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Is Intracranial Pressure Waveform Analysis Useful in the Management of Pediatric Neurosurgical Patients?

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Key Words

Intracranial pressure · Single waves · Signal quality · Waveform analysis

Abstract

Background: We have reported casuistic observations that intracranial pressure (ICP) waveform analysis may be useful in the management of pediatric patients. ***Method:*** We here report our whole patient material of 65 children undergoing ICP monitoring with storage of their ICP raw data files during the years 2002–2005. We retrospectively explored the clinical symptoms/findings and radiological cerebral ventricular size before ICP monitoring. Mean ICP was the actively treated ICP parameter. Using an algorithm for identification of cardiac-beat-induced pressure waves we retrospectively determined the mean ICP wave amplitude and latency, in addition to mean ICP. Outcome with regard to change in symptoms/findings during a 1-year period was determined in 55 children. ***Results:*** The material includes children with hydrocephalus, craniosynostosis, shunt failure, benign intracranial hypertension and others. The ICP recordings gave wrong diagnostic information due to bad signal quality in 5 of 65 patients (7.7%). The mean ICP wave amplitude was increased in those with papilledema, lethargy and nausea. The main observations were that the mean ICP wave amplitude (not mean ICP) was increased in those that improved from clinical symptoms/findings after treatment and in those that were unchanged/worse after not being treated. ***Conclusions:*** Waveform analysis with computation of the mean ICP wave amplitude was more useful by providing information about the quality of the ICP recording, by comparing better with the symptoms/findings at the time of ICP monitoring and by best predicting outcome. Most significantly, 14 of 55 patients (25%) with high amplitudes and left untreated did not recover spontaneously.

We have previously reported results of continuous intracranial pressure (ICP) monitoring during the management of pediatric neurosurgical patients [1–3]. When applying the established mean ICP, the clinical usefulness of ICP monitoring was questionable in children with hydrocephalus [1], craniosynostosis [2] and shunt failure [3]. However, with new method of ICP waveform analysis, casuistic observations in pediatric neurosurgical patients were reported suggesting that the mean ICP wave amplitude may be more useful than the established mean ICP [4]. In adults with idiopathic normal pressure hydrocephalus, the mean ICP wave amplitude was very predictive for patients that improved after cerebrospinal fluid (CSF) shunting [5, 6].

In our department ICP monitoring in children became less used after our earlier reports indicating a less significant role of mean ICP [1–3]. Nevertheless since 2002 the ICP recordings of children undergoing ICP monitoring have been stored as raw data files on the hos-

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Table 1. Demographic data

	All patients	Hydrocephalus	Craniosynostosis	BIH	Shunt failure	Other
Total number	65	30	18	7	6	4
Sex (F/M)	14/51	6/24	3/15	2/5	2/4	1/3
Median age, months	66 (3–220)	71 (4–195)	27 (4–129)	84 (25–158)	97 (65–120)	69 (3–220)
Treatment after ICP	24	5	10	4	3	2

Figures in parentheses represent ranges. BIH = Benign intracranial hypertension.

Table 2. The presence/absence of symptoms related to ICP parameters in 60 pediatric patients

Symptoms	Present/absent	Mean ICP, mm Hg	Mean ICP wave amplitude, mm Hg	Mean ICP wave latency, s
Headache	present (33)	10.6 (–12.3 to 49.2)	4.9 (1.7–19.8)	0.18 (0.12–0.29)
	absent (27)	10.7 (0.5–25.7)	4.4 (2.2–13.1)	0.17 (0.12–0.22)
Reduced psychomotor	present (17)	11.4 (6–16.9)	4.9 (2.5–8.7)	0.18 (0.12–0.20)
development	absent (43)	10.7 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.29)
Epileptic seizures	present (4)	13.0 (12.1–25.7)	6.9 (4.9–13.1)	0.21 (0.16–0.22)
	absent (56)	10.7 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.29)
Papilledema	present (11)	12.1 (3.6–49.2)**	7.4 (4.5–17.2)***	0.20 (0.15–0.26)**
	absent (49)	10.4 (–12.3 to 32.6)	4.5 (1.7–19.8)	0.17 (0.12–0.29)
Lethargy	present (19)	10.8 (0.5–49.2)	5.1 (3.1–19.8)**	0.19 (0.13–0.29)
	absent (41)	10.7 (–12.3 to 30.1)	4.5 (1.7–13.1)	0.17 (0.12–0.26)
Anorexia	present (10)	11.5 (1.8–32.6)	5.1 (3.4–12.6)	0.17 (0.13–0.29)
	absent (50)	10.7 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.26)
Nausea	present (24)	11.0 (0.5–49.2)	4.9 (3.1–19.8)*	0.18 (0.13–0.29)
	absent (36)	10.7 (–12.3 to 25.7)	4.6 (1.7–13.1)	0.18 (0.12–0.26)
Increased head	present (3)	6.5 (5.2–10.6)	5.1 (3.5–5.8)	0.18 (0.12–0.18)
circumference (>95%)	absent (57)	10.8 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.29)
Reduced head	present (6)	13.6 (7–16.9)	4.8 (2.6–8.6)	0.16 (0.14–0.23)
circumference (<5 %)	absent (54)	10.7 (–12.3 to 49.2)	4.7 (1.7–19.8)	0.18 (0.12–0.29)
Irritability	present (9)	12.1 (4.7–16.9)	4.7 (2.3–8.6)	0.17 (0.12–0.22)
	absent (51)	10.7 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.29)
Sleep disturbance	present (12)	13.6 (6–16.9)	5.8 (2.5–8.6)	0.18 (0.13–0.26)
	absent (48)	10.5 (–12.3 to 49.2)	4.6 (1.7–19.8)	0.18 (0.12–0.29)

Data on ICP parameters given as medians (ranges). Present/absent: figures in parentheses are numbers of patients. * $p < 0.05$; ** $p \leq 0.01$; *** $p = 0.001$ (1-way ANOVA).

pital server. We decided to retrospectively assess all pediatric patients in whom ICP was recorded and stored as raw data files during the 4-year period 2002–2005. During this time period the established mean ICP was still used to guide management. From our database of childhood ICP recordings, we retrieved data of 65 children; we here report the results of retrospectively analyzing their symptoms/findings and ventricular size before ICP monitoring and change in symptoms/findings after ICP monitoring.

Clinical Materials and Methods

Patient Material

The patient material includes all 65 children undergoing ICP monitoring with storage of ICP raw data during the 4-year period 2002–2005 in this department (table 1).

ICP Monitoring

Continuous ICP monitoring was performed as previously described using a solid ICP sensor (Codman MicroSensor™, Johnson & Johnson, Raynham, Mass., USA) introduced 1–2 cm into the frontal brain parenchyma (not intraventricular) [1–4]. Monitoring of ICP was initiated during the afternoon and continued until the next morning; the children stayed in bed for the whole recording time. The ICP recordings were stored as raw data files on the hospital server (sampling rate 100 or 200 Hz). We included the whole monitoring time, not to exclude any sections of their recordings.

At the time of ICP monitoring, the mean ICP was used to guide patient management. Established practice in this department has been to consider sustained mean ICP <10 mm Hg as normal, mean ICP between 10 and 15 mm Hg as borderline and mean ICP >15 mm Hg as abnormal [1–3].

ICP Wave Analysis

The ICP waveform analysis was performed as previously described [4]. The mean ICP was computed during 6-second time windows, independently of the ICP waveform. The ICP waveform analysis incorporates an algorithm for identification of the cardiac-beat-induced single pressure wave, determining the amplitude (i.e. difference between beginning diastolic pressure and systolic pressure) and the latency (i.e. time interval from beginning diastolic pressure to systolic pressure) of the single ICP waves and then computing the pressure parameters mean ICP wave amplitude and latency during subsequent 6-second time windows [4].

Using the waveform algorithm, the quality of the ICP recordings is determined as percentage of 6-second time windows that were rejected because of artifacts in the ICP signal [4]. This procedure reduces the impact of noise in the ICP signal, e.g. caused by patient movement, head position, crying or coughing.

For every ICP trend plot we computed the average values of mean ICP, mean ICP wave amplitude and mean ICP wave latency (fig. 1, 3, 4). The correlations between these ICP parameters were determined (fig. 1). For mean ICP wave amplitude, we also determined the percentage of time when it was either ≥2, ≥3, ≥4, ≥5, ≥6 or ≥7 mm Hg (fig. 2, 4).

Clinical and Radiological Assessment

From the patient records we retrieved information about clinical symptoms/findings before ICP monitoring (table 2).

Linear radiological measures of ventricular size were determined before ICP monitoring as previously described [7] (table 3).

Information about clinical symptoms/findings and radiological measures was determined for each patient prior to the retrospective ICP analysis.

Outcome Determination

Outcome during the 1-year period after ICP monitoring was evaluated in patients with tentative normal or high mean ICP at the time of ICP monitoring. Outcome was not assessed in patients with ICP recordings of bad signal quality, patients whose ICP recording revealed hypotension (i.e. negative mean ICP) and patients recorded during external drainage of CSF. Outcome was defined as change in symptoms/findings within 1 year after ICP monitoring and divided into 2 main categories: (1) lasting relief/improvement of symptoms/findings during the 1-year period and (2) lasting unchanged/worse symptoms/findings during the 1-year period. Assessment was variably done 3, 6 and 12 months after ICP monitoring. The 2 main categories were then further divided into the 2 subcategories (a) treatment or (b) no treatment after ICP monitoring (i.e. whether ICP monitoring had initiated further treatment or no treatment, respectively) (table 4).

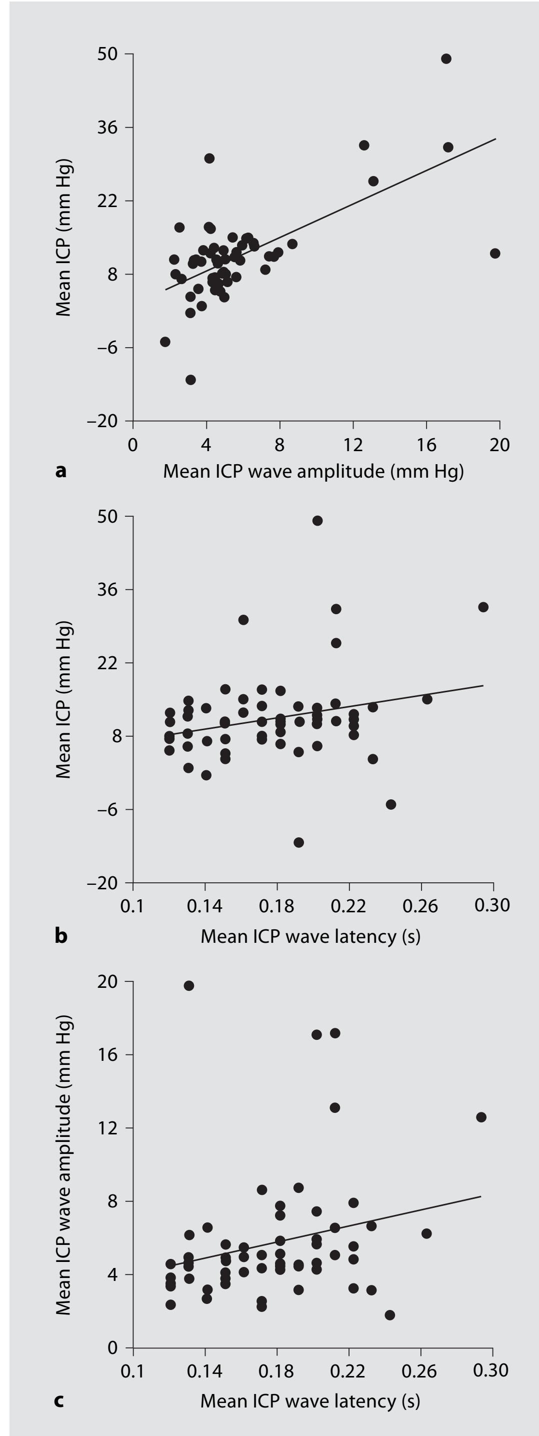

Fig. 1. Correlations between average values of 65 corresponding trend plots of mean ICP and mean ICP wave amplitude (**a**), mean ICP and mean ICP wave latency (**b**) and mean ICP wave amplitude and mean ICP wave latency (**c**).

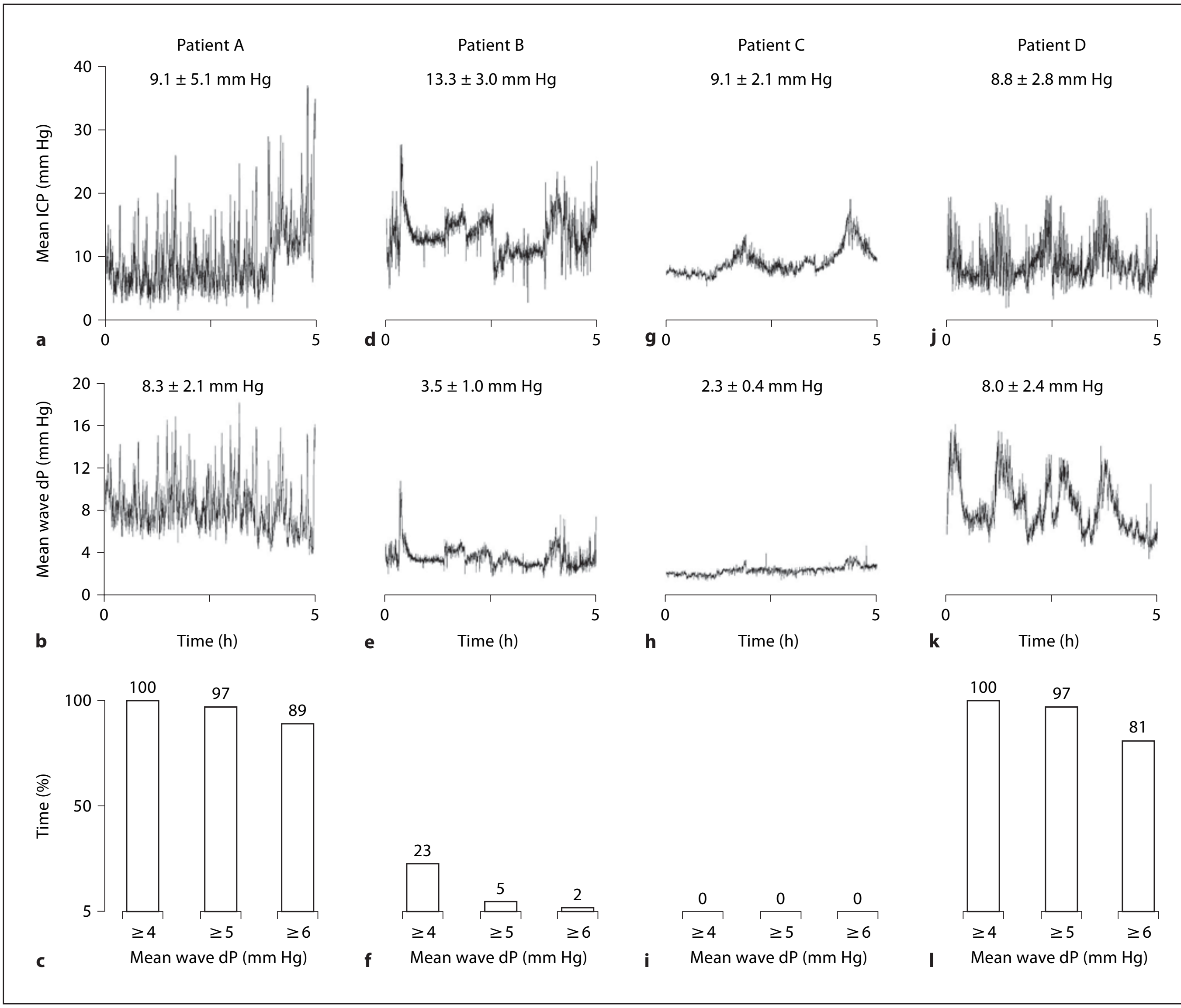

Fig. 2. Trend plots of mean ICP (**a**, **d**, **g**, **j**) and mean ICP wave amplitude (**b**, **e**, **h**, **k**) and percentage of time with mean ICP wave amplitude either ≥4, ≥5 or ≥6 mm Hg (**c**, **f**, **i**, **l**) are shown for 1 child of each of the 4 outcome categories. For every trend plot the mean value ± SD is shown.

Statistics

The computer program PC-SPSS, version 12.0 (SPSS Inc., Chicago, Ill., USA), performed the statistical analysis. Comparisons between groups were performed by 1-way ANOVA with Bonferroni-corrected posthoc tests. Correlations were determined as the Pearson correlation. Each box plot shows the median value (highlighted line within the box), the 25th percentile (lower end of the box), the 75th percentile (upper end of the box) and the ranges (lines from upper and lower ends of boxes) (fig. 3, 4). Significance was accepted at the 0.05 level.

Results

Patient Material

The patient categories of the 65 children are shown in table 1. Treatment was done in 24 of the 65 cases (37%).

The ICP Parameters Mean ICP and Mean ICP Wave Amplitude/Latency

The ICP recordings of these 65 patients had a median duration of 16.3 h (range = 1.3–38.2); the median percentage of accepted 6-second time windows was 94.7% (range = 0–99.3).

The signal quality was bad in 5 of the 65 ICP recordings (7.7%); only 0–12% of 6-second time windows were accepted in these recordings. Hence, these 5 recordings were mostly built up of artifact-induced waves, caused by noise and not cardiac-beat-induced waves. In 4 cases ICP was considered as normal, while surgery was advocated in another. Subcutaneous sensor location was verified in 1 patient.

When considering the average values of the 65 trend plots, there was a significant correlation between mean ICP and mean ICP wave amplitude (Pearson correlation = 0.65, $p < 0.001$; fig. 1a), but neither between mean ICP and mean ICP wave latency (Pearson correlation = 0.24, $p > 0.05$; fig. 1b) nor between mean ICP wave amplitude and mean ICP wave latency (Pearson correlation = 0.24, $p > 0.05$; fig. 1c).

ICP Parameters and Symptoms/Findings

For patients with or without symptoms/findings before ICP monitoring, we have given the levels of the ICP parameters in table 2. Though the mean ICP was significantly higher in those with papilledema (12.1 vs. 10.4 mm Hg), it was borderline in both groups (i.e. 10–15 mm Hg). In those with papilledema the mean ICP wave amplitude was markedly and significantly higher than in those without (7.4 vs. 4.5 mm Hg); also the mean ICP wave latency was significantly longer. In 2 cases with papilledema the mean ICP wave amplitude probably was somewhat reduced, since a lumbar puncture had been done a few days beforehand. The mean ICP wave amplitude was elevated in those with lethargy and nausea as well. Regarding the presence/absence of other symptoms, there were no differences of ICP parameters (table 2).

ICP Parameters and Radiological Ventricular Size

There was no correlation between the linear measures of ventricular size and the ICP parameters mean ICP or mean ICP wave amplitude for all patients or the category hydrocephalus, though there was a significant positive correlation between ventricular size (i.e. Evan's index, cella media index and ventricular score) and mean ICP wave amplitude in 11 patients with craniosynostosis (table 3).

Linear measures of ventricular size were not different between the hydrocephalus patients with relief/improvement (n = 16) or unchanged/worse (n = 9) symptoms/findings ($p > 0.2$; 1-way ANOVA).

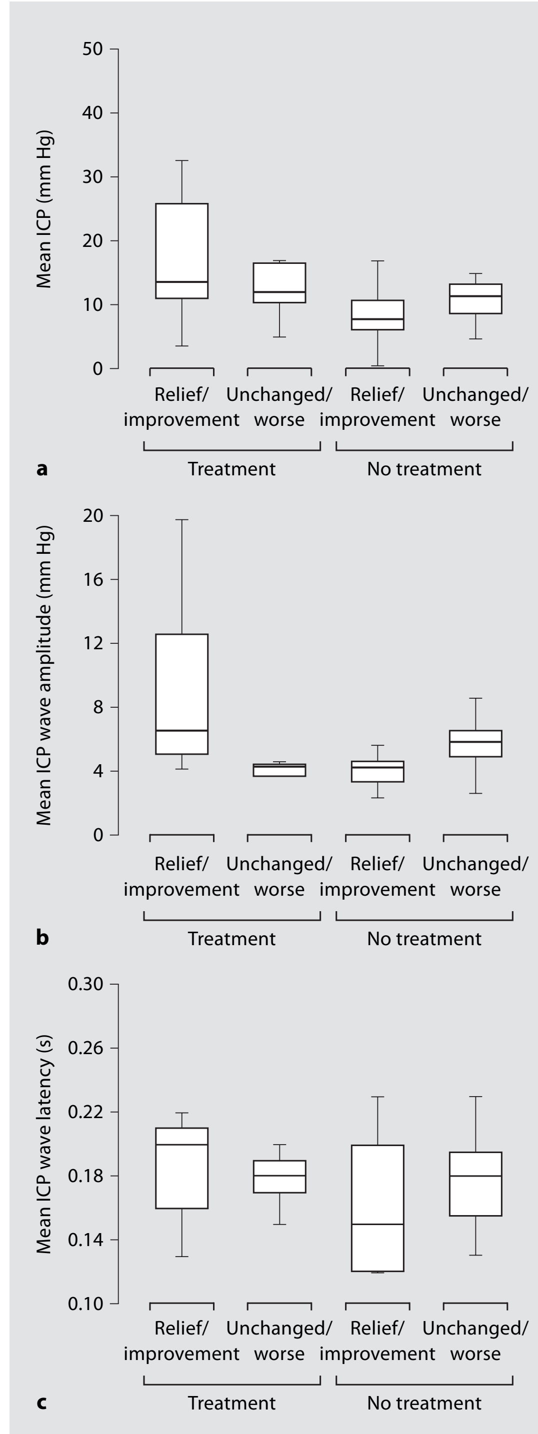

Fig. 3. The average values of the trend plots of the ICP parameters mean ICP (**a**), mean ICP wave amplitude (**b**) and mean ICP wave latency (**c**) are presented for the 2 main categories improvement after treatment (n = 17), unchanged/worse after treatment (n = 5), improvement after no treatment (n = 18) and unchanged/worse after no treatment (n = 15).

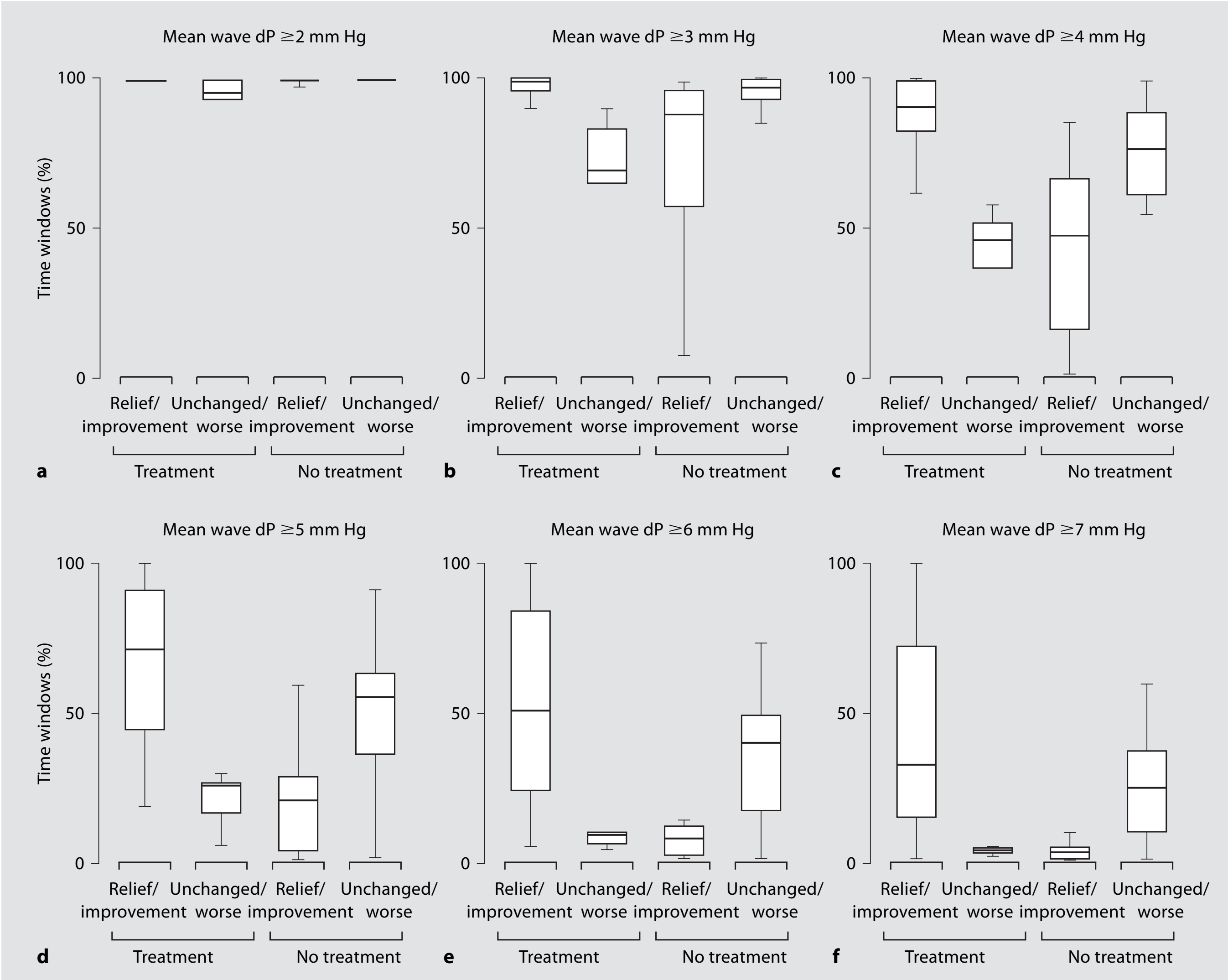

Fig. 4. The percentages of time with mean ICP wave amplitudes either being ≥2 mm Hg (**a**), ≥3 mm Hg (**b**), ≥4 mm Hg (**c**), ≥5 mm Hg (**d**), ≥6 mm Hg (**e**) or ≥7 mm Hg (**f**) are shown for the 2 outcome categories improvement after treatment (n = 17), unchanged/worse after treatment (n = 5), improvement after no treatment (n = 18) and unchanged/worse after no treatment (n = 15).

ICP Parameters and Clinical Outcome

Outcome within 1 year could be determined in 55 of 65 patients; 5 were excluded due to bad ICP signal quality and 5 because of verified intracranial hypotension or CSF drainage during ICP monitoring.

In the 55 patients outcome within the first year after ICP monitoring could be dichotomized into (1) 35 cases (64%) with relief/improvement of symptoms/findings and (2) 20 cases (36%) being unchanged/worse regarding symptoms/findings. Between these 2 main categories there were no differences in average values of mean ICP (p = 0.4) or mean ICP wave amplitude (p = 0.3). These 2 main categories were then further divided into those that had been treated (n = 24) or those not treated (n = 41) as a result of ICP monitoring.

Figure 2 shows the trend plots of mean ICP and mean ICP wave amplitude of 4 children, 1 (patient A) with marked clinical improvement after treatment (fig. 2a–c), 1 (patient B) being unchanged/worse after treatment (fig. 2d–f), 1 (patient C) with spontaneous relief/improvement of symptoms/findings without treatment (fig. 2g–i) and 1 untreated (patient D) that was unchanged/worse in

Table 3. Correlations between linear measures of ventricular size and the ICP parameters mean ICP and mean ICP wave amplitude

Ventricular size	All patients (n = 44)		Hydrocephalus (n = 25)		Craniosynostosis (n = 11)	
	mean ICP	mean ICP wave amplitude	mean ICP	mean ICP wave amplitude	mean ICP	mean ICP wave amplitude
Evan's index	0.07	0.12	–0.01	–0.004	0.32	0.88**
Third ventricle index	0.20	0.12	0.17	0.02	0.30	0.13
Cella media index	0.06	0.03	–0.11	–0.16	0.60	0.62*
Ventricular score	0.14	0.12	0.07	0.01	0.57	0.63*

Figures are Pearson correlation coefficients (R). * $p < 0.05$; ** $p < 0.001$ (significance of Pearson correlations).

Table 4. Relief of clinical symptoms and findings depending on preoperative thresholds of mean ICP and mean ICP wave amplitude

Threshold levels	Patients	Treatment		No treatment	
		improvement	unchanged/worse	improvement	unchanged/worse
Average of trend plots					
Mean ICP ≥15 mm Hg	9	6	2	1	
Mean ICP 10–15 mm Hg	25	8	2	5	10
Mean ICP <10 mm Hg	21	3	1	12	5
Mean ICP wave amplitude ≥5 mm Hg	25	14	0	1	10
Mean ICP wave amplitude 4–5 mm Hg	19	3	3	9	4
Mean ICP wave amplitude <4 mm Hg	11	0	2	8	1
Percentage of time					
Defined as abnormal in adults[a]	37	16	1	6	14
Defined as normal in adults[b]	18	1	4	12	1

[a] Mean wave ICP amplitude either ≥4 mm Hg in ≥70% of time, ≥5 mm Hg in ≥40% of time, or ≥6 mm Hg in ≥10% of time.
[b] Mean ICP wave amplitude either ≥4 mm Hg in <70% of time, ≥5 mm Hg in <40% of time, or ≥6 mm Hg in <10% of time.

symptoms/findings (fig. 2j–l). It should be noted that the levels of mean ICP wave amplitude varied considerably despite mean ICP being borderline or normal (i.e. <15 mm Hg). Case D is the most important with elevated mean ICP wave amplitude (normal mean ICP) and no spontaneous recovery.

The 5-hour trend plots shown in figure 2 are for illustration. The average values of the whole trend plots (median duration 16.3 h) of the ICP parameters are presented in figure 3. The mean ICP was nonsignificantly increased in those being treated ($p = 0.8$; fig. 3a), probably related to the fact that this was the actively treated parameter. The most significant observation was that in those treated after ICP monitoring, the mean ICP wave amplitude was elevated in those improving as compared to those being unchanged/worse ($p = 0.009$; fig. 3b). There were no differences between categories regarding mean ICP wave latency ($p > 0.05$; fig. 3c).

When presenting mean ICP wave amplitudes as percentage of time when being either ≥2 mm Hg (fig. 4a), ≥3 mm Hg (fig. 4b), ≥4 mm Hg (fig. 4c), ≥5 mm Hg (fig. 4d), ≥6 mm Hg (fig. 4e) or ≥7 mm Hg (fig. 4f), it became even more evident that the percentage of time with mean ICP wave amplitudes being ≥4, ≥5 or ≥6 mm Hg were much higher in those that improved after treatment than in those being unchanged/worse, and also higher in those not treated that were unchanged/worse than in those improving spontaneously (fig. 2, 4).

Prediction of Clinical Outcome

In table 4 we have shown the clinical outcome categories for given thresholds of the ICP parameters mean ICP and mean ICP wave amplitude.

In only 9 of 55 patients was the average mean ICP ≥15 mm Hg, 6 of these improved after treatment, while 2 were unchanged/worse after treatment and 1 spontaneously recovered despite no treatment. Among those 25 with mean ICP being in the borderline area (i.e. 10–15 mm Hg), 10 remained unchanged/worse without any treatment (table 4).

For mean ICP wave amplitude, on the other hand, among those 25 cases with an average of trend plot ≥5 mm Hg, all 14 that were treated improved, while 10 of the 11 untreated cases were left unchanged/worse. The results became less clear when the average mean ICP wave amplitude was 4–5 mm Hg (table 4).

Table 4 also presents the outcomes when using the threshold levels for percentage of time with mean ICP wave amplitude previously determined in this department (i.e. mean ICP wave amplitudes are abnormally elevated when being either ≥4 mm Hg in ≥70% of time, ≥5 mm Hg in ≥40% of time or ≥6 mm Hg in ≥10% of recording time) [5, 6]. When using these thresholds 37 of 55 patients (67%) had abnormally elevated mean ICP wave amplitudes. Seventeen of the 37 patients were treated, of whom 16 had relief/improvement of symptoms/findings; only 1 was left unchanged/worse. Among those 20 of 37 that were not treated, 14 (70%) remained unchanged/worse, while 6 (30%) had spontaneous relief/improvement. Long-term follow-up of those 14 remaining unchanged/worse beyond the 1-year period, revealed that 1 died of respiratory failure, 4 had severely delayed psychomotor development, 4 had marked symptoms with change of behavior, and 1 had a satisfactory development after shunt treatment, while only 3 had a spontaneous recovery.

Discussion

Patient Material

The pediatric patient categories undergoing ICP monitoring during the years 2002–2005 (table 1) compare with our earlier reports [1–3]. This department has no trauma patients, and storage of ICP recordings as raw data files was not done within the pediatric neurointensive care unit during this period. Therefore, the present patient material may be somewhat different from other centers, as head injury is the most common indication for ICP monitoring [8].

The present 65 cases constitute about 3% of the pediatric patients undergoing neurosurgery during the years 2002–2005 in this department. This is a lower percentage than in earlier years, since ICP monitoring became less used subsequent to our earlier reports [1–3] showing that the established mean ICP was of minor help during diagnostic workout in children. The low percentage reflects that the 65 cases are those without clear-cut signs of abnormal ICP; otherwise surgery would have been done instead of ICP monitoring.

The ICP Parameters Mean ICP and Mean ICP Wave Amplitude/Latency

The established mean ICP is computed relative to atmospheric pressure, not considering whether the ICP signal contains cardiac-beat-induced single ICP waves or not [4].

The mean ICP wave amplitude and latency, on the other hand, are computed after applying an algorithm of identifying the cardiac-beat-induced ICP waves [4]. We have already shown how the mean ICP wave amplitude provides new and different information than the established mean ICP [4–6]. We here also showed how levels of mean ICP wave amplitude varied considerably despite mean ICP being normal or borderline (fig. 2). Hence, even though there is a relationship between average values of mean ICP and mean ICP wave amplitude (Pearson correlation 0.65; fig. 1a), the mean ICP wave amplitude cannot be predicted by merely computing the mean ICP.

Quality of ICP Recordings

ICP signals of good quality contain single ICP waves created by the cardiac contractions, with a smaller proportion of artifacts. In clinical practice the quality of pressure signals can be verified from visually inspecting the ICP waveform on the screen of the vital signs monitor or by assessing the numerical differences between systolic and diastolic pressures. Despite such type of quality control, the ICP recordings of 5 of the present 65 cases (7.7%) were of such bad quality that they gave false diagnostic information. This concurs with our previous report [9]. The importance of this aspect is that although the ICP recordings gave false diagnostic information in these 5 patients, ICP was considered as normal in 4, while surgery was done in another. Possible causes of bad signal quality are sensor failure and extracranial (e.g. subcutaneous) sensor location. Subcutaneous sensor location was verified in 1 patient; in the others the cause of bad signal quality remains unknown.

When using the automatic waveform algorithm during online ICP monitoring, the bad ICP signal quality would have been recognized [4, 9]. According to our experience quality assessment with assurance that the ICP signal is created of cardiac-beat-induced waves, not artifact-induced waves, is an important advantage of incorporating waveform analysis during ICP monitoring.

Another advantage of automatic signal quality determination is that the possibility for erroneous ICP data caused by noise in the signal (e.g. caused by patient movement, head position, crying or coughing) is reduced. Using this algorithm 6-second time windows with noise in the ICP signal are excluded for further analysis. Therefore the present study included the complete ICP trend plots, i.e. ICP recordings both when the patients were awake and asleep.

ICP Parameters and Symptoms/Findings

The symptoms/findings referred to here are often used as indicators of abnormal ICP [1–3, 10]. When comparing cases with and without symptoms we did not find differences in mean ICP, except for a significantly higher mean ICP in those with papilledema (12.1 vs. 10.4 mm Hg; table 2), though borderline mean ICP was found in both groups. This concurs with a previous report [11] that mean ICP was higher in those with papilledema, though the presence of papilledema had a low sensitivity but higher specificity for the presence of elevated mean ICP in children.

Regarding symptoms/findings the most significant observation was elevated mean ICP wave amplitudes (and latencies) in those with papilledema (7.4 vs. 4.5 mm Hg; table 2). In the 2 patients with an average mean ICP wave amplitude <5 mm Hg, a spinal puncture had been done shortly before arrival at our department. From our experience spinal puncture and lumbar CSF drainage will abruptly lower the mean ICP wave amplitudes [unpublished observations]. Thus, the presence of papilledema had a sensitivity equal to 1 for elevated mean ICP wave amplitudes; on the other hand, the sensitivity was low for elevated mean ICP, as previously reported [11]. Thus, papilledema strongly indicates elevated mean ICP wave amplitudes unless a diagnostic procedure (e.g. CSF drainage) or medical treatment has been done.

The mean ICP wave amplitudes were elevated in those with lethargy and nausea but no differences were found for the other symptoms/findings (table 2).

Except for the finding papilledema and to some extent the symptoms lethargy and nausea, the main message of table 2 is that in children without clear-cut symptoms or signs of high ICP, symptoms and signs are less likely to help the physician in predicting levels of ICP parameters.

ICP Parameters and Radiological Ventricular Size

When using radiological linear measures to estimate ventricular size, we found no relationship between ventricular size and the ICP parameters mean ICP and mean ICP wave amplitude/latency for the total patient group or the group with hydrocephalus (table 3). This concurs with our previous observations in children [7] and adults [5]. Hence, though radiological ventricular size is widely used to indicate abnormal ICP in hydrocephalus patients, we question this practice [7].

Moreover, ventricular size was not different between the hydrocephalus patients with relief of symptoms/findings and those with unchanged/worse symptoms/findings. This compares with our results of treating aqueduct stenosis using endoscopic third ventriculostomy, namely that change in ventricular size cannot be used for outcome determination [unpublished observations].

On the other hand, in 11 patients with craniosynostosis there was a significant positive correlation between ventricular size and the mean ICP wave amplitude (not mean ICP). This is an interesting finding but should be verified in a larger group of craniosynostosis patients.

ICP Parameters and Prediction of Outcome

In these patients mean ICP was the actively treated parameter; when guiding management according to this parameter, ICP monitoring was less useful. This concurs with our earlier experience [1–3].

The most significant observation of this retrospective study was different levels of mean ICP wave amplitude in the different outcome categories (fig. 2, 4). As previously described for other patient categories [5, 6], the mean ICP wave amplitudes were either presented as average values of trend plots (fig. 1, 3) or as percentage of time when the mean ICP wave amplitude was above given thresholds (fig. 2, 4). The latter strategy gave the most significant results. Mean ICP wave amplitudes were either ≥4, ≥5 or ≥6 mm Hg in a large percentage of recording time in the children with relief/improvement of symptoms/findings after treatment and in those remaining unchanged/worse when left untreated (fig. 4, table 4). Based on the experience from adults we tentatively suggest that mean ICP wave amplitudes are abnormally elevated when being either ≥4 mm Hg in ≥70% of time, ≥5 mm Hg in ≥40% of time or ≥6 mm Hg in ≥10% of recording time [5, 6]. When applying these thresholds to the present material, 37 of 55 patients (67%) had abnormally elevated mean ICP wave amplitudes. Seventeen of these 37 patients underwent treatment, and of these 16 had relief/improvement of symptoms/findings.

Among the 20 of 37 patients with elevated mean ICP wave amplitudes that were not treated, as many as 14 (70%) remained unchanged/worse, while only 6 (30%) improved spontaneously (table 4). One child that did not recover when left untreated is illustrated in figure 2d, showing normal mean ICP but high mean ICP wave amplitude. This indicates low compliance and requirement for surgery. In fact, the 14 patients that did not receive treatment and did not improve for 1 year represent 25% of the study population. The observation that children with high mean ICP wave amplitudes are less likely to recover spontaneously has changed the management strategy in this department.

Further research is required to determine the predictive role of different thresholds of mean ICP wave amplitudes in childhood; nevertheless the present results appear promising for improvement of patient care.

ICP Parameters and Intracranial Compliance

While the mean ICP represents the static pressure difference against the atmospheric pressure, the mean ICP wave amplitude reflects the dynamic pressure response caused by the intracranial volume (not pressure) change induced by every cardiac beat [4]. The mean ICP wave amplitude is highly dependent on the intracranial compliance, which has been shown using the Spiegelberg compliance monitor [12]. In animals there was a significant relationship between intracranial compliance and the intracranial pulse pressure amplitudes [13]. Hence, the mean ICP wave amplitude can be considered an indicator of the intracranial compliance, i.e. low intracranial compliance when mean ICP wave amplitudes are being elevated. Consequently, in children with inconclusive signs of shunt malfunction or underlying hydrocephalus or other reason for raised ICP (craniosynostosis), high mean ICP wave amplitudes may indicate low intracranial compliance, and intervention should be considered.

Conclusions

In this cohort of pediatric neurosurgical patients ICP monitoring using the parameter mean ICP was less useful for guiding management. Waveform analysis with computation of the mean ICP wave amplitude was more useful by providing information about the quality of the ICP recording, by comparing better with the symptoms/findings at the time of ICP monitoring and by best predicting outcome. In particular, children with high amplitudes and left untreated were less likely to recover spontaneously. It is suggested that the mean ICP wave amplitude predicts the intracranial compliance, which is the target for management in those with suspected intracranial hypertension. Further research is required to determine which thresholds of mean ICP wave amplitude can be regarded as abnormal in childhood.

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