Simultaneous measurements of intracranial pressure parameters in the epidural space and in brain parenchyma in patients with hydrocephalus

Clinical article

PER KRISTIAN EIDE, M.D., PH.D., AND WILHELM SORTEBERG, M.D., PH.D.

Department of Neurosurgery, Oslo University Hospital—Rikshospitalet, Oslo, Norway

Object. In this study, the authors compare simultaneous measurements of static and pulsatile pressure parameters in the epidural space and brain parenchyma of hydrocephalic patients.

Methods. Simultaneous intracranial pressure (ICP) signals from the epidural space (ICP
EPI
) and the brain parenchyma (ICP
PAR
) were compared in 12 patients undergoing continuous ICP monitoring as part of their diagnostic workup for hydrocephalus. The static ICP was characterized by mean ICP and the frequency of B waves quantified in the time domain, while the pulsatile ICP was determined from the cardiac beat–induced single ICP waves and expressed by the ICP pulse pressure amplitude (dP) and latency (dT; that is, rise time).

Results. The 12 patients underwent a median of 22.5 hours (range 5.9–24.8 hours) of ICP monitoring. Considering the total recording period of each patient, the mean ICP (static ICP) differed between the 2 compartments by ≥ 5 mm Hg in 8 patients (67%) and by ≥ 10 mm Hg in 4 patients (33%). In contrast, for every patient the ICP pulse pressure readings from the 2 compartments showed near-identical results. Consequently, when sorting patients to shunt/no shunt treatment according to pulsatile ICP values, selection was independent of sensor placement. The frequency of B waves also compared well between the 2 compartments.

Conclusions. The pulsatile ICP is measured with equal confidence from the ICP
EPI
 and ICP
PAR
 signals. When using the pulsatile ICP for evaluation of hydrocephalic patients, valid measurements may thus be obtained from pressure monitoring in the epidural space. Recorded differences in the mean ICP between the epidural space and the brain parenchyma are best explained by differences in the zero setting of different sensors. (DOI: 10.3171/2010.7.JNS10483)

Key Words • intracranial pressure • epidural pressure • brain parenchyma pressure • single intracranial pressure wave • pulsatile intracranial pressure • intracranial pressure B wave

Continuous ICP monitoring is useful for assessment of intracranial hydrodynamics in neurosurgical patients.6,10,12 The ICP sensor is usually placed in the subdural space, in the brain parenchyma, or in a cerebral ventricle, but it is rarely in the epidural space. Placing the ICP sensor in the epidural space, however, seems attractive because the risk of hemorrhage inside the dura mater would become marginal. It would thus be of particular advantage in patients at high risk for intracranial bleeding; for example, those with acute liver failure or hemorrhagic diseases.2,23

Since epidural ICP monitoring was first done clinically using dedicated epidural ICP sensors,26 many reports have documented that the epidural ICP monitoring provided erroneous static ICP values, usually exaggerating the ICP.4,5,14,19,20,25,27,32–41,42 For this reason, epidural ICP monitoring has not been advocated. Recently, however, Poca et al.30,31 argued that epidural ICP monitoring...
may be useful when evaluating the B wave activity (the profile of the trend plot) of the static ICP. Hence, they showed that the B wave activity was similar in the cranial epidural space and in the lumbar subarachnoid space. Moreover, Eide observed that ICP monitoring in the epidural space and in the brain parenchyma provided equivalent readings with regard to the pulsatile ICP, but not for the static ICP. In the study by Eide, however, the ICP readings were obtained using a sensor not specially developed for epidural pressure monitoring.

The aim of the present study was to compare simultaneous measurements of ICP parameters in the epidural space and in brain parenchyma by using commercially available sensors developed especially for pressure measurements in the respective compartments. To this end, static and pulsatile ICP measurements were obtained from the epidural space (ICP\textsubscript{EPI}) and the brain parenchyma (ICP\textsubscript{PAR}) in 12 patients undergoing continuous ICP monitoring as part of their diagnostic workup for hydrocephalus. We characterized the static ICP by mean ICP and the frequency of B waves quantified in the time domain, while the pulsatile ICP was determined from the cardiac beat–induced single ICP waves.

**Methods**

*Patient Population*

The study included 12 patients (9 women and 3 men) with median age of 61 years (range 18–72 years). The patients underwent continuous ICP monitoring as part of our standardized preoperative evaluation of hydrocephalus. One patient was excluded from the study because her epidural ICP sensor was unintentionally removed shortly after implantation. The study was approved by the Regional Ethical Committee of Health Region South in Norway (S-04308). Informed consent from each patient was obtained prior to study inclusion.

*Intracranial Pressure Monitoring*

Placement of the ICP sensors was done in the operating room under local anesthesia. A skin incision was made 3 cm lateral to the midline and frontal to the coronal suture, and a bur hole of 1–1.5 cm was thereafter made in the cranium. The dura was carefully loosened more than 2 cm from the bone to allow placement of the epidural sensor (NeuroDur-P, Raumedic AG) freely under the bone. It was crucial to free the dura so that no force was used when placing the sensor, with its sensor side toward the dura. On no occasion was there any unintentional opening of the dura. Thereafter, a 1-mm opening of the dura was made for introduction of the ICP sensor (NeuroVent-P, Raumedic AG) 1–2 cm into the brain parenchyma. The size of the dura opening was intentionally made that small to avoid CSF leakage. The angulation between the 2 sensors was 90°, thus giving a maximal distance between the 2 sensor tips of less than 3 cm. The skull defect from the trepanation was filled with bone wax before the skin was sutured.

After sensor placement, the patient returned to the neurosurgical ward for surveillance. Both ICP sensors were connected to a DataLogger MPRI monitor (Raumedic AG), and the ICP signals were retrieved in digital format to a laptop computer with Sensometrics Software (DPCom AS) performing the ICP analysis online. The continuous ICP signals from the 2 sensors were thus sampled simultaneously with identical time reference (sampling rate 136 Hz).

*Intracranial Pressure Analysis*

The ICP signals from the epidural space and the brain parenchyma sensors were processed simultaneously with simulation calculations of the static and the pulsatile ICP. The ICP analysis was done in the time domain, as previously described.

The static ICP was characterized by the mean ICP and the frequency of Lundberg B waves. The mean ICP represents the average of pressure values divided by the number of samples, with the mean ICP being determined for every consecutive 6-second time window. The B wave analysis was based on plotting mean ICP against time, that is, providing a trend plot of the mean ICP (Fig. 1A and B). The B waves hence represent pressure changes in this trend plot (Fig. 1C). The pressure changes are indicated by peaks and valleys in the trend plot of the mean ICP (Fig. 1A) and ICP\textsubscript{PAR} (Fig. 1B) signals, respectively. We quantified differences in mean ICP ≥ 10, ≥ 15, and ≥ 20 mm Hg to compare B wave frequency between the ICP\textsubscript{EPI} and ICP\textsubscript{PAR} signals. This was done automatically by the software, as indicated in Fig. 1A and B.

The pulsatile ICP was determined automatically by the software, incorporating an automatic method for identification of cardiac beat–induced single intracranial pulse pressure waves (Fig. 2A and B). Using this method, pressure waves related to noise in the signal were excluded from the analysis. For every cardiac beat–induced single pressure wave, the amplitude (that is, the pressure difference from diastolic minimum to systolic maximum [dP]), the rise time (that is, the time interval from diastolic minimum pressure to systolic maximum pressure [dT]), and the rise time coefficient (amplitude divided by latency) were computed (Fig. 2C). The automatic routine further computes the ICP pulse parameters for every 6-second time window as the mean ICP wave amplitude, ICP wave rise time, and ICP wave rise time coefficient, as previously described in detail.

Finally, we also determined the differences in amplitude for every single wave pair of the simultaneous ICP\textsubscript{PAR} and ICP\textsubscript{EPI} signals.

*Results*

Sex, age, type of hydrocephalus, recording time of ICP monitoring, and number of accepted 6-second time windows of the ICP\textsubscript{EPI}/ICP\textsubscript{PAR} signals available for comparison in the 12 patients are presented in Table 1. For all patients combined, a total of 106,908 6-second time windows were available for analysis.

For the recording periods reported here, there was no reduction in the quality of the ICP\textsubscript{EPI} or ICP\textsubscript{PAR} signals.
Epidural intracranial pressure monitoring

over time. There were no complications related to the ICP monitoring.

*Static ICP*

Considering the average of mean ICP for the entire recordings, we found a difference in mean ICP between the 2 compartments of $\geq 5$ mm Hg in 8 (67%) of 12 patients ($ICP_{EPI}$ highest in 6 patients) and $\geq 10$ mm Hg in 4 (33%) of 12 patients ($ICP_{EPI}$ highest in all 4) (Table 2). In contrast, the percentage of B waves $\geq 10$, $\geq 15$, and $\geq 20$ mm Hg from the $ICP_{EPI}$ and $ICP_{PAR}$ measurements were similar in all patients (Table 3).

*Pulsatile ICP*

Average values of the pulsatile ICP parameters (mean ICP wave amplitude, rise time, and rise time coefficient) of the 12 patients are presented in Table 2. Only marginal differences between the $ICP_{EPI}$ and $ICP_{PAR}$ signals were

![Fig. 1. A 10-minute trend plot of the mean ICP (static ICP), calculated every subsequent 6-second time window, for the epidural space (A) and the brain parenchyma (B) sensors. The detection routine identifies peaks and valleys in the trend plot, and all increases in mean ICP (dICP) $\geq 10$, $\geq 15$, and $\geq 20$ mm Hg are identified. The profile of each trend plot of the mean ICP could be quantified (C).](image-url)

**TABLE 1: Demographic data and ICP recordings**

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Age (yrs), Sex</th>
<th>Type of Hydrocephalus</th>
<th>Recording Time (hrs)</th>
<th>No. of Accepted 6-Sec Time Window Pairs</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>62, F</td>
<td>iNPH</td>
<td>5.9</td>
<td>2,798</td>
</tr>
<tr>
<td>2</td>
<td>36, F</td>
<td>congenital hydrocephalus</td>
<td>24.3</td>
<td>12,578</td>
</tr>
<tr>
<td>3</td>
<td>51, F</td>
<td>iNPH</td>
<td>12.1</td>
<td>5,024</td>
</tr>
<tr>
<td>4</td>
<td>45, F</td>
<td>aqueductal stenosis</td>
<td>19.9</td>
<td>7,631</td>
</tr>
<tr>
<td>5</td>
<td>60, M</td>
<td>iNPH</td>
<td>16.4</td>
<td>7,182</td>
</tr>
<tr>
<td>6</td>
<td>67, M</td>
<td>iNPH</td>
<td>24.2</td>
<td>10,946</td>
</tr>
<tr>
<td>7</td>
<td>67, F</td>
<td>iNPH</td>
<td>23.0</td>
<td>13,358</td>
</tr>
<tr>
<td>8</td>
<td>20, F</td>
<td>congenital hydrocephalus</td>
<td>22.4</td>
<td>11,398</td>
</tr>
<tr>
<td>9</td>
<td>18, F</td>
<td>Chiari malformation</td>
<td>23.0</td>
<td>8,558</td>
</tr>
<tr>
<td>10</td>
<td>70, F</td>
<td>iNPH</td>
<td>24.8</td>
<td>13,276</td>
</tr>
<tr>
<td>11</td>
<td>72, M</td>
<td>iNPH</td>
<td>22.5</td>
<td>6,979</td>
</tr>
<tr>
<td>12</td>
<td>64, F</td>
<td>iNPH</td>
<td>19.4</td>
<td>7,180</td>
</tr>
</tbody>
</table>
Fig. 2. The raw signal of the epidural space (A) and the brain parenchyma ICP signal (B) showing the cardiac beat–induced waves from which the pulsatile ICP is determined. For every cardiac-induced wave, the following pulsatile ICP parameters are determined: amplitude, rise time, and rise time coefficient (C). The time window shown in panels A and B lasts 6 seconds, which is the time window for determining the mean ICP wave amplitude, rise time, and rise time coefficient.

TABLE 2: Mean values of static and pulsatile ICP parameters within the epidural space and brain parenchyma compartments*

<table>
<thead>
<tr>
<th>Case No.</th>
<th>Static ICP (mm Hg)</th>
<th>Static ICP Wave Amplitude (mm Hg)</th>
<th>Static ICP Wave Rise Time (sec)</th>
<th>Static ICP Wave Rise Time Coefficient (mm Hg/sec)</th>
<th>Pulsatile ICP (mm Hg)</th>
<th>Pulsatile ICP Wave Amplitude (mm Hg)</th>
<th>Pulsatile ICP Wave Rise Time (sec)</th>
<th>Pulsatile ICP Wave Rise Time Coefficient (mm Hg/sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>8.3 ± 4.4</td>
<td>6.6 ± 4.5</td>
<td>9.0 ± 2.9</td>
<td>8.9 ± 2.6</td>
<td>0.29 ± 0.02</td>
<td>0.29 ± 0.02</td>
<td>31.3 ± 9.5</td>
<td>31.0 ± 8.6</td>
</tr>
<tr>
<td>2</td>
<td>15.2 ± 13.6</td>
<td>4.1 ± 5.5</td>
<td>3.0 ± 0.7</td>
<td>2.9 ± 0.7</td>
<td>0.15 ± 0.03</td>
<td>0.14 ± 0.03</td>
<td>22.8 ± 5.8</td>
<td>22.5 ± 5.5</td>
</tr>
<tr>
<td>3</td>
<td>4.8 ± 3.8</td>
<td>1.2 ± 4.0</td>
<td>3.9 ± 1.4</td>
<td>3.8 ± 1.0</td>
<td>0.28 ± 0.02</td>
<td>0.27 ± 0.03</td>
<td>14.6 ± 5.3</td>
<td>14.6 ± 4.0</td>
</tr>
<tr>
<td>4</td>
<td>6.2 ± 5.1</td>
<td>1.2 ± 3.7</td>
<td>6.7 ± 1.9</td>
<td>6.7 ± 1.9</td>
<td>0.22 ± 0.03</td>
<td>0.22 ± 0.03</td>
<td>32.5 ± 10.4</td>
<td>32.6 ± 10.5</td>
</tr>
<tr>
<td>5</td>
<td>7.4 ± 4.1</td>
<td>14.8 ± 7.8</td>
<td>3.9 ± 1.1</td>
<td>3.8 ± 0.9</td>
<td>0.27 ± 0.04</td>
<td>0.27 ± 0.03</td>
<td>14.7 ± 4.5</td>
<td>14.7 ± 3.8</td>
</tr>
<tr>
<td>6</td>
<td>18.2 ± 3.5</td>
<td>0.1 ± 3.1</td>
<td>4.4 ± 0.7</td>
<td>4.1 ± 0.7</td>
<td>0.25 ± 0.05</td>
<td>0.24 ± 0.06</td>
<td>19.2 ± 5.6</td>
<td>19.3 ± 7.0</td>
</tr>
<tr>
<td>7</td>
<td>5.8 ± 3.9</td>
<td>13.0 ± 3.5</td>
<td>6.8 ± 1.4</td>
<td>7.1 ± 1.4</td>
<td>0.14 ± 0.05</td>
<td>0.15 ± 0.05</td>
<td>55.2 ± 15.2</td>
<td>56.7 ± 15.9</td>
</tr>
<tr>
<td>8</td>
<td>31.3 ± 15.8</td>
<td>15.3 ± 11.0</td>
<td>8.2 ± 4.7</td>
<td>8.0 ± 4.5</td>
<td>0.17 ± 0.04</td>
<td>0.16 ± 0.04</td>
<td>53.6 ± 34.5</td>
<td>53.7 ± 33.7</td>
</tr>
<tr>
<td>9</td>
<td>22.3 ± 4.5</td>
<td>11.7 ± 3.2</td>
<td>3.6 ± 1.3</td>
<td>3.2 ± 1.2</td>
<td>0.21 ± 0.03</td>
<td>0.22 ± 0.03</td>
<td>17.9 ± 7.2</td>
<td>16.0 ± 6.9</td>
</tr>
<tr>
<td>10</td>
<td>2.3 ± 3.1</td>
<td>4.5 ± 3.3</td>
<td>3.6 ± 0.8</td>
<td>3.6 ± 0.8</td>
<td>0.21 ± 0.03</td>
<td>0.21 ± 0.03</td>
<td>17.4 ± 3.6</td>
<td>17.4 ± 3.7</td>
</tr>
<tr>
<td>11</td>
<td>10.0 ± 6.9</td>
<td>4.4 ± 4.3</td>
<td>3.2 ± 0.6</td>
<td>3.1 ± 0.6</td>
<td>0.24 ± 0.04</td>
<td>0.24 ± 0.04</td>
<td>14.8 ± 3.8</td>
<td>14.4 ± 3.7</td>
</tr>
<tr>
<td>12</td>
<td>1.7 ± 4.6</td>
<td>5.1 ± 3.5</td>
<td>4.4 ± 1.2</td>
<td>4.3 ± 1.2</td>
<td>0.27 ± 0.02</td>
<td>0.27 ± 0.02</td>
<td>16.5 ± 4.5</td>
<td>16.2 ± 4.5</td>
</tr>
</tbody>
</table>

* Values are presented as the mean ± SD. The shaded values are considered to be abnormal as described by Eide and Sorteberg.12
single wave pairs were available for analysis. Negligible differences in single wave amplitude were seen in every patient.

### Relationship Between the Static B Waves and the Pulsatile Mean ICP Wave Amplitude

Table 5 presents the Spearman correlations between percentages of B waves (percentage of changes in ICP ≥ 10, ≥ 15, and ≥ 20 mm Hg) and percentages of ICP wave amplitudes (ICP wave amplitude ≥ 3, ≥ 4, ≥ 5, or ≥ 6 mm Hg). No positive correlation was seen between the percentages of B waves and the percentages of ICP wave amplitudes (Table 5). In fact, a significant negative correlation was seen between the percentage of B waves ≥ 20 mm Hg and the percentage of ICP wave amplitudes.

### Discussion

Many researchers regard ICP monitoring as the preferable way of assessing intracranial dynamics, although most neurosurgeons do not consider it routine in hydrocephalic patients. In our department, however, diagnostic ICP monitoring in patients with CSF disorders is routine. Thus, among the 130 patients who underwent shunt treatment for iNPH in a 6-year period (2002–2007), we found significant shunt response in 90% of the individuals with elevated pulsatile ICP (ICP wave amplitudes), whereas only 10% of those with low pulsatile ICP had a shunt response. Intracranial pressure monitoring may be used for measuring static as well as pulsatile ICP. In the present study, static ICP was expressed by mean ICP and by Lundberg B waves, whereas pulsatile ICP was expressed by the change in ICP generated by the individual cardiac beats. Hence, the (static) mean ICP expresses the difference between the pressure obtained at the location of the pressure sensor and the atmospheric pressure. Also, whereas B waves are short-lasting increases in the static ICP (in our study derived from the trend plot of the mean ICP with a resolution of 6
Our pulsatile ICP is expressed by the ICP pulse waves generated by the individual heartbeats (determined here at 136 Hz). The static ICP B wave and the pulsatile ICP wave amplitude (pulse pressure wave) are thus fundamentally different types of waves. Correspondingly, no positive correlation was seen between the percentages of B waves and the percentages of ICP wave amplitudes. The negative correlation between B waves ≥ 20 mm Hg and ICP wave amplitudes is best explained by sudden shifts in static ICP not accompanied by changes in pulsatile ICP, as recently described by Eide et al.10

**Static ICP**

The present observations on the mean ICP confirm the

---

**Fig. 3.** The distribution of differences (Diff) in single pressure wave amplitude (dP) between the 2 compartments (ICP_{par} – ICP_{epi}) is shown in all patients. The following data are presented as the mean ± SD with the number of single waves (SWs) in parentheses.  

- **A:** Case 1, −0.13 ± 0.55 mm Hg (15,816).  
- **B:** Case 2, −0.09 ± 0.20 mm Hg (98,269).  
- **C:** Case 3, −0.09 ± 0.74 mm Hg (31,474).  
- **D:** Case 4, −0.03 ± 0.25 mm Hg (61,492).  
- **E:** Case 5, −0.04 ± 0.46 mm Hg (39,129).  
- **F:** Case 6, −0.31 ± 0.28 mm Hg (63,509).  
- **G:** Case 7, 0.23 ± 0.27 mm Hg (116,920).  
- **H:** Case 8, −0.22 ± 0.42 mm Hg (85,497).  
- **I:** Case 9, −0.36 ± 0.23 mm Hg (54,216).  
- **J:** Case 10, 0.004 ± 0.16 mm Hg (102,233).  
- **K:** Case 11, −0.05 ± 0.22 mm Hg (46,413).  
- **L:** Case 12, −0.07 ± 0.27 mm Hg (43,606).
Epidural intracranial pressure monitoring

TABLE 5: Spearman correlation between percentage of B waves and pulse waves recorded from the brain parenchyma and the epidural compartments*

<table>
<thead>
<tr>
<th>% ICP Wave Amplitude (mm Hg)</th>
<th>≥10 mm Hg</th>
<th>≥15 mm Hg</th>
<th>≥20 mm Hg</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ICP\textsubscript{EPI}</td>
<td>ICP\textsubscript{PAR}</td>
<td>ICP\textsubscript{EPI}</td>
</tr>
<tr>
<td>≥3</td>
<td>p = 0.15 (NS)</td>
<td>R = -0.47 (NS)</td>
<td>R = -0.73 (p = 0.01)</td>
</tr>
<tr>
<td>ICP\textsubscript{EPI}</td>
<td>p = 0.21 (NS)</td>
<td>R = -0.45 (NS)</td>
<td>R = -0.69 (p = 0.01)</td>
</tr>
<tr>
<td>ICP\textsubscript{PAR}</td>
<td>p = 0.36 (NS)</td>
<td>R = -0.33 (NS)</td>
<td>R = -0.65 (p = 0.02)</td>
</tr>
<tr>
<td>≥5</td>
<td>p = 0.21 (NS)</td>
<td>R = -0.45 (NS)</td>
<td>R = -0.68 (p = 0.02)</td>
</tr>
<tr>
<td>ICP\textsubscript{EPI}</td>
<td>p = 0.36 (NS)</td>
<td>p = -0.35 (NS)</td>
<td>R = -0.68 (p = 0.02)</td>
</tr>
<tr>
<td>ICP\textsubscript{PAR}</td>
<td>p = 0.40 (NS)</td>
<td>p = -0.35 (NS)</td>
<td>R = -0.65 (p = 0.02)</td>
</tr>
</tbody>
</table>

* NS = non-significant; p = Spearman significance (2-tailed); R = Spearman correlation.

extensive literature that absolute values of the static ICP may differ considerably between the epidural space and the brain parenchyma compartments.\textsuperscript{4,5,14,19,20,25,27,32–34,41,42} Because the maximum distance between our epidural space and brain parenchyma sensors was less than 3 cm, any differences in mean ICP explained by differences in sensor locations should be no more than the accuracy of the sensor itself (1 mm Hg, according to the manufacturer). The differences in absolute mean ICP thus represent differences in baseline pressure between the parenchymal and epidural sensors. Eide\textsuperscript{7} previously observed the same phenomena for different ICP sensors placed closely together within the brain parenchyma. Epidural ICP monitoring therefore seems to be of limited value when considering the mean ICP alone.

While others have previously estimated B wave activity in the frequency domain,\textsuperscript{13} we presently quantified B waves in the time domain by identifying the increases in mean ICP in the trend plot. We then determined the percentages of increases in mean ICP ≥ 10, ≥ 15, and ≥ 20 mm Hg, respectively (Fig. 1C). Here it is crucial to understand that our B waves express short-lasting increases in the static ICP but do not give the absolute value of the static ICP. Using our approach, we could accurately compare the B wave activity from the ICP\textsubscript{EPI} and ICP\textsubscript{PAR} signals, finding them to be similar in the 2 compartments in all of our 12 hydrocephalic patients. Our results support those of Poca et al.,\textsuperscript{30–32} assessing the profile of the trend plot of mean ICP and finding that any type of swift alteration in ICP was correctly assessed by the epidural space pressure sensor.

Lundberg B waves refer to sharp increases in static ICP, occurring as rhythmic oscillations with a frequency of approximately 1 per minute (range 0.5–2 per minute) and with amplitudes ranging from discernible to 50 mm Hg.\textsuperscript{24} It has been debated extensively what may be considered as normal/abnormal frequency of B waves and whether B waves occur more frequently in hydrocephalic patients.\textsuperscript{3,16,28,31,35,36,39,40} Thus, although epidural ICP monitoring provides a reliable determination of the B wave activity, the clinical significance of a given percentage of B waves remains disputable.

Pulsatile ICP

A consistent finding in our study was that the pulsatile ICP was measured with equal confidence from the ICP\textsubscript{EPI} and ICP\textsubscript{PAR} signals. This compares with the first author's previous findings using Codman sensors for pressure monitoring from both compartments.\textsuperscript{8} It is also in accordance with the findings by Raabe et al.\textsuperscript{34} when they used the frequency domain method with fast Fourier transformation to compare waveforms between signals from their epidural space and parenchymal (or ventricular) ICP sensors. Similar results have also been obtained by Weinstabl et al.\textsuperscript{42}

The pulsatile ICP (mean ICP wave amplitude) provides information about intracranial compliance in patients; that is, the ICP volume reserve capacity.\textsuperscript{11} In the normal situation (good physiological condition), the intracranial compliance is high, with the small changes in intracranial volume generated by cardiac pulsations (in the range of 0.5 to 1 ml)\textsuperscript{10} creating small ICP wave amplitudes. In contrast, as the total volume of fluid in the intracranial cavity of hydrocephalic patients increases, intracranial compliance becomes reduced with the cardiac pulsations creating large ICP wave amplitudes. Simi-
lar observations of increased ICP wave amplitudes during reduced intracranial compliance have previously been observed in animals.15,17,18

The Future of Pulsatile ICP Measurements in Hydrocephalic Patients

We have previously published how we quantify the various levels of ICP wave amplitudes when we perform diagnostic ICP monitoring, and how we use the scores in the evaluation of patients with regard to iNPH and hydrocephalus.12 The present work documents that pulsatile ICP parameters are recorded with equal confidence when using ICP_EPI and ICP_PAR Sensors. Consequently, in the future, we may evaluate and determine the treatment of hydrocephalic patients merely from assessing the pulsatile ICP from an epidurally located pressure sensor.

Conclusions

The pulsatile ICP is measured with equal confidence from the ICP_EPI and ICP_PAR signals. Consequently, when sorting patients to shunt/no shunt treatment according to pulsatile ICP values, selection is independent of sensor placement. Epidural ICP monitoring may therefore be used in the evaluation of hydrocephalic patients. Recorded differences in the mean ICP between the epidural space and the brain parenchyma are best explained by differences in the zero setting of different sensors.

Disclosure

The authors are grateful to Raumedic AG for providing the NeuroDur ICP sensors. The Sensometrics Software used for analysis of the ICP recordings is manufactured by dPCom AS, wherein Per Kristian Eide, M.D., Ph.D., has a financial interest. Author contributions to the study and manuscript preparation include the following. Conception and design: both authors. Acquisition of data: both authors. Analysis and interpretation of data: both authors. Drafting the article: both authors. Reviewed final version of the manuscript and approved it for submission: both authors.

References

Epidural intracranial pressure monitoring


37. Reilly P: In normal pressure hydrocephalus, intracranial pressure monitoring is the only useful test. J Clin Neurosci 8:66–69, 2001


42. Weinstabl C, Richling B, Plainer B, Czech T, Spiss CK: Comparative analysis between epidural (Gaeltec) and subdural (Camino) intracranial pressure probes. J Clin Monit 8:116–120, 1992


Accepted July 14, 2010.

Please include this information when citing this paper: published online August 27, 2010; DOI: 10.3171/2010.7.JNS10483.

Address correspondence to: Per Kristian Eide, M.D., Ph.D., Department of Neurosurgery, Oslo University Hospital–Rikshospitalet, 0027 Oslo, Norway. email: per.kristian.eide@rikshospitalet.no.