for assessing patients with occlusive disorders of intracranial arteries. Such patients may be considered as candidates for extracranial-intracranial bypass operations.[6 11 13] Short-term medical management with the aid of repeated angiography for surveying the individual course of disease has been advocated.[6 7 11] In follow-up and for the timing of control angiography, TCD could be a useful asset in the management of these patients.

Intravenous digital subtraction angiography, albeit increasingly employed to visualise extracranial carotid lesions, often does not permit assessment of intracranial artery stenosis.[24–26] TCD and digital angiography could therefore be considered as complementary methods forming the basis of a less invasive approach to the evaluation of patients under consideration for carotid endarterectomy. Furthermore, by using TCD investigations to assess flow conditions in distal vessels, relevant additional information on individual haemodynamic conditions are obtained.[17] Noninvasive assessment of intracranial arteries seems particularly relevant clinically if carotid endarterectomy without any preceding angiographic procedure[27 28] is contemplated.

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