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**DISSERTATION**



Course: MCh Neurosurgery

Course Duration: January 2003 to December 2005

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**APPLICATION OF TRANSCRANIAL DOPPLER IN  
NEUROSURGICAL INTENSIVE MONITORING-  
A Study In Patients With Vasospasm, Raised Intracranial  
Pressure And Brain Death**

Dissertation submitted for MCh Neurosurgery Examination

Course Duration: January 2003 to December 2005

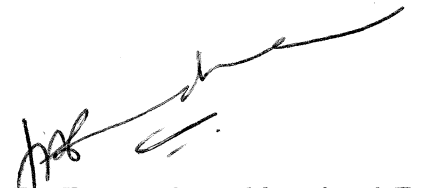
Candidate: Dr Purandare Harshad R.

## CERTIFICATE

I, Dr Purandare Harshad R, hereby certify that the submitted dissertation work '*Application of transcranial Doppler in neurosurgical intensive monitoring - A study in patients with vasospasm, raised intracranial pressure and brain death*', is authentic, genuine, ethical and has been carried out under strict guidance and supervision, without any falsifications.

Thiruvananthapuram

Date: 03 November 2005

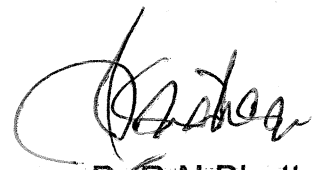


Dr Purandare Harshad R

FORWARDED: This is to certify that Dr Purandare Harshad R. has carried out the above study under appropriate guidance had has completed the same satisfactorily.

Thiruvananthapuram

Date: 03 November 2005



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## **INTRODUCTION**

The Doppler effect was first described by Austrian physicist Christian Andreas Doppler in 1842 to explain colour shifts in the visible light of double stars. As developments in ultrasonography and its outbranching into Doppler Sonography occurred due to technical progresses, Doppler found widespread clinical applications as a non invasive monitor, especially in cardiovascular system, which was its mainstay application. The use of Doppler ultrasound to measure blood flow was first proposed by Satomora in 1959.

Solomon and Kaneka in 1969 were perhaps the first clinicians to use pulsed Doppler in neurosurgical patient, for intraoperative monitoring.<sup>1</sup> However routine application was hampered by the skull vault which acted as a high resistance for penetration of ultrasound waves from the typical 5-10MHz probes. In 1982, Aaslid developed a 2MHz probe based clinical module which overcame this barrier and ushered in widespread neurological and neurosurgical applications of Transcranial Doppler (TCD). Color spectral Doppler and Duplex sonography has greatly enhanced the anatomic as well quantitative study.<sup>2</sup> Yet, a number of procedures and parameters await validation and standardization.

## **AIMS AND OBJECTIVES**

To study the clinical application of TCD and its aid in therapeutic decision making in neurosurgical intensive care patients with specific emphasis on vasospasm, associated with subarachnoid hemorrhage (SAH), raised intracranial pressure (ICP) and brain death.

1. To evaluate correlation between TCD vasospasm and clinical grade, outcome, CT scan and Digital Substraction Angiography (DSA) findings in SAH, as a guide to therapeutic decision making.
2. To study spectral changes in raised ICP, with attention to correlation with clinical status and symptomatology, as well as resolution of the same on treatment.
3. To evaluate TCD in validation of clinical brain death, as an alternative to Electroencephalogram (EEG) record, for early detection of the same.

## PHYSICS AND PRINCIPLES OF TCD

Doppler principle implies that a reflected wave has a higher frequency as compared to the incident wave, when the reflector is moving towards the source due to compression of these waves. Similarly when the reflector is moving away, the reflected wave has a lower frequency. This change of frequency, called 'frequency shift or Doppler shift' is directly related to the speed of the reflector (blood flow velocity) and transmitted frequency and inversely related to cosine of angle of insonation.<sup>3</sup> The frequency shift in physiological blood flow is between 0.5 and 15 kHz. Hence,

$$\text{Reflector speed} = \frac{\text{Doppler shift} \times \text{propagation speed}}{2 \times \text{incident frequency} \times \cos \delta}$$

### Pulsed Doppler

Range gated, short pulses (5 to 30 cycles) of ultrasound used to target and sample a specific discrete region or point, thus determining the depth of reflector by using the range equation. There has to be an adequate time interval or gating between the two pulses to allow all signals to return, and this factor fundamentally limits the Doppler shifts that can be evaluated.

### Spectral Analysis

Signals received are composed of multiple frequency components moving at different velocities, since the sample volume is relatively large. This spectrum can be displayed by Fourier Transform technique, giving Spectral Doppler. A variety of parameters, criteria and indices can be used on this pattern to evaluate velocity and flow characteristics.

## TCD Ultrasonography And Skull

The detailed acoustic properties of skull were described by White in 1978. With exception of air, bone has the highest acoustic impedance. Temporal bone, being the thinnest, with limited diploe, is the most conducive to successful insonation despite a significant loss of acoustic power (even upto 80%)

Though ultrasound related cavitations, thermal effects and risk of cataract formation has been quoted, routine pulsed wave ultrasound generated spatial peak temporal average (SPTA) intensities are well below the  $100\text{mW}/\text{cm}^2$ , rendering it a completely safe modality.

### Acoustic Windows:<sup>4</sup>

**Orbital Window** – used for insonation of Internal carotid artery (ICA) siphon and ophthalmic artery. Transducer is placed over the closed eyelid, directed towards the optic canal (medial tilt) in the horizontal plane. Power output is to be reduced to 10-25% of the maximum to minimize eye exposure to ultrasound waves.

**Temporal Window** – insonation of distal ICA, Middle cerebral artery (MCA), Anterior cerebral artery (ACA) and Posterior cerebral artery (PCA) is obtained. Bone over the region above the zygomatic process and anterior to the ear is insonated. Anterior, middle and posterior temporal windows have been defined. Power output is kept at 100% for maximal penetrance. Variation in depth and direction of insonation enable to target individual vessels. Temporal insonation failure rate ranges from 5 to 20% and is related to thick and cancellous temporal bone. Failure rate is higher in elderly and in women.

**Table 1: Criteria For Artery Identification On Transcranial Doppler**

<b>VESSEL</b>	<b>WINDOW</b>	<b>TRANSDUCER ORIENTATION</b>	<b>DEPTH (mm)</b>	<b>FLOW DIRECTION</b>	<b>WAVEFORM</b>	<b>IPSILATERAL CAROTID COMPRESSION</b>	<b>CONTRALATERAL CAROTID COMPRESSION</b>
<b>OA</b>	Orbital	Slightly medial	40-55	Towards	High Resistance	-	-
<b>ICA(siphon)</b>	Orbital	Slightly medial	55-70	Bidirectional	Low Resistance	-	-
<b>MCA</b>	Temporal	En face	35-60	Towards	Low Resistance	Reduced velocities	No change
<b>ACA</b>	Temporal	Anteriorly	60-75	Away	Low Resistance	Flow reversal	Increased velocity
<b>PCA</b>	Temporal	Posteriorly	55-70	Towards	Low Resistance	Increased velocity or no change	No change
<b>VA</b>	Suboccipital	Superioly and obliquely	45-75	Away	Low Resistance	-	-
<b>BA</b>	Suboccipital	Superiorly	75-120	Away	Low Resistance	-	-

**Foramen Magnum Window** – the beam is directed upwards between atlas and base of skull and enables study of the vertebrobasilar (VBA) system

### Technique Of Transcranial Doppler Study

TCD system uses a pulsed Doppler operating at a low frequency of 2MHz for higher bone and soft tissue penetration, with range gating for depth determination (25mm to 100mm depth). Sample volume may range from to 3 x 3mm to 6 x 6mm, thus sampling all velocities within the lumen, projecting a broadened spectral waveform, with velocity along the y axis by a microprocessor guided Fast Fourier Transform Analysis of the signal.<sup>5</sup>

As per the equation, the measured velocity is a function of the angle of insonation of the vessel, more specifically, the cosine value of that angle. Thus, even if it is assumed that the angle of insonation ranges from 0 to 30 degrees, its cosine would range from 1 to 0.86. This would amount to a maximum error of 15% in the determined velocity, thus yielding a significantly accurate result. Further based on the above variations, precise estimate can be made by applying the equation  $V=0.039f$ , where V is the velocity in cms/sec, and f is the Doppler frequency shift.<sup>6</sup>

### Data Parameters

The peak or systolic velocity (PV) and the end diastolic velocity (EDV) can be directly measured from the spectral display by computed algorithms. The mean velocity (MV) may be approximated using the formula

$$MV = [ PV + (2 \times EDV) ] / 3$$

MV is the least dependent on systemic factors and has a higher correlation with perfusion than PV or EDV, with less inter-individual variations.<sup>5</sup>

**Table 2: Normal Reference Flow Velocities In Adults**

Arterial Segment	Velocities (cms/sec)		
	Peak systolic (Vs)	End diastolic (Vd)	Mean (Vm)
MCA	91 ± 17	44 ± 11	56 ± 13
ACA	66 ± 12	23 ± 9	36 ± 14
PCA	51 ± 11	29 ± 8	41 ± 9
VA	56 ± 8	23 ± 6	36 ± 12
BA	56 ± 13	27 ± 7	39 ± 9

**Doppler Calculated Flow Indices**

In addition to MV, variations in spectral waveforms can be used to calculate ratios or indices which reflect patterns of flow. The two important indices are

**Gosling's Pulsatility Index (PI)<sup>7</sup>**

$$PI = (PV - EDV) / MV$$

PI is a measure of the amplitude of the flow velocity waveform and reflects the peripheral vascular resistance. Vessels with high systolic velocity and rapid upstroke (spiked

waveform) exhibit elevated PI, whereas, vessels with slow upstroke of peak velocity and delayed peak velocity latencies (dampened waveform) show a low PI.

Changes in pulsatility reflect changes in arterial perfusion territory only if other systemic variables are unchanged. Studies by Lindegaard as well as Sorteberg bring forth extensive inter-individual variations in this value. Mean PI has been reported as  $0.69 \pm 0.11$ , with minimal and insignificant side to side variability

### **Pourcelot's Resistance Index (RI):<sup>8</sup>**

$$RI = (PV - EDV) / PV$$

It is also a measure of peripheral vascular resistance, with low vascular resistance characterized by high diastolic velocity and low RI and vice versa. It more specifically correlates with Cerebral perfusion pressure (CPP) and hence to ICP. Mean RI reported has a range of  $0.59 \pm 0.13$ .

### **Validation Of TCD Study Localization Value**

Ringlestein et al<sup>9</sup> report an overall sensitivity and specificity of 87.5% for TCD in evaluation of localization of vessels and their anomalies, when compared with conventional angiography. Maximum sensitivity and specificity was observed for region of ICA siphon and MCA, while insonation of the mid to distal BA was a major limitation

### **Pitfalls In TCD Diagnosis<sup>10</sup>**

1. Anatomic – variations of circle of Willis, hypoplastic vessels, PCA from ICA.

2. Technical – small or inadequate temporal window, displacement of arteries by space occupying lesion (ICSOL).
3. Instrumentation – large sample volume, poor angle, inadequate gain control, leading to poor signal to noise ratio.
4. Interpretation errors – Misdiagnosis of hyperdynamic states or vasospastic states as increased flow due to stenosis.
5. Blind spots – branch occlusions, proximal PCA or ACA occlusion, very low flows, poor insonation of Anterior communicating artery (Acomm), Posterior communicating artery (Pcomm) and aneurysms directly.

## **APPLICATIONS OF TCD – A REVIEW OF LITERATURE**

### **TCD IN SAH INDUCED VASOSPASM**

Angiographic evidence of vasospasm is noted in 25-70% cases with SAH and is the maximum at 7-10 days after the bleed. Recent data suggest the incidence of focal deficits in the period of 2 weeks following SAH to be upto 30%. Rebleed, hematoma, hydrocephalus, metabolic derangements, raised ICP and vasospasm may be the incriminated factors. Statistically 80% of the delayed deficits are attributable to vasospasm.<sup>11</sup> Until the recent past, angiographic confirmation of the vasospasm was mandatory for confirming and establishing the clinical diagnosis of vasospasm. However, after its initial demonstration by Aaslid et al, extensive studies have fostered an increasing acceptance of the role of TCD Doppler in non invasive detection of vasospasm, as well as regular monitoring by repeat follow up Doppler studies.<sup>12</sup>

### **Pathology And Hemodynamics Of Vasospasm**

Exposure to oxyhemoglobin and other blood degradation products in the basal cisterns and the subarachnoid space are the primary triggers for smooth muscle spasm with reduction of vascular diameters, predominantly in the basal vessels, especially the MCA and ICA. Associated smooth muscle damage with cell migration and proliferation in the intima complete the damage. Free radicals, eicosanoids, endothelial dysfunction, failed autoregulatory and vasodilator activity and inflammation contribute to the multifactorial pathogenesis of vasospasm.<sup>13</sup> Associated hemodynamic disturbances contribute significantly to outcome.<sup>14</sup> Several studies have demonstrated that Cerebral flow (CBF) is reduced after SAH, with a relatively higher frequency, though not consistently, in higher

grades of SAH. A strong correlation exists between severe vasospasm and clinically significant reduction in CBF. Flow values between 20-30ml/100gm/min demonstrate reduced levels of consciousness, less than 20ml/100gm/min have severe and often irreversible deficits.

SAH is associated with elevated ICP. The late phase of raised ICP correlates with the period of vasospasm. Severe vasospasm is associated with brain edema and elevation of ICP, resulting in fall of CPP below 40mmHg leading to severe compromise of CBF. Associated loss in autoregulation seen with vasospasm leads to further worsening of ICP and CPP changes

### **DSA And Vasospasm**

Though angiographic estimation of vessel diameter bears a fair correlation to the morphologic diameters, it holds true primarily for the vessels of the circle of Willis and to some extent, to its first and second order branches. Narrowing of the vessels in spasm leads to loss of sharpness with reduced amount of contrast in the lumen and altered absorption effects. Thus luminal diameters may not be optimally measured. Other angiography related technical factors may further hamper the estimation.

This leads to highly variable detection of vasospasm on angiography, with visual assertion of 'present' or 'absent' leading only to a moderate to fair degree of intra and inter-observer agreement, even for the main vessel trunks. Difficulty and technical limitations in repeated DSA studies hampers follow up evaluation of patients with vasospasm.<sup>15</sup>

A large number of grading and description schemes exist for description of vasospasm on DSA. Morphometric classification variedly describes vasospasm as **diffuse or extensive (type I), mutisegmental/ nodular / tapering (type II) and local (type III)**. These confusing terms themselves are non-quantifying and do not yield any clinical correlation.<sup>16</sup>

Though it is generally accepted that more than 50% diameter narrowing on DSA is definitely associated with neurological manifestations, a large number of patients with lesser degrees of luminal narrowing are symptomatic and vice versa.<sup>17</sup>

### TCD Investigations In Vasospasm

MCA velocity profiles correlates best with the degree of vasospasm due to limited collateral network. MCA velocity increases with vessel narrowing, with an inverse relation between flow velocity and vessel diameter, such that halving the vessel diameter corresponds to a fourfold increase in velocity.<sup>1,12,18</sup> Flow changes are also recorded from ICA, ACA and PCA, though data is limited and variable with lack of similar proportional correlation between diameter and velocity, so as to set any specific parameters for assessment.<sup>19</sup> With increase in vasospasm, musical murmurs with pure tonal qualities are heard in region of ICA bifurcation in systole and diastole which indicates periodic formation of vortices.

In general, MV elevation to 120 cm/sec correlates with mild angiographic vasospasm (less than 25% narrowing), velocities between 120 and 200 cm/sec correlates with moderate angiographic spasm (25-50% narrowing) while velocities greater than 200cm/sec are associated with severe vasospasm (greater than 50% narrowing)<sup>20</sup>

## Doppler Characteristics Of Vasospasm<sup>21</sup>

### MCA

#### Grades

- Mild vasospasm - MV above 120 cm/s
- Moderate vasospasm - MV between 120 and 200 cm/s
- Severe vasospasm - MV above 200 cm/s

#### Turbulence

- "Doppler Bruits" - high intensity, low frequency
- Bi-directional signals

#### MCA/ICA velocity ratio (Lindegaard index):<sup>19, 22</sup>

- Normal:  $1.7 \pm 0.4$
- Moderate vasospasm  $> 3$
- Severe vasospasm  $> 6$

### VB system:<sup>23</sup>

BA velocity  $>90$  cm/s

BA spasm index (ratio of BA flow velocities to extracranial) of  $>2.5$

**Other vessels:** Though no guidelines exist, an increase of 50% or more above baseline is considered indicative of vasospasm.<sup>19, 23</sup>

Rapid rise in MV of more than 25% rise per day or values greater than 200cm/sec are often associated with MCA territory infarcts and poor outcomes. There is no significant difference in the time course or severity of rate of change of FV in various grades of SAH.<sup>12</sup> Some investigators have attempted to estimate changes in CBF on basis of FV changes. Studies by Aaslid and Lindegaard in experimental settings found that though correlation existed between the two parameters, it was non linear. In clinical setting, fall / of both FV and flow volume were noted with increasing constriction, with volume and CBF falling more rapidly than FV. Moreover, blood pressure, hematocrit, PCO<sub>2</sub>, and ICP also alter CBF. Hence FV is not a reliable index of CBF in vasospasm.<sup>24,25</sup> According to Doberstein, simultaneous measurements of FV by Doppler with CBF techniques such as Xe -133 CT or SPECT with calculation of ratio of slope index of these studies to FV correlates more closely with rCBF.<sup>26</sup> Hassler and Chioff showed progressive loss of vasodilatory capacity to hypercapnia with increasing severity of vasospasm. Increased FV, increased PI, loss of cerebrovascular reactivity correlate with incipient ischemia and poor prognosis.<sup>27</sup>

### **Pitfalls In FV Measurement By Doppler**

Among the technical and anatomical factors cited earlier, the most important factors which alter measurements include a suboptimal temporal window in 15-35% patients and anatomical variations in Circle of Willis in 55% patients. Also post operative clip artifacts, brain swelling and brain shifts due to retraction may cause difficulty in picking up focal signal variations. Very severe vasospasm may reduce FV to such a low level that signal

may weaken and may be inaudible. Proximal vessel stenosis, arrhythmia, blood pressure fluctuation, hematocrit as well as volume depletion often leads to suboptimal waveform and subsequent incorrect FV measurement.<sup>12, 22</sup>

Severe raised ICP with significant vasospasm or otherwise, impairs CPP and CBF and leads to low FV. Studies have shown significant fall of MCA-FV with ICP more than 30mm Hg and CPP less than 40mm Hg. In such cases RI can act as a guide. Low FV with RI more than 0.6 is seen with ICP more than 20mm Hg. Thus, with  $RI \leq 0.5$ , the changes in mean FV reflect the actual time course and severity of vasospasm.<sup>28</sup>

Autoregulation impairment leads to loss of reactivity to hypocarbia with  $P_{CO_2}$  alteration affecting FV.<sup>27</sup> Therapeutic interventions in SAH may alter FV for a given degree of stenosis. Though triple 'H' therapy increases CBF, the net effect on FV has not been clearly documented, though the fall in hematocrit in the treatment may lead to a positive increment in the FV.<sup>29</sup> Mannitol may increase the CBF and MV by causing vasodilation and decreasing the viscosity. Calcium channel blockers (nimodipine, nifedipine) reduce the intensity and severity of vasospasm and reduce the FV.<sup>30</sup> Dramatic reduction in FV can be seen in patients undergoing transluminal angioplasty for vasospasm and it has been suggested that TCD can be an adjuvant for non invasive monitoring of such therapeutic modalities.<sup>31</sup>

### **Sensitivity And Specificity Of TCD In Vasospasm**

A large number of studies have assessed the correlation of TCD findings with vasospasm, comparing it with the gold standard imaging – cerebral angiography, thus evaluating false positive and negative results and determining its predictive value.

## MCA

Studies by Grolimund et al,<sup>32</sup> Crompton et al,<sup>33</sup> Lindegaard et al,<sup>22</sup> and many others suggest that TCD can detect MCA vasospasm with sensitivity of 78-94%, specificity of 90-100%, positive predictive value of 57-90% and negative predictive value of 80-97%. Though the ideal threshold values have not been definitely established for MCA, as discussed earlier, roughly accurate parametric correlation of MCA-FV to DSA observed degree of vasospasm are commonly used to guide clinical decision making. Lowering the threshold values is seen to increase the sensitivity at the cost of specificity.

Other MCA indices have been postulated to increase the sensitivity and specificity. Aaslid and Lindegaard evaluated the ratio of MCA-FV to extracranial ICA-FV, to predict vasospasm as well as to distinguish it from the common confounding factor of hyperemia and hyperdynamic flow increase.<sup>34</sup> The normal ratio is  $1.7 \pm 0.4$ . Hyperemia induces increase in both the velocities in similar proportion and the ratio is unaltered or even if elevated, is less than 2.5. A ratio of  $\geq 3$  is seen in mild to moderate spasm, while a ratio of  $>6$  distinguishes between moderate and severe vasospasm and correlates with higher risk for infarct and overall poorer outcomes. This value has a substantial clinicoradiological correlation.<sup>19, 22</sup>

Jacobsen assessed the ratio of higher obtainable MCA-FV with CBF called Spasm Index (Spl) as measured by Xe-133 technique. A value of greater than 8 correlated with severe clinical vasospasm and poorer clinical grade with value of over 11 correlating with CBF of  $<30\text{ml}/100\text{gm}/\text{min}$  and poorer outcomes. However the ratio alters with elevation in ICP and no study have quantitatively correlated the ratio to clinical outcome.<sup>35</sup>

MCA vasospasm is noted in 45-86% of the patients with clinical and radiological vasospasm. Yet it may be difficult to reconcile the patients clinical status with MCA-FV alone as the clinically relevant spasm may involve another territory. Hence, only MCA study may lead to an incomplete assessment of spasm.<sup>33</sup>

### **ACA**

In the two important studies by Grolimund et al<sup>32</sup> and Lenninhan et al,<sup>36</sup> angiographic evidence of vasospasm was 15% and 18% respectively. Using the criteria of 50% increase in FV in the first study and mean FV of  $\geq 100$ cm/sec in the second study, a wide range of sensitivity(10-71%) and specificity(67-95%) was obtained yielding significant false positive and negative values. Consequently ACA Doppler study is hampered by a wide range of positive and negative predictive values (6-100%), relatively small sample size, an overall low prevalence of ACA vasospasm and a highly variable anatomy in ACA – Acomm territory that hampers optimum vessel targeting. Hence the criteria for diagnosis of ACA vasospasm on TCD are variable and not widely accepted, and the recordings need to be interpreted with caution.

### **Other vessels**

Only a few studies, conducted by Sloan et al are available which evaluate role of TCD in vasospasm involving PCA, vertebral artery and basilar artery.<sup>12</sup> The mean FV in PCA more than 90cm/sec and basilar artery more than 60cm/sec may be indicative of vasospasm. However, angiographic correlation with PCA and BA vasospasm was noted in only 20% and 22% patients respectively. Thus the sensitivity appears to be only mild to moderate for PCA and BA.

In a recent study, Soustiel and colleagues<sup>37</sup> evaluated the additional value of an intracranial / extracranial FV ratio in the posterior circulation - Basilar modified 'Lindegaard' ratio to cope with shortcoming of TCD in the diagnosis of BA vasospasm. The normal ratios between intracranial and extracranial VA FVs were 1.6 on both sides, whereas the ratio between the BA FVs and the mean extracranial VA FVs was 1.7. In patients with SAH, 41.2% had DSA or CTA evidence of BA vasospasm. A FV threshold of 90 cm/s was indicative of BA vasospasm in 92.8% and BA/VA ratio was more than 2 in all patients with BA vasospasm (100% sensitivity). Thus, the ratio may contribute to an improved discrimination between BA vasospasm and vertebrobasilar hyperemia and enhance the accuracy and reliability of TCD in the diagnosis of BA vasospasm.

#### **TCD As A Guide To Decision Making Following SAH.**<sup>38</sup>

Limitations of TCD must be considered in individual situations. Serial TCD measurements are critical in evaluation of temporal progression of vasospasm. Most protocols recommend serial TCD studies from third or fourth day of SAH and repeating the study every 2 to 3 days in the period of risk.

A patient whose condition is deteriorating and has a normal or non diagnostic TCD, should be considered for angiography if no other cause is detected. A patient with diagnosed vasospasm, whose condition fails to improve or deteriorates despite aggressive medical management, should be considered candidates for urgent angioplasty. Patient's clinical status should be the main guiding factor, aided by TCD findings. In other cases, elevated PI and RI, with decreased peak systolic and diastolic FV's may give hemodynamic evidence to complement clinical and radiological findings of raised ICP, thus guiding appropriate treatment.

There is little effect on physiological effects of triple 'H' therapy on FV values, and does not aid in predicting therapeutic outcomes or decisions.<sup>29</sup> Patients with high initial mean FV (>150cm/sec), rapid rise of mean FV (>25% rise daily) or features of decreased CBF or altered autoregulation (loss of reactivity to hypocarbia) in the first or second week after SAH has been correlated with poor operative outcomes, especially if associated with episode of hypotension (absolute or relative) during the procedure. It is assumed that after 2 weeks, surgery can be performed with relative safety, even in the presence of high velocities, as long as adequate CPP is maintained.<sup>39</sup>

#### TCD IN ASSESSMENT OF RAISED ICP AND CPP

Maintaining CPP is the basic tenet in management of patient with raised ICP, based on assumption that maintaining CPP preserves CBF, and is based on the simple yet physiologically complex equation

$$CPP = MAP - ICP$$

For bedside evaluation, ICP can be measured by a number of devices or roughly correlates with the jugular venous pressure. With measurement of MAP, a rough clinical estimate of CPP (and indirectly CBF) can be obtained, substituting the need for complex and often clinically and practically infeasible techniques of Xe133 scan or nitrous oxide washout techniques.<sup>40</sup> On the other hand, TCD is a non invasive and bedside procedure providing serial though indirect estimates of ICP, CPP, CBF and intracranial compliance.

Blood FV is proportional to blood flow as long as the lumen of the vessel insonated and the volume of tissue perfused are unchanged. Hence when the CBF is constant, the pulsatile changes of FV in the TCD waveform varies with the Cerebral vascular resistance (CVR), thus reflecting changes in ICP.

### Waveform Changes

Hassler et al<sup>41</sup> described qualitative changes in TCD waveform with progressive increasing ICP. They found that as ICP reached the diastolic blood pressure, end diastolic flow disappeared. As ICP exceeded the diastolic pressure, reversal of direction of flow during diastole is seen, as evident by reversal of waveform. These findings were not quantified and all patients in the study died, suggesting that when the ICP is high enough to obliterate diastolic flow, it may be too late to intervene.

### Changes In PI And RI

Analysis of pulsatile flow velocity changes require understanding of *Windkessel effect*, that postulates storage of systolic energy in the elastic arterial tree temporarily to release it in form of pressure in diastole.<sup>40, 41</sup> Thus, it is a measure of the intrinsic resistance and compliance of the arterial tree. When ICP is low, the compliance of the arterial tree or the *Windkessel effect* is the dominant factor determining arterial pulsatility. When ICP is high, stiff poorly compliant intracranial space dominates over arterial resilience reducing arterial pulsatility. This change affects both, the peak or systolic as well as diastolic velocity with elevated PI being one of the earliest manifestations of increasing ICP. With rise in ICP, as diastolic flow ceases EDV=0. In such a situation,  $PI \approx PV/MV$  and  $RI \approx PV/PV \approx 1$ .

Bellner et al<sup>42</sup> performed TCD to assess PI in 81 patients with raised ICP as measured by an intraventricular cannula system. Elevated PI was observed in all patients with raised ICP irrespective of the cause. ICP can be estimated from PI within 2 standard deviations of the measured value in all patients. At ICP <20mmHg, it had a high sensitivity and moderate specificity. At ICP range of 20 to 40mmHg, the sensitivity decreased while the specificity increased. The correlation was better as compared to similar studies in head injury patients.

There are conflicting reports on the utility of these indices in assessing ICP. Natakani et al<sup>40</sup> identified that though FV decreased linearly with rise in ICP, while RI rose significantly only when ICP rose above 40mm Hg. Thus simultaneous monitoring of FV by TCD and ICP is essential for evaluation of cerebral hemodynamics, especially in early stages of increased ICP. Further studies by Klingelhöfer et al<sup>43</sup> suggest that RI is a reliable but only an indirect measure of ICP. They concluded that it is theoretically possible to calculate ICP by calculating  $(MAP \times RI) / MV$ , in patients without an intact cerebral autoregulation, vasospasm or any significant stenosis. Unfortunately, most of the critically ill patients do not meet these criteria.

### **TCD IN BRAIN DEATH**

The ICU environment is often non-conductive for meeting the published technical requirements for determining electrocerebral silence. Since brain death is associated with cerebral circulatory arrest, secondary to ICP elevation, loss of autoregulation with fall in CPP as well as due to impaired venous return. Cerebral angiography has demonstrated

non filling of intracranial circulation. Radioisotope studies are inadequate for posterior fossa. Since TCD is a relatively fast, inexpensive, and non-invasive test, it is being increasingly used to confirm BD.<sup>40</sup> The following systematic pattern is noted in brain death.<sup>41, 42, 44</sup>

1. Low diastolic flow velocity: rapid decline of diastolic velocity to near zero. Anterograde flow in entire cycle. PI is elevated. Cerebral perfusion is preserved.
2. Systolic peaks: Sharp peaked waveform which may last thru the entire cycle, no diastolic flow is noted. May be reversible when ICP elevations are treated.
3. Oscillating blood flow: Anterograde sharp spikes alternating with brief sharp retrograde diastolic flow. Net velocity very low or even zero. Often considered irreversible.
4. Short systolic spikes: Brief anterograde spike waveform that last only for a brief portion of the cycle. No flow on angiography.
5. Absence of TCD signal: It has 96% sensitivity and 100% specificity to confirm brain death when corroborated with clinical parameters.

As per the 1998 World Federation of Neurology criteria, characteristic blood flow changes should be recorded in the MCA, VA, and ICA. However study by de Frietas et al,<sup>45</sup> in 94 clinically brain dead patients showed isolated flow in the ICA in 12% of patients, which would reduce the sensitivity of TCD to a much lower level than the 96.3% reported in other studies. One mechanism for persistence of flow in the extracranial ICA with clear evidence of intracranial circulatory arrest involves direct shunting of blood from the ICA

into the external carotid system without perfusion of the brain. Another plausible hypothesis is that arrest of blood flow may occur at a higher level than the carotid bifurcation. They proposed that ICA should not be routinely investigated and that circulatory arrest is confirmed when both the MCA and VA exhibit characteristic flow patterns.

In another study of 148 patients with brain death and TCD record, false positives have been noted in 3 patients, with TCD pattern of brain death in MCA noted in patients with spontaneous though weak respiration, 12 to 24 hours before brain death.<sup>46</sup> Conversely, 2 patients with clinical brain death show oscillating pattern or systolic peaks, and on one occasion, even forward flow pattern. SPECT and angiography in these patients confirmed intracranial circulatory arrest. Though confounding, these tend to disappear with serial measures. For this reason, insonation of all vessels is often considered essential. Oscillating patterns or short systolic spikes present in all examined intracranial vessels usually confirms imminent brain death. Stable signal recorded from each vessel for minimum 30 seconds, preferably 3 minutes and total duration of TCD examination of at least 30 minutes, especially with a repeat examination 2 hours later, negates all errors associated with TCD.<sup>40, 44</sup>

TCD cannot be used for confirmation of brain death in neonates and infants under the age of at least 18 months. Also, patients with open head injury may have locally preserved signs of flow.<sup>40</sup>

## **OTHER TCD APPLICATIONS IN NEUROLOGY AND NEUROSURGERY**

After introduction of TCD in clinical use, it has found widespread applications in a spectrum of neurological and related disorders. An increasing number of often conflicting reports confuses the clinician about the actual productive application of this modality for a specific illness. Sloan, Alexandrov, Babikian and others constituting the committee of American Academy of Neurology, reported on evidence based assessment of therapeutic and technical efficacy of TCD, which has been summarized below.<sup>47</sup>

### **Arteriovenous Malformations (AVM)**

High flow AVM induces vascular steal and vasodilation of surrounding vessels, with ischemia with low flow values (<40ml/100gm/min) documented at surgery in the surrounding vessels. Also hemodynamics of AVM feeders demonstrate loss of autoregulation in the feeders and AVM bed.

The characteristic TCD signal is characterized by elevated velocities and decreased pulsatility in the feeding vessels and AVM nidus as well as the arterialized draining veins. However the magnitude of velocity elevation does not approach that of vasospasm. Also anatomical delineation into components is not possible, though although trace of the complex vascular pattern can be obtained by identifying parametric changes in specified vessels. Due to multidirectional flow in the nidus, complex multispectral pattern is often obtained.

Pulsatility index is significantly lower in the AVM feeders as compared to normal vessels. This can be used during surgery to identify and differentiate feeders for *en passant* vessels, thus minimizing damage to normal brain and ensuring complete resection of AVM. In a study by Dempsey et al, the mean pre-resection PI in feeding vessel was 0.34 ( $\pm 0.01$ ) while that in normal vessels and feeder vessels after AVM resection was 0.62 ( $\pm 0.04$ ).<sup>48</sup> In large complex and high flow AVM's, high velocity and low pulsatility signals can be obtained from almost any insonated site.

Several factors confound TCD evaluation in AVM's. Raised ICP, alterations in PaCO<sub>2</sub> levels, low hematocrit, etc may by themselves alter flow velocities and PI, thus hampering true measurements.

### **Acute Cerebral Infarction**

Cerebral angiography shows acute occlusion in 76% of acute MCA territory infarcts within 6 hours of stroke onset. TCD can detect these angiographic occlusions with high (>90%) sensitivity, specificity, positive predictive value, and negative predictive value.<sup>49</sup>

Additionally, TCD can detect VA, and BA occlusions with fair to good (70 to 90%) sensitivity and positive predictive value and excellent specificity and negative predictive value occlusions. Intracranial arterial occlusions detected by TCD are associated with poor neurologic recovery, disability, or death after 90 days, whereas normal results predict early improvement.<sup>50</sup> When combined with carotid duplex sonography, the presence of suspected steno-occlusive lesions by TCD in patients with TIA or ischemic stroke were associated with an increased risk of further vascular events (usually stroke) and death

within 6 months. TCD-detected MCA (M1 segment) occlusions within 6 hours of stroke onset may be an independent predictor of spontaneous hemorrhagic transformation.<sup>51</sup>

The relative value of TCD compared with MRA or CTA remains to be determined.

### **Intracranial Stenosis**

Intracranial atherosclerosis is responsible for up to 10% of transient ischemic attacks (TIA) and strokes. Stenosis and occlusion of the ICA siphon, proximal (M1) segment of the MCA, intracranial VA, proximal BA, and proximal (P1) segment of the PCA can be reliably detected by TCD. The sonographic study of intracranial arterosclerotic arteries is characterised by an increase of the turbulence and velocity, located in a segment of the artery. Sensitivity, specificity, positive predictive value, and negative predictive value of TCD are generally higher in the anterior circulation owing to more variable anatomy and technical difficulties in insonation of the vertebrobasilar circulation. In patient with stenosis inferior to 50% of the vascular area, the transcranial Doppler is not able to establish the stenosis diagnosis regularly. Though sensitive, data is still inadequate to define TCD criteria for diagnosis of > 50% occlusion of vessels or to assess the progress of stenosis.<sup>52</sup>

### **Extracranial ICA Stenosis**

TCD can detect hemodynamic consequences of severe extracranial ICA stenosis, such as reversal of the direction of ophthalmic artery flow, presence of collateral flow patterns, absence of ophthalmic or carotid siphon flow, and reduced MCA flow velocity and pulsatility. For patients with angiographically or pathologically confirmed stenosis of

>70%, accuracy varies according to diagnostic criteria. However, when highly specific carotid duplex criteria are added, sensitivity and specificity are considerably improved.<sup>53</sup>

### Vasomotor Reactivity Testing

TCD evaluation of large basal conducting vessels can provide an index of relative flow changes in response to small blood pressure changes and physiologic stimuli to assess autoregulation and vasomotor reactivity (VMR) of the distal cerebral arteriolar bed. VMR testing techniques of static or dynamic (after provocative stimuli) cerebral autoregulation include measuring changes in flow velocities with the following changes:

- 1) Hemodynamic stimuli: rapid leg cuff deflation, Valsalva maneuver, deep breathing, ergometric exercise, head-down tilting, etc.
- 2) CO<sub>2</sub> inhalation (hypercapnia) / Hyperventilation (hypocapnia),
- 3) breath-holding index (BHI),
- 4) acetazolamide injection, and
- 5) Transient hyperemia response and its variants.

VMR testing techniques with TCD have been used evaluate patients with symptomatic or asymptomatic extracranial ICA stenosis or occlusion, cerebral small artery disease, head injury, and aneurysmal SAH. Patients with impaired collaterals have the greatest reduction in VMR. An exhausted VMR in the ipsilateral MCA was an independent predictor of occurrence of ipsilateral TIA and stroke. TCD vasomotor reactivity testing is considered probably useful for the detection of impaired cerebral hemodynamics in patients with asymptomatic severe (>70%) stenosis of the extracranial ICA, patients with

symptomatic or asymptomatic extracranial ICA occlusion, and patients with cerebral small artery disease.<sup>54</sup>

### **Head Injury**

A number of studies show lower MCA velocities with increasing severity of head injury, associated with early death (within 72 hours, <30cm/sec, 80% mortality). Also, PI >1.5 has been shown to be associated with consistently poorer outcomes. Monitoring with TCD and jugular bulb oxygen saturation may be used to optimize ventilatory and pharmacologic management of patients with severe closed head injury.<sup>55</sup> The sensitivity and specificity of TCD against angiography for the detection of post traumatic vasospasm has not been reported. Patients showing TCD criteria similar to post aneurysmal SAH have been detected to have poor outcomes.<sup>56</sup>

### **Sickle Cell Disease**

One large cohort study with long-term follow-up showed that elevated time-averaged mean maximum blood flow velocity of  $\geq 200$  cm/s in the ICA or MCA by TCD is strongly associated with stroke risk associated with an occlusive vasculopathy involving the distal ICA and the proximal MCA. TCD screening is effective in age group of 2 to 16 years to identify stroke risk though the timing and frequency of the examination is undermined.<sup>57</sup>

**Table 3: Evidence Based Applications Of Transcranial Doppler**

Indication	Sensitivity, %	Specificity, %	Reference standard	Evidence/Class
Sickle cell disease	86	91	Conventional angiography	A/I
Right-to-left cardiac shunts	70-100	>95	Transesophageal echocardiography	A/II
Intracranial stenoc-occlusive disease:			Conventional angiography	
Anterior circulation	70-90	90-95		B/II-III
Posterior circulation	50-80	80-96		B/II
Occlusion:				
MCA	85-95	90-98		B/III
ICA, VA, BA	55-81	96		B/II
Extracranial ICA stenosis			Conventional angiography	
Single TCD variable	3-78	60-100		C/II-III
TCD battery	49-95	42-100		C/II-III
TCD battery and carotid duplex	89	100		C/II-III
Vasomotor reactivity testing ≥70% extracranial ICA stenosis/occlusion			Conventional angiography, clinical outcomes	B/II-III
Carotid endarterectomy			EEG, MRI, clinical outcomes	B/II
Cerebral microembolization			Experimental model, pathology, MRI, neuropsychological tests	
General				B/II-IV
Coronary artery bypass graft surgery microembolization				B/II-III
Prosthetic heart valves				C/II
Cerebral thrombolysis			Conventional angiography, MR angiography, clinical outcome	B/II-III
Complete occlusion	50	100		
Partial occlusion	100	76		
Recanalization	91	93		
Vasospasm after spontaneous subarachnoid hemorrhage:			Conventional angiography	I-II
Intracranial ICA	25-30	83-91		
MCA	39-94	70-100		
ACA	13-71	65-100		
VA	44-100	82-88		
BA	77-100	42-70		
PCA	48-60	78-87		
Vasospasm after traumatic subarachnoid hemorrhage			Conventional angiography	I-III
Cerebral circulatory arrest and brain death	91-100	97-100	Conventional angiography, EEG, clinical outcome	II

## **MATERIALS AND METHODS**

### **SAH And Vasospasm**

72 consecutive patients admitted to Neurosurgical Intensive care unit of this referral institute between period of November 2004 and July 2005 with clinical, CT or lumbar puncture proven diagnosis of SAH were screened. All patients underwent DSA after initial workup within 2 days of admission. 50 patients with DSA confirmed aneurysmal SAH bleed were included in the study. Detailed clinical history and examination so as to ascertain WFNS grade of the patients were performed. Fisher's grade was ascertained on CT scan. Presence or absence of vasospasm, its location and degree (mild, moderate and severe; as described earlier) on DSA was estimated by 2 radiologists, performing the study. Patients underwent a baseline TCD study on inclusion, using a 2 MHz probe, RIMED, Intraview Doppler ultrasound system (CDS, Medasonics). 47 patients underwent surgical clipping within 3 days of admission. 2 patients, one in grade IV and the other in grade V, were not operated due to morbid condition and refusal by the patient's relatives. Post operative TCD was performed within 48 hours of surgery and subsequently thereafter on every third day in the period of risk. Additional evaluations were done whenever indicated. Extracranial ICA study, using the 4 MHz probe was done whenever elevated velocities were detected on transcranial study, to calculate the Lindegaard index. All basal vessels were screened. CT scan and biochemical evaluation was performed as a routine in all postoperative patients, and specifically in all patients with deterioration to rule out other causes of deterioration such as hydrocephalus, infarct, electrolyte imbalance, etc. Routine post operative angiography was not performed unless therapeutic endovascular intervention was considered for vasospasm.

Data was evaluated for incidence of vasospasm as detected by TCD and its correlation with WFNS and Fisher grade as well as location of the maximal bleed in the cisterns. Also, angiographic correlation as to presence/absence of vasospasm, corroboration of location and severity was also attempted with the Doppler findings. Specific attempt was made to correlate flow elevations of borderline degree, specifically MCA mean FV >90cm/sec but <120cm/sec to patients symptomatic deterioration, in absence of other causes. The date of onset of vasospasm with respect to the date of ictus was determined and correlated to the severity of bleed. Attempt was also made to study the specificity and sensitivity of Doppler detection of vasospasm in other vessels, specifically ACA, in correlation to DSA findings. Statistical evaluation to detect the sensitivity and specificity as well as the predictive value of Doppler in relation to angiography was done. The mean MCA velocities in the symptomatic as well as the asymptomatic group were correlated using the paired t test.

### **Raised ICP**

15 consecutive patients with severe elevated ICP, clinically evident by headache, vomiting, neck pain, blurring of vision or photophobia, papilledema with or without localizing signs, with CT or MRI evidence of same in form of mass lesion, hydrocephalus, midline shift or imminent herniation were screened with TCD before surgery to identify waveform and indicial values and their correlation to patients overall clinical condition, specifically sensorium and alertness. Postoperative TCD was done within 48 hours and electively thereafter as per necessity, to check for persistence or resolution of the Doppler changes and correlating them with patient clinical status and post-operative CT scan findings.

## **Brain Death**

10 patients with clinically proven brain death (absent brainstem reflexes, positive apnea test), attributable to varied etiologies, after elimination of other systemic, metabolic, toxic or iatrogenic factors, were screened with TCD of basal vessels and extracranial ICA on clinical declaration of brain death or within 2 hours of the same. Absent TCD flow pattern or presence of abnormal flow pattern was looked for. Any flow pattern was followed up by repeated study at every 2 hourly interval, till absent flow was obtained. Chronological and etiological correlation of abnormal waveforms was studied.

## **RESULTS**

### **TCD In SAH Induced Vasospasm**

72 consecutive patients admitted to ICU of the institute between period of November 2004 and July 2005 with clinical, CT or lumbar puncture proven diagnosis of SAH, were screened. All patients underwent DSA after initial workup within 2 days of admission. 50 patients with DSA confirmed aneurysmal SAH bleed were included in the study. The study group included 20 male and 30 female patients. Their mean age was 48.84 years (range: 20 - 77 years).

Their WFNS grades were as follows - Gr I: 30 patients (60%), Gr II: 12 patients (24%), Grade III: 3 patients (6%), Grade IV: 4 patients (8%) and Grade V: 1 patient (2%), (Chart 1). The mean duration from ictus to admission was 2.6 days (range: 0 – 9 days). 43 patients had CT scan proven SAH. Of the remaining 7 patients, 5 had lumbar puncture documented evidence of subarachnoid hemorrhage. The remaining 2 patients had normal CSF study, however, due to classical symptomatology in these patients, they were screened by a CT angiography which revealed an aneurysm (patient no 23: left MCA bifurcation aneurysm, patients no 28, right ICA aneurysm). They subsequently underwent a DSA.

CT scan determined Fisher's grades were as follows – Gr I: 7 patients (14%), Gr II: 21 patients (42%), Gr III: 14 patients (28%) and Gr IV: 8 patients (16%) (Chart 2). While 5 of the 8 patients with Fisher's grade IV had poor WFNS grade, there was no significant correlation between other clinical and radiological grades. The distribution of bleed on CT scan (Chart 3) was as follows – interhemispheric: 32 patients (64%), sylvian: 34 patients

(68%), suprasellar and basal cisterns: 24 patients (48%) and perimesencephalic: 12 patients (24%). The study group included 7 patients admitted with CT angiography proven, and 2 patients with MR angiography proven aneurysms with SAH. They subsequently underwent DSA.

On DSA, 59 aneurysms were noted in 50 patients (Chart 4). 5 patients had multiple aneurysms (3 patients had 2 aneurysms while 2 patients had 4 aneurysms). These included 2 giant aneurysms (3.4%) and 4 large aneurysms (6.8%). The location of these aneurysms included Acomm: 23 (38.9%), DACA: 1 (1.7%), ICA: 9 (15.2%; bifurcation - 4, clinoid segment - 1, ophthalmic segment - 2, communicating segment - 2), MCA bifurcation: 14 (23.7%), Pcomm: 7 (11.8%), PCA: 1 (1.7%), Basilar: 3 (5.1%).

Vasospasm was noted on DSA in 22 patients (44%). The distribution of vasospasm was as follows: left ACA: 2 patients, right ACA: 5 patients, bilateral ACA: 6 patients (total 13 patients; 26%), left MCA: 5 patients, right MCA: 7 patients, bilateral MCA: 6 patients (total 18 patients; 36%), left PCA: 2 patient (4%), BA: 1 patient (2%). Thus, MCA involvement was seen in 81.81% cases with vasospasm, while ACA involvement was seen in 59.09% cases of vasospasm, with a total of 19 ACA's and 24 MCA's showing vasospasm. 65% patients with vasospasm had Fishers grade III or IV on CT scan.

On performing TCD (pre-operative and post-operative), the distribution of vasospasm in these patients showed ACA segment involvement in total of 6 ACA segments (left ACA: 2 patients, right ACA: nil patients, bilateral ACA: 2 patients). For MCA, vasospasm was detected in a total of 19 MCA segments (left MCA: 7 patients, right MCA: 4 patients, bilateral MCA: 4 patients). There were no false positive records (DSA negative, Doppler positive). Other detected vasospastic segment included left PCA in both patients having

DSA proven PCA spasm. Thus vasospasm was detected by Doppler in 16 patients (32%), (Chart 5 and Chart 6).

Postoperative deterioration to varied degrees was noted in 22 patients. This included altered sensorium, drowsiness and deterioration of GCS in 16 patients, limb weakness in 9 patients (monoparesis: 1 patient, hemiparesis: 6 patients, hemiplegia: 2 patients), cranial nerve deficits in 3 patients, neurogenic pulmonary edema in 2 patients. Additionally, the two poor grade patients treated conservatively also had further deterioration of GCS. Thus a total of 24 patients (48%) had clinical deterioration. This was correlated to Doppler vasospasm in 10 of these patients. CT brain in these patients was relatively normal in 2 patients, showed diffuse edema in 4 patients and infarct in 4 patients (ACA: 1 patient, MCA : 2 patients, MCA-PCA watershed: 1 patient). 3 patients who had post-operative deterioration had vasospasm on DSA (all in ACA territory) not detected by Doppler. Thus Doppler detected 10 of 13 cases of symptomatic, DSA proven vasospasm. Another 6 patients had Doppler features suggestive of raised intracranial pressure. CT brain in these patients showed diffuse edema in 2 patients, hydrocephalus in 2 patients and infarct with edema in 2 patients (one ACA territory, one MCA territory). 2 patients with no evidence of vasospasm had hydrocephalus and one patient needed CSF diversion procedure (Endoscopic third ventriculostomy). 3 patients had electrolyte disturbances which were appropriately managed.

In the remaining 9 patients with DSA detected vasospasm, Doppler corroborated with the DSA findings in 6 patients. All 9 patients were clinically asymptomatic (Chart 7).

Comparing mean MCA velocities in patients with vasospasm, of the 15 patients showing MCA vasospasm (total 19 MCA's), the average MCA mean velocity in symptomatic group

was 164cm/sec (maximum: 199cm/sec, minimum: 140cm/sec), while that in the asymptomatic group was 139cm/sec (maximum: 158cm/sec, minimum: 120cm/sec). Moreover, in the symptomatic group, persistent high velocities or even increasing velocities on follow up Doppler study were seen in 7 of the 9 patients, while a similar trend was seen only in 2 of the 6 asymptomatic patients. As compared to both groups, the average MCA mean velocity in patients with no vasospasm on Doppler was 65cm/sec, (Chart 8).

Similar analysis of the ACA mean velocities is not significantly contributory. While the highest mean velocities in 2 patients with symptomatic vasospasm were 92cms/sec and 84cms/sec respectively, these solitary recordings had no consistent elevated values over follow up studies as seen in MCA evaluation, nor did it show any specific trend in progression of the velocities. Subsequently the average ACA mean velocities in symptomatic and asymptomatic Doppler vasospasm group were 76cms/sec and 70cms/sec respectively. The average ACA mean velocity in patients not showing vasospasm on Doppler 31cms/sec (chart 8).

Though the 4 patients with symptomatic vasospasm who had infarct on CT scan showed higher average MCA mean velocities (180cm/sec v/s 151cms/sec), the sample size is too small for statistical conclusions, though the trend is obvious. In the asymptomatic group, 2 patients had infarct on CT scan, with no specific trend in mean velocities. The patient with ACA territory infarct had the maximal ACA flow velocity (92cms/sec).

Recordings in other vessels are very few in number to draw any logical analysis and conclusions.

4 patients with symptomatic Doppler vasospasm and rapidly developing deficits (dense hemiplegia in all patients), underwent endovascular papaveraine injection into the spastic segment. 2 patients resolved completely, one had partial improvement to Grade 3/5, while one failed to improve. Both patients had evidence of infarct on CT scan.

The overall outcome was analysed by the Glasgow Outcome Score (GOS) scale. In 22 patients with vasospasm, the outcome was as follows: GOS 1: 2 patients (9.09%), GOS 2: 2 patients (9.09%), GOS 3: 1 patient (4.54%), GOS 4: 6 patients (27.27%), GOS 5: 11 patients (50%). In the remaining 28 patients with no vasospasm, outcome was as follows: GOS 1: 2 patients (7.14%), GOS 2: 2 patients (7.14%), GOS 3: 2 patient (7.14%), GOS 4: 3 patients (10.71%), GOS 5: 19 patients (67.86%).

Another important factor was the technical difficulties in performing Doppler study. While optimal MCA recordings were obtained in all patients, optimal ACA recordings could not be obtained in 3 patients bilaterally and 2 patients unilaterally (total 5 patients, 10%), while the vertebrobasilar system could not be adequately insonated in as much as 15 patients (30%).

### **TCD In Raised Intracranial Pressure**

15 patients included in this study had features of elevated intracranial pressure secondary to intracranial mass lesion, both clinical (headache, vomiting, visual blurring, bradycardia, altered sensorium and papilledema, with or without localizing signs) as well as radiological on CT or MRI (edema, mass effect, midline shift, imminent herniation,

cisternal effacement, hydrocephalus with periventricular leucencies, mass lesions), in varying extent and combinations.

The study included 10 males and 5 females. Their mean age was 37.46 years (range: 11 to 55 years). The average duration of ICP symptoms was 5.2 weeks (range: 1 to 16 weeks). 8 patients were evaluated with CT scan, 2 patients with MRI, while in the remaining 5 patients, both CT and MRI was obtained. Hydrocephalus, in addition to mass effect and midline shift was seen in 5 of the 10 patients. 6 patients were in a state of altered sensorium, with excessive drowsiness, reduced arousability and irritability, while 2 patients were alert but had altered cognition. 4 patients had localizing signs (3 patients: hemiparesis with upper motor neuron facial paresis, 1 patient: VIIth, VIIIth, lower cranial nerve palsy with cerebellar signs).

Preoperative transcranial Doppler showed a normal mean MCA velocity (60.2cms/sec, normal range:  $56 \pm 14$  cms/sec) in all patients. On the other hand 11 of 15 patients had a lowered diastolic velocity (27.8 cms/sec, observed range 20 to 37 cms/sec, normal range:  $44 \pm 11$  cms/sec). The lowest velocities were observed in 5 of the 6 patients who had altered sensorium and corresponding maximal mass effect on imaging. PI and RI were also maximally elevated in these patients correspondingly (0.98 and 0.84 respectively), though the mean values of all the 15 patients were in normal range, being 0.78 and 0.61 respectively. Systolic peaks were observed in 8 patients and biphasic waveforms were observed in 2 patients. These also correlated to maximal mass effect and poorer sensorium in a majority of patients. To eliminate error due to altered velocities resulting from direct mass compression or vessel displacement by the tumor itself, velocities and indices on the side opposite the lesion were taken for evaluation. No significant difference

in the values was seen in patients with or without hydrocephalus or with relation to location of the lesion. Maximal parametric changes were observed in patients with maximal mass effect on imaging and patients having altered sensorium.

All patients underwent surgery - lesion excision or decompression in 14 patients, endoscopic septostomy with ventriculoperitoneal shunt in 1 patient with thalamic glioma. Post-operatively, 5 of the 8 patients in altered sensorium improved in alertness and sensorium, 1 remained the same and 2 deteriorated. Of the remaining 7 patients, 3 patients deteriorated while the remaining improved. Post op CT in the deteriorated patients (total 6 patients), showed hematoma with mass effect in 2 patients, increasing hydrocephalus in 2 patients and increasing edema with mass effect and increased midline shift in 2 patients.

Five of the 8 patients with preoperative Doppler changes had significant clinical and radiological improvement. Post-operative Doppler showed complete resolution of diastolic flow velocity reduction (mean: 45.42 cms/sec) and normal waveform. The remaining 3 patients failed to improve, 2 of them deteriorating. There was persistent edema and mass effect in 2 patients and hydrocephalus in one patient. All 3 patients had persistent diastolic slowing, with 2 patients having systolic peaks and one patient having a biphasic flow.

In the other 7 patients who had normal sensorium preoperatively, 3 patients had deteriorated, with corroborative clinical and imaging findings. All these patients similarly had diastolic slowing, with systolic peaks in 3 patients and biphasic diastolic flow in 1 patient (Chart 9).

The diastolic velocity mean in these 6 patients who had post operative deterioration was 27cms/sec, which is significantly lower than that in patients who had clinical improvement.

Comparing the final outcome, in the 6 patients who had deteriorated with positive Doppler findings, the final GOS scores were as follows: GOS - 5: 1 patient, GOS - 4: 1 patient, GOS - 3: 1 patient, GOS – 2, GOS – 1: 1 patient. Of the 9 patients who had normalization of Doppler findings on post operative follow up evaluation, 7 patients had GOS score of 5 while 2 had GOS score of 4, with no significant morbidity or mortality (Chart 10).

### **TCD In Brain Death**

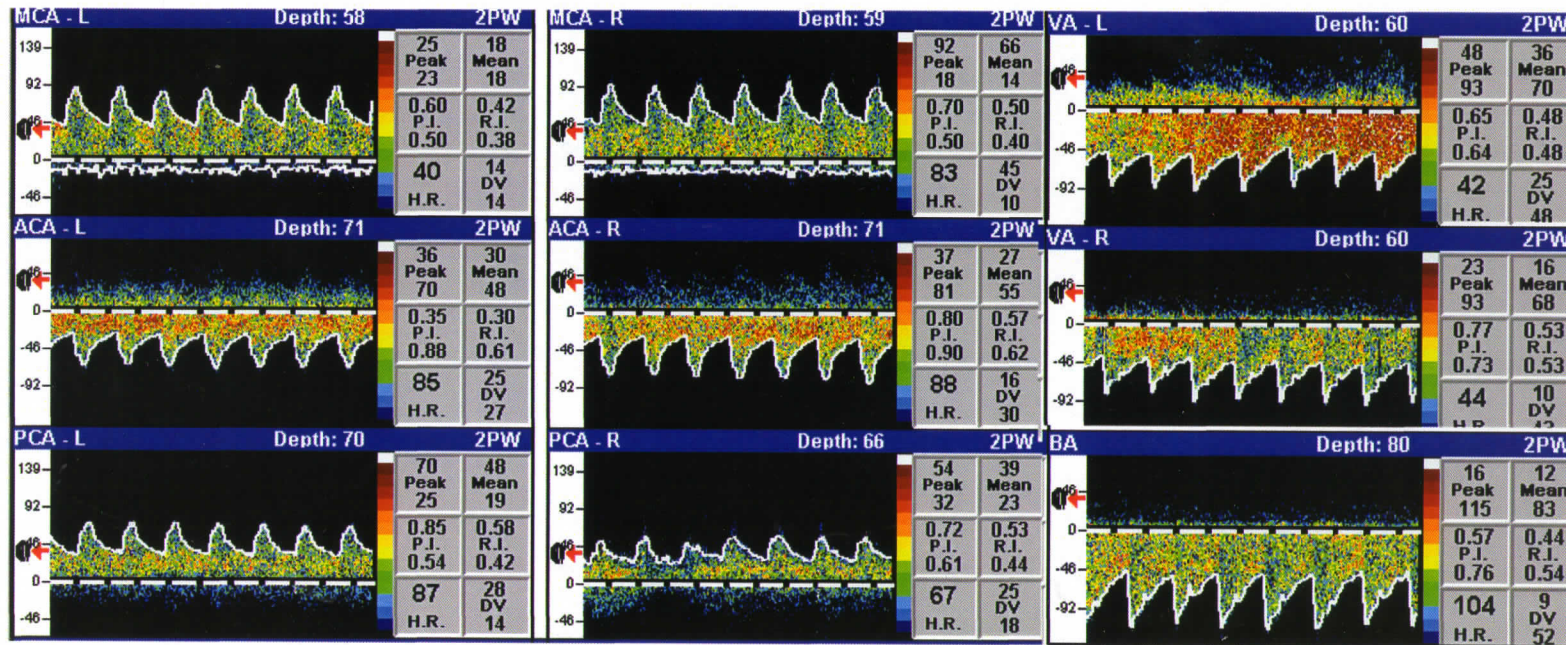
10 patients with clinically certified brain death were included in this study. There were 4 males and 6 females. Their mean age was 52.5 years (range: 25 to 70 years). 6 patients had undergone surgery while 4 brain deaths were recorded in unoperated patients (3 patients had rebled aneurysms preoperatively, 1 patient had CSF rhinorrhea with fulminant meningitis). Doppler was done before clinical brain death documentation to confirm presence of flow in the basal vessels. The first Doppler recording at clinical confirmation of brain death or within 2 hours showed no flow in any of the basal vessels in 7 patients. In the remaining 3 patients, varied but pathological ICA flow was noted in 3 patients. 2 of these 3 patients also showed MCA flow. None of the 10 patients showed any vertebral flow. The patient with only ICA flow showed biphasic oscillations. In the other 2 patients with both ICA and MCA flow, biphasic oscillations were noted in one while the other showed combined biphasic and systolic spike patterns. All the 3 patients

had rapid deterioration following SAH rebleed (2 patients) and intraparenchymal cerebellar bleed (1 patient).

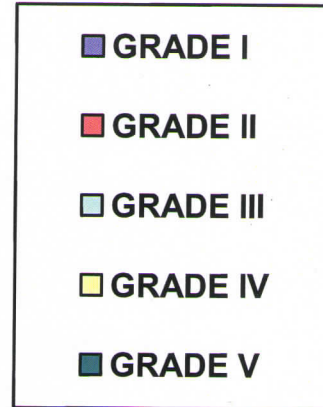
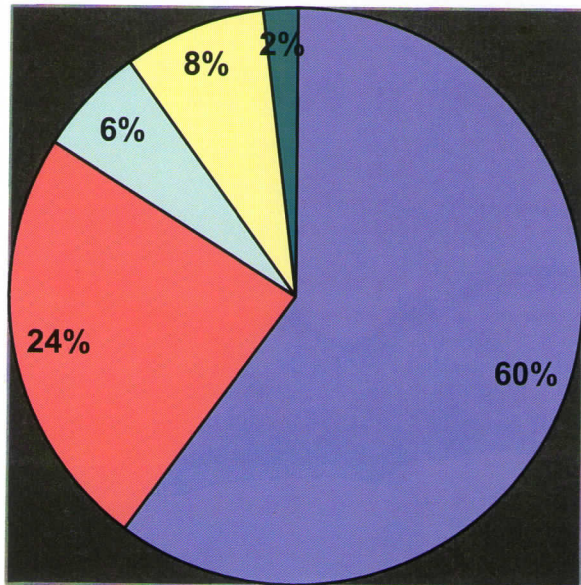
Repeat Doppler study in these patients after 2 hours (within 4 hours of clinical brain death) showed presence of systolic spikes in ICA flow in one patient. There was no flow noted in any of the vessels in the other 2 patients. No flow was noted in the other patients who had no flow on the initial Doppler. None of the 10 patients had vertebral flow.

On repeat Doppler study after another 2 hours (within 6 hours of clinical brain death), no patient showed any flow in any of the vessels.

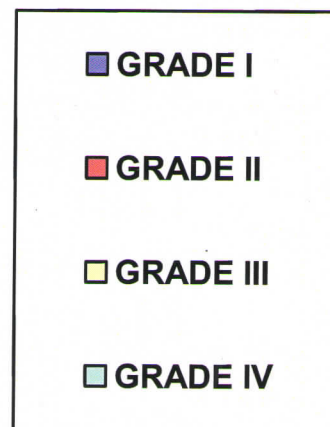
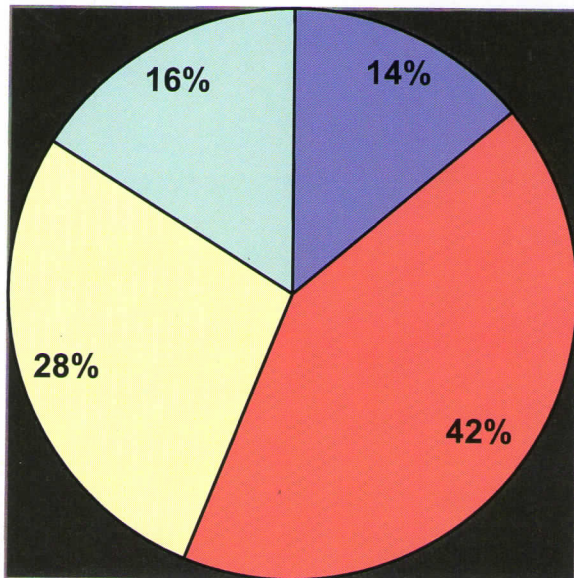
### Colour Plate 1 – Normal Transcranial Doppler



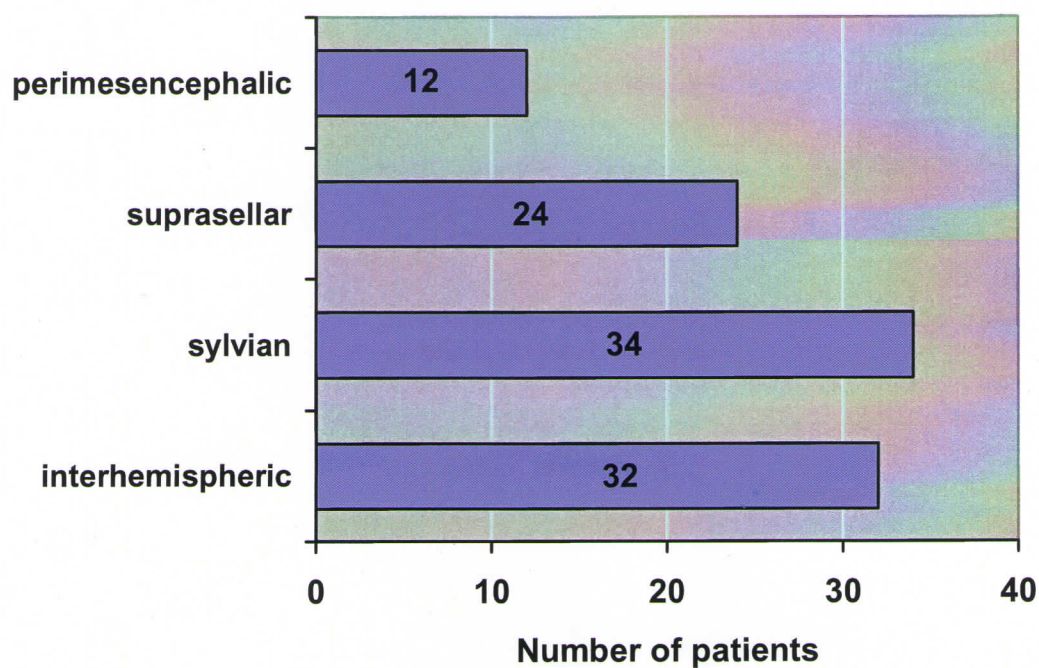
**Chart 1: SAH distribution by WFNS Grade**



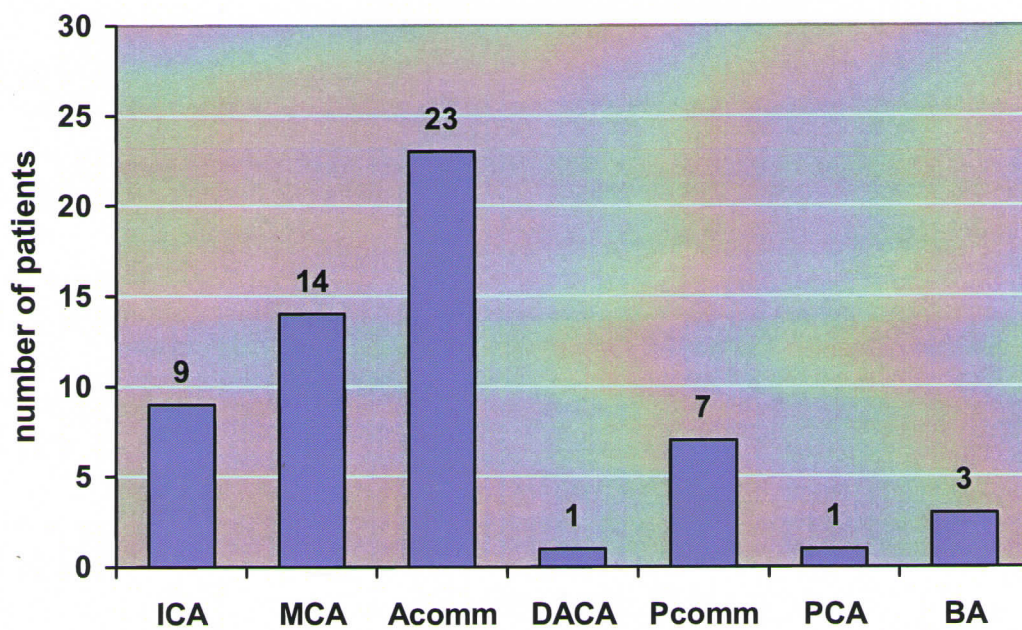
**Chart 2: SAH distribution by CT scan Fisher's grades**



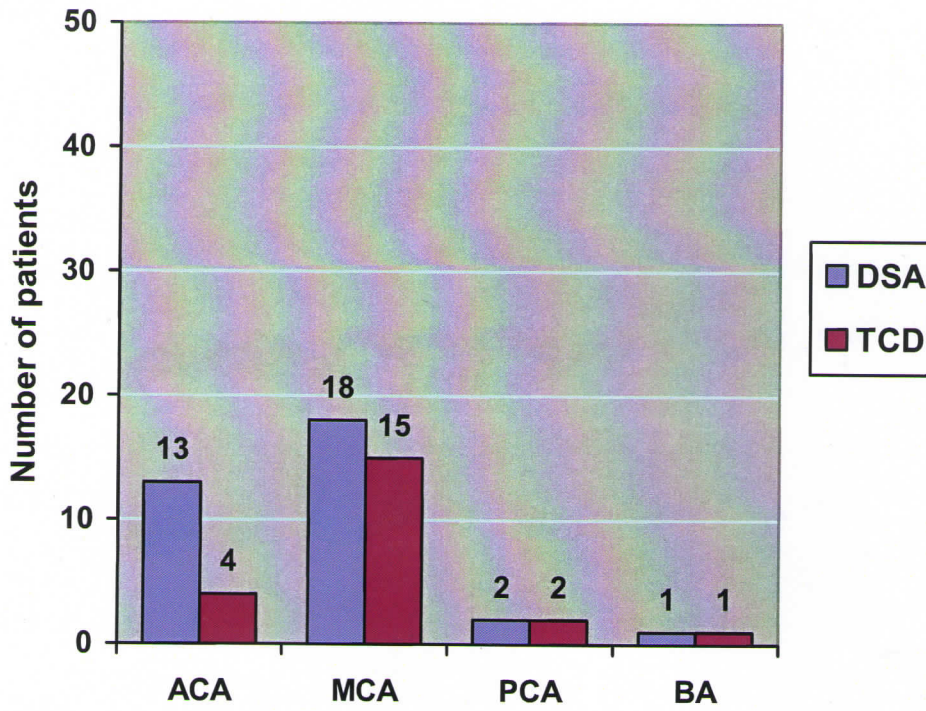
**Chart 3: Distribution of SAH on CT scan**



**Chart 4: Distribution of aneurysms on DSA**



**Chart 5: Patient distribution of Vasospasm**



**Chart 6: Vascular territory distribution of vasospasm**

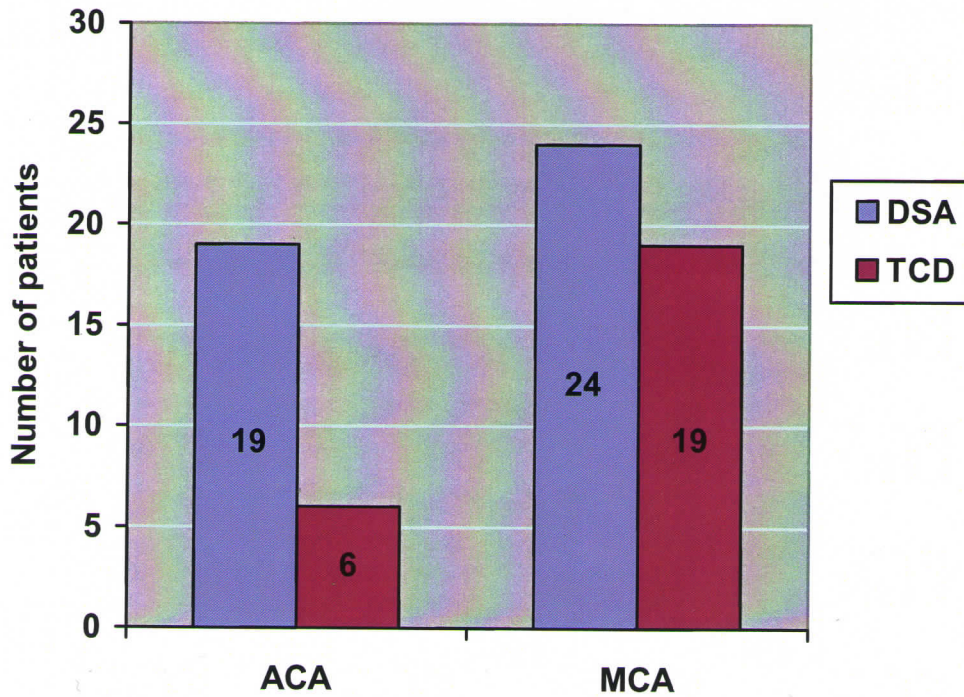


Chart 7: Clinical status and relation to vasospasm

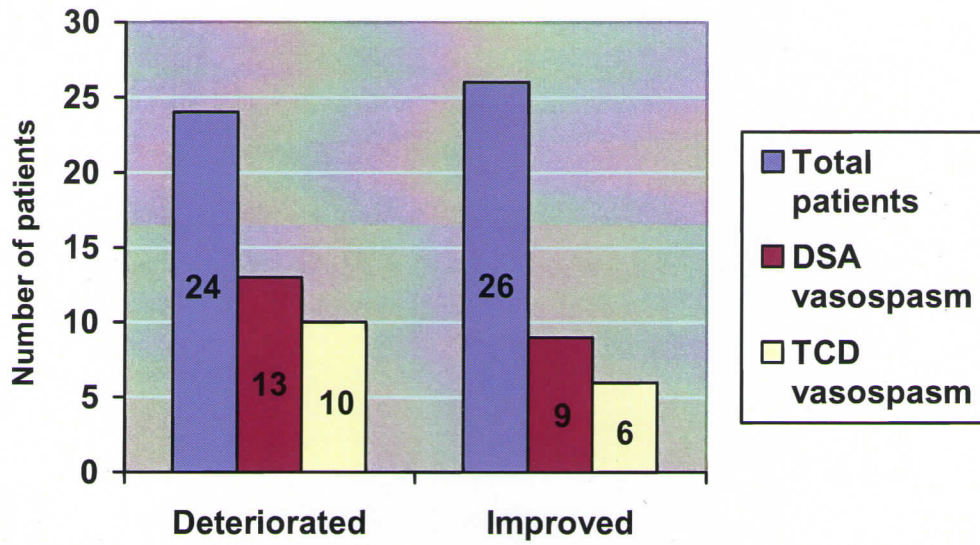


Chart 8: Relation of TCD velocity and symptomatology

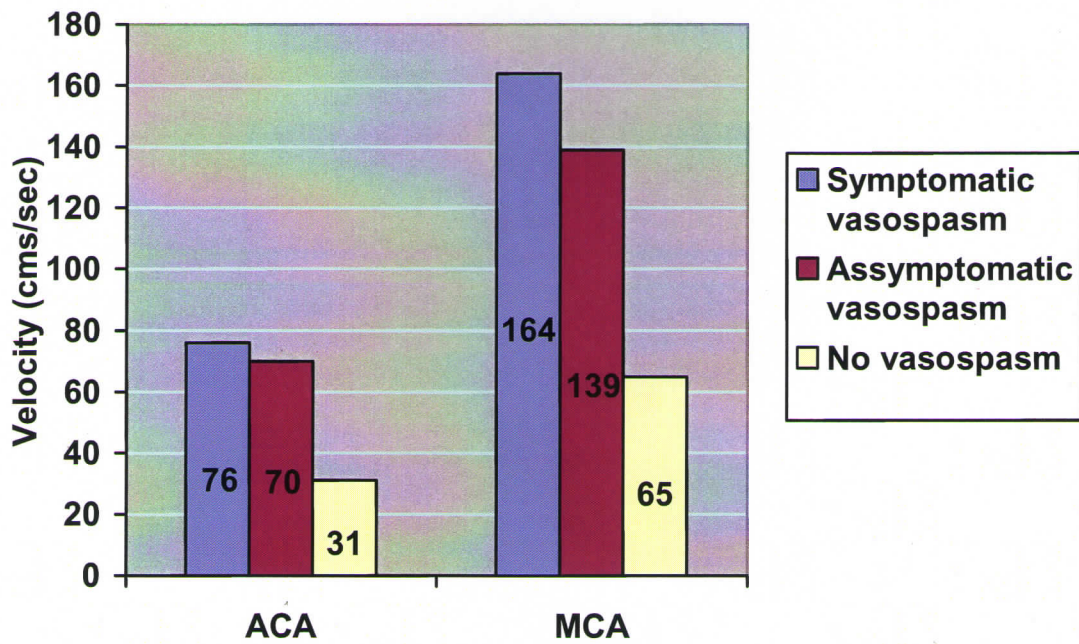


Chart 9: Doppler findings in raised ICP

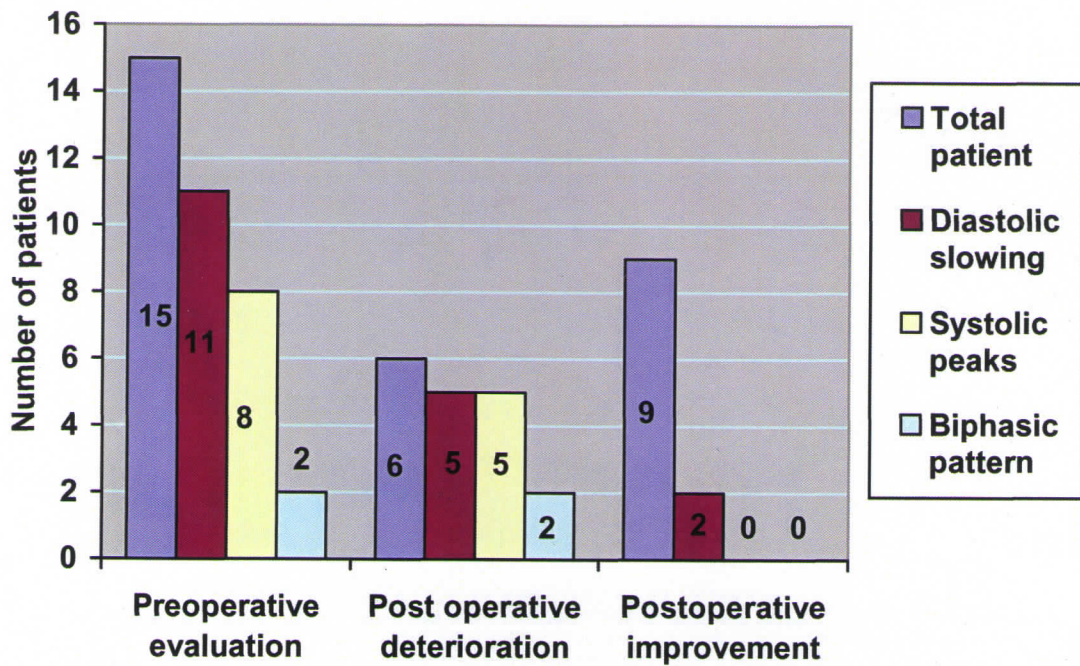
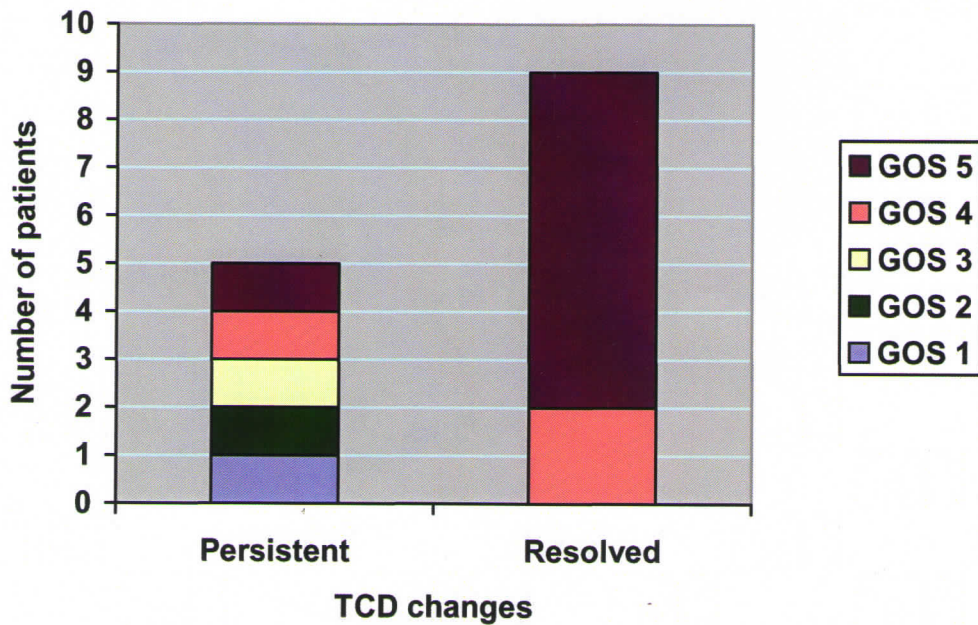
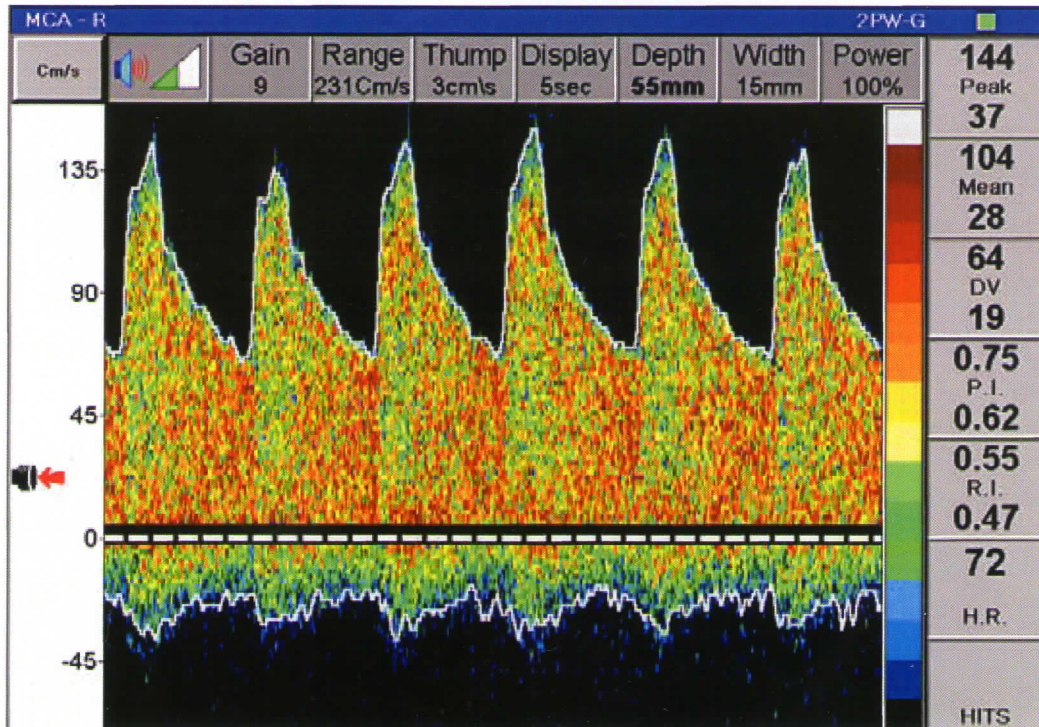


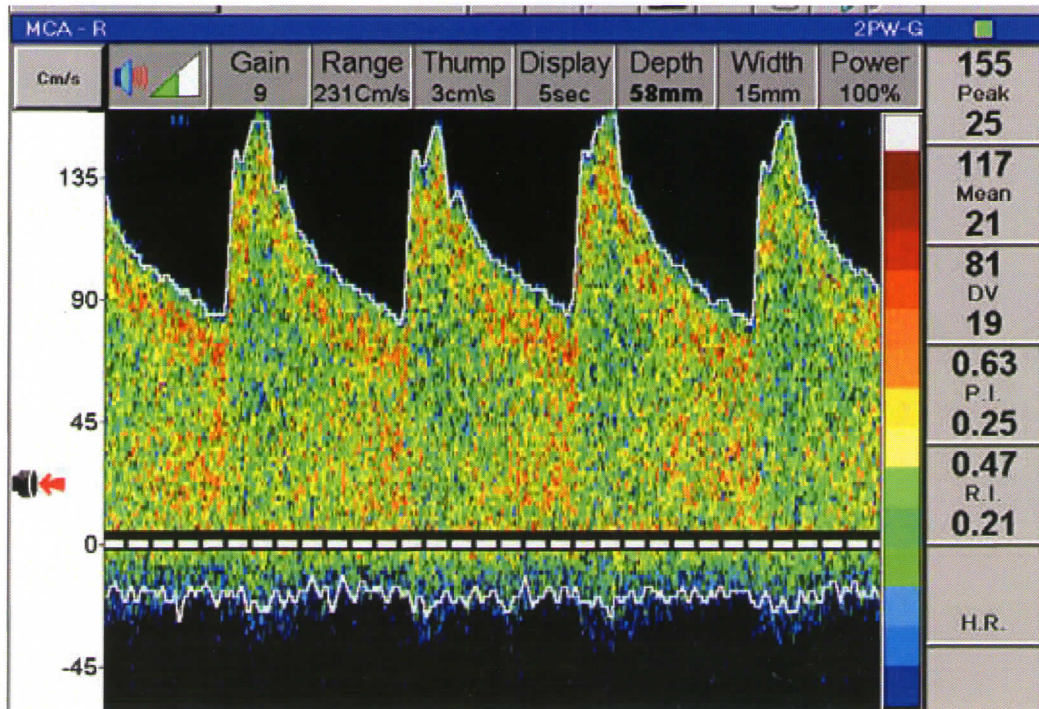
Chart 10: Doppler findings and outcome in raised ICP



**Colour Plate – 2 : MCA Territory vasospasm - 1**

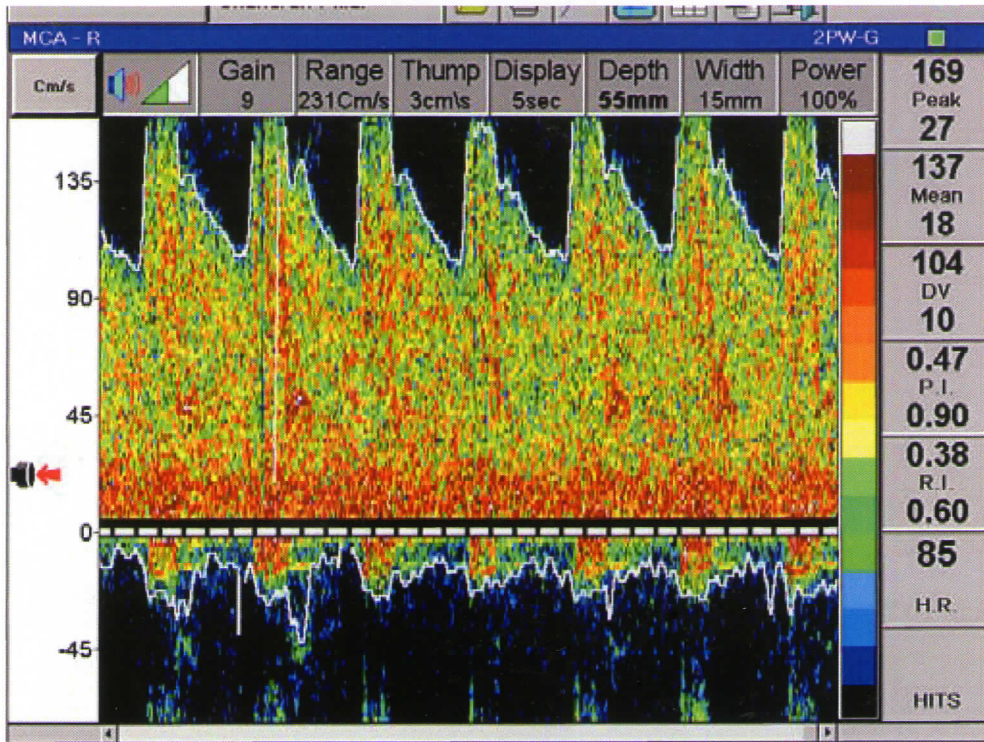


**Border line MCA velocity elevation**

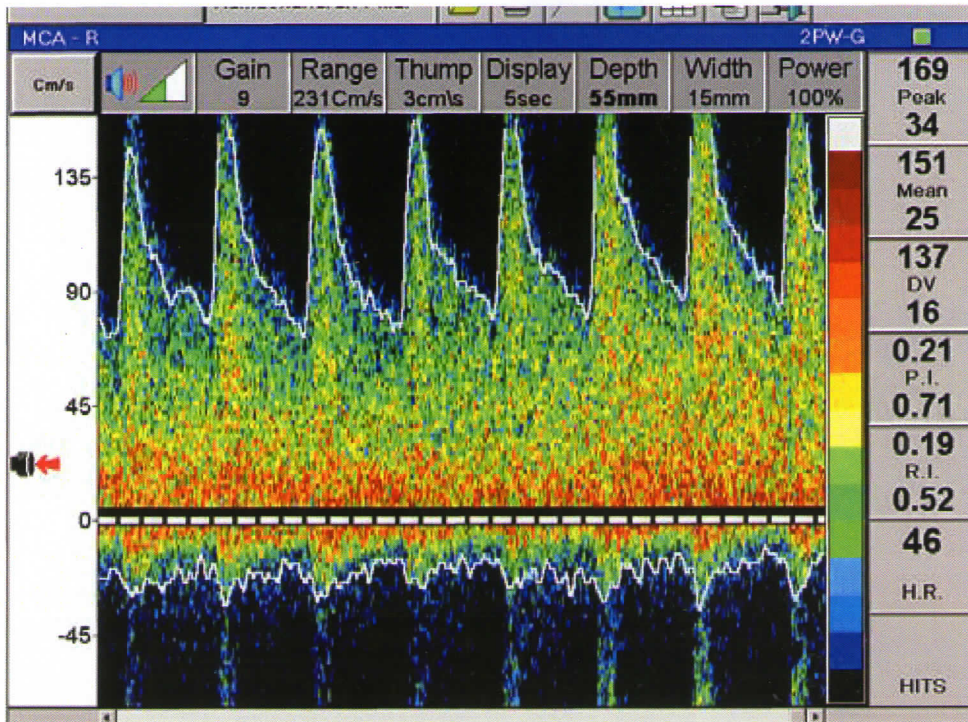


**Mild / Early vasospasm**

**Colour Plate – 3 : MCA Territory vasospasm - 2**

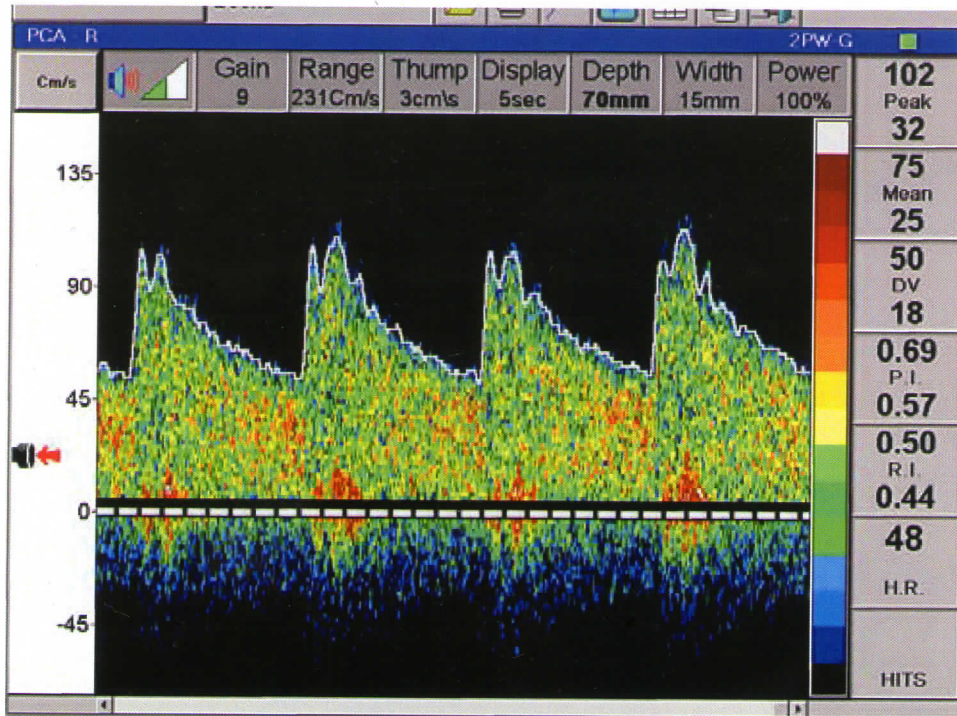


**Moderate Vasospasm**

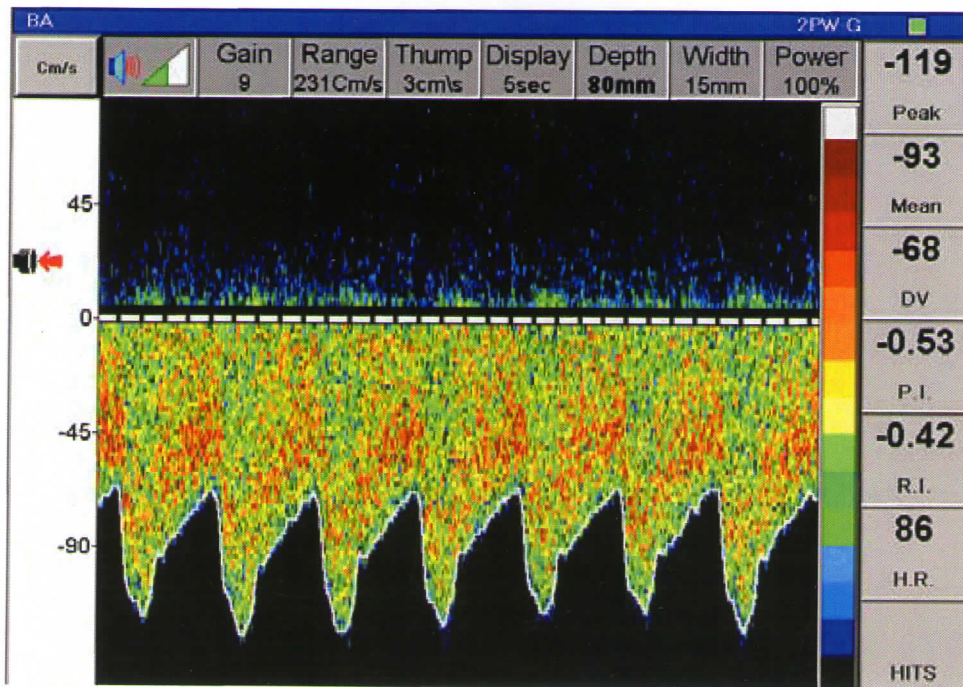


**Severe Vasospasm**

### Colour Plate – 4 : Other territory vasospasm

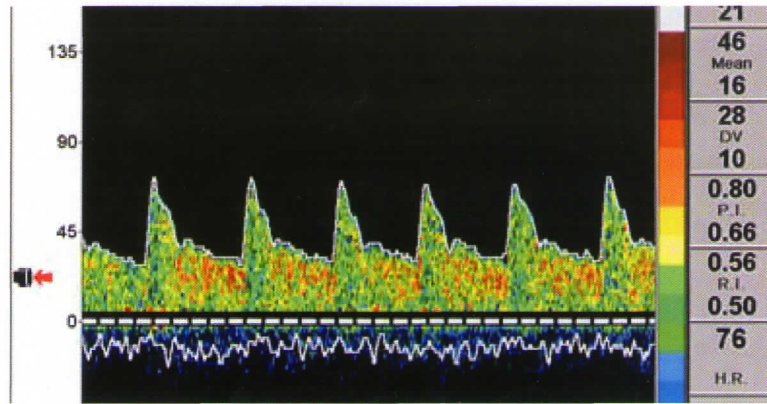


PCA

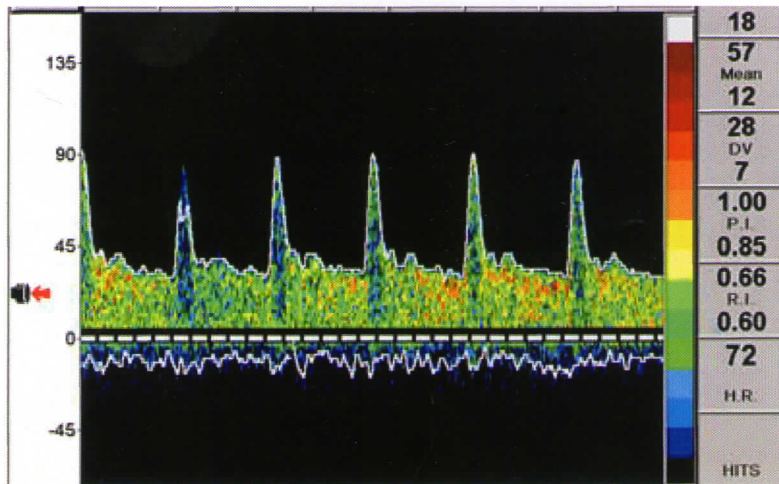


BA

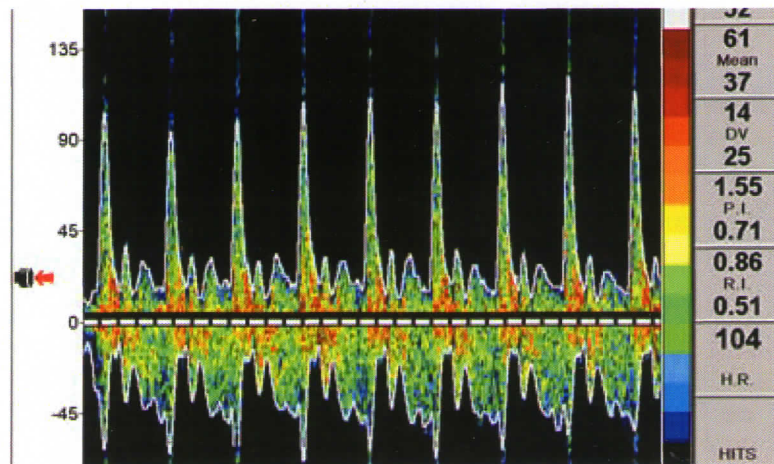
### Colour Plate – 5 : Raised ICP



Reduced DV and dampened waveform

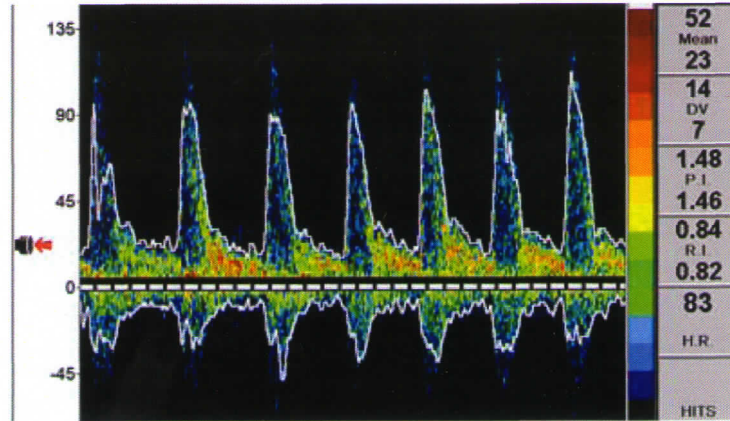


Systolic peaks

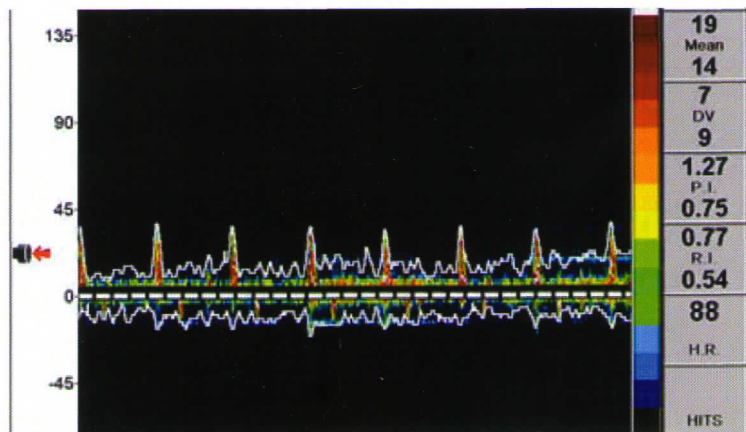


Biphasic flow

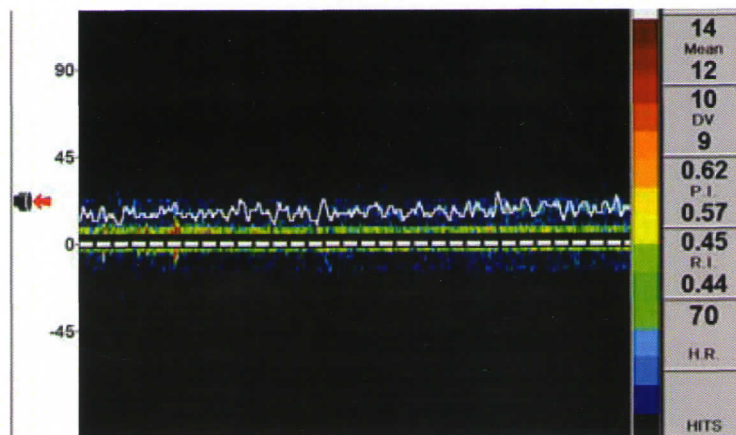
**Colour Plate – 6 : Brain death**



**Biphasic oscillations, elevated PI and RI**



**Systolic spikes**



**Absent flow**

## **DISCUSSION**

Since its clinical introduction in 1982 by Aaslid, newer and widespread neurological and neurosurgical applications of TCD have ushered in a reproducible, bedside, non invasive, technically simple and safe mode of monitoring patient progression, permitting rapid and effective clinical decisions, thus reducing overall morbidity and mortality, despite having numerous anatomical and technical restricting factors.<sup>8</sup> Real time Duplex monitoring has further broadened the avenues for newer applications. It already has proven efficacy in the clinical setting of SAH vasospasm, with defined parameters. Also, though a number of studies have commented on flow changes in raised intracranial pressure and brain death, quantitative correlation has often been hampered by selection bias and small sample size.<sup>18</sup> This study was a preliminary attempt to evaluate the Doppler changes in the above 3 conditions in our clinical ICU setting and determine preliminary guidelines in clinical decision making.

### **TCD In SAH Vasospasm**

22 patients (44%) in this study had evidence of vasospasm on DSA. This correlates with various studies which give a range of 20 to 100% incidence with an average of 50% incidence of vasospasm.<sup>58</sup> The commonest segment involved was the MCA in 81.81% and the ACA in 59.09% (Chart 5). The presence and degree of vasospasm correlated to the Fisher's grade with 65% of vasospasm seen in grade III and IV patients. It also correlated well with the region of maximal clot on imaging. Doppler detected vasospasm in 16 patients, with no false positive values. This yielded a sensitivity of 72.72% and specificity of 100%, PPV of 100% and NPV of 84.62%. The sensitivity, though at the lower range of most available studies, can be explained on basis of a preliminary

exposure to the procedure and learning curve of neurosurgical resident and faculty carrying out the study, without any previous exposure to use of ultrasound, as well as the absence of regular supervision of a trained radiologist. Considering this fact, these early results can be viewed quite optimistically with a definite scope for improvement upon them. This also points to the ease of learning the technique by doctors managing the patient, preventing laborious trips to the radiology suite.

On comparing the individual vessel segment screened, MCA vasospasm in 24 MCA segments on DSA corresponded with Doppler vasospasm in 19 vessels (sensitivity: 79.17%). However, ACA vasospasm in 19 segments corresponded to Doppler vasospasm in only 6 segments (sensitivity: 31.58%), (Chart 6). The recordings in other segments were not adequate for any statistical analysis. Thus the best correlation between TCD and Doppler vasospasm has been seen in MCA, as has been already shown in other studies.<sup>12,19</sup> Doppler correlated to 10 of the 13 patients with symptomatic vasospasm (sensitivity: 76.92%), and 6 of the 9 patients (sensitivity: 66.67%) with asymptomatic vasospasm (Chart 7). Thus, there is no significant difference in both groups.

MCA flow velocities have been the most significant factor in determining outcome of patients with vasospasm evaluated with Doppler. Mean velocity over 120cms/sec has often been the threshold for defining Doppler vasospasm. Studies by Seiler et al suggested that no patient with velocities less than 140cms/sec had infarct, while velocities in excess of 200cms/sec had the highest risk of ischemic episodes and infarcts.<sup>59</sup> In this study, the average MCA mean velocity in symptomatic group was 164cm/sec, while that in the asymptomatic group was 139cm/sec, which was statistically

significant ( $p=0.043$ ), (Chart 8). Moreover in the patients who developed infarct, the mean MCA velocities were significantly higher at 180cms/sec. Though we could not establish a specific rate of change of values as a threshold for determining and predicting deterioration or poor outcomes as seen in other studies,<sup>12,17</sup> in the symptomatic group, persistent high velocities or even increasing velocities on follow up Doppler study were seen in 7 of the 9 patients, while a similar trend was seen only in 2 of the 6 asymptomatic patients. Thus repeated Doppler evaluation at regular intervals enable comparison of velocities in segments with proven vasospasm, to assess progress and plan timely intervention. It is important to note that even in the patients who developed infarct, the MV did not exceed 200 cms/sec. The contribution by elevated ICP, altered regional CBF and altered autoregulation secondary to vasospasm possibly lowers the overall susceptibility. Thus the treating clinician cannot be complacent about the risk of infarct just on the basis of values below the critical threshold.

Repeated Doppler is also an easy way of evaluation of at risk segments of the vessels, especially MCA, which have elevation of velocities to less than threshold levels. Of the 50 patients included in this study, 16 MCA segments had velocities over 100cm/sec at some point of the repeated Doppler studies. Only 6 patients reverted to normal while the remaining patients went on to develop defined vasospasm in these segments. The mean Lindegaard index in the patients who reverted to normal was 1.7, while in the patients who went on to develop clinical vasospasm was 2.5. Thus though there are no defined parameters set for the above transition, regular Doppler monitoring is an easy way to keep a track of such segments, especially in the clinical setting of neurological alterations, not attributable to any other cause. Monitoring the Lindegaard index in such patients may be a more sensitive method of early detection borderline vasospasm.

Though ACA velocity threshold quoted in literature ranges from 70cms/sec to 100cms/sec, all symptomatic and asymptomatic vasospasm patients in this study with ACA vasospasm had velocities over 70 cms/sec, though there was no significant difference in the symptomatic (mean 76 cms/sec) and asymptomatic group (mean 70cms/sec).

In all the 3 symptomatic vasospasm patients who had normal Doppler recordings, vasospasm involved the ACA segments. Thus, this study brings out the previously reiterated fact that the reduced sensitivity of Doppler in evaluation of ACA territory (31.58%) is a major confounding factor in routine clinical application in therapeutic decision making. This is especially significant since 40% of all aneurysms in this study involved the Acomm – ACA territory, with DSA vasospasm in ACA territory in 42% of these patients. This group also comprises 54.16% (13 out of 24 patients), with clinical deterioration, often with vague, non localizing symptoms, with only 1/3<sup>rd</sup> of the cases being attributed to causes other than vasospasm.

The number of patients with vasospasm involving other segments is too small to come to any specific conclusions, though Doppler has been able to pick up the changes in all the above patients.

Of the 24 patients who had deterioration, while 13 were attributable to vasospasm, 6 patients had Doppler evidence of elevated intracranial pressure, with slowing of diastolic flow in all 6 patients, systolic peaks, elevated PI and RI in 4, and biphasic oscillations in one. Thus Doppler has an advantage of being a simultaneous, non invasive, reproducible monitor of elevated intracranial pressure. Patients with vasospasm associated elevated ICP have been shown to have a higher risk of infarct and overall poor outcomes.

A major limitation of Doppler highlighted in this study is the technical shortcoming of inadequate insonation of intracranial vessels, as noted with 10% of patients with inadequate ACA records and 30% patients with inadequate VBA records. This also hampers defining parameters for these segments to determine vasospasm. Anatomical variations, tortuosity as well as bony hindrances contribute to a suboptimal study.

In patients with symptomatic vasospasm, 23.6% patients had a GOS score of 3 or less at discharge, while another 23.6% had a GOS score of 4. Thus the significant morbidity associated with vasospasm indicates the need for close and repeated surveillance of these patients, which can be well achieved with Doppler. Doppler reduces the need of postoperative or repeated DSA study, thus limiting invasive procedures in these patients. Doppler enables selection of patients who are best to undergo therapeutic endovascular intervention, thus improving the overall outcome.

This study, though definitely emphasizing the applicability of Doppler in ICU monitoring, has a number of limitations. Being only a preliminary evaluation of Doppler in monitoring vasospasm patients, a small sample size and lack of comparative groups hinders any definite conclusions on determination of a Doppler based management protocol. Further studies to verify the same as well as to clearly characterize flow velocity thresholds in vessels other than MCA are merited. The combined effects of vasospasm with ICP on overall outcome as well as its confounding effects on Doppler flow patterns, as a comparative group, has not been studied. Further comparative studies aimed to analyze the trends in flow velocity in borderline elevation are also indicated, so as to guide early intervention.

## TCD In Raised Intracranial Pressure

In neurointensive care, the knowledge of ICP is essential and is often obtained by invasive monitoring. Studies with Doppler flow measurements, though an indirect assessment of CPP by measurement of cerebral blood flow velocity has been shown to have strong correlation to ICP, especially with diastolic velocity and PI. This has been found to be independent of the pathology or its location.<sup>42</sup> The correlation with CPP has been shown to have good sensitivity and specificity in the normal ICP range while at ICP values of 20 to 40 mm Hg, the sensitivity increases while the specificity decreases.

In this study, 78.57% patients had slowing of diastolic velocities, with lowest diastolic flow values and maximally elevated PI in all patients with altered sensorium and maximal mass effect on imaging. This result suggests increased cerebrovascular bed resistance and is dominated by the effect of elevated ICP and results in a reduced CPP. This has been proven by the study of Moreno et al in a study of head injury patients wherein, PI of more than 0.7 correlates well with CPP.<sup>60</sup>

While systolic peaks suggestive of significant diastolic slowing were seen in 8 patients, biphasic pattern suggestive of loss of diastolic flow was seen in 2 patients. While one patient improved completely postoperatively, the other had a final GOS score of 2 (Chart 9). Studies by Hassler et al<sup>41</sup> have suggested that diastolic reversal often indicates an end stage with no effective intervention possible. However, the survival of both patients with significant improvement in one patient, can be explained in the light of only single vascular segment recording of these findings, suggestive of an increased local mass effect rather than a global reduction of perfusion secondary to terminal ICP elevation affecting the entire circulation as described by Hassler.

All patients who had improvement post operatively showed complete resolution of their Doppler findings. On the other hand, patients who had normal flow initially but deteriorated in the postoperative period secondary to elevated ICP had development of the pathological waveforms. This corroborated with clinical and radiological findings of elevated ICP. The overall outcomes in patients who had persistent Doppler changes in post operative period was significantly poorer with 4 of the 6 patients having a GOS score of 3 or less, while all 9 patients with normalized post operative Doppler had a GOS score of 4 (2 patients) or 5 (7 patients), (Chart 10).

Thus transcranial Doppler is a simple, bedside and effectively reproducible way of detecting ICP elevations in ICU patients, adequately guiding treatment as well as prognosticating outcome. This may be beneficial in specifically monitoring and managing head injury patients, doing away with invasive and time consuming intracranial monitoring devices, especially in high flow centres. Diastolic flow reversals and biphasic oscillations have been shown to indicate non reversible status, thus enabling treating physicians in triage of their therapeutic efforts to more salvageable patients. Reproducibility of the study is another advantage.

Doppler can simultaneously detect early post traumatic vasospasm, which can be missed due to the poor GCS of the patient, which may be solely attributed to primary injury or elevated ICP (which often simultaneously coexists) and vasospasm may cause irreversible injury.

This study has included only a limited number of patients, all having intracranial tumors. Due to technical limitations, patients with head injury could not be included. However, a large number of studies have proven the similarity in both pathologies with respect to

Doppler results. We have not monitored ICP invasively in any of the patients. Hence, even though definite correlation of Doppler findings with outcome has been seen, a larger study group with correlative ICP measurements is required to establish quantitative parameters to guide therapeutic interventions.

### TCD In Brain Death

While the diagnosis of brain death is predominantly and primarily clinical, a period of observation may be needed to confirm irreversibility. Criteria currently used, guided by the 1981 Presidents Commission Report and modified by the American Association of Neurology 1995 working guideline parameters, are still employed, with a waiting period of 12 to 24 hours advised especially in case of uncertain diagnosis or coexistent confusing secondary problems. Use of confirmatory tests may eliminate this waiting period, especially in straight forward cases such as craniocerebral trauma or intracerebral hematomas, which are often considered for organ donation. Delay in such patients may be inappropriate as many can become hemodynamically unstable in the waiting period, rendering them unfit for donation.

EEG is the most often recommended electrophysiological test, with the earliest confirmatory record in a clinically brain dead patient being electrocerebral silence at 6 hours. Stringent technical criteria are set for an optimal record, which are often not adequately adhered to. Electrical interference from monitors, patient heartbeat artifacts, interference by ventilator electrical circuits make recording difficult. Other tests recommended to show absent cerebrovascular flow are angiography and radionuclide

scan, which are time consuming, cumbersome, often invasive and psychologically disturbing to the patients relative.

TCD has been used to evaluate basal cerebral flow in brain death since 1987. The effect of progressive elevation of ICP, venous occlusion and vascular dilatation secondary to loss of autoregulation in combination with reduction in MAP secondary to brainstem dysfunction and impaired autonomic reflexes ultimately results in reduction of CPP and diastolic slowing. Diastolic reversal with biphasic oscillations, indicating a net zero flow is regarded as the critical irreversible level.

In this limited study of 10 patients with clinical brain death who had normal flow at baseline record, the first Doppler recording done at clinical confirmation of brain death or within 2 hours showed no flow in any of the basal vessels in 7 patients. In the remaining 3 patients, biphasic oscillations were seen in all three, while one also had systolic peak pattern, in one of the vascular segments. All the 3 patients had historically a rapid deterioration following SAH rebleed (2 patients) and intraparenchymal cerebellar bleed (1 patient). Repeat Doppler study in these patients after within 4 hours of clinical brain death showed presence of systolic spikes in ICA flow in one patient. There was no flow noted in any of the vessels in the other 2 patients who had ICA and MCA flow in the initial Doppler. Repeat Doppler at 6 hours showed no flow in any of the vessels. No flow was noted in the other 7 patients who had no flow on the initial Doppler. None of the 10 patients had vertebral flow.

Thus Doppler has been demonstrated to be non invasive, inexpensive, reliable and effective in confirming brain death, as a bed side ICU procedure. As described in other reviews, confounding flow patterns are recorded in a small subset of patients, especially

within early hours of clinical brain death. This has been seen in 3 patients, all of them having a state of rapid deterioration, while those with prolonged preexisting elevated ICP have no flow from the onset. Possibly, a sudden elevation of ICP, though ceasing the blood flow, preserves compliance of the vessels resulting in transmission of the vascular pulsations. As the duration progresses, increased vascular resistance prevents any transmission.

It has to be noted that flow patterns in all 3 patients were those proven to be incompatible with recovery. Also serial records have shown a rapid disappearance of the same. No patient had vertebral flow, indicating that it may be more specific for early diagnosis.

Thus Doppler silence was noted in all the patients studied at 6 hours from clinical brain death, at the same chronological point where EEG electrocerebral silence is expected for confirmation. Though we have not carried out simultaneous EEG to correlate the same, we feel that repeat clinical and repeat Doppler evaluation confirmation makes it unnecessary. Even in patients who have persistent flow patterns, their irreversible nature facilitates early mobilization of resources needed to effectively execute multi-organ donation, before hemodynamic deterioration

Loss of flow signal in a previously visualized vessel is significant. If a vessel cannot be insonated initially, the test cannot be relied on to indicate no flow following clinical brain death. Also since the flow loss may be initially compartmental due to localization of the lesion, insonation of bilateral basal vessels is indicated. Technical difficulties previously cited for Doppler study may lead to suboptimal record in about 15 to 30 % cases.

## **CONCLUSION**

### **General**

1. TCD is a convenient, bed side, non invasive, easily reproducible and 'physiological' form of monitoring of patients under neurointensive care, providing a temporal profile of progress of patients condition, permitting early therapeutic intervention, reducing morbidity and mortality.
2. TCD performance skills can be easily attained by treating surgeon and intensivists, eliminating unnecessary trips to the radiology - sonography suite.
3. TCD application as an intraoperative monitor in neurovascular surgery provides a real time evaluation of flow alterations, which can aid prediction of possible post operative difficulties and complications, thus guiding appropriate post operative therapy and intervention.

### **SAH and Vasospasm**

1. TCD has a very good sensitivity, specificity and predictive value for SAH induced vasospasm, approaching that of DSA, eliminating the need of invasive monitoring in such patients. It enables early detection and selection of patients for therapeutic endovascular intervention.
2. MCA velocity has the best correlation to prediction of degree of vasospasm as well as its outcome. Velocities over 140 cms/sec have a higher chance of ischemic deficits, which are imminent with velocities over 200 cms/sec. Thus therapeutic intervention threshold has to be quite low for prevention of such outcomes.

3. ACA territory is involved in vasospasm in upto 40% cases, and often has varied and confounding symptomatology. Inadequate insonation of ACA territory in 10 to 15% cases, and failure of TCD to detect vasospasm in 55 to 60% cases, is a major drawback of TCD evaluation.
4. Parameters and threshold values for ACA, PCA and VBA systems need to be determined to improve the guiding value of this modality.
5. Simultaneous detection of elevated ICP is a major advantage of TCD in patients with neurological deterioration, more so in those with normal flow velocity study.

### Raised ICP

1. TCD changes in raised ICP have very high correlation to the degree of ICP elevation, mass effect on imaging as well as the neurological status of the patients, specifically, overall alertness and general sensorium. Resolution of TCD changes corresponds to improved clinical and radiological status.
2. TCD changes are unrelated to the type of lesion, location of the lesion as well as presence or absence of hydrocephalus.
3. To eliminate distortions related to mass effect by the tumor in case of laterally located tumors, recordings done from the contralateral side can be equally effective, except in cases with early mass effect.
4. Patients with persistent TCD changes post-operatively have a significantly poor outcome and GOS scores on follow-up. Thus persistent TCD changes should

guide further imaging and appropriate therapeutic intervention, either medical or surgical.

### **Brain death**

1. Focal, transient and abnormal waveforms may be detected in early TCD evaluation in brain death in occasional patients. These are irreversible and often indicate only transmitted pulsations than any actual flow. Repeat evaluation shows complete disappearance of any waveform on TCD within 6 hours of brain death in all patients.
2. Insonation of atleast the three major vessels, ICA, MCA and VBA is essential and facilitates early declaration of brain death, avoiding use of EEG or any other invasive monitoring. This may aid an early decision regarding organ donation.
3. No patient, including those showing transient MCA or ICA flow had any evidence of VBA flow. This effectively indicates termination of brainstem blood flow and thereby, irreversible brain death.
4. If TCD done prior to clinical brain death has failed to document flow in any of the segments, related to anatomical or technical constraints of the procedure, then such a study done following brain death is of no value in confirming brain death. This is a major limitation of the procedure.

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