Prospective study of methodological issues in intracranial pressure monitoring in patients with hydrocephalus

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Object. Continuous intracranial pressure (ICP) monitoring is performed in selected patients with hydrocephalus to determine whether shunt placement is required. The mean ICP is usually calculated from end-hour readings manually recorded by nurses. The aim of this study was to evaluate the accuracy of manual recordings by comparing nurses’ end-hour ICP readings with those of an online computerized ICP monitoring system that records one ICP value per second.

Methods. Continuous ICP monitoring was performed using a fiberoptic extradural sensor in 115 patients with hydrocephalus of different origins. A notebook computer was connected to an ICP monitor and was programmed to register one ICP value per second. In all patients, mean ICP values were calculated from data recorded manually by nurses at the end of every hour and from data recorded by the computer within the preselected time period. The two methods were compared using correlation analysis and the Bland and Altman method.

The median number of ICP values noted manually by the nurses in each patient was 17 (interquartile range 15–18 readings), and that recorded by the software was 61,200 (interquartile range 54,000–64,800 readings). The correlation coefficient of the mean ICP values recorded by both methods was $r = 0.99$ ($p < 0.001$). The Bland and Altman analysis revealed a mean difference of $0.3 \pm 1.26$ mm Hg between the two methods and that they were equally valid with all mean ICP values.

Conclusions. The recording of end-hour ICP values by nurses is an accurate method of calculating the mean ICP after prolonged ICP monitoring in patients with hydrocephalus.

KEY WORDS • hydrocephalus • intracranial pressure • computer-based monitoring system

Continuous ICP monitoring is currently used as a therapeutic guide in patients with severe head injury, as well as in other patients in neurocritical care units who are at risk for intracranial hypertension. This protocol is also used as a diagnostic tool in selected neurosurgical patients, especially in those with certain types of hydrocephalus (NPH, suspected shunt dysfunction, ventriculostomies, and so forth). When ICP is continuously monitored as a diagnostic tool in neurosurgical departments (usually with less sophisticated equipment than in intensive care units), nurses usually record a single ICP value manually every hour (“end-hour” ICP reading). These values are used to calculate the mean ICP in the total recording period, as well as to differentiate between diurnal and nocturnal mean ICP. In patients with hydrocephalus, however, various factors influence ICP, such as the presence of A or B waves, postural changes in bed, eating, and other maneuvers. These factors, which are not routinely recorded by the nurses, can temporarily increase ICP values and may cast doubt on the validity of manual recordings in estimating patients’ mean ICP.

In the last few years, some ICP monitors have contained integrated computerized systems that allow us to analyze large samples of ICP data, and that provide more complete information (descriptive statistics, histograms, and so forth). These computer-based systems are not always available, however, in which case manual ICP recording at the bedside in the neurosurgical ward constitutes the main source of information. Our objective in this study was to evaluate the accuracy of manual recordings in calculating the mean ICP, by comparing the end-hour values recorded by nurses with an online computerized ICP monitoring system that records one ICP value per second and calculates the mean ICP automatically within the preselected time period.

Clinical Material and Methods

Patient Population

Of 453 patients with hydrocephalus who underwent continuous ICP monitoring in the Department of Neurosurgery...
of the Vall d’Hebron University Hospital between August 1990 and December 2000, 115 (25.4%) were prospectively included in this study. This was the maximum number of patients who could be included because of the facilities available in our department during this period (three ICP monitors and only one computer system adapted to one ICP monitor). There were 56 female and 59 male patients, whose mean age was 51.7 ± 22.3 years (median 54, range 13–85 years). Informed consent to participate in the study was obtained in all cases from patients or a close relative. All patients in this series presented with increased ventricular size (Evan Index ≥ 0.3) on computerized tomography scanning or magnetic resonance imaging, combined with various clinical symptoms. The different causes of hydrocephalus are summarized in Table 1. The decision to shunt CSF was based on continuous ICP monitoring, combined in some patients with the study of CSF dynamics, which confirmed the clinical and neuroimaging data.

**Sensor Implantation Method for ICP Monitoring**

In all patients continuous ICP monitoring was performed using a fiberoptic extradural sensor (Ladd Research Industries, Inc., Williston, VT). The ICP sensor was implanted parasagittally in the precoronal region, usually of the left hemisphere, through a burr hole after induction of local anesthesia. An incision of 2.5 to 3 cm was made in the scalp 10.5 to 11 cm from the nasion and 3 cm from the midline. A 14-mm burr hole was made, followed by dissection of the epidural space (~25 mm) in a forward direction from the burr hole in the anterior 180° arc. The dissection of the epidural space was completed in the posterior 180° arc (~10–15 mm). The sensor was calibrated to 0 and introduced into the epidural space, where the sensitive side of the device was applied against the dura mater. Finally, the incision was closed, taking care not to damage the interconnecting tubing that contains the optical fibers.

The ICP sensors were always connected to an S-series monitor (model S2000 or SP2000; Ladd Research Industries, Inc.). The monitor’s slow response mode, which records pressure changes of 6 mm Hg per second, was select-
ed. In all patients, ICP monitoring was performed for at least 48 hours, including overnight recording. The patients routinely alternated between periods of 17 to 24 hours when they were connected to the ICP monitor while remaining flat in bed, and periods of 24 hours without monitoring, in which they could sit up or walk around.

**Quantitative Analysis of ICP**

The ICP value observed on the monitor was manually recorded on a specific chart (Fig. 1) at the patient’s bedside by a nurse at the end of each hour. If this recording coincided with a maneuver by the patient that could produce an artifact in the reading (for example, movements, Valsalva maneuver, and so on), the nurses were instructed to allow a time interval of several minutes for the ICP to stabilize before recording the final value. For quantitative analysis of the ICP recordings, the arithmetic mean ICP corresponding to the total recording period was calculated. Data obtained from 8:00 a.m. to 11:00 p.m. were used to calculate diurnal mean ICP, and data obtained from 12:00 a.m. to 7:00 a.m. were used to calculate nocturnal mean ICP.

**Qualitative Analysis of ICP**

Hard copies of the ICP values were obtained using a single-channel recorder (Yokogawa 3021 Pen Recorder; Alder S.A., Madrid, Spain) with a paper speed of 20 or 60 cm/hour. The presence of A waves (ICP elevations of at least 20 mm Hg above the resting line, with abrupt onset and end, and lasting between 5 and 20 minutes) and B waves (0.5–2 ICP waves/minute, lasting for at least 10 minutes) was evaluated and expressed as the percentage of the
total monitoring time. The B waves were subdivided according to amplitude into high-amplitude (≥ 10 mm Hg) and low-amplitude (< 10 mm Hg) values (Fig. 2). 

Types of Hydrocephalus and Criteria for Shunt Placement

The hydrocephalus classification system used in this study assigned grades according to the presence or absence of A and/or B waves and the mean ICP values obtained from the epidural sensor. To avoid artifacts related with the use of epidural sensors, however, ICP values measured by the epidural sensor were compared and corrected with the pressure values obtained simultaneously from a lumbar puncture performed to study CSF dynamics in patients with communicating hydrocephalus. Accordingly, each patient was included in one of the following categories: 1) active hydrocephalus (mean ICP ≥ 12 mm Hg with the presence of A and/or B waves); 2) compensated hydrocephalus (mean ICP ≥ 12 mm Hg with the presence of A and/or B waves); 3) arrested hydrocephalus (mean ICP ≤ 12 mm Hg with no abnormal waves in the total recording time); and 4) brain atrophy (ex vacuo hydrocephalus: patients with suspected NPH who presented with mean ICP levels ≤ 12 mm Hg but with no abnormal waves in the entire recording time). All patients who had active or compensated hydrocephalus were selected for shunt placement.

Characteristics of the Computer-Based System

A notebook computer (Amstrad ALT-286 microprocessor with 64 KB of random access memory) was connected to the ICP monitor with an analog-to-digital converter that converts the pressure signal from the transducer to a binary form (Fig. 3). The computer software was programmed to register one ICP value from the monitor per second; this software is able to record ICP values between 10 and 185 mm Hg. The computer acquires the ICP values transmitted by the monitor without filtering; thus, no ICP values are excluded. At the end of the programmed monitoring period, the software summarized the data, providing the total time, number of valid ICP readings, and the ICP values (maximum, minimum, mean, SD, and mode), as well as a histogram of the data (Fig. 4).

Comparison of Manual and Computer Measurements

In all patients the median period of continuous ICP monitoring, in which simultaneous recordings were made by nurses and the computer-based system, was 17 hours (interquartile range 15–18 hours; minimum 11, maximum 24 hours). The ICP monitoring was always started after lunch and continued until the next day (end point 9:00 a.m. ± 1 hour). The correlation between these two methods was investigated by pairing the mean ICP values obtained manually by nurses and those recorded by the computer was evaluated using the Spearman rank cor-

Statistical Analysis

All descriptive statistics were analyzed and summarized using commercially available programs (SigmaStat for Windows, version 3.0; SPSS Inc., Chicago, IL). The assumption that data were normally distributed was verified using the Kolmogorov–Smirnov test. In normally distributed data, the mean ± SD was used to summarize the variables. In skewed samples, the median and the interquartile range were used. The correlation between the mean ICP values obtained manually by nurses and those recorded by the computer was evaluated using the Spearman rank cor-
Comparison of computer- and nurse-recorded ICP values

The correlation coefficient. The agreement between the two monitoring procedures was assessed using the method proposed by Bland and Altman.

The nonparametric Mann–Whitney rank-sum test was used to compare the mean ICP calculated by the two methods in the following paired groups: 1) patients with intracranial hypertension and those with a mean ICP of 12 mm Hg or less; 2) patients with A waves and those without; and 3) patients who presented with high-amplitude B waves for more than 25% of the study period and those who presented with high-amplitude B waves for 25% of the study period or less. Significance was considered at probabilities less than or equal to 0.01.

Results

Simultaneous manual and computerized ICP recordings in 115 patients were evaluated. The median number of ICP readings recorded manually by nurses was 17 (interquartile range 15–18; minimum 11, maximum 24 readings), and that recorded by the software was 61,200 (interquartile range 54,000–64,800; minimum 39,600, maximum 86,400 readings). In 44 patients, the mean ICP calculated by both methods was identical. In 45 patients the computer system recorded a higher mean ICP than the manual method, and in 26 patients the computer system recorded a lower mean ICP. The median difference in the 115 mean ICP values recorded by both methods was 0 mm Hg, with a maximum and minimum difference of 5 and 4 mm Hg, respectively, and an interquartile range of 0 and 1 mm Hg.

Their scattering did not vary over the range of mean ICP values, a systematic relationship between measurement error and the true value could be excluded, thus confirming the validity of both methods throughout the entire range of mean ICP values.

According to the classification used in this study, hydrocephalus was active in 44 patients (38.3%), compensated in 63 (54.7%), and arrested in four (3.5%); brain atrophy was found in the four remaining patients (3.5%). No statistically significant differences were found in the mean ICP between patients with intracranial hypertension (active hydrocephalus; p = 0.735) and those without intracranial hypertension (compensated and arrested hydrocephalus and brain atrophy; p = 0.937).

Nocturnal and/or diurnal A waves with a plateau of 40 mm Hg or more were found in 11 (9.6%) of 115 patients. No statistically significant differences were found between patients with A waves (p = 0.896) and those without A waves (p = 0.901).

Thirty-two (27.8%) of 115 patients presented with high-amplitude B waves for more than 25% of the total record-

Fig. 5. Histogram of differences in mean ICP values recorded by manual and computerized methods. The median difference in the mean ICP values recorded by both methods was 0 mm Hg, with a maximum and minimum difference of 5 and 4 mm Hg, respectively, and an interquartile range of 0 and 1 mm Hg.

Fig. 6. Graph showing correlation of mean ICP values calculated by the computer software and mean ICP values calculated manually with nurses’ end-hour ICP readings (Spearman rank correlation analysis).

Fig. 7. Scatterplot showing analysis of agreement with the Bland and Altman method. The difference between the methods (y axis) is plotted against their mean (x axis). The mean difference between the two methods is 0.296 ± 1.256 mm Hg. As can be seen, because their scattering did not vary over the range of mean ICP values, both methods are equally valid throughout the entire range of values.
ing time. No statistically significant differences were found between these patients (p = 0.856) and those presenting with high-amplitude B waves for 25% or less of the total recording time (p = 0.927).

Discussion

Continuous ICP monitoring in patients in neurocritical care units must provide immediate and clear information, both numerically and graphically. This allows clinicians to analyze patients’ responses to treatment and to act quickly according to changes in ICP. When this value is continuously monitored in patients with chronic hydrocephalus, in whom the main objective is to determine whether CSF shunting is required, analysis of the data can usually be delayed and should include more detailed analysis of recordings, such as mean ICP values, the presence and percentage of ICP waves, nocturnal ICP findings related to different sleep stages, and so forth.15 In patients with hydrocephalus, the integration of a computer-based system in the analysis of ICP provides additional advantages such as a more detailed mathematical analysis and compilation of data for subsequent diagnosis or research purposes. Furthermore, the need for large quantities of paper recordings that are sometimes unwieldy is avoided. Computerized systems are not available in all neurosurgical departments, however, and even when available they cannot be used in all monitored patients. In these cases, the main source of information remains the graphic paper recording and the numerical ICP values recorded by nurses.

Patients with adult chronic hydrocephalus are normally cooperative and their ICP values are less influenced by nursing manipulations than those in patients admitted to neurocritical care units, who require frequent aspiration of tracheobronchial secretions, passive movements in bed, and wound care, among other needs. Nevertheless, patients with hydrocephalus can also perform movements or maneuvers (turning of the head, speaking, laughing, eating, and so forth) that can transiently increase ICP. An additional characteristic of these patients is that they present with various percentages of A or B waves, which can markedly increase ICP above the resting level (Fig. 2). This casts doubt on whether the mean ICP values calculated from the data collected manually each hour are truly representative of a patient’s mean ICP. In a previous study of five severely head injured patients, Turner, et al.,19 demonstrated that the end-hour ICP readings recorded by nurses were an accurate estimate of the patients’ mean ICP in that hour. These authors compared a single ICP value observed by a nurse on the ICP monitor screen at the end of an hour with a sample of 720 ICP readings recorded by a computerized system in the same hour.19 They demonstrated that 84% of the nurse-and computer-recorded values differed by no more than 6 mm Hg, and that the end-hour value recorded by the nurses provided an accurate estimate of patients’ mean ICP calculated by the computer in that hour. In our study, which was performed in patients with more or less stable ICP recordings, and which always included monitoring periods of at least 11 consecutive hours, the correlation between the data obtained by nurses and those obtained by the computer was even closer (median difference in mean ICP obtained by both methods was 0 mm Hg, with a maximum recorded difference of 5 mm Hg).

The Bland and Altman analysis demonstrated that the two methods of calculating mean ICP can be used interchangeably and that they are equally valid with all ranges of mean ICP values. Another relevant finding in our study is the absence of statistically significant differences in mean ICP between the methods when they are applied in patients with intracranial hypertension (active hydrocephalus) or in patients with unstable ICP readings who present with plateau waves or a high percentage of high-amplitude B waves.

Conclusions

We demonstrate that recording of end-hour ICP values by nurses is an accurate method of calculating mean ICP after prolonged monitoring in patients with hydrocephalus. This method is equally valid in patients with and without intracranial hypertension, as well as in those who present with A waves or a variable percentage of high-amplitude B waves in the ICP recording.

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Comparison of computer- and nurse-recorded ICP values

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