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Two computerized methods used to analyze intracranial pressure B waves: comparison with traditional visual interpretation

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Object. Slow and rhythmic oscillations in intracranial pressure (ICP), also known as B waves, have been claimed to be one of the best preoperative predictive factors in idiopathic adult hydrocephalus syndrome (IAHS). Definitions of B waves vary widely, and previously reported results must be treated with caution. The aims of the present study were to develop a definition of B waves, to develop a method to estimate the B-wave content in an ICP recording by using computer algorithms, and to validate these procedures by comparison with the traditional visual interpretation.

Methods. In eight patients with IAHS, ICP was continuously monitored for approximately 20 hours. The ICP B-wave activity as a percentage of total monitoring time (B%) was estimated by using visual estimation according to the definition given by Lundberg, and also by using two computer algorithms (Methods I and II). In Method I each individual wave was classified as a B wave or not, whereas Method II was used to estimate the B-wave content by evaluating the B-wave power in 10-minute blocks of ICP recordings.

Conclusions. The two computerized algorithms produced similar results. However, with the amplitude set to 1 mm Hg, Method I yielded the highest correlation with the visual analysis (r = 0.74). At least 5 hours of monitoring time was needed for an acceptable approximation of the B% in an overnight ICP recording. The advantages of using modern technology in the analysis of B-wave content of ICP are obvious and these methods should be used in future studies.

KEY WORDS • intracranial pressure • B wave • idiopathic adult hydrocephalus syndrome

SLOW and rhythmic oscillations in the ICP, that is, B waves, were first described in Nils Lundberg's thesis in 1960.[13] In later reports,[9,18] B-wave analysis has been purported to be one of the best preoperative predictive tests for outcome of shunt surgery in IAHS. The possibility of using this type of analysis to track compliance or elastance during ICP monitoring after severe head injury and to predict failing compensatory mechanisms has been proposed. In addition to their presence in IAHS, B waves have also been described in traumatic brain injury, subarachnoid hemorrhage, and during sleep in healthy adults.[2,7,10,15] The genesis of these waves is not fully understood.[1,6,11]

The original definition of a B wave as a period of 0.5 to 2 minutes and an amplitude ranging from discernible levels to 50 mm Hg[13] was modified in later studies,[4,5,16] and the methods for estimation have not yet been validated. Furthermore, interpretation has usually been performed visually by a clinician, whose training in identifying B waves has not been included in the reports.

The technology of modern computers and the digital signal analysis of data have made it possible to develop algorithms that can be used to estimate objectively the B-wave content in an ICP recording. In this report we introduce and evaluate two new objective methods for B-wave analysis that use a strict definition of B waves, and compare them with a visual interpretation made in accordance with Lundberg's method.

Clinical Material and Methods

Patient Population

The population in this prospective study was part of a larger project in which patients with IAHS were evaluated using intracranial monitoring of ICP, microdialysis, and brain tissue PO_2. Informed consent was obtained from each patient and all aspects of the study were approved by the local ethics committee. In our study, eight consecutive patients with IAHS were included and the data presented in this article refer to the ICP monitoring in the larger study. The mean age of the patients was 75 years (range

Abbreviations used in this paper: B% = ICP B-wave activity as a percentage of total monitoring time; $B\%_I$ = B% for Method I; $B\%_{II}$ = B% for Method II; $B\%_{VISUAL}$ = manual estimate of B%; IAHS = idiopathic adult hydrocephalus syndrome; ICP = intracranial pressure; P_I = threshold amplitude for Method I; P_{II} = threshold amplitude for Method II; RMS = root mean square; SD = standard deviation.

66–78 years). A couple of weeks after the ICP monitoring was performed, all patients underwent placement of a cerebrospinal fluid shunt.

Surgical Procedure and Data Acquisition

An ICP transducer (Microsensor; Codman, Raynham, MA) was inserted intraparenchymally in the right frontal lobe. The ICP was recorded continuously from approximately 12 a.m. to 8 a.m. (range 17.5–20.8 hours). During the recordings the patients were lying in bed awake or asleep. From the bedside monitor, ICP data were transferred as an analog signal and recorded in a personal computer (Power PC 7600; Apple, Inc., Cupertino, CA) by using a multimodal recording system that included a data acquisition card, MIO16X50 (National Instruments, Inc., Austin, TX) and commercially available software (LabVIEW; National Instruments). The sampling rate was 250 Hz. The samples were averaged over 1 second and subsequently analyzed with a sampling rate corresponding to 1 Hz. The ICP recordings were analyzed with specially designed software developed in LabVIEW.

Analysis of B Waves

The B% was defined as the accumulated time with B waves divided by the monitoring time. A manual estimation of B-wave content ($B\%_{VISUAL}$) was performed according to the method of Lundberg,[13] who defined B waves as oscillations in the ICP that had a period of 0.5 to 2 minutes and amplitudes ranging from discernible levels to 50 mm Hg. The ICP recordings were printed on paper with the axis corresponding to the same speed (5 mm/minute) and amplitude (4 mm = 1 mm Hg) as Lundberg used in his thesis. Two neurologists (A.Å.W. and J.M.) independently reviewed the recordings without knowing to which patient each recording related. If there was any interpretive disagreement, the reviewers conferred and reached an agreement.

The $B\%_{VISUAL}$ was compared with the B-wave content that had been determined using the two different computerized methods. The technical aspects of each computerized method are described in detail in Fig. 1. Briefly, the computerized Method I was an individual wave analysis. All waves that had a period of 0.5 to 2 minutes and that reached a defined threshold amplitude were collected (Fig. 1b). The P_I (Fig. 1b) varied between 0.25 mm Hg and 4 mm Hg. The corresponding $B\%_I$ was noted for each threshold value.

Computerized Method II was a power analysis. The software was used to estimate the local B-wave content by calculating the RMS amplitude for 10-minute blocks of filtered ICP data (Fig. 1c). The $B\%_{II}$ for the total monitoring time was calculated as the sum of all time intervals in which the RMS amplitude was larger than the predefined P_{II}, divided by the total measurement time.

The $B\%_{VISUAL}$, $B\%_I$, and $B\%_{II}$ values were determined over the full monitoring time for all patients. In addition, $B\%_I$ and $B\%_{II}$ were determined at shorter monitoring times (1, 2, 5, and 10 hours). For each patient at each monitoring time, these estimations were repeated 20 times at randomly chosen starting points within the total monitoring curve. The mean values and SDs of $B\%_I$ and $B\%_{II}$ were calculated for each monitoring time.

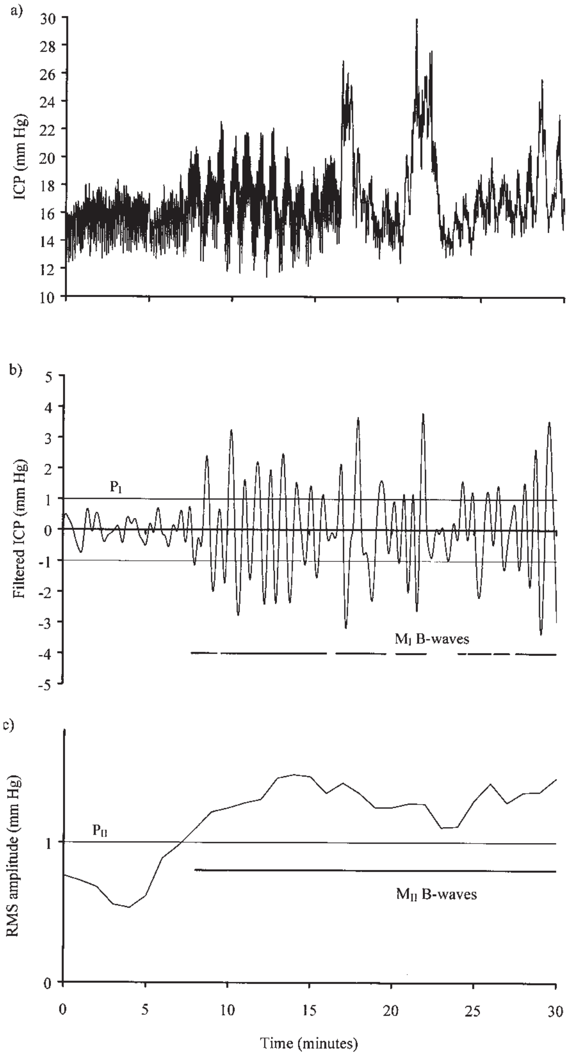

FIG. 1. a: Sample recording of ICP obtained in the patient in Case 8. b: Tracing showing filtered data. For both computerized methods the ICP data were filtered using a digital bandpass Butterworth-type filter (5th order) with cutoff frequencies corresponding to a periodicity of 0.5 and 2 minutes. For Method I (M_I) a computer algorithm for an individual wave analysis was used. A wave was classified as a B wave if the absolute value of the peak or trough of the wave was at least as large as the P_I. A wave was defined as a new wave when the data passed the zero level. In Method I B waves are marked with a *horizontal line*. The $B\%_I$ was calculated as the accumulated time with intervals classified as B waves divided by the total time. The $B\%_I$ was 60% for this sample with a P_I of 1 mm Hg. c: For Method II (M_{II}) the filtered ICP was divided into consecutive 10-minute blocks in which the first element of each block was delayed 1 minute compared with the first element of the previous block. For every block, trends and offset were eliminated by fitting a linear model against it and subtracting the predicted values from the filtered data. A power-related value of each block was evaluated using the RMS amplitude. The magnitude of the RMS amplitude gave an estimation of the local B-wave content in that block. Stepping through the time series with this algorithm produced the local B-wave content (RMS amplitude) as a function of time, with the points separated by 60 seconds. The $B\%_{II}$ was found by summing every time interval *(horizontal line)* with an RMS amplitude larger than a predefined P_{II}, and dividing it by the total measurement time. The $B\%_{II}$ was 74% for this sample with a P_{II} of 1 mm Hg.

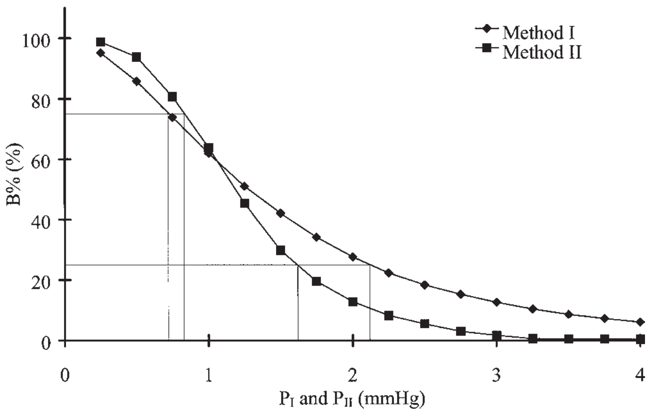

FIG. 2. Graph showing the mean $B\%_I$ and $B\%_{II}$, which were estimated from the maximum monitoring time, as a function of P_I and P_{II} for the eight patients. The similarity of the curves indicates that on average the methods produced the same results, but the definitions of their threshold values differed. The *grid lines* indicate the thresholds for a B-wave activity of 75% and 25% for both methods.

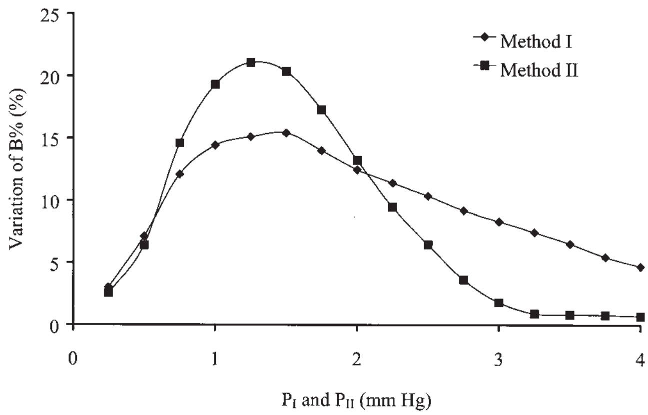

FIG. 3. Graph showing the B% interpatient variation displayed by the SD in the eight patients as a function of P_I and P_{II}. The variation was larger for Method II than for Method I for thresholds between 0.75 mm Hg and 2.0 mm Hg.

Results

Threshold Dependence

In Fig. 2, the mean $B\%_I$ and $B\%_{II}$ are plotted against the different amplitudes (that is, P_I and P_{II}). With increasing threshold values, B% fell rapidly for all patients. The pattern of $B\%_I$ and $B\%_{II}$ as a function of the threshold values was similar but fell off faster for Method II (Fig. 2). The threshold interval for B% (range between 75% and 25%) was 0.72 to 2.12 mm Hg for Method I and 0.83 to 1.63 mm Hg for Method II (Fig. 2). The general patterns were quite similar for all patients. The differences between patients were largest in the threshold range of 0.75 to 2 mm Hg, with SDs of both $B\%_I$ and $B\%_{II}$ exceeding 10% (Fig. 3).

Manual Methods Compared With Computerized Analysis

The correlation between the $B\%_{VISUAL}$ and the computerized methods ($B\%_I$ and $B\%_{II}$) with regard to different amplitudes (P_I and P_{II}) is summarized in Table 1. Correlation analysis showed that $B\%_I$ correlated significantly with $B\%_{II}$ for thresholds between 0.25 mm Hg and 3 mm Hg. The significant and highest correlation between the $B\%_I$ and $B\%_{VISUAL}$ was found at a P_I between 0.5 mm Hg and 1 mm Hg. A significant correlation was found between $B\%_{II}$ and $B\%_{VISUAL}$ for P_{II} of 0.5, 0.75, 3.0, and 3.25 (Table 1). However, $B\%_{II}$ for the 3.0 and 3.25 thresholds was close to 0% for all patients (Figs. 2 and 3).

Monitoring Time

Figure 4 shows the SD corresponding to a monitoring time of 1, 2, 5, and 10 hours for computerized Methods I and II. The SD of $B\%_I$ and $B\%_{II}$ increased significantly (analysis of variance, $p < 0.001$) at shorter monitoring times. Figure 4 also shows that the SD of the B% estimates was significantly lower for Method I than for Method II for monitoring times of 1, 2, and 5 hours ($p < 0.05$) and close to significant at 10 hours ($p = 0.11$).

Discussion

We believe that if evaluation of B waves is to be used as a diagnostic tool, a broad consensus concerning interpretation of the ICP recording is required. A computerized analysis of the ICP recording is both fast and objective. In the present study, two new computerized methods to quantify the proportion of B waves in a continuous ICP recording were evaluated. We found an acceptable correlation between the reference analysis and each of the new methods. To get a reliable estimate of B%, a monitoring time of 5 hours or more was needed.

Definition of B Waves

Throughout the years, the original definition of B waves set forth by Lundberg has been modified. Some authors believe that an amplitude exceeding a certain limit above the baseline ICP should be used as the standard,[5] whereas others require B waves to be present for more than 10 minutes to qualify.[8] Some authors have proposed that the appearance of a single wave, that is, the morphology of the wave, could be of fundamental importance.[16,17] The common denominator among all of these studies is that they have been reported in small, descriptive series without gaining widespread acceptance. Until recently, most of the reading of the ICP curve has been manually performed. There are no data in the literature about the experience of the interpreters, or what qualifications should be required of an interpreter to consider him or her experienced. In addition, interrater reliability has never been studied.

Comparison of Methods

The two computerized methods described in this study were based on the calculation of B-wave content according to a predefined frequency range and a threshold value (that is, amplitude), and the algorithms used could easily be applied to any modern bedside monitoring equipment. However, there were some fundamental differences between the two methods in the way in which the data were analyzed. Both methods were focused on the same frequency range as in Lundberg's definition, although the

TABLE 1

Correlations between the estimated B% as a function of threshold values

Threshold P_I & P_{II} (mm Hg)	Comparison (r value)		
	$B\%_I$ W/ $B\%_{VISUAL}$	$B\%_{II}$ W/ $B\%_{VISUAL}$	$B\%_I$ W/ $B\%_{II}$
0.25	0.69	0.31	0.78*
0.5	0.82*	0.81*	0.97†
0.75	0.79*	0.75*	0.99†
1.0	0.74*	0.57	0.96†
1.25	0.69	0.47	0.95†
1.5	0.66	0.36	0.92*
1.75	0.58	0.33	0.91*
2.0	0.52	0.36	0.91*
2.25	0.46	0.37	0.93*
2.5	0.39	0.40	0.93*
2.75	0.37	0.56	0.92*
3.0	0.35	0.74*	0.81*
3.25	0.33	0.72*	0.19
3.5	0.32	0.65	0.05
3.75	0.30	0.65	0.06
4.0	0.32	0.65	0.02

* Significant correlation at $p < 0.05$.
† Significant correlation at $p < 0.01$.

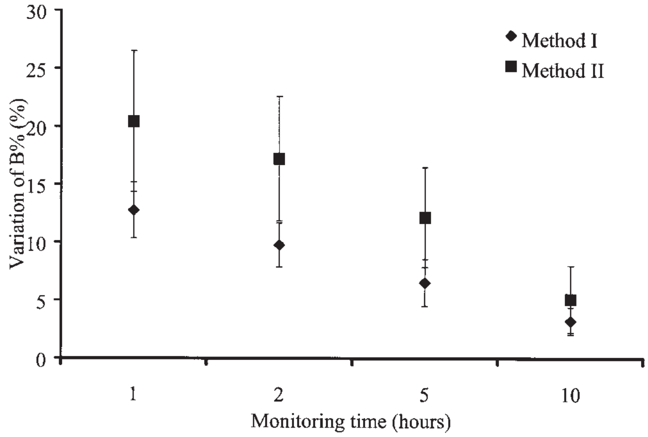

FIG. 4. Boxplot showing that the SD of the estimated B%, calculated from 20 randomly chosen starting points, depends on the monitoring time and indicates the potential precision of the method. The mean SD in the eight patients is plotted as a function of monitoring time for both methods. Error bars represent the SD of mean SD in eight patients.

minimum amplitude that should be required is less clear. To obtain a high resolution and to visualize even small variations in amplitude, Lundberg magnified the printed ICP recordings but did not define any lower limit. A computer-based analysis of the ICP recordings demands strictly defined amplitudes, that is, the use of threshold values. The minimum amplitude is explicitly met in Method I, because variations were regarded as B waves if the absolute value of the wave's extreme point exceeded the chosen P_I. The length of the wave package was not taken into account in Method I; in it we investigated every single wave separately. In Method II the B-wave content over a 10-minute interval was examined, and a value related to the power in the B-wave frequency range was calculated. This value was the mean of the amplitudes of the waves during that period and was compared with the predefined P_{II}.

Criteria for a B-Wave Analysis

To choose an appropriate method and to propose an adequate threshold value for that method we suggest a number of criteria that must be used for the analysis.

First, to be predictive, the pathological limit for the B% should be well removed from the asymptotic ends (0% and 100%). At the same time we expect the patients with IAHS to experience increased activity and to be in the upper half. All eight patients in this study had a diagnosis of IAHS. This criterion guides us to look for thresholds that produce B% ranging from 50 to 100%, and not all close to 100%. This excludes all threshold values except 0.75 mm Hg and 1.0 mm Hg for both methods (Figs. 2 and 3).

Another criterion is that the method should not be very sensitive to choice of threshold value, because we expect a variation within the sample of patients. It is the general increase in B-wave activity for a group of patients that we want to detect and a less sensitive method will make the group more homogenous, that is, there will be a lower variation within the group. The lower threshold sensitivity (Fig. 2) and the corresponding lower variation (Fig. 3) of the individual wave analysis clearly favors Method I.

The third criterion is that the method should correlate with the subjective manual visual method of B-wave activity estimation. The correlation between visual analysis and Method I was generally higher than the corresponding values for Method II. This difference was most pronounced for threshold 1.0 mm Hg (Table 1).

The monitoring time should be minimized; the method should have good accuracy in a short monitoring time. Because sleep is known to increase the amount of B waves,[10] researchers should either control the wakefulness of the patient or use a long investigation time to let it average out. In this study the latter alternative was chosen, which probably reduced the accuracy of the test with shorter monitoring time. Method I yielded higher precision for shorter monitoring times, but still a sampling duration of at least 5 hours is needed for a reliable result (Fig. 4).

Suggested Standard for B-Wave Analysis

Our data show that both computerized methods produced objective results in an easy and reliable way. However, Method I, set to a threshold value of 0.75 or 1.0 mm Hg, seemed to be the most accurate method with which to replace visual analysis performed according to Lundberg's method. For simplicity we suggest the 1.0 mm Hg threshold limit as a standard for future evaluations.

Clinical Importance

In patients with a typical clinical and radiological picture of IAHS (definite IAHS), the postoperative improvement rate is approximately 70% at hospitals with a large experience in the investigation of IAHS.[3,12,14] However, most of the patients admitted are less typical cases (probable or possible IAHS). For them there is a need for variables with which to predict the success of the operation as far as clinical outcome; overnight ICP monitoring has been proposed as one of the most reliable methods for confirming the diagnosis of IAHS.[9,18] However, the scientific support for this hypothesis is weak, and further studies are needed. It has also been questioned whether the presence of B waves actually is a sign of an intracranial disorder, because similar spontaneous ICP oscillations have been described in healthy adults.[15] Thus, we do not know what percentage of time B waves must be present to be considered pathological. In future studies in which the researchers use an objective B-wave analysis according to our proposed Method I, the full implications and origin of the B waves will be investigated.

Conclusions

The advantages of modern technology in the analysis of B wave content in ICP are obvious, and no other method should be used. For a reliable result with a minimized monitoring time the analysis should be performed using an individual wave algorithm according to our proposed Method I, and with the amplitude threshold value set to 1.0 mm Hg. For determining the B-wave analysis potential in predicting response to shunt placement, a large group of less typical cases in patients with IAHS should be analyzed. Our study supplies the objective and well-defined method needed to perform such analyses.

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