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 (MCA's), 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 36 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: ultrasound · 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
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. Sonograms 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 sonogram (a).
Pulsatility index and resistance index

gPI (Gosling Pulsatility index) = \frac{(Fv_{sys} - Fv_{dia})}{Fv_{mean}}

RI (Purcelot Resistance Index) = \frac{(Fv_{sys} - Fv_{dia})}{Fv_{sys}}

PI (spectral) = \frac{F1}{FV_{mean}}

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
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)
Clinical data:

Fig. 2. Mean values of 2800 one-minute averaged parameters expressed as functions of CPP (x-axis): (A) FVs, FV, FV – 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

ABP (mmHg)

FV (cm/s)
PI increases during arterial hypotension. What happens to ICP?
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

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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:

\[
\begin{align*}
Z(f=0) &= \frac{CPP_m}{FV_m} = \frac{A_1}{1} = \frac{A_1}{1} \\
F_4 &= \frac{A_1}{|Z(HR)|} \\
FV_m &= \frac{CPP_m}{|Z(0)|} \\
PI &= \frac{F_1}{FV_m} = \frac{A_1}{CPP_m} \cdot \left| \frac{Z(0)}{Z(HR)} \right| \\
Z(j\omega) &= \frac{R_e}{j\omega C_a} = \frac{R_e}{j\omega R_e C_a + 1} \\
|Z(j\omega)| &= \sqrt{\frac{R_e^2}{R_e^2 C_a^2 \omega^2 + 1}} \\
\Rightarrow PI &= \frac{A_1}{CPP_m} \cdot \sqrt{\left(\frac{R_e C_a}{HR} \cdot \frac{1}{(2\pi)^2 + 1}\right)} \\
\approx \frac{A_1}{CPP_m} \cdot \sqrt{\left(\frac{TAU \cdot HR}{10}\right)^2 + 1}
\end{align*}
\]

Thanks to Dr. Nico de Riva
PI ‘calculated’ versus ‘model’ in plateau+hypocapnia group

Plot of Fitted Model

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

Graph showing changes in ABP (mmHg), FV (cm/s), F1 (cm/s), and PI over time.
Statistics:

$p = 0.0033$

Before: 0.77
After Diamox: 0.65
Pulsatality 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

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<td>0</td>
<td>1</td>
<td>0.32</td>
<td>0.52</td>
<td>0.72</td>
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Arterial hypotension  normotension

Hypocapnia  Normocapnia  Hypercapnia

Baseline ICP  high ICP

Summary of experimental results

Thanks to Raj
Pulsatility and CPP

Thanks to Raj
Pulsatility and CPP - clinical (TBI)

Graph showing the relationship between PI and CPP, and SPI and CPP. The correlation coefficients are $r=0.59; p<0.001$ and $r=-0.73; p<0.0001$.
95% confidence limit for predictors 5 mm Hg
Things are not so optimistic in our own material (95% confidence limit = +/- 20 mm Hg)
PI

p < 0.002

No spasm

Probable spasm (FV > 120 cm/s)
Pulsatality index and outcome after TBI

\[ p = 0.017 \]

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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<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>
</tr>
<tr>
<td>GPI</td>
<td>0.77 (0.11)</td>
<td>0.06 (0.05)</td>
<td>0.16</td>
</tr>
<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

![Graph showing symmetry of gPI in contralateral and ipsilateral spasm with p=0.003]
Carotid artery stenotic disease

![Graph showing gPl values for contralateral and ipsilateral sides with p=0.0083]
Asymmetry of PI in unilateral ICA stenotic disease

\[ P_{\text{left}} - P_{\text{right}} \]

R = -0.48; p < 0.04

Stenosis of left ICA-right ICA [%]
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

* However, if at a bedside I see PI>2; and I am sure MAP is normal and PaCO2>30; I am cautious that ICP may be elevated