TRANSCRANIAL DOPPLER IN CEREBROVASCULAR DISEASE

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ABSTRACT

Transcranial doppler is a new technique which uses 2MHz ultrasound beams to measure the velocity of blood flow in the intracranial cerebral arteris. Normal flow velocity is easily distinguished from the accelerated velocities associated with vasospasm, arterial stenoses and arteriovenous malformations. The effect of extracranial occlusion and stenosis on cerebral hemodynamics and the pattern of collateral flow in the circle of Willis can be deciphered. Medical and surgical attempts to improve cerebral perfusion can be monitored repeatedly, non-invasively and in complete safety. Continuous intraoperative monitoring during carotid endarterectomy and open-heart surgery appears promising and future developments may make it possible to monitor intracranial pressure indirectly with this technique.

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INTRODUCTION

The use of 'through-the-skull' doppler ultrasonography to measure intracranial cerebral blood flow became possible in 1981 when the Norwegian physiologist Rune Aaslid developed a prototype transcranial doppler device. He established that it was possible to record reflected ultrasound waves from intracranial blood vessels with sufficient signal-to-noise ratio when he used pulses of 2MHz sound waves. This was a dramatic progression from the first use of echoencephalography in 1955. The first description of TCD in man appeared only in December 1982(1) and since then numerous applications of transcranial doppler (TCD) have evolved and they range from detection of vasospasm after subarachnoid haemorrhage (2,3) to monitoring embolisation techniques in arteriovenous malformations.

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DOPPLER PRINCIPLES IN TCD

The Doppler technique in TCD is based on the principle that ultrasound waves (say, of frequency Fo) directed at a stream of moving red blood cells will be reflected back with a changed frequency. This change or shift in frequency, Fs is known as the Doppler shift and is determined by the Doppler formula:

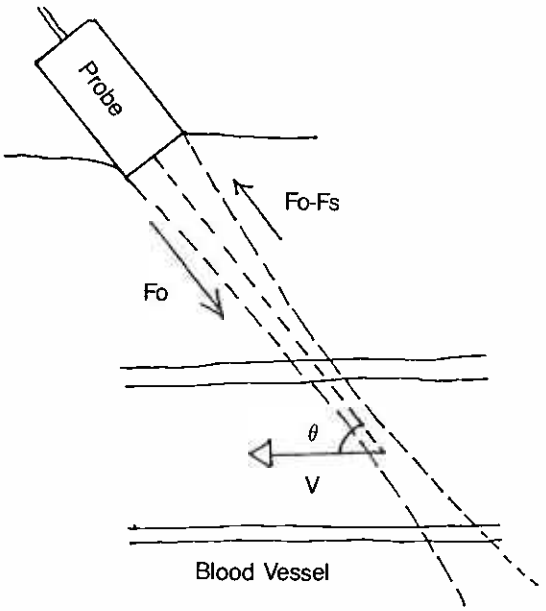
$$Fs = \frac{2\ Fo.\ V.\ Cos\theta}{C}$$ (see Fig 1A)

where Fo = frequency of incident ultrasound beam
V = velocity of blood flow
θ = angle between ultrasound beam and axis of blood flow (Insonation angle)
C = velocity of sound in the medium (soft tissues)

The velocity of blood flow is thus proportional to the Doppler shift and can be easily calculated once θ and C (1,550 m/s in soft tissues) are known. A positive or negative Doppler shift would tell you which direction the blood is flowing. In duplex carotid imaging the angle θ can be accurately determined from the B-mode image. The difference in TCD measurements is that the angle of incidence cannot be determined because there is no B-mode map of the cerebral arteries. We therefore try to improve accuracy by insonating at very small angles. Fortunately the actual velocity is very close to the measured doppler shift velocity for small angles of insonation (fig 1B). When θ is O, cos θ is 1 and V = Fs. 39 (when V is in cm/s and Fs in Hz).

INSTRUMENTATION

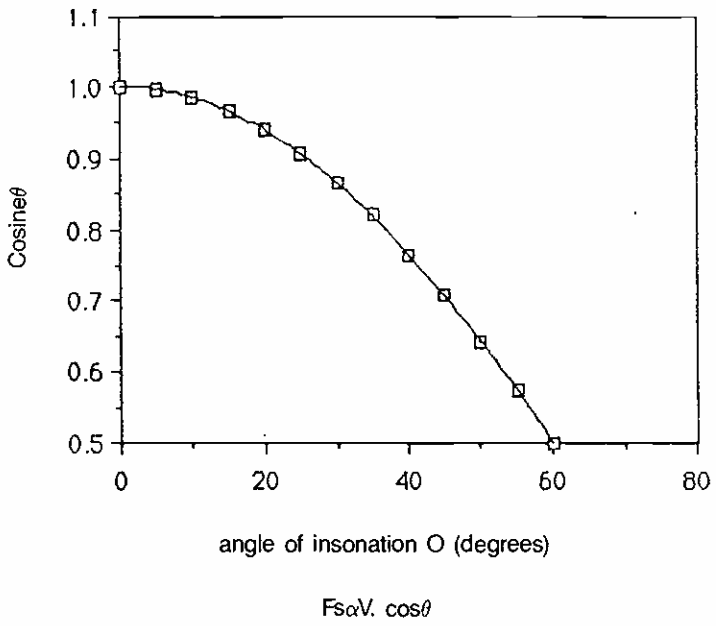
The first commercially available TCD machine was the TC2-64 (Eden Medizinische Elektronik GMBH). This is a com-



Fo = frequency of incident ultrasound beam

Fo-Fs = frequency of reflected ultrasound waves

Fig. 1 (A) THE DOPPLER PRINCIPLE



$Fs \alpha V. \cos\theta$

FIG. 1 (B) RELATIONSHIP OF THE DETECTED DOPPLER SHIFT Fs to the angle of insonation θ

pact, portable machine weighing 8.5 kg. It has a 2MHz hand-held probe and a built-in computerized 64-point sliding-average FFT spectrum analyser displaying 132 spectral line resolution on a 12X9 cm monitor screen. The transcranial probe is 22mm in diameter; the beam is focused and samples a volume of tissue measuring 5x8 mm. The depth of this sample can be electronically adjusted from 30 to 120mm in steps of 5mm. Ultrasound intensity can be varied from 10 mW/cm² (for transorbital recordings) to 75-100 mW/cm² (for transcranial recordings). Pulse repetition frequency is 5-10KHz, pulse length 13us, gate width 13us, vessel wall filter 150KHz and low pass filter 10KHz. A elastic-velcro strap-on probe holder is available for continous monitoring. Hard copies are made on an Epson RX-80 dot matrix printer.

A further development of this technique announced recently is the 3-dimensional transcranial doppler scanner which produces ultrasonic flow 'maps' in three projections (anterior-posterior, horizontal and lateral). These 'maps' are colour coded for flow velocity and direction. These maps should allow for easier identification of individual arteries. Although the initial scan may be more laborious, it is possible to store a memory of the coordinates from the previous study so that repeat studies can be performed more quickly. It remains to be seen if results are more reproducible with the 3-dimensional scanner.

EXAMINATION TECHIQUE

The first step in TCD examination is to obtain a "window" through which the ultrasound beam can gain accesso the basal cerebral arteries without losing too much of its energy during its approach as well during its return journey to the probe. Three "windows" have been described (1) and they are: A) transtemporal, B) transorbital and C) suboccipital/transforamenal (fig 2). The transtemporal 'window' is located above the zygomatic arch and is sufficiently large for division into anterior, middle and posterior 'window'.

The patient is usually examined supine except with the suboccipital approach when it is often helpful to have the patient sitting up with the neck flexed. The window is then searched for meticulously and it may vary from patient to patient. The direction of insonation and depth of insonation are varied as the basal cerebral vessels are sampled; it may even be necessay to make minor variations in the angulation of the probe during the insonation of one vessel at various depths in order to obtain the optimal signal.

Information obtained includes direction of blood flow, peak systolic velocity (Vs), diastolic velocity (Vd), mean velocity (Vm), and pulsatility index. Pulsatility index is defined as PI = (Vs — Vd)/Vm. In some applications, the pulsatility transmission index (PTI) is also obtained: PTI = PI/PIref where PIref is the pulsatility index of the corresponding unaffected cerebral artery. The identity of the vessels insonated may be inferred from the direction of insonation, depth of insonation, and various manouvers. These include: eye opening and closing; and compression tests. Eye opening has been demonstrated to increase flow in the posterior cerebral arteries by 10-15%(4) while compression of the common carotid artery can help to identify various vessels by their predictable effect on flow velocity and even directional changes. Compression tests can also provide informaion on the nature and adequacy of collateral circulation provided certain precautions are taken in the performance of these tests. Fig 3 is an illustration of a typical TCD recording of the basal cerebral arteries, the eyes opening maneuver being used to confirm the identity of the posterior cerebral artery.

Table 1: CLINICAL USES OF TCD

1. Detect vasospasm (after SAH) (14,15,16,17,18,19)
   - timing of angiography
   - trial of drugs, selection and control of therapy
2. Detect intracranial stenoses and occlusions (20,21,22,23,24)
3. Diagnose AVMs and aneurysms (25,26,27,28)
4. Detect raised ICP, brain death (29,30)
5. Diagnose disturbances of autoregulation (31)
   e.g. primary orthostatic cerebral ischaemia
6. Monitoring during procedures that may compromise cerebral perfusion (32,33,34)
   a) carotid endarterectomy
   b) interventional neuro-radiological procedures
      - embolisation of AVMs
      - transvascular treatment of aneurysms
   c) open-heart surgery
7. Evaluating procedures that attempt to improve cerebral perfusion (35)
   a) medical therapy
      e.g. hypervolaemic haemodilution, low molecular weight dextran
   b) surgical therapy
      e.g. superficial temporal artery to middle cerebral artery bypass, posterior circulation bypss grafts, vertebral endarterectomy
8. Haemodynamic evaluation of extracranial cerebral arterial disease and tandem lesions (36)
9. Evaluation of collateral capacity in Circle of Willis (37.38)
10. Provide supplementary evidence of misely perfusion (cerebral claudication) by demonstrating absence of vasodilator response to hypercapnia (39,40,41)

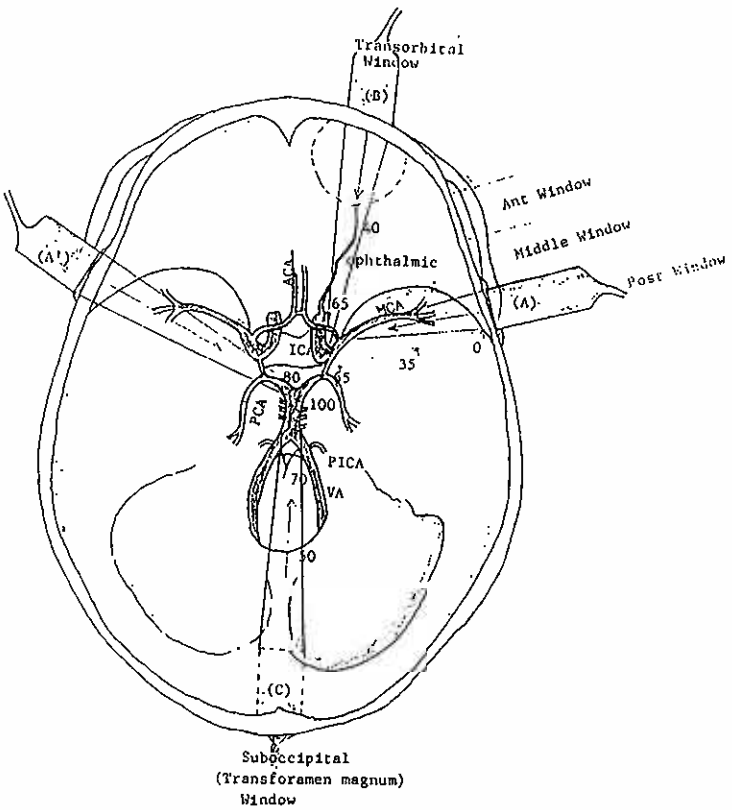


Fig. 2 THE THREE MAJOR WINDOWS FOR TRANSCRANIAL DOPPLER WITH AVERAGE DEPTH SETTINGS INDICATED (MM)

(A) transtemporal insonation of the middle cerebral artery via the posterior window (A') transtemporal insonation of the posterior cerebral artery
(B) transorbital insonation of the ophthalmic artery and the internal carotid artery siphon
(C) suboccipital insonation of the basilar artery

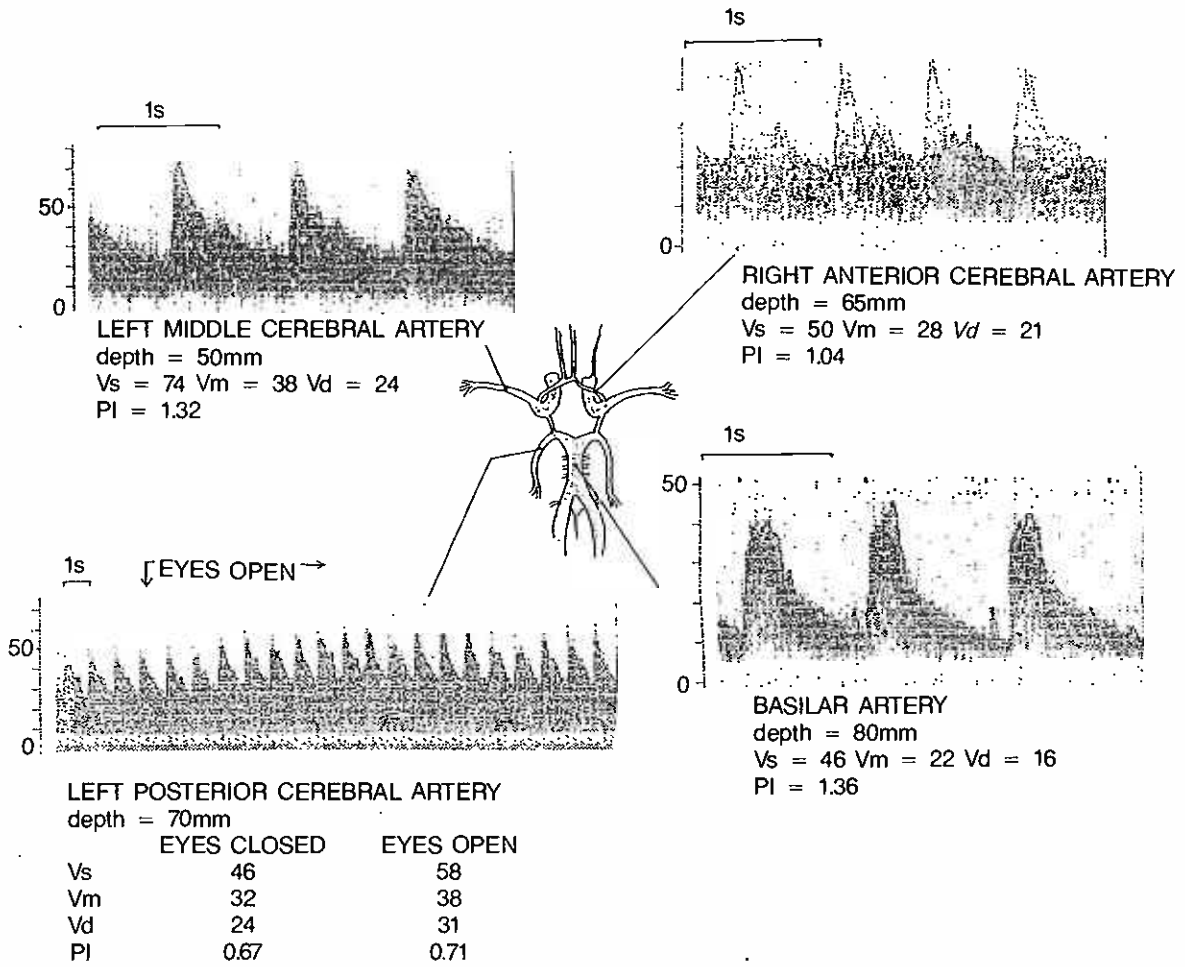
NORMAL VALUES

Systolic (peak) velocity, diastolic velocity and mean values in normal adults have been reported (1,5,6,7). These values are almost invariably higher in the middle cerebral artery [mean ± 2SD = 65 ± 17 cm/s, systolic ± 2SD = 94 ± 23, diastolic ± 2SD = 46 ± 12](5) and anterior cerebral artery than the basilar [mean ± 2SD = 39 ± 9 cm/s, systolic ± 2SD = 56 ± 13, diastolic ± 2SD = 27 ± 7] and posterior cerebral arteries. The valus decrease with age and are lowest in infancy; an average decrease of 20% has been described from healthy adults aged 30 to similar adults aged 80(5). Values for newborn infants, term and preterm, have recently been reported (8). Increases in haematocrit have been correlated with decreases in mean velocity in the middle cerebral artery as measured by TCD. In one study the relationship was defined by V mean = e-.035 Hct + 5.4 with a coefficient of correlation of 0.88 (9).

VALIDATION OF TCD MEASUREMENTS

The refraction and differential attenuation of incident ultrasound beams by the curved diploe of the skull was of major concern initially. Anatomical validation of the ability of TCD to sample the individual basal cerebral arteries faithfully has, however, been accomplished in comparison studies with B-mode ultrasound measurements in infants and measurements in cadavers (10).

The validation of velocity measurements obtained by TCD has been more difficult because of difficulty in finding a suitable model. Direct comparison of measurements by TCD with those obtained during intracranial operations is not possible because of the altered conditions of the open skull and general anaesthesia. In general, however, the flow patterns established with intraoperative devices have been established faithfully by TCD (11). A study of 17 patients with sickle cell anaemia and a wide haematocrit range (17 to 38) revealed a linear relationship between mean velocity in the middle cerebral artery stem (as measured by TCD) and Xenon-133 cerebral blood flow [ISI = 0.49 * mean velocity + 32.5; r = 0.92, and FI = 1.2 * mean velocity + 10.3; r = 0.95](12). An earlier study showing a poor correlation between middle cerebral artery peak velocity (by TCD) and cerebral blood flow measured by intravenous Xenon-133 (Novo Cerrbrograph 10A) has been complicated by the fact that all their 17 pa-



	EYES CLOSED	EYES OPEN
Vs	46	58
Vm	32	38
Vd	24	31
PI	0.67	0.71

Fig 3. TRANSCRANIAL DOPPLER RECORDING IN A HEALTHY SUBJECT: Vs = systolic velocity (cm/s) Vm = mean velocity Vd = diastolic velocity PI = pulsatility index

tients (aged 41 to 70 years) had symptomatic cerebrovascular disease (13). In this study, the absolute measurement of velocity showed a poor correlation with hemispheric cerebral blood flow ($r = 0.424$, p 0.01) due to wide between-patient variations at rest; but the blood flow response to hypercapnia, expressed as a reactivity index, showed a good correlation ($r = 0.849$, p 0.001).

APPLICATIONS OF TCD

TCD has been shown to be useful in a wide variety of neurological and neurosurgical conditions (see Table 1).

One of the first applications of TCD was the detection of cerebral vasospasm occurring as a complication of subarachnoid hemorrhage (14,15). The evaluation of vasospasm is based on the principle that velocity of blood flow in a vessel is inversely related to its diameter. Time-mean velocities of 120-230 cm/s in the middle cerebral artery are frequently encountered during vasospasm after subarachnoid haemorrhage with velocities up to 350 cm/s in isolated cases. 'Musical murmurs' of pure tone quality (140-820 Hz) have been detected (18) during vasospasm — during the transition state from silent, high velocity laminar flow to the development of audible bruit. Current clinical experience suggests that mean velocities of 120-140 cm/s are well compensated by cerebral autoregulation and are associated with normal clinical status. Velocities over 200 cm/s appear to be critical with a tendency to cerebral ischaemia. The time course of vasospasm has been elegantly charted by TCD and found to correlate well with clinical status and amount of blood visualised by CT scan (16). Initial experience has shown that patients operated during the phase when vasospasm is rapidly increasing generally show even greater velocities post-operatively. This did not occur in patients operated during a phase of decreasing velocities (18). TCD therefore appears promising as a guide to the timing of operation and angiography as well as an excellent tool for the evaluation of medical therapy.

Intracranial arterial stenosis also results in increased velocity over the involved segment with a loss of pulsatility (the 'damping effect' or 'throttling effect' due to energy expended in overcoming the increased resistance of the narrowed lumen) in the distal segments. Lindegaard et al (20) have shown an inverse relationship between angiographically demonstrated residual lumen diameter and TCD measured flow velocity in ten patients. Many of the recordings from stenosed vessels contained low-frequency, broad band noise (interpreted as due to disturbed flow and vessel wall flutter) throughout the cardiac cycle and a distal throttling effect was

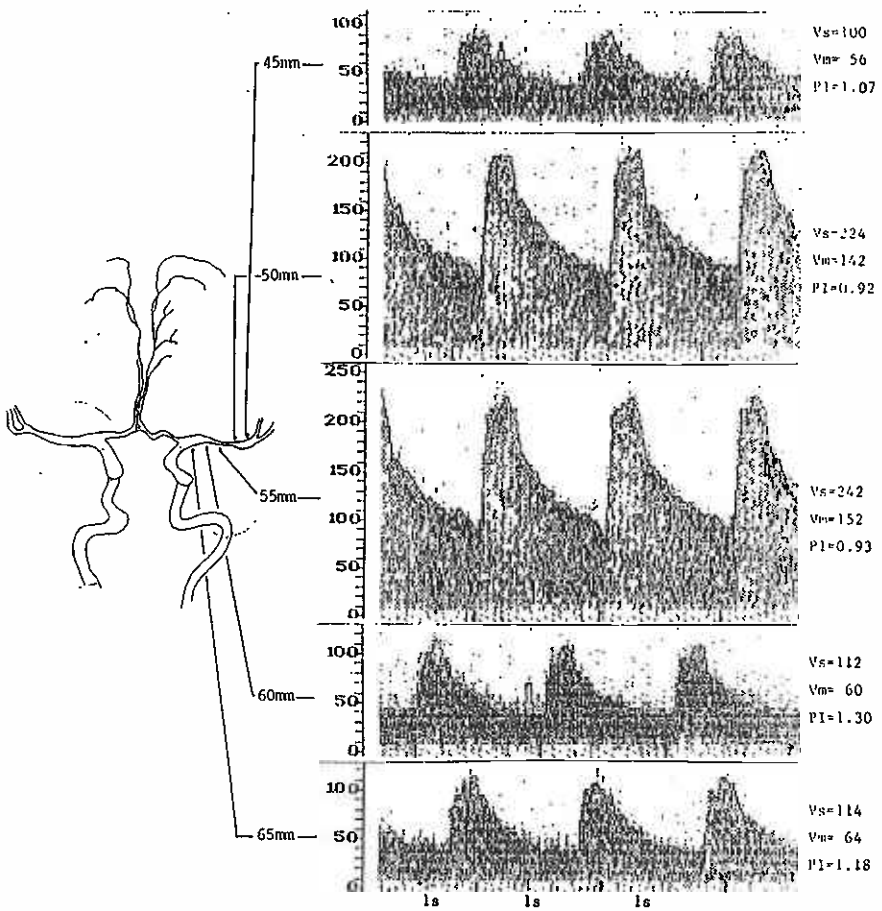


Fig 4. TCD FINDINGS IN LEFT MIDDLE CEREBRAL ARTERY STENOSIS: markedly increased velocities with diminished pulsatility over a short segment (50-55mm).

seen only if stenosis resulted in more than 60% diameter reduction. They also described the detection of total middle cerebral artery occlusion in one patient; proven at necropsy. Spencer et al (21) have developed criteria for the diagnosis of intracranial internal carotid artery stenosis based on transorbital TCD. They reported 95% specificity, 73% sensitivity and 88% overall accuracy based on arteriograms of 33 intracranial internal carotid arteries. Figure 4 is the record from a 82 year old male with findings of very localised increased velocities. Subsequent angiography confirmed the presence of middle cerebral artery stem stenosis (70%). Figure 5 demonstrates the ability of TCD to document increased velocity and turbulence at a stenosis in the posterior circulation. The ability to monitor these lesions repeatedly over a period of time should prove useful in management.

The diagnosis of total occlusion is generally more difficult than that of stenosis because one must be certain than an adequate ultrasonic window is indeed present. The possibility of anatomical variation is especially troublesome in the anterior cerebral artery because of the 7% incidence of hypoplasia of one anterior cerebral artery. Anomalies of the main stem of the middle cerebral artery is extremely rare and it is reasonable to make a diagnosis of total occlusion when no signal is detected provided a good ultrasound window is assured by the easy localisation of the anterior and posterior cerebral arteries (20).

It remains to be seen if TCD will decrease the need for cerebral angiograpy although it will certainly increase the confidence of centres which are already proceeding with carotid endarterectomy on the basis of duplex ultrasonography alone. The ability to monitor intracranial stenosis and occlusions repeatedly over a period of time should prove invaluable in clarifying the natural history of these lesions. The intensive use of TCD in the course of acute stroke is likely to teach us much about the pathophysiology of the condition e.g. the timing and degree of reperfusion of an acutely occluded artery.

Cerebral arteriovenous malformations (AVMs) behave like shunts which lead blood rapidly from its arterial 'feeders' into the venous system. AVMs are characterised by low resistance and hence their feeders exhibit high flow as well as low pulsatility. The high flow velocity result in increased viscous drag and result in intra-arterial pressures which are lower than normal in the feeder arteries. This contributes further to the reduced pulsatility of the vessel. Normal intracranial cerebral arteries, however, show considerable interindividual variability in pulsatility and the use of pulsatility transmission index has been shown to be more useful in the diagnosis of AVMs (25). In a series of 28 patients reported by Lindegaard et al (25), TCD permitted non-invasive diagnosis of AVMs in 26 and the information obtained was found helpful in the hemodynamic evaluation of the individual

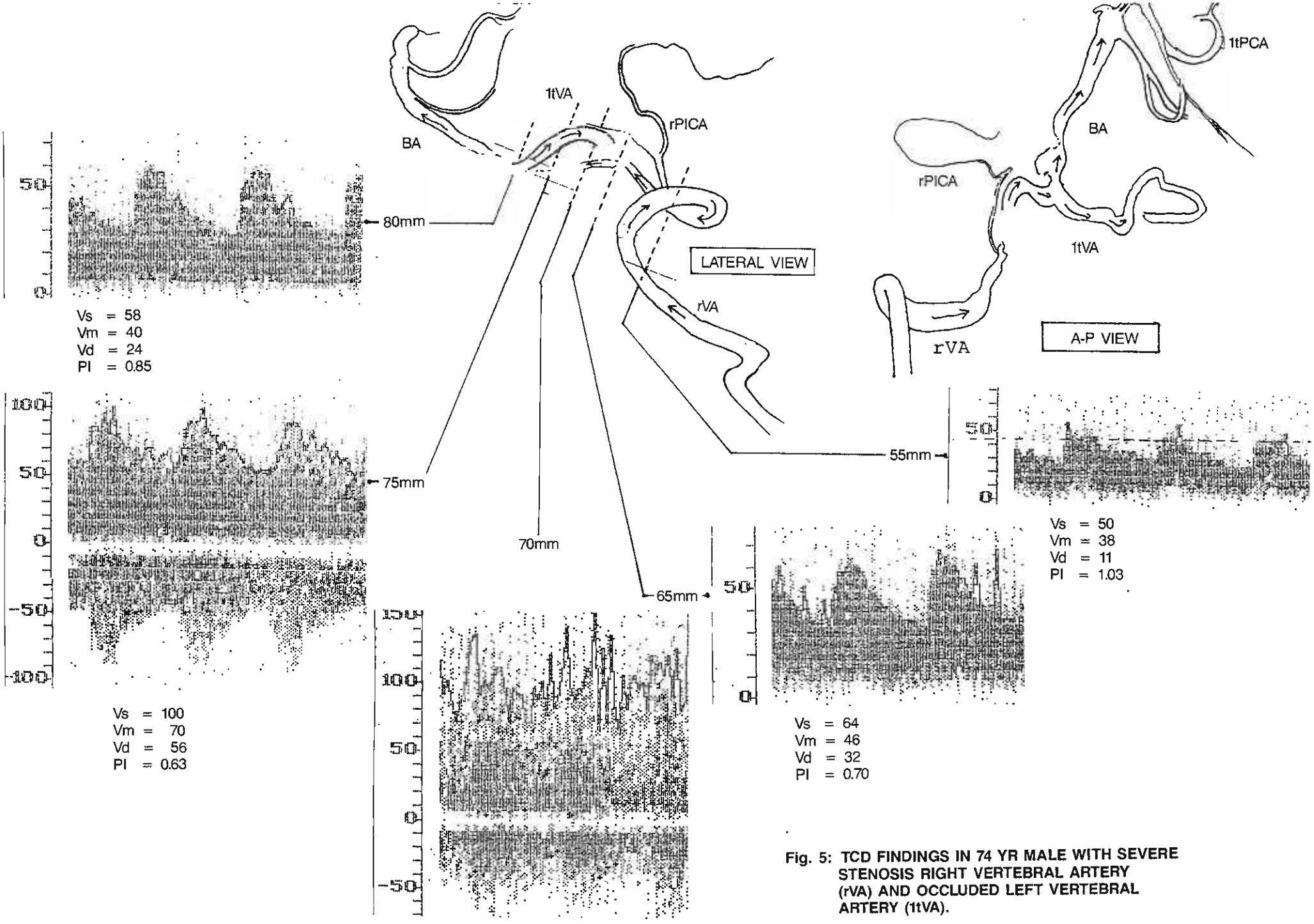


Fig. 5: TCD FINDINGS IN 74 YR MALE WITH SEVERE STENOSIS RIGHT VERTEBRAL ARTERY (rVA) AND OCCLUDED LEFT VERTEBRAL ARTERY (1tVA).

AVM — over and above that provided by angiography. They have suggested that the finding of flow velocities above 150cm/s in long feeders may be a warning sign of chronically impaired perfusion in the adjacent normal brain i.e. significant 'steal' phenomenon. Most cases of false-negative TCD diagnosis were small AVMs i.e. less than 2cm diameter. In one series, the use of pulsatility transmission index increased the sensitivity of TCD in diagnosing feeder vessels from 50% (using pulsatility index alone) to 93% (26). The hemodynamic characteristics of venous cerebral angiomas and dural extracerebral angiomas as opposed to cerebral AVMs have been described in isolated cases only (28).

Raised intracranial pressure (ICP) is a result of brain injury and by itself can contribute to further, and sometimes irreversible, injury. It is believed that agressive treatment of ICP may improve the outcome in a wide variety of neurological and neurosurgical conditions. Unfortunately current techiques of ICP monitoring are invasive and present problems of hemorrhage and infection. It was hoped that TCD would provide an indirect technique of monitoring ICP by measuring its effect on flow velocity. TCD is certainly able to demonstrate the reverbatory (to-and-fro) blood flow that occurs in the state of extremely high ICP characteristic of brain death. Indeed, the progressive decline from high flow (high velocity and low pulsatility seen in some cases immediately after head injury) to high resistance (increasing pulsatility) and finally to reverbatory blood flow in the middle cerebral artery has been well demonstrated by TCD (29,30). A close correlation between ICP and flow velocity as measured by TCD has not been demonstrated to date and current effort is directed towards establishing a relationship between ICP, arterial blood pressure and various parameters in the TCD recording.

While the role of TCD in ICP monitoring is still evolving, its use in the monitoring of cerebral blood flow during surgical or neuroradiological procedures that may compromise cerebral perfusion has been better established (32,33,34). Its use during open-heart surgey may help avoid hyperperfusion as well as hypoperfusion during critical stages (30). TCD monitoring has also been used during carotid endarterectomy to determine if a shunt is needed. The magnitude of the drop in time-mean velocity during temporary clamping of the common carotid artery is used as the guide. The drop in velocity, sometimes to zero flow, occurs before electroencephalographic changes are detected.

The ability of TCD to provide information about flow velocity as well as direction of flow in all the basal cerebral arteries in most patients has made it possible to construct a flow diagram of the circle of Willis non-invasively. Retrograde flow in an anterior cerebral artery due to collateral cross-filling from one carotid supply feeding a large hemispherical convexity AVM on the contralateral side has been demonstrated repeatedly (26). Similar retrograde flow has also been reported following internal carotid artery occlusion and also in middle cerebral artery stem disease(38). Even when normal anterograde flow has been demonstrated, it is possible to test for collateral capacity by compression of the common carotid artery or even vertebral artery on the ipsilateral side(37). The status of the circle of Willis pre and post extracranial-to-intracranial bypass can also be assessed by the above maneuvers in addition to compression of the external carotid artery(35). The failure of extracranial to intracranial bypss to benefit patients selected on the basis of angiographic criteria in a recent multi-center trial has made it necessary for the clinician to seek further and more physiological evidence of cerebral hypoperfusion in such cases. TCD, in addition to other techniques of measuring cerebral blood flow and metabolism, may assist in this process. Attempts have been made to correlate TCD measurements with the results of positron emission tomography (40). The use of hypercapnia to differentiate between a maximally dilated, low flow and hypoperfused territory (little or no reserve capacity) from a non-dilated and appropriately low flow territory (increased flow on vasodilatation with hypercapnia i.e. good reserve capacity) has been applied to TCD (39,41).

LIMITATIONS OF TCD

TCD measures doppler shift and hence can only provide information on the spectrum of flow velocities in the vessel(s) insonated. It does not provide information on the volume of blood flow per unit time i.e. the rate of flow. Cerebral autoregulation acts to maintain cerebral blood flow within narrow limits despite changes of velocity induced by narrowed lumen. TCD readings therefore cannot be interpreted as directly or easily as cerebral blood flow images obtained by Xenon-133 or Technetium-99m HPOA images. Current technique also does not allow sampling of the axial mid-stream laminar flow and hence the detection of increased turbulence within the axial flow cannot be obtained as in duplex scanning. The possibility of signals from two adjacent vessels merging to give one Doppler spectrum is also present and would limit its use in the more peripheral branches of the cerebral arteries. The use of smaller sample volumes would partly overcome this problem but at the expense of increasing the amount of noise in the signal.

A small percentage of subjects (5-7) do not have one or more suitable acoustic windows. This is seen more frequently with increasing age. A certain degree of patient cooperation is still necessary and the restless patient with a small acoustic window may defeat the most enthusiastic investigator.

DEVELOPMENTS IN TCD

The availablity of 3-dimensional commercial TCD equipment has been mentioned above. It would appear possible to measure relative changes in volume flow by using the changes in signal spectral amplitude together with the more conventional indices of flow velocities(42). A more exciting research development in recent months has been transcranial duplex scanning(43). Using an ATL Ultramark 2.25 MHz 2-D system and the Vingmed 3 MHz color Doppler system, Spencer has reported transtemporal imaging of short arterial segments including cortical branches of the middle cerebral artery (of sufficient quality to permit diameter measurements). The anterior clinoid processes could be readily visualised and in addition to other bony landmarks provided a 2-D map to help localise the source of intracranial Doppler signals. The images, however remain suboptimal and high energy beams were required.

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