Noninvasive detection of elevated intracranial pressure using a portable ultrasound system

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Abstract

Objective: The aim of this study is to prospectively compare the accuracies of transcranial color-coded sonography (TCCS) and transcranial Doppler (TCD) in the diagnosis of elevated intracranial pressure.

Methods: A prospective, blinded, head-to-head comparison of TCD and TCCS methods using intracranial pressure (ICP) measured continuously via an intraparenchymal catheter as the reference standard in 2 groups of 20 neurocritical care patients each: high ICP (group 1) and normal ICP (group 2). Middle cerebral artery (MCA) pulsatility index (PI) recordings from all patients' sonographic reports were selected based on the highest left or right recorded MCA PI. Transcranial Doppler was performed using a dedicated TCD device, and TCCS was performed using a portable ultrasound system.

Results: The PI values obtained did not differ significantly between the 2 methods (group 1, P = .46; group 2, P = .11). Linear regression analysis identified a significant relationship between PI obtained with both methods (r = 0.897; P < .0001). The duration of PI measurement was statistically longer with TCCS than TCD (group 1, P < .01; group 2, P < .01). Diagnostic accuracies were good and similar for both methods (TCD area under curve, 0.901; TCCS area under curve 0.870; P = .69).

Conclusions: This work is a pilot study comparing TCCS and TCD in the detection of elevated ICP. This study suggests that a bedside portable ultrasound system may be useful to determine MCA PI with accuracy similar to that of a dedicated TCD device.

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1. Introduction

Patients with altered levels of consciousness may be having elevated intracranial pressure (ICP) due to a variety of causes. Conventional imaging methods are sometimes unavailable in emergency situations, and ICP monitoring remains difficult because of delays in obtaining blood coagulation test results or lack of surgical availability [1]. Simple, noninvasive bedside methods have been developed
to rapidly assess the risk of high ICP [2-5]. The middle cerebral artery (MCA) transcranial Doppler (TCD)–derived pulsatility index (PI) has been shown to reflect decreases in cerebral perfusion pressure (CPP) due to ICP increases [3,5,6]. Introduced by Aaslid et al [7] in 1982, TCD was gradually replaced by transcranial color-coded sonography (TCCS), which allows the exact identification of different feeding arteries [8]. The aim of this pilot study was to prospectively compare the accuracies of TCD and TCCS in the diagnosis of elevated ICP measuring MCA PI in neurocritical care patients.

2. Materials and methods

2.1. Study design and patient selection

We conducted a prospective, blinded, observational study with a convenience sample at the intensive care unit of the Sainte Anne Military Teaching Hospital of Toulon (France). From January to December 2008, 2 groups of 20 adult patients each were enrolled. All participants were neurocritical care patients (traumatic brain injury, stroke, subarachnoid hemorrhage) requiring sedation, mechanical ventilation, and ICP monitoring. Group 1 included 20 patients with high ICP (exceeding 20 mm Hg). Group 2 included 20 patients with normal ICP (≤20 mm Hg). All patients were sedated with intravenous midazolam and sufentanil. Pregnant women and patients who were younger than 18 years, hemodynamically unstable, or who had already participated in a clinical trial were excluded.

2.2. Treatment protocol and materials

All ultrasound examinations were performed and interpreted by investigators trained in TCD and TCCS, with experience providing more than 150 examinations (BP, YA, or GL) and were not involved in patient care. A head-to-head comparison of TCD and TCCS methods was conducted; ICP measured continuously via an intraparenchymal catheter (Neuromonitor-Microsensor kit; Codman, Chatenay Malabry, France) inserted into the frontal lobe was used as the reference standard. Ultrasound results were all obtained after placement of the ICP monitoring device. Suitability of temporal bone acoustic window was defined by the ability to insonate blood flow velocity in the MCA when studied with TCD and TCCS. Before inclusion in the study, all patients were tested with TCD and TCCS by an independent operator (BP, YA, or GL) to ensure suitability of temporal bone acoustic window. Patients with unilateral or bilateral absence of temporal bone acoustic window when studied with TCD and/or TCCS were excluded. The order of performance of the sonographic examinations was determined randomly in a 2-ball ballot box. A first operator performed the first sonographic examination (TCD or TCCS); and immediately after, a second operator performed the second sonographic examination (TCCS or TCD). Both investigators were blinded to ICP results and other ultrasound examination results. No major treatment intervention was undertaken between ultrasound studies. In case of neurosurgery, both sonographic studies were performed either before or after the intervention. All patients were placed in a proclive position with head elevated to 30° to the horizontal. The duration of each sonographic study was timed.

Transcranial Doppler sonography was performed at the bedside using a dedicated TCD device (Looki TC, model year 2004; Atys Medical, Soucieu en Jarrest, France) with a hand-held transducer operated in a range-gated, pulse-waved mode at 2.0 MHz. Right and left MCAs were insonated through the temporal window at a depth of 50 to 60 mm; and tracings were recorded on 10 cardiac cycles, in accordance with the technique described by Aaslid et al [7].

Transcranial color-coded sonography was performed at the bedside through the temporal windows following published guidelines [9,10]. A portable ultrasound system (TITAN, model year 2006; SonoSite, Bothell, WA) equipped with a C15 4-2 MHz probe for 2-dimensional, color Doppler and pulsed wave Doppler was used (Fig. 1). The M1 segment of the MCA was identified with 2-dimensional gray scale and color imaging, and a 3-mm wide sample volume was placed on the color image of the artery at the site of the best Doppler signal. Middle cerebral artery flow velocity was recorded at depths of 50 to 60 mm. The mean time–averaged maximum blood flow velocity (Vmean), peak systolic velocity (Vps), and end-diastolic velocity (Ved) were calculated by manual tracing of the maximum frequency envelope of the Doppler waveform. The manual tracing on 10 cardiac cycles was performed by the investigators during the examination.

The MCA PI recordings from all patients’ sonographic reports were selected based on the highest left or right...
recorded MCA PI. Pulsatility index was defined by the equation PI = (Vps − Ved)/Vmean, with Vmean = (Vps + 2 Ved)/3. Pulsatility index was independent of the angle of insonation. Arterial pressure was monitored continuously, via a femoral catheter (4F, Seldicath; Plastimed, Le Plessis Bouchard, France). Cerebral perfusion pressure was calculated as the difference between mean arterial pressure (MAP) and ICP. Elevated ICP was defined as any ICP exceeding 20 mm Hg for more than 10 minutes. Such episodes were detected using trend data from the patient monitor (IntelliVue MP40/MP50; Philips Medical Systems, Eindhoven, The Netherlands). Patient care was in line with existing protocols and was not modified by this study. The study design was approved by the Local Research and Ethics Committee of Sainte Anne Hospital, Toulon, France; and written informed consent was obtained from each patient or his/her family.

2.3. Objectives

The main objective of the study was to establish that the PI values obtained by 2 different methods were not statistically different in patients with elevated or nonelevated ICP.

Additional objectives were to compare the duration of both sonographic methods and to construct a receiver operating characteristic (ROC) curve to assess their accuracies during the detection of elevated ICP.

2.4. Statistics and data analysis

The Student paired t test was used to compare PI from TCD and TCCS in the normal and elevated ICP groups. Furthermore, a linear regression equation was built; and a 1-way analysis of variance F test was made on the null hypothesis that there are no differences between the 2 ultrasound methods. The Student paired t test was used to compare the durations of PI measurement using TCD and TCCS in the normal and elevated ICP groups. The accuracy of each ultrasound method during the detection of elevated ICP was estimated by total area under the ROC curve. Receiver operating characteristic curves were constructed based on a set of sensitivity and specificity pairs, determined for an ICP greater than 20 mm Hg. Evaluation of the significance of the difference between the 2 area under the curve (AUC) values was performed using a parametric Z test.

Data are presented as numbers (%) for nominal variables and as the mean ± SD for continuous variables. Comparison of the groups was made using Fisher exact test for nominal variables and the Student t test for continuous variables. All statistical analyses were provided by JMP (JMP 8.0 for Mac OS X; SAS Institute, Cary, NC) and SPSS (SPSS 15.0.1; SPSS, Inc, Chicago, IL). P < .05 was considered statistically significant.

The sample size was calculated considering the SD of PI at admission in the study of Asil et al [11]. For sample size calculations, a power of 0.9 and P value of .05 were used. With 0.24 as SD of PI and with an anticipated significant difference between TCD and TCCS groups of 20%, a sample size of 18 patients per group was obtained. Preliminary results of this work were presented at the 51st meeting of the Société Française d’Anesthésie Réanimation in Paris, France, September 23 to 26, 2009.

3. Results

3.1. Patient characteristics

Bilateral absence of temporal bone acoustic window was reported in 3 patients when studied with both conventional TCD and TCCS. Unilateral absence of temporal bone acoustic window was reported in 1 patient when studied with TCD and in 1 patient when studied with TCCS. These 5 patients were not included in the study. Twenty patients were then enrolled in each group, and their clinical characteristics are listed in Table 1. The 2 groups did not differ significantly in demographic characteristics and severity scores. The ICP and MAP values were significantly lower in patients with normal ICP than in those with high ICP, whereas the CPP values were significantly higher in patients with normal ICP than in those with high ICP. The groups did not differ significantly with regard to heart rate, norepinephrine infusion, plasma sodium concentration, bladder temperature, or arterial carbon dioxide partial pressure.

<table>
<thead>
<tr>
<th>Table 1 Patient characteristics</th>
<th>High ICP</th>
<th>Normal ICP</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, y</td>
<td>49 ± 17</td>
<td>50 ± 18</td>
<td>.95</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>76 ± 13</td>
<td>75 ± 13</td>
<td>.96</td>
</tr>
<tr>
<td>Male sex, %</td>
<td>80</td>
<td>75</td>
<td>.99</td>
</tr>
<tr>
<td>ICU length of stay, d</td>
<td>19 ± 13</td>
<td>20 ± 16</td>
<td>.98</td>
</tr>
<tr>
<td>SAPS II</td>
<td>42 ± 14</td>
<td>39 ± 10</td>
<td>.69</td>
</tr>
<tr>
<td>Data during sonography</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ICP, mm Hg</td>
<td>26 ± 3</td>
<td>14 ± 3</td>
<td>&lt;.01</td>
</tr>
<tr>
<td>MAP, mm Hg</td>
<td>97 ± 9</td>
<td>91 ± 6</td>
<td>.04</td>
</tr>
<tr>
<td>CPP, mm Hg</td>
<td>72 ± 12</td>
<td>78 ± 6</td>
<td>.03</td>
</tr>
<tr>
<td>Heart rate, beats per minute</td>
<td>84 ± 16</td>
<td>82 ± 16</td>
<td>.58</td>
</tr>
<tr>
<td>Norepinephrine infusion, %</td>
<td>65</td>
<td>45</td>
<td>.34</td>
</tr>
<tr>
<td>Plasma sodium concentration, mmol/L</td>
<td>140 ± 2.2</td>
<td>139 ± 2.3</td>
<td>.56</td>
</tr>
<tr>
<td>Bladder temperature, °C</td>
<td>36.9 ± 0.7</td>
<td>37.1 ± 0.5</td>
<td>.27</td>
</tr>
<tr>
<td>PacO2, kPa</td>
<td>5.0 ± 0.2</td>
<td>5.1 ± 0.1</td>
<td>.18</td>
</tr>
<tr>
<td>PaCO2, mm Hg</td>
<td>37 ± 1</td>
<td>38 ± 1</td>
<td></td>
</tr>
</tbody>
</table>

ICU indicates intensive care unit; SAPS II, simplified acute physiology score; PaCO2, arterial carbon dioxide partial pressure.
3.2. Comparison of PI values

The PI values obtained by the 2 different methods are shown in Table 2 and did not differ statistically between groups ($P = .46$ in the high ICP group; $P = .11$ in the normal ICP group). Linear regression analysis identified a significant relationship between PI obtained with TCD and TCCS ($r = 0.897; P < .0001; F$ test; Fig. 2).

3.3. Comparison of durations of PI measurement

The duration of PI measurement obtained by the 2 different methods is shown in Table 2. Measurement duration was statistically longer in the TCCS group ($P < .01$ in the high ICP group; $P < .01$ in the normal ICP group).

3.4. Diagnostic accuracy regarding elevated ICP

To compare the performances of PI obtained with TCCS and TCD in the detection of elevated ICP, the ROC curves are shown in the same figure panels (Fig. 3). Pulsatility index obtained with TCD accurately predicted elevated ICP (AUC, 0.901; 95% confidence interval [CI], 0.794-1.000). The best PI cutoff value was 1.35 (sensitivity 80%; specificity 90%). Pulsatility index obtained with TCCS accurately predicted elevated ICP (AUC, 0.870; 95% CI, 0.759-0.981). The best PI cutoff value was 1.34 (sensitivity 80%; specificity 95%). The difference between the 2 AUC values was not statistically significant ($P = .688; Z$ test).

4. Discussion

This work is an observational pilot study comparing TCCS and TCD in the detection of elevated ICP. These results illustrate that the PI values obtained by TCCS with the SonoSite TITAN and by TCD with Looki TC do not differ significantly in patients with normal or high ICP. The duration of measurement was much longer with TCCS than with TCD. Furthermore, this study showed that the overall accuracy of TCCS in the detection of elevated ICP by the measurement of the MCA PI is similar to the accuracy of TCD.

The 2 ultrasound systems used are very different. Looki TC is a device dedicated to TCD examination and is made for hospital use and requiring an electric connection. By comparison, the SonoSite TITAN is a portable ultrasound system used for many different sonographic examinations; it is made for stationary and mobile usage, thanks to its small size ($29.97 \times 27.69 \times 7.62$ cm), its low weight (3.76 kg), and it provides accurate and reliable PI values.
its ability to function with autonomy for approximately 2 hours under battery power. This device can be used in out-of-hospital situations, such as prehospital emergency medicine or military medicine. Therefore, it is interesting to know that this device can detect elevated ICP with accuracy similar to that of a dedicated TCD system.

The 2 sonographic methods used to obtain MCA PI are also different. With conventional TCD, cerebral arteries are not imaged but are obtained in a “blind” manner [8]. The identification of each intracranial vessel is based on the following elements: (a) velocity and direction of blood flow, (b) depth of signal capture, (c) possibility of following the vessel its entire length, (d) spatial relationship with other vessels, and (e) response to homolateral and contralateral carotid compression [12,13]. Transcranial color-coded sonography allows the exact identification of different feeding arteries, which enables the operator to place the sample volume precisely at the location of the highest velocity acceleration [8]. This technical advantage of TCCS compared with TCD has the inconvenience of increasing the duration of PI measurement, as shown in our results. Transcranial color-coded sonography also permits better assessment of intracranial circulation, particularly in pathologic vascular processes, such as arteriovenous malformations [13].

Transcranial Doppler is a tool for the bedside monitoring of static and dynamic cerebral flow and treatment response [12]. Introduced by Aaslid et al [7] in 1982, it has become indispensable in clinical practice [12]. The main fields of clinical application of TCD are assessment of vasospasm, detection of stenosis of the intracranial arteries, evaluation of cerebrovascular autoregulation, noninvasive estimation of ICP and of degree of intracranial hypertension, measurement of effective downstream pressure, and assessment of brain death [3,7,12,14]. This technique further provides practicable, noninvasive bedside monitoring of therapeutic measures [4]. The usual threshold PI value for high ICP is 1.4 [4]. Pulsatility index will increase with increased cerebral vascular resistance as ICP increases [15]. The PI may also be influenced by other physiologic or pathologic states. Hemodynamic variables that increase pulsatility include bradycardia, aortic insufficiency, or increased vascular resistance distal to the large conductance vessels. Factors that may decrease pulsatility include proximal vascular stenosis or lowered vascular resistance distal to the basal cerebral vessels [15]. Transcranial Doppler–derived PI displayed significant correlations between the left and right sides [16]. However, both transcranial sonographic methods (TCCS and TCD) have a primary limitation, which is that unsatisfactory images are obtained in approximately 5% to 20% of patients, even in expert hands when a temporal window is used [3,10,15].

In 1993, Schöning et al [17] compared TCCS and TCD in 49 healthy adult volunteers. The studies were carried out blindly by different examiners at separate appointments. The Vps, Ved, time-averaged maximum flow velocity, and PI were measured by both techniques. The TCCS signals were recorded in 98% of both MCAs and anterior cerebral arteries; with TCD, signals were recorded in 98% of MCAs and 87% of anterior cerebral arteries. Although in both vessels the angle-corrected Vps and time-averaged maximum flow velocity were approximately 10% to 15% higher in TCCS than in TCD measurements, correlation of flow velocities between both techniques was significant (P < .0001); differences between sides and age dependence of flow velocities corresponded as well. They concluded that the advantage of TCCS was associated more with a qualitative aspect than a quantitative one. On the contrary, in 2007, Krejza et al [18] found that TCD velocities are significantly higher than TCCS velocities but are not different from angle-corrected TCCS velocities and that TCCS identifies the major intracranial arteries more effectively than TCD.

In 2007 also, Krejza et al [19] showed that the success rate of insonating the intracranial vessels through the temporal bone acoustic window is the same for conventional TCD and TCCS. In 2009, Swiat et al [20] compared the accuracy of TCCS and TCD in the detection of MCA vasospasm in 81 patients and found that accuracies were similar but that TCCS was more sensitive than TCD.

4.1. Study limitations

This trial is a single-center study with convenience sample and small numbers (20 patients per group). Patients with absence or poor temporal acoustic bone windows were excluded, which might result in case selection bias and may also limit clinical application; but this is a daily clinical situation. The visual approach of TCCS does not overcome this difficulty. It is the main limit of these devices because it concerns up to 20% of the patients. Therefore, this pilot study can provide only very limited information. Training aspects with learning curve of novice practitioners have not been evaluated. Furthermore, the use of these techniques in emergency situations or field setting will be even more difficult.

5. Conclusion

A bedside portable ultrasound system is useful to determine the MCA PI with accuracy similar to that of a TCD device. Transcranial color-coded sonography with the SonoSite TITAN ultrasound system represents an efficient noninvasive technique for detecting elevated ICP. The technical characteristics of this device make it usable in out-of-hospital situations, such as prehospital emergencies, where it may have therapeutic impact as in osmotherapy. Larger studies will be required to confirm these data and specify the global benefits for patient care in emergency department or field setting.
References
