Evaluation of cerebrovascular spasm with transcranial Doppler ultrasound

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The use of an ultrasonic transcranial Doppler technique for noninvasive evaluation of cerebral vasospasm is described. Middle cerebral arteries (MCAs), classified as spastic on angiography, demonstrated blood-flow velocity between 120 and 230 cm/sec. The flow velocities in these arteries had a clear inverse relationship to the diameter as measured from angiograms in 38 patients with recent subarachnoid hemorrhage. This relationship in the proximal anterior cerebral artery (ACA) was found to be more complicated to assess due to the collateral channels in the anterior part of the circle of Willis. The authors conclude, however, that the new method of measuring vasospasm will also detect spasm in the ACA if it has a hemodynamically significant effect upon flow resistance.

Key Words: ultrasonic • blood flow velocity • subarachnoid hemorrhage • cerebral vasospasm • hemodynamics

Fig. 1. Left: Angiogram of a 46-year-old woman with aneurysm of the right internal carotid artery 7 days after subarachnoid hemorrhage. The right middle and anterior cerebral arteries were clearly spastic, while those on the left side had normal caliber. Right: Spectral display of the Doppler signals from both middle cerebral arteries (MCA R and MCA L) in the same patient. The flow velocity in the right MCA was markedly elevated (150 cm/sec) when compared to 58 cm/sec measured on the left side (within normal range).
Fig. 2. *Left:* Flow velocity in the middle cerebral arteries (MCA's) as a function of the diameter of that section of the lumen as measured on angiography. *Triangles:* Cases without angiographic evidence of aneurysm. *Circles:* Cases with aneurysms. *Filled circles:* Cases with aneurysms and clear angiographic evidence of vasospasm. The *dotted line*, \( y = 55 + 167/x^2 \), was found by nonlinear regression analysis of the entire series. The correlation was \( r = 0.75 \). *Right:* Flow velocity in the anterior cerebral artery (ACA) as a function of the diameter of that section of the lumen as measured on angiography. Symbols as in *left*. The numbers refer to cases discussed in the text; “1” signifies the patient shown in Fig. 1, “2” indicates a case of bilateral ACA spasm, and “3” a case with one hypoplastic ACA.
Time course of blood velocity changes related to vasospasm in the circle of Willis measured by transcranial Doppler ultrasound

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Spasm: Left: FV=250 cm/s, LR=5
Right FV=150 cm/s, LR=3.5
Left CBF=25 ml/min/100g
Right CBF=37 ml/min/100g

Confounding picture:
Left FV=155 cm/s, LR=5
Right FV=45 cm/s, LR=1.5
Left CBF=56 ml/min/100g
Right CBF=41 ml/min/100g
Changes in internal carotid artery flow velocities with cerebral vasodilation and constriction
MG Beasley, JN Blau and RG Gosling
Stroke 1979;10:331-335

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**Figure 1.** (a) Sonogram for one cardiac cycle from the internal carotid artery of a healthy male aged 28 years. The waveform displays 3 peaks. Systole is from the foot of the first peak to the end of the second peak. (b) Waveform shape redrawn to show derivation of Pulsatility Index (PI = 0.7).

**Figure 2.** Sonagrams for one cardiac cycle from the carotid arteries of a healthy male aged 27 years: (a) Internal Carotid just below the angle of the jaw. (b) External Carotid just below the angle of the jaw. (c) Common Carotid at the base of the neck. Pulsatility Indices (PI's) are 0.8, 2.2 and 1.7 respectively. Waveform shape is characteristic of each of these vessels. Note the smaller variation in systolic to diastolic flow velocities, which typifies the internal carotid sonagram (a).
Pulsatility index and resistance index

\[ gPI \ (\text{Gosling Pulsatility index}) = \frac{(Fvsys - Fvdia)}{Fvmean} \]

\[ RI \ (\text{Purcelot Resistance Index}) = \frac{(Fvsys - Fvdia)}{Fvsys} \]

\[ PI \ (\text{spectral}) = \frac{F1}{FVmean} \]

All indices theoretically independent of the angle of insonation
What they measure- many thought that higher PI means higher CVR
Gosling Pulsatility Index and Resistance Index are linearly related

\[ \text{GPI} = \frac{FV_{pp}}{FV_{mean}} \]

\[ R = 0.97; \quad p = 1.3 \times 10^{-7} \]
Gosling Pulsatility index and ‘spectral’ PI are also linearly related

\[ \text{GPI} = 0.4 + 1.2 \times \text{PI} \]

\[ R = 0.81 \quad p < 0.0001 \]
Plateau wave of ICP: Widening of CBFv peak-to-peak amplitude, mean CBFv decreases
CBFv during ICP plateau waves:
With lowering ABP, FV systolic and diastolic react differently – experimental data

Thanks to Mr.K.Budohoski

Czosnyka et al. *Neurosurgery* 1994: 35(2)
Fig. 2. Mean values of 2800 one-minute averaged parameters expressed as functions of CPP (x-axis): (A) FVs, FV, Fvd – absolute values; (B) percentage changes in FV, FVd, FVs (100% is the baseline recorded for CPP from 55 to 75 mmHg); (C) CVR calculated for diastolic (CVRd), systolic (CVRs) and mean (CVR) values of FV and CPP waveforms; (D) amplitudes of ICP (ICPa) and FV (FVa) waveforms; (E) pulsatility (PI) and standardized pulsatility (SPI) indices; (F) RAP and FV diastolic to FV time average ratio.
Change in the shape of CBFv waveform during intracranial hypertension
PI is a useful index of decreasing CPP
Decrease in Doppler Pulsatility during arterial hypertension
PI increases during arterial hypotension. What happens to ICP?
Arterial hypotension, with probably exhausted vascular reactivity
Infusion test. Pressure monitoring interrupted at the end. TCD pulsatility indicated plateau wave!
The same study: PI increases faster during plateau than during infusion.
The effect of changes in cerebral perfusion pressure upon middle cerebral artery blood flow velocity and jugular bulb venous oxygen saturation after severe brain injury

KWAN-HON CHAN, F.R.C.S., J. DOUGLAS MILLER, M.D., PH.D., F.R.C.S., F.R.C.P.,
SUSAN MIDGLEY, F.F.A.R.C.S.

Department of Clinical Neurosciences, University of Edinburgh, Western General Hospital, Edinburgh, Scotland
Rise in PI does not indicate lower limit of autoregulation

Richards HK, Czosnyka M, Whitehouse H, Pickard JD. Increase in transcranial Doppler pulsatility index does not indicate the lower limit of cerebral autoregulation. Acta Neurochir (Suppl) 1998; 71:229-232
Pulsatility Index does not describe CVR under all circumstances.

Hypercapnia

Decrease in CPP
Study in volunteers (Student’s project 1997)
Plateau wave changes

Thanks to Dr. Nico de Riva
Hypocapnia changes

Thanks to Dr. Nico de Riva
‘Analytical’ presentation of PI:

\[ Z(f=0) = \frac{C_{PPm}}{FV_m} = R_a \]

\[ |Z(\omega)| = \frac{A_1}{FV_m} \]

\[ \text{PI} = \frac{F_1}{FV_m} = \frac{A_1}{C_{PPm}} \cdot \left| \frac{Z(0)}{Z(\text{HR})} \right| \]

\[ F_1 = \frac{A_1}{|Z(\text{HR})|} \quad \text{and} \quad FV_m = \frac{C_{PPm}}{|Z(0)|} \]

\[ Z(j\omega) = \frac{\frac{R_a}{j\omega C_a}}{R_a + \frac{A_1}{j\omega C_a}} = \frac{R_a}{j\omega R_a C_a + 1} \]

\[ |Z(j\omega)| = \sqrt{\frac{R_a^2}{R_a C_a \omega^2 + 1}} \]

\[ \Rightarrow \text{PI} = \frac{A_1}{C_{PPm}} \cdot \sqrt{\left(\frac{R_a C_a}{R_a C_a H R^2 (2\pi)^2 + 1}\right)} \]

\[ \approx \frac{A_1}{C_{PPm}} \cdot \sqrt{\frac{1}{(T_A U \cdot H R / \text{HR})^2 + 1}} \]

Thanks to Dr. Nico de Riva
Plot of Fitted Model

Thanks to Dr. Nico de Riva
Vasodilation after Diamox - PI decreases
Statistics:

Before: 

After Diamox: 

$p = 0.0033$
Pulsatility and ABP, PaCO2 and ICP- experimental study

Thanks to Raj
Pulsatilty indices versus experimental rise in ICP

Thanks to Raj
Pulsatility index versus experimental change in PaCO2

Thanks to Raj
Means and 95.0 Percent LSD Intervals

<table>
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<tr>
<th></th>
<th>0.32</th>
<th>0.52</th>
<th>0.72</th>
<th>0.92</th>
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<td>cabp</td>
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Summary of experimental results

Thanks to Raj
Pulsatility and CPP

Thanks to Raj
Pulsatility and CPP- clinical (TBI)
**Transcranial Doppler Sonography Pulsatility Index (PI) Reflects Intracranial Pressure (ICP)**

Johan Bellner, M.D.,* Bertil Romner, M.D., Ph.D.,* Peter Reinstrup, M.D., Ph.D.,* Karl-Axel Kristiansson, M.L.T.,† Erik Ryding, M.D., Ph.D.,† and Lennart Brandt, M.D., Ph.D.†

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Graph demonstrating a significant correlation between the ICP and the PI with a correlation coefficient of 0.938 ($p < 0.0001$) and a correlation formula of $ICP = 10.927 \times PI - 1.284$. The dotted lines are the 95% confidence interval for the regression line, which can be significantly affected by outliers when PI is large.

95% confidence limit for predictors 5 mm Hg
Things are not so optimistic in our own material (95% confidence limit= +/- 20 mm Hg)
The graph shows the PI (Pulse Inhibition) values for two groups: No spasm and Probable spasm (FV > 120 cm/s). The Probable spasm group has a significantly lower PI value, indicated by the lower bar graph with a p-value of <0.002.
Pulsatality index and outcome after TBI

![Graphs](image)

Fig 2. Left and right Gosling’s pulsatility index (GPI). (a) Scatter plot, left versus right. (b) Bland-Altman graph.

Table 1  Average Values, Average Absolute Left-Right Differences, and 95% Confidence Limits for the Left-Right Difference in Mean Flow Velocity and Every Transcranial Doppler–Derived Hemodynamic Index (standard deviations in parentheses)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Average Value (SD)</th>
<th>Average Absolute Left-Right Difference (SD)</th>
<th>95% Confidence Limit for Left-Right Difference</th>
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<tbody>
<tr>
<td>FV&lt;sub&gt;m&lt;/sub&gt;</td>
<td>64 (11) cm/s</td>
<td>8.5 (6.5) cm/s</td>
<td>20 cm/s</td>
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<tr>
<td>GPI</td>
<td>0.77 (0.11)</td>
<td>0.06 (0.05)</td>
<td>0.16</td>
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<tr>
<td>Mx</td>
<td>0.18 (0.19)</td>
<td>0.07 (0.07)</td>
<td>0.18</td>
</tr>
<tr>
<td>CCP (mm Hg)</td>
<td>14.9 (24)</td>
<td>4.8 (4.3)</td>
<td>13</td>
</tr>
<tr>
<td>nCPP (mm Hg)</td>
<td>74 (9.25)</td>
<td>2 (1.3)</td>
<td>4.6</td>
</tr>
</tbody>
</table>

FV<sub>m</sub> = mean flow velocity, GPI = Gosling’s pulsatility index, CCP = critical closing pressure, Mx = mean index of cerebral autoregulation, nCPP = noninvasive estimator of cerebral perfusion pressure.
Symmetry of gPI in unilateral spasm
Carotid artery stenotic disease

gPl

p=0.0083

contralateral  ipsilaterial
Asymmetry of PI in unilateral ICA stenotic disease
TCD Pulsatility index

What it is:
Useful indicator of cerebral hemodynamic asymmetry
Indicator of low Cerebral Perfusion Pressure

What it isn’t:
Descriptor of Cerebrovascular Resistance
Reliable predictor of raised ICP
Indicator of autoregulation limit