**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.†

*Department of Neurosurgery, Department of Anesthesiology & Intensive Care and †Department of Neurophysiology, University Hospital of Lund, Lund, Sweden


**BACKGROUND**

In patients with intracranial pathology, especially when comatose, it is desirable to have knowledge of the intracranial pressure (ICP). To investigate the relationship between ICP and transcranial Doppler (TCD) derived pulsatility index (PI) in neurosurgical patients, a prospective study was performed on patients admitted to our neurointensive care unit.

**METHODS**

Daily TCD mean flow velocity (mFV) measurements were made. TCD measurements were routinely performed bilaterally on the middle cerebral artery (MCA). PI (peak systolic-end diastolic velocities/mean flow velocity) was calculated.

**RESULTS**

Eighty-one patients with various intracranial disorders who had an intraventricular catheter for registration of the ICP were investigated: 46 (57%) patients had subarachnoid hemorrhage, 21 (26%) patients had closed head injury, and 14 (18%) patients had other neurosurgical disorders. A total of 658 TCD measurements were made. ICP registrations were made parallel with all TCD measurements. A significant correlation (p < 0.0001) was found between the ICP and the PI with a correlation coefficient of 0.938: ICP = 10.93 × PI – 1.28.

In the ICP interval between 5 to 40 mm Hg the correlation between ICP and PI enabled an estimation of ICP from the PI values with an SD of 2.5. The correlation between the cerebral perfusion pressure (CPP) and PI was significant (p < 0.0001) with a correlation coefficient of −0.493.

When separating the measurements in severely elevated (>120 cm/s) and subnormal (<50 cm/s) TCD mFV values, the correlation coefficient between ICP and PI was 0.828 (p < 0.002) and 0.942 (p < 0.638), respectively.

**CONCLUSIONS**

Independent of the type of intracranial pathology, a strong correlation between PI and ICP was demonstrated. Therefore, PI may be of guiding value in the invasive ICP placement decision in the neurointensive care patient. © 2004 Elsevier Inc. All rights reserved.

**KEY WORDS**

Transcranial Doppler, pulsatility index, intracranial pressure, head injury, subarachnoid hemorrhage.

Transcranial Doppler sonography (TCD) was primarily established as a sensitive method for detection of changes in cerebral blood flow velocities in patients with aneurysmal subarachnoid hemorrhage (SAH) indicating vasospasm [2]. The TCD technique is noninvasive and can easily be repeated bedside without any risk for the patient. The agility of the TCD equipment has also raised hopes for ultra early assessment of intracranial dynamics following head injury [13]. The value of TCD recordings in patients with head injury is, however, controversial even though changes in flow velocities may enable early detection of potentially treatable cerebral blood flow (CBF) disturbances.

In patients with intracranial pathology, especially when comatose, it is often paramount to have continuing knowledge of the intracranial pressure (ICP). Exact ICP measurement is obtainable only by an invasive intracranial pressure device [7,11]. However, a relationship between ICP and the pulsatility index (PI) in head injured patients has been described [8,14]. These findings have been further evaluated in an experimental mathematical model [21]. No prospective study on the possible relationship between ICP and PI has, to our knowledge, been performed on patients with intracranial pathology equipped with intraventricular ICP moni-
ting. Presently, such a study was carried out on the postulation that increased ICP is paralleled by an increase in PI.

**MATERIALS AND METHODS**

**PATIENT POPULATION**

Eighty-one patients were included with the following types of intracranial disorders, verified by computerized tomography (CT): 46 (57%) had aneurysmal subarachnoid hemorrhage, 21 (26%) severe head injury, 7 (9%) spontaneous intracerebral hemorrhage, and 7 (9%) had other neurologic disorders [encephalitis (n = 1), meningitis (n = 3), meningioma (n = 1), idiopathic intracranial hypertension (n = 1), and sagittal sinus thrombosis (n = 1)].

**INTRACRANIAL PRESSURE MONITORING**

All patients received an intraventricular catheter for continuous recording of the intracranial pressure (HanniKath, 7F, pvb Medizintechnik GmbH & Co. kg, Kirchseeon, Germany). The TCD measurements were routinely performed bilaterally on the middle cerebral artery (MCA). Recordings were documented on a videographic printer for later analysis (Sony VP 850). The depth and angle of insonation giving the highest mean flow velocity (mFV) in MCA was always chosen. Normal mFV in MCA was defined as 62 ± 12 cm/s [1]. Consequently, mFVs were considered subnormal when below 50 cm/s and supranormal when above 74 cm/s. mFVs above 120 cm/s were considered severely elevated indicating vasospasm or hyperemia [2,16]. Normal values for PI are 0.7 ± 0.3 [20].

**CALCULATIONS AND STATISTICAL METHODS**

PI was calculated according to the method of Gosling [6]. PI is derived from the difference in the systolic and diastolic flow velocity divided by the mFV.

The PI data were correlated to ICP and CPP and the correlation coefficient calculated. To control the linear correlation, the residuals were tested for normal distribution around the regression line with Kolmogorov-Smirnov’s test. An estimated ICP from PI was determined from the regression equation. The validity of the TCD(PI) method for ICP measuring was tested by a Bland & Altman plot [3]. Sensitivity and specificity for ICP(PI) were calculated in the ICP range of 0 to 20 and 0 to 40 mm Hg.

**RESULTS**

Eighty-one patients (37 males and 44 females) aged 2 to 79 years (mean 52 years) were investigated daily with a total of 658 PI measurements. The patients had a mean (± SD) arterial partial pressure of carbon dioxide (PCO2) of 4.84 ± 0.64 (range 3.25–7.5) kPa, a heart frequency of 79 ± 17 (range 47–142), 97.3% with regular sinus rhythm, and a mean arterial blood pressure (MAP) of 92 ± 16 mm Hg (range 48–162) at the time of investigation.

The correlation between the cerebral perfusion pressure (CPP) and PI was significant (p < 0.0001) with a correlation coefficient of −0.493 (Figure 1). This finding was paralleled by a similar significant correlation (p < 0.0001) between CPP and ICP where the similar correlation coefficient was −0.477.

In the overall results there was a significant correlation (p < 0.0001) between the ICP and the PI with a correlation coefficient of 0.938 (Figure 2). When separating severely elevated (>120 cm/s) and subnormal (<50 cm/s) TCD mFV values, the correlation coefficient between ICP and PI was 0.828 (p < 0.002) and 0.942 (p < 0.638 because of a low number of measurements), respectively (Figures 3 and 4). Only in one of 658 measurements (0.15%), the mFV exceeded 120 cm/s in conjunction with an ICP above 20 mm Hg (Figure 3). However, only in the ICP interval 5 to 40 mm Hg were the data normal distributed around the regression line. Omitting repeated measurements, and only considering the initial TCD-ICP recording in each subject (n = 81) for the interval, 5 to 40 mm Hg R² was 0.733 (p < 0.0001) with a SD 2.5. The regression line is ICP(PI) = 11.1 × PI – 1.43. Using the regression equation we get ICP(PI) = ICP ± 2.5 (SD) with a 95% confidence interval of ±4.2.

A Bland and Altman plot of all measurements confirmed that the difference between the observed ICP and the ICP predicted from the PI was within the ±4.2 of the observed ICP (Figure 5).

In an ICP span between 0 and 20 mm Hg, the method had for all measurements a sensitivity of 0.88 and a specificity of 0.69, and for the first measurement only a sensitivity of 0.91 and a specificity of 0.79, for detecting an ICP >10 mm Hg. To detect
an ICP > 20 in a population with ICP between 10 and 40, the method had for all measurements a sensitivity of 0.83 and a specificity of 0.99, and for the first measurement only a sensitivity of 0.89 and a specificity of 0.92.

**DISCUSSION**  
**TRANSCRANIAL DOPPLER IN NEUROINTENSIVE CARE**

The mobility of the equipment, the possibility of repeated bedside investigations together with the noninvasive nature of the technique, makes TCD measurements attractive in the attempt to estimate CBF in acute care settings. The basic technical limitation, i.e., measuring cerebral blood flow velocity and not true volume flow, has triggered further development in the utilization of acquired data from the TCD investigations.

In neurointensive care, knowledge of ICP is often essential. When measuring ICP the use of an intraventricular catheter has for decades been considered as gold standard [11].

In the present study, we found independent of intracranial pathology, a significantly strong positive correlation between PI and intraventricular ICP monitoring. Notably, the correlation was still strong in the patient subgroup demonstrating mFV values above and below normal interval.

A less clear correlation (−0.493) between PI and CPP was seen. In head injured patients, Chan et al [4], reported a correlation (−0.725) between PI and

---

[Graph 1](image1.png) Graph demonstrating a significant correlation between the CPP and PI with a correlation coefficient of −0.493 ($p < 0.0001$) and a correlation formula of: $CPP = 89.646 - 8.258 \times PI$. The correlation between CPP and PI is mainly when PI >3. The dotted lines are the 95% confidence interval for the regression line, which can be significantly affected by outliers when PI is large.

[Graph 2](image2.png) 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.
CPP with an even better correlation (−0.942) as CPP decreased below a critical value of 70 mm Hg. In an experimental mathematical model study, Ursino et al [21], described relationships between perfusion pressure, autoregulation and TCD waveform during various settings in cerebrovascular hemodynamics. These theoretical models indicate that during normoventilation within normal blood pressure range, sudden increases in PI are only attainable with a rise in ICP. Our clinical results are in agreement with these findings. However, to rely on PI in daily practice one has to determine the sensitivity and specificity of the method. In the acceptable ICP interval of 0 to 20 mm Hg, the TCD is highly sensitive with a medium high specificity. In the supranormal ICP range between 10 and 40 mm Hg the sensitivity decreases while the specificity increases. Consequently, the TCD-PI measurement gives a fairly good estimation of the ICP, which might be of value in unconscious patients.

**PI IN ANEURYSMAL SUBARACHNOID HEMORRHAGE**

The correlation between ICP and PI was still intact in SAH patients suffering vasospasm detected by TCD (Figure 3). Cerebral vasospasm in SAH is characterized by a high mFV through the vasospastic artery, often exceeding 120 cm/s [2]. In such cases there will be a decrease in CBF because of an increase in cerebrovascular resistance through the artery [17]. The high flow velocity is only obtainable if the peripheral vascular resistance remains at a relatively low level. As a result a high mFV is usually not found in patients with high ICP as they
have a concomitant increase in small vessel resistance [9]. In the present study, only once in 658 measurements was an mFV exceeding 120 cm/s observed in conjunction with an ICP above 20 mm Hg (Figure 3).

**PI IN HEAD INJURY**

With repeated carotid Doppler sonograms, Steiger [19] investigated PI in patients with severe head injury as compared to healthy volunteers. This extracranial utilization of PI revealed values between 1.5 to 2.0 in control subjects with a gradual increase in cases with posttraumatic brain edema. PI values >3 were associated with severe intracranial hypertension, and in cases of angiographically demonstrated cerebral circulatory arrest, PI values in the range of 6 to 8 were found.

Presently a significant correlation between PI and ICP was found, the correlation being stronger as compared to previous studies. Homburg et al [8], investigated 10 head injured patients and demonstrated a positive exponential correlation between PI and the epidural pressure \( r = 0.82 \). McQuire and colleagues [13] performed TCD measurements within 3 hours after injury on 22 head injured patients. Thirteen of the patients had either computed tomography verified space-occupying hematomas or brain swelling. Among these cases 10 had an increased PI in this ultra-early phase. Recently, Moreno et al [14] correlated TCD measurements with ICP and CPP values in 125 patients with severe head injury. They found that an elevated PI predicts poor outcome (PI 1.56), and furthermore, a correlation between ICP and PI \( (R^2 = 0.69) \) was found. In severe head injured patients, Martin et al [12] reported significantly higher PI values on Day 0, compared to Days 1 through 3 and Days 4 through 14 post-trauma. These findings strongly suggest the presence of high distal vascular resistance in the early phase after head injury. The authors also showed that one-third of patients with severe head injuries have vasospasm, and that vasospasm will significantly change both mFV and PI. In our study we found that PI reflected ICP even when mFV was above 120 in the ICP range of 0 to 20 mm Hg, but with only one reading above 20 mm Hg.

With data obtained by TCD, Czosnyka and associates [5] made estimations of CPP after head injury and concluded that such measurements may be of value in situations where direct measurements of CPP are not readily available. Moreno et al [14] found a positive correlation of 0.60 between PI and CPP. This correlation is probably dominated by the ICP. In our experience, reduced mFV after head injury always indicates reduced volume flow in the insonated artery, and can hence be helpful to indicate compromised cerebral perfusion, and a low mFV postinjury should guide the choice of blood pressure targets that should be used during the cerebral resuscitation [16]. An example of this is our findings of frequently reduced mFV in measurements where ICP exceeded 20 mm Hg with a corresponding rise in PI.

**PI IN HYDROCEPHALUS**

In hydrocephalic children a decrease of PI in the postshunting test as compared with the preshunting test has been shown [15]. Furthermore, after endoscopic third ventriculostomy for the treatment of obstructive hydrocephalus, pre- and postoperative PI measurements have been shown useful for evaluation of fenestration patency [22]. Recently, the value of PI measurements was confirmed in a study of 21 hydrocephalic patients [18].

**FACTORS THAT INFLUENCE PI**

Flow velocity, the velocity pattern, and thereby the PI may be influenced by different factors, like hemodynamic, respiratory, and hematologic parameters, and, in the case of brain vessels, tissue compliance. For this reason, the absolute value of this index is, in general, not considered sufficient to characterize overall intracranial hemodynamic conditions if no other information is simultaneously provided. The main advantage of PI is that, being a ratio; it is not affected by the angle of insonation.

The arterial pressure in large and medium sized cerebral arteries is only slightly reduced compared...
to the pressure created by the heart, but in the arterioles the normal mean pressure drops. During elevated intracranial pressure, the arterioles are easily compressed creating a high peripheral vascular resistance reducing the flow, and thereby, the denominator of the PI. The numerator of the PI derives from the difference between systolic and diastolic flow velocities. The elasticity of the normal vascular system dampens the flow and flow velocity fluctuations because of blood pressure changes, which is in contrast to a rigid tube where the pressure is directly proportional to the flow velocity [21]. A clinical setting where this is apparent is the elevation of PI in diabetic patients with cerebral microangiopathy and hence depressed vessel compliance [10]. An increased intracranial pressure always results in reduced compliance of the entire brain tissue including increased rigidity of the brain arteries augmenting the velocity variations, which in turn increases the denominator of the PI. Consequently, this index is sensitive to ICP changes. The flow velocity pattern in cerebral arteries is affected both by cerebrospinal fluid pulsatility and the action of cerebrovascular control mechanisms. In a situation with severely raised ICP one might expect not only a decrease in mFV, but in particular an effect on velocity pattern during diastole. The reduction in mFV during this phase is more pronounced and rapid. These factors will thus, according to the equation, increase the PI. This pattern is, to the most extreme, seen when total brain infarction is present. Then mFV approaches zero and the calculated PI thus reaches extreme values.

**Conclusion**

Our data shows a highly significant correlation between PI and ICP independent of intracranial pathology. Accordingly, in patients with suspected increase in ICP or where an increased ICP has to be excluded, PI may be of guidance and repeated PI measurements might prove a useful tool in neurointensive care settings.

**References**

21. Ursino M, Giulioni M, Lodi CA. Relationships among...

COMMENTARY
Bellner et al have added to the growing body of knowledge regarding transcranial Doppler sonography and its use in various neurosurgical clinical problems. This study has the advantage of being prospective with a good statistical analysis of the data. Although they are able to describe the results of the technique in several different pathologies, it is important to realize that the intracranial dynamics and the cause of increased intracranial pressure would vary with pathology type, e.g., between subarachnoid hemorrhage and traumatic brain injury. Although the correlation between pulsatility index and intracranial pressure was strong, the transcranial Doppler study can only be done intermittently. Obviously, in the pathology described, intracranial pressure is a moving target. This limits its clinical applicability significantly. However, as the authors point out, I think it could be a useful technique in patients in whom elevated intracranial pressure was suspected or in those patients in whom it would be important to exclude.

Gaylan L. Rockswold, M.D.
Professor of Neurosurgery
University of Minnesota
Minneapolis, Minnesota