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Assessment of Childhood Intracranial Pressure Recordings Using a New Method of Processing Intracranial Pressure Signals

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Key Words
Intracranial pressure · Hydrocephalus · Craniosynostosis · Intracranial decompensation

Abstract
Background: Intracranial compliance may be more reliably predicted by the pulsatile component (pulse pressure) than the steady (mean pressure) component of intracranial pressure (ICP). A new method of processing continuous ICP signals assessing both components of ICP is described and applied to the ICP recordings of 6 pediatric cases. ***Method:*** The new method was applied to each subsequent 6-second time sequence window of a continuous ICP signal. For time sequence windows including single ICP waves, the following time sequence (TS.x)-related parameters were computed: (a) mean ICP (i.e. TS.MeanP) was computed according to the currently used and known technology; (b) the mean ICP wave was computed according to the new method, characterized by mean wave amplitude (i.e. TS.MeanWavedP) and mean wave latency (i.e. TS.MeanWavedT). Cases No. 1–4 were treated for hydrocephalus and cases No. 5 and 6 for craniosynostosis. ***Results:*** In 5 children, clinical intracranial hypertension was associated with elevations of mean ICP above 15–20 mm Hg of variable durations. The ICP recordings of the 5 children with intracranial hypertension and successful outcome after surgery revealed mean wave amplitude values above 5 mm Hg. Mean wave latency was more variable, ranging between 0.10 and 0.25 s. ***Conclusions:*** In the children with intracranial hypertension and successful outcome after surgery, mean wave amplitude was variably above 5 mm Hg. It is suggested that mean wave amplitude may be a useful parameter by more directly predicting cerebral compliance than mean ICP.

Continuous intracranial pressure (ICP) monitoring has a place in the preoperative assessment of childhood hydrocephalus [1, 2] and craniosynostosis [3, 4], though it is discussed which ICP levels are abnormal or borderline. A major reason for ICP monitoring in such cases is to detect impaired intracranial compensatory capacity (i.e. reduced cerebral compliance or increased cerebral elastance) with potential risk of brain damage [3].

The ICP waves created by the cardiac beats consist of a pulsatile component (pulse pressure) and a steady component (mean pressure). Several lines of evidence suggest that intracranial compliance is more reliably predicted by pulse pressure than by mean pressure [5–9]. Increased pulse pressure amplitude evaluated by short sequences of ICP charts was a predictor of adult hydrocephalus requir-

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Table 1. Demographic and clinical data

Case No.	Sex	Age months	Diagnosis	Preoperative clinical symptoms and findings	Treatment	Postoperative outcome	Post-perative observation period months
1	M	89	hydrocephalus	headache, lethargy, anorexia, papilledema, epileptic seizures	VP shunt	excellent, disappearance of preoperative symptoms/ findings	12
2	M	42	hydrocephalus	headache, nausea, ↑head circumference, epileptic seizures	3VCS	excellent, normal development, antiepileptic medication	8
3	M	25	hydrocephalus	bilateral papilledema, ↑head circumference, ↓psychomotoric development	LP shunt	excellent, disappearance of papilledema, normal development	17
4	M	98	hydrocephalus	headache, nausea, anorexia	shunt revision	bad, lasting symptoms, repeated shunt revisions	8
5	M	53	craniosynostosis	↓psychomotoric development	fronto-orbital advancement	excellent, normal development	17
6	M	32	craniosynostosis	headache, irritability, sleep disturbance, epileptic seizures	tiara plastic advancement	good, marked improvement of preoperative symptoms	7

VP = Ventriculoperioneal; 3VCS = endoscopic third ventriculostomy; LP = lumboperitoneal.

ing treatment [9]. However, it has been difficult to extract information about pulse pressure from the ICP signal in a clinically useful way. Hence, ICP recordings are mostly evaluated according to mean pressure, not pulse pressure. When modern vital sign monitors/pressure transducers compute mean pressure (including systolic/diastolic pressures), this strategy is at least partly based on the previous observations of a linear relationship between mean pressure and pulse pressure, at least when mean ICP is below about 30 mm Hg [5–7, 10–12].

This paper describes a new method of processing continuous ICP signals considering both the pulsatile (pulse pressure) and steady (mean pressure) pressure components. The new method was applied to the continuous ICP recordings of children treated surgically for hydrocephalus or craniosynostosis. The results of ICP analysis were related to the outcome of surgery.

Patients and Methods

Patient Population

This study included all 6 consecutive patients treated surgically after continuous ICP monitoring for suspected intracranial hypertension, in whom the observation period after surgery lasted a minimum of 6 months. Demographic data and clinical data of the included patients are given in table 1. Cases No. 1–4 underwent continuous ICP monitoring as part of the diagnostic workout of hydrocephalus, and cases No. 5 and 6 were examined for craniosynostosis. Patient management at the time of pressure monitoring was not related to the ICP analysis described here.

Intracranial Pressure Monitoring

The procedure of ICP monitoring is shortly described. In general narcosis, a solid sensor (Codman MicroSensor™, Johnson & Johnson, Raynham, Mass., USA) was introduced 1–2 cm into the brain parenchyma via a minimal opening in the dura, after calibration against atmospheric pressure. The sensor then was coupled to a Codman® pressure transducer (Codman ICP Express™, Johnson & Johnson), which in turn was coupled to a vital sign Siemens 9000 XL Series Monitor (Siemens Medical Systems Inc., Danvers, Mass., USA). By means of the Siemens Infinity Gateway Software (Siemens Medical Systems Inc.), continuous pressure signals were transferred via the hospital network to a personal computer for further processing. Sampling frequency was 100 Hz. The continuous pressure signals were processed according to a new method that is described in detail in the following paragraph. The method is implemented in the software SM NeuroWave version 2.0 (Sensometrics AS, Oslo, Norway).

A New Method for Processing Continuous Pressure Signals

An overview of the method for processing continuous ICP signals is shown in figure 1. Samples of continuous ICP signals are obtained at specific intervals, and the sampled pressure signals are converted to pressure-related digital data with a time reference. For defined time sequence windows, the method identifies single pressure waves related to cardiac beat-induced pressure waves, and pressure waves related to artifacts or a combination of artifacts and

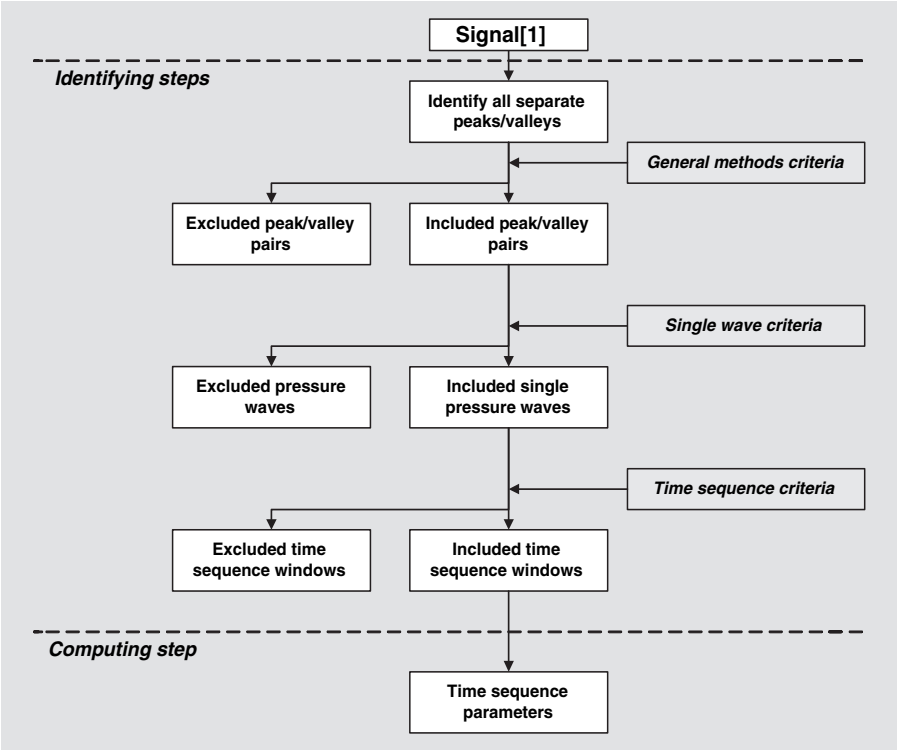

Fig. 1. A flow chart of the method of processing continuous pressure signals including the identifying steps and computing step that result in the determination of time sequence (TS.x)-related parameters.

cardiac beat-induced pressure waves. Time sequence (TS.x)-related parameters are computed for individual time sequence windows.

For the sake of clarity, some comments concerning notation should be given. A recording is one or more simultaneous signals with identical time reference. The notation Recording[1].Signal [m].Time Sequence[o].Single Wave[q] denotes a specific single wave [q] within a specific time sequence [o] within a specific signal [m] within a specific recording[1]. The ordering always starts with 1, e.g. the first available time sequence window within the first available signal within a recording is denoted as Signal[1].Time Sequence[1]. A signal refers to a number of sequential and available pressure-related samples during a time period, each sample containing a pressure value at a specific time. A time sequence window refers to a selected time frame of the pressure-related digital data with a time reference.

As indicated in figure 1, the process of identifying single pressure waves related to cardiac beats includes identification of peaks and valleys in the sampled ICP signal. Each peak and each valley is a sample with a pressure value and a time stamp or location. By applying general methods criteria, pair combinations of peaks and valleys in the signal are identified. Included, i.e. accepted, pair combinations of valleys and peaks correspond to included, i.e. accepted, pair combinations of diastolic minimum pressure ($SW.P_{min1}$) and systolic maximum pressure ($SW.P_{max}$), which characterize single pressure waves created by cardiac beat-induced pressure waves. Amplitude and latency values for each peak/valley pair were determined, and criteria required single wave amplitude (SW.dP) to be between 1.0 and 35.0 mm Hg and single wave latency (SW.dT) to be between 0.08 and 0.40 s (i.e. single wave criteria). Time sequence criteria were subsequently applied to time sequence windows with included, i.e. accepted, single pressure waves. The criterion used in this study was that numbers of single pressure waves should be between 4 and 18.

Further details about the identification of peak/valley pairs are illustrated in figure 2a and b. An example is given considering time sequence 605 of signal 1 (ICP signal) of recording 109 (i.e. Recording[109].Signal[1].Time Sequence[605]), corresponding to one individual time sequence window in a continuous series of time sequence windows (Time Sequence[1] to Time Sequence[1,310]) during this recording (Recording[109]). In figure 2a, all identified peaks (filled squares) and valleys (open circles) are shown. In figure 2b, the included peak/valley pairs corresponding to included, i.e. accepted, pair combinations of systolic maximum pressure ($SW.P_{max}$) and starting diastolic minimum pressure ($SW.P_{min1}$) are shown. Such pair combinations characterize included single pressure waves created by the cardiac beat-induced pressure waves. The included single pressure waves (identified by included $SW.P_{max}$/$SW.P_{min1}$ pairs) are shown in figure 2b (termed SW[1], SW[2], SW[3], SW[4], SW[5], SW[6], SW[7], SW[8], SW[9], SW[10], and SW[11]).

The time sequence criteria also determine that single pressure waves occurring between two consecutive time sequence windows are placed in one or the other of the two consecutive individual time sequence windows. A first single pressure wave within a time sequence window must have its ending diastolic minimum pressure value ($SW.P_{min2}$) within this time sequence window (illustrated by SW[1] in Time Sequence[605]; fig. 2b). A last single pressure wave within a time sequence window must have both its starting ($SW.P_{min1}$) and ending ($SW.P_{min2}$) diastolic minimum pressure values within the time sequence window (illustrated by SW[11] in Time Sequence[605]; fig. 2b).

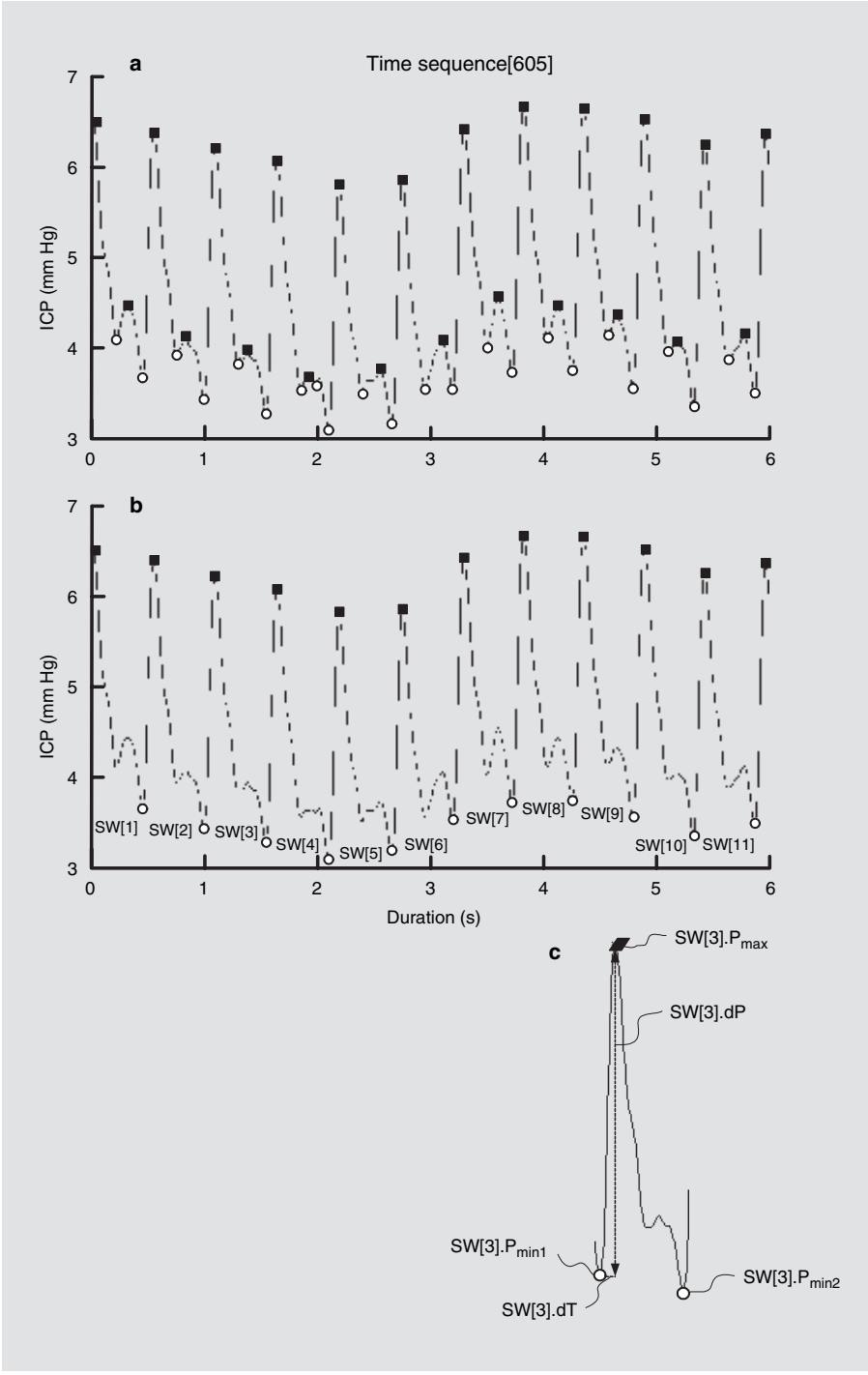

Fig. 2. A time sequence window of 6 s duration [Time Sequence[605] showing all identified peaks (maximum pressure values) and valleys (minimum pressure values)] in the continuous ICP signal (Signal[1].ICP) (**a**), and only the included (i.e. accepted) minimum/maximum ($SW.P_{min1}$/$SW.P_{max}$) pairs after removal of all wrong peaks and valleys (**b**). Each accepted minimum/maximum ($SW.P_{min1}$/$SW.P_{max}$) pair represents an accepted single pressure wave, corresponding to the 11 included single pressure waves SW[1] to SW[11]. **c** For SW[3], the single wave (SW.x) parameters are indicated. ■ = All identified peaks; ○ = valleys.

Figure 2c shows the different single pressure wave (SW.x)-related parameters of SW[3] of Time Sequence[605] of Signal[1].ICP (i.e. Signal[1].Time Sequence[605].SW[3]). $SW[3].P_{min1}$ is the starting diastolic minimum pressure defining the start of the single pressure wave, $SW[3].P_{min2}$ is the ending diastolic minimum pressure defining the end of the single pressure wave. $SW[3].P_{max}$ is the systolic maximum pressure of the single pressure wave. The two relative values are amplitude (SW[3].dP), defined as the pressure difference when pressures increase from diastolic minimum pressure ($SW[3].P_{min1}$) to systolic maximum pressure ($SW[3].P_{max}$) of the single wave, and latency (SW[3].dT), defined as the time interval when the pressures change from diastolic minimum pressure ($SW[3].P_{min1}$) to systolic maximum pressure ($SW[3].P_{max}$) of the single wave.

Table 2. A small part of the matrix showing single wave distribution of the time sequence window presented in figure 2b

Wave latency, s			Wave amplitude, mm Hg							
mean	range	midpoint	mean	0.5	1.0	1.5	2.0	2.5	3	3.5
			range	0.5<dP<1.0	1.0<dP<1.5	1.5<dP<2.0	2.0<dP<2.5	2.5<dP<3.0	3.0<dP<3.5	3.5<dP<4.0
			midpoint	0.75	1.25	1.75	2.25	2.75	3.25	3.75
0.08	0.08<dT<0.09	0.085								
0.09	0.09<dT<0.10	0.095						3		
0.1	0.10<dT<0.11	0.105						8		
0.11	0.11<dT<0.12	0.115								
0.12	0.12<dT<0.13	0.125								
0.13	0.13<dT<0.14	0.135								
0.14	0.14<dT<0.15	0.145								
0.15	0.15<dT<0.16	0.155								

For the included time sequence windows, various time sequence (TS.x)-related parameters were computed in the computing step (fig. 1). First, mean pressure was computed according to the currently used and known technology. Absolute mean ICP (TS.MeanP) was computed as the sum of all pressure sample levels divided by the numbers of samples, as detailed in equation 1.

$$\text{TS.MeanP} = \frac{\sum_{i=1}^{\text{TS.SampleCount}} \text{TS.Samples}[i]}{\text{TS.SampleCount}} \quad (1)$$

The currently used and known technology computes mean pressure (mean ICP) according to equation 1, independent of whether pressure sample levels are related to cardiac beat-induced single pressure waves or not. Thus, mean ICP (TS.MeanP) is computed for all time sequence windows of a continuous pressure signal, not involving the process described in figure 1. For the time sequence window shown in figure 2b, mean ICP was 5.0 mm Hg (TS.MeanP = 5.0). The sum of pressure levels was 3,000 mm Hg and the number of samples (TS.SampleCount) for this time sequence was 600 (sampling rate of 100 Hz over a 6-second duration).

The mean wave of a time sequence window is computed as the time sequence (TS.x) parameter mean wave amplitude (TS.MeanWavedP) and mean wave latency (TS.MeanWavedT). The procedure of computing TS.MeanWavedP and TS.MeanWavedT for the time sequence window shown in figure 2b is described. A matrix is created based on determining numbers of single pressure waves with preselected values related to amplitude (SW.dP) and latency (SW.dT), one axis of the matrix being related to an array of preselected values of pressure amplitude (SW.dP) and the other axis of the matrix being related to an array of preselected values of latencies (SW.dT) (table 2). For each matrix cell at respective intersections, a number of occurrences of matches between a specific pressure amplitude (SW.dP) and a specific latency (SW.dT) is indicated. Table 2 indicates the distribution of SW.dP and SW.dT combinations of the 11 accepted single pressure waves (SW[1] to SW[11]) presented in figure 2b. This matrix contains 1,920 cells, including 60 columns (i.e. 60 amplitude groups ranging from 0 to 30.0 mm Hg with intervals of 0.5 mm Hg) and 32 rows (i.e. 32 latency groups ranging from 0.08 to 0.40 s with intervals of 0.01 s).

The method computes the balanced position of matrix numbers of occurrences of amplitude (SW.dP) and latency (SW.dT) combinations during each time sequence window; this balanced position corresponds to mean wave amplitude (TS.MeanWavedP) and mean wave latency (TS.MeanWavedT).

The term 'i^{th} SW.dT row and j^{th} SW.dP column cell' refers to a matrix cell with the coordinates 'i^{th} row (r) and j^{th} column (c) cell'. Latency (SW.dT) mean value (row mean), with respect to the amplitude (SW.dP) values (columns) is determined (m_i) for each latency (SW.dT) row, using equation 2.

$$m_i = \sum_{j=1}^{c} A_j w_{ij} \quad (2)$$

A_j is the j^{th} column midpoint, referring to an amplitude (SW.dP) group value, and w_{ij} is the frequency (count) of the i^{th} SW.dT row and j^{th} SW.dP column cells. Thereafter,

$$\text{Row mean} = \text{Mean}(dt) = \frac{\sum_{i=1}^{r} m_i B_i}{\sum_{i=1}^{r} mi} \quad (3)$$

B_i is the i^{th} row SW.dT midpoint value. The calculations are shown in more detail in table 3, using the data of table 2 to calculate the mean row value by means of equations 2 and 3 [i.e. row mean = mean (dT) = 0.103 s].

Amplitude (SW.dP) mean value (column mean), with respect to the latency (SW.dT) values (rows), is determined (m_j) for each amplitude (SW.dP) column, using equation 4.

$$m_j = \sum_{i=1}^{r} B_j w_{ij} \quad (4)$$

B_i is the i^{th} row SW.dT midpoint, referring to a latency (SW.dT) group value, and w_{ij} is the frequency for the i^{th} SW.dT row and j^{th} SW.dP column cells. Thereafter,

$$\text{Column mean} = \text{Mean}(dP) = \frac{\sum_{j=1}^{c} m_j A_j}{\sum_{j=1}^{c} mi} \quad (5)$$

Table 3. Computation of row (latency) mean with respect to columns (amplitude)

m_i	$SW.dT_i$	$m_i \times SW.dT_i$
$3 \times 2.75 = 8.25$	0.095	0.784
$8 \times 2.75 = 22.0$	0.105	2.310
Sum = 30.25		3.094
Row mean: 3.094/30.25 = 0.103 s		

Table 4. Computation of column (amplitude) mean with respect to rows (latency)

m_j	$SW.dP_j$	$m_j \times SW.dP_j$
$3 \times 0.095 = 0.285$	2.75	0.784
$8 \times 0.105 = 0.84$	2.75	2.31
Sum = 1.125		3.09
Column mean: 3.09/1.125 = 2.75 mm Hg		

A_j is the j^{th} column SW.dP value midpoint (c = column). The calculations are shown in table 4, using the data of table 2 to calculate the mean column value by means of equations 4 and 5 [i.e. column mean = mean (dP) = 2.75 mm Hg].

Thus, the mean ICP wave of the time sequence window shown in figure 2b had a mean wave latency of 0.103 s (TS[605].MeanWavedT = 0.103 s) and an mean wave amplitude of 2.75 mm Hg (TS[605].MeanWavedP = 2.75 mm Hg).

Trend plots were created for the time sequence parameters TS.MeanP, TS.MeanWavedP and TS.MeanWavedT in order to compare the clinical significance of the currently used and known technology (i.e. TS.MeanP) against the new method (i.e. TS.MeanWavedP and TS.MeanWavedT). For these trend plots, the mean value and standard deviation were computed according to equations 6 and 7, respectively.

The mean value of a trend plot is the sum of values for all time sequence windows, divided by the number of time sequences within the trend plot (Trend.TSCount; equation 6). Such mean values are shown in figures 3–5.

$$\text{Trend.x.Mean} = \frac{\sum_{n=1}^{\text{Trend.TSCount}} \text{TS[n].x}}{\text{Trend.TSCount}} \quad (6)$$

The standard deviation of a trend plot is further shown in equation 7.

$$\text{Trend.x.Std} = \sqrt{\frac{\sum_{n=1}^{\text{Trend.TSCount}} (\text{TS[n].x} - \text{Trend.x.Mean})^2}{\text{Trend.TSCount}}} \quad (7)$$

The trend plots of the individual cases presented in figure 3a–r all lasted 6 h, and were derived from the same time period (00:00:00 to 06:00:00) to compare recordings between cases. In the 6 cases presented here, the median total recording time was 16 h 38 min (range 14 h 43 min to 25 h 35 min).

Results

Figure 3a–f shows the continuous ICP recordings of cases No. 1 (fig. 3a–c) and 2 (fig. 3d–f) treated surgically for hydrocephalus. Both cases had marked symptoms of intracranial hypertension (table 1) that disappeared after surgical treatment (i.e. extraventricular shunt treatment in case No. 1 and endoscopic third ventriculostomy in case No. 2). In case No. 1, mean ICP (fig. 3a) was considered as normal at the time of ICP monitoring, but shunt treatment was performed after 1 month due to lasting symptoms. In both cases, the mean wave amplitude (TS.MeanWavedP; fig. 3b, e) was variably above 5 mm Hg, with mean values of trend plots (Trend.MeanWavedP.Mean) being 5.7 and 6.4 mm Hg for cases No. 1 (fig. 3b) and 2 (fig. 3e), respectively. The mean of the trend plot of mean wave latency (Trend.MeanWavedT.Mean) was 0.22 s for both cases (fig. 3c, f).

Figure 3g–i shows the ICP recording of case No. 3 that presented with bilateral papilledema and increasing head circumference without symptoms of intracranial hypertension (table 1). Mean ICP (TS.MeanP; fig. 3g) was considered as abnormal with elevations above 20 mm Hg. The mean value of the trend plot of mean wave amplitude (Trend.MeanWavedP.Mean) was 6.5 mm Hg (fig. 3h). The mean of the trend plot of mean wave latency (Trend.MeanWavedT.Mean) was 0.22 s (fig. 3i). The ophthalmologist verified that the papilledema disappeared after implantation of a lumboperitoneal shunt. This child has a normal development.

In case No. 4 (fig. 3j–l), a shunt revision was performed due to symptoms indicating shunt malfunction (table 1). At the time of ICP monitoring, overdrainage was suspected due to somewhat low mean ICP (fig. 3j). In this case, mean wave amplitude (TS.MeanWavedP) generally was below 5 mm Hg (fig. 3k), with a mean of the trend plot of mean wave amplitude (Trend.MeanWavedP.Mean; fig. 3k) of 3.7 mm Hg, and a mean of the trend plot of mean wave latency (Trend.MeanWavedT.Mean) of 0.11 s (fig. 3l). In this case, symptoms had been lasting; in the course, repeated shunt revisions had been performed without relief of symptoms.

Figure 3m–r presents the continuous ICP recordings of cases No. 5 (fig. 3m–o) and 6 (fig. 3p–r) treated surgi-

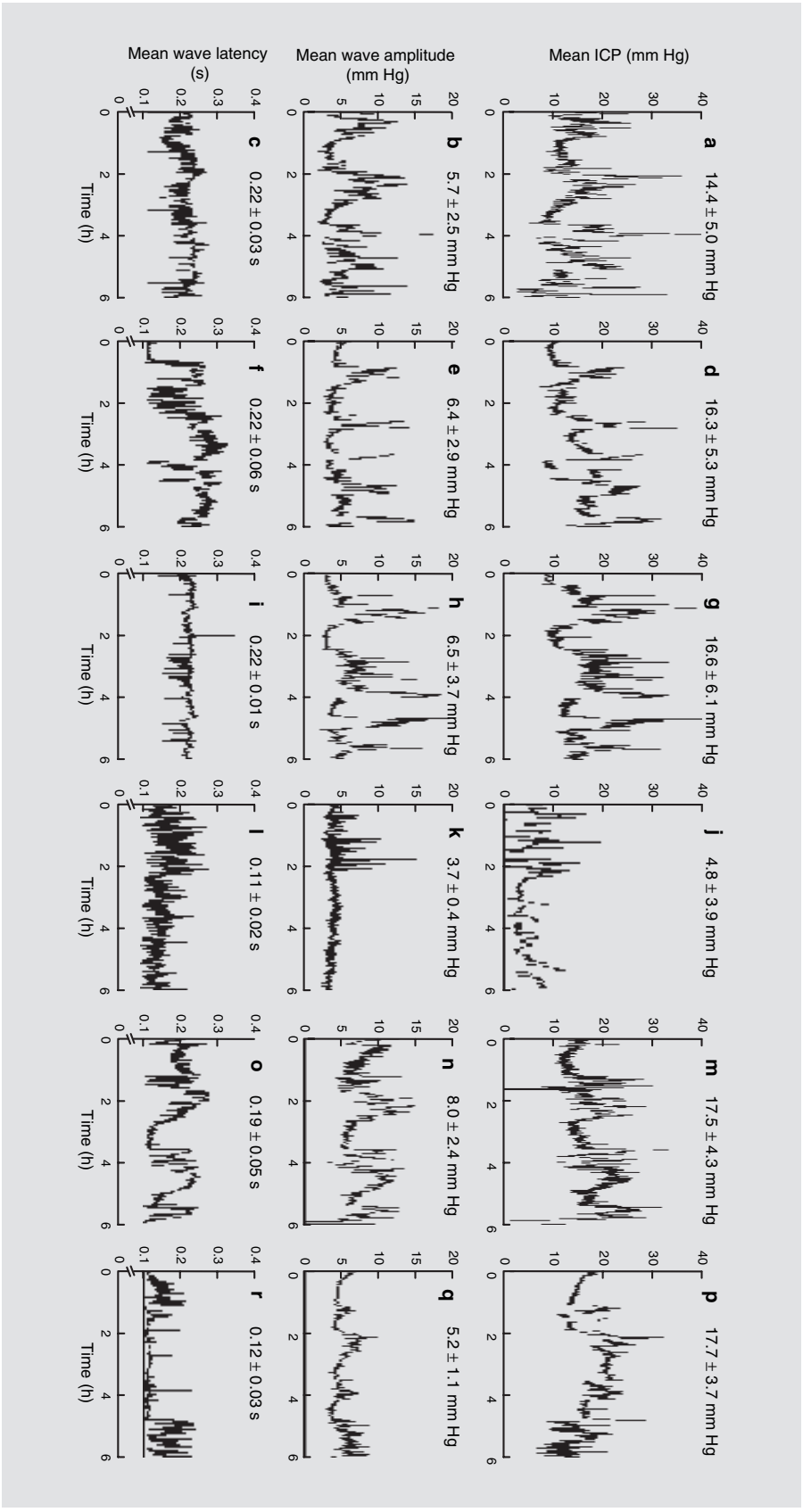

Fig. 3. The continuous ICP recordings of cases No. 1 (**a–c**), 2 (**d–f**), 3 (**g–i**), 4 (**j–l**), 5 (**m–o**), and 6 (**p–r**) are presented as trend plots of mean ICP (TS.MeanP) (**a**, **d**, **g**, **j**, **m**, **p**), mean wave amplitude (TS.MeanWavedP) (**d**, **e**, **h**, **k**, **n**, **q**) and mean wave latency (TS.MeanWavedT) (**c**, **f**, **i**, **l**, **o**, **r**), computed each consecutive 6-second time sequence window. For the whole trend plot of a duration of 6 h, the mean value ± standard deviation is shown as well. The number of accepted time sequence windows was 3,404 for case No. 1 (**a–c**), 2,727 for case No. 2 (**d–f**), 3,546 for case No. 3 (**g–i**), 1,131 for case No. 4 (**j–l**), 3,150 for case No. 5 (**m–o**), and 3,346 for case No. 6 (**p–r**).

cally for craniosynostosis. Both cases had marked symptoms of intracranial hypertension (table 1), with a very good clinical response to cranial expansion procedures. Mean ICP (TS.Mean P) was rather high with elevations above 20 mm Hg in both cases (fig. 3m and p). Mean wave amplitude (TS.MeanWavedP) was higher in case No. 5 (fig. 3n) than in case No. 6 (fig. 3q), with a mean of the trend plot of mean wave amplitude (Trend.MeanWavedP.Mean) of 8.0 mm Hg in case No. 5 (fig. 3n) and 5.2 mm Hg in case No. 6 (fig. 3q). Clinical outcome was even better in case No. 5 than in case No. 6, though the latter case also experienced a marked clinical improvement after surgery.

Discussion

This study describes the continuous ICP recordings of children with intracranial hypertension due to hydrocephalus or craniosynostosis. The most important observation was that mean wave amplitude (TS.MeanWavedP) was variably above 5 mm Hg in those children with intracranial hypertension and that outcome after surgery was successful.

It has been assumed that cerebral compliance is more reliably predicted by pulse pressure than by mean pressure [5–8], though it has been difficult to extract reliable information about pulse pressure from the ICP signal in a clinically useful way. Previously pulse pressure was examined by means of pressure charts of short time periods [5, 6, 9, 12], or pulse amplitudes were derived from spectral analysis using fast Fourier transformation [7, 13–16], or by computer-assisted determinations of pressure differences between systolic and diastolic pressures [10, 17]. The author did not find fast Fourier transformation useful for correct determination of pulse pressure amplitudes [unpubl. data]. Problems related to the use of fast Fourier transformation were lack of control of the impact of artifacts in the signal, and lack of control of whether pulse amplitude is derived from cardiac beat-induced waves. Advantages of the method described here are the algorithm for correct identification of single pressure waves caused by cardiac beats, not artifact-induced waves, and the approach of computing mean wave amplitude for short time sequence windows (6 s), which reduces the impact of beat-to-beat variations in pulse pressure amplitude.

It is suggested that mean wave amplitude (TS.MeanWavedP) provides information about intracranial compliance/elastance. Compliance (C) is the inverse of elastance (E; E = 1/C); elastance describes the relationship between change in pressure and change in volume ($E = \Delta P/\Delta V$). In cases with impaired intracranial compensatory capacity, cerebral compliance is reduced, i.e. cerebral elastance is increased. In the presence of increased elastance, a small intracranial volume increase causes a large mean ICP increase, as previously shown in several studies exploring intracranial pressure-volume relationships [18–21]. A linear relationship between mean and pulse pressures in both animals [6, 7, 12] and humans [5, 10, 11] has previously been shown. Thus, in the presence of reduced compliance (i.e. increased elastance), pulse pressure amplitude values are increased.

This is a descriptive study including all childhood cases treated surgically for hydrocephalus or craniosynostosis after ICP monitoring. The observation period after surgery was more than 6 months. There were no postsurgical ICP recordings. In these cases, the raw data files of ICP signals sampled at 100 Hz were available. Hence, the ICP recordings could be processed according to the method described. At the time of ICP monitoring, patient management was based on computation of mean ICP (TS.MeanP). The parameter mean wave amplitude (TS.MeanWavedP) was computed retrospectively.

Historically a number of strategies have been used to analyze continuous ICP recordings [8]. The currently used and known technology usually computes mean ICP for a duration of 5–10 s as the sum of all pressure levels divided by the number of samples (comparable to TS.MeanP in the present study). This approach only takes into account the steady component of ICP. Concerning mean ICP in children, it has been discussed which values are abnormal or not. Most authors consider mean ICP below 10 mm Hg as normal, mean ICP between 10 and 15 mm Hg as borderline and mean ICP above 15 mm Hg as abnormal, though the normal frequency of these mean ICP levels remain unclear [1–4]. At the time of ICP monitoring, the present cases No. 1–3 and 5 and 6 were treated for intracranial hypertension on the basis of mean ICP (though mean ICP was considered as normal in case No. 1. In all these cases, elevations of mean ICP above 20 mm Hg of variable durations were found.

The method described here directly computes mean ICP (TS.MeanP) and mean ICP wave amplitude/latency (TS.MeanWavedP/TS.MeanWavedT) from the ICP signal itself, thus providing information both about the steady and pulsatile components of ICP. An important aspect is an algorithm of correctly identifying the single pressure waves corresponding to the cardiac beat-induced pressure waves. This algorithm has been extensively test-

ed to verify that each cardiac beat-induced pressure wave is correctly identified by its diastolic minimum and systolic maximum pressure values. The impact of variations in single wave amplitudes (SW.dP) is reduced since the mean distribution within a time sequence window is computed.

The present material of 6 cases is too small to conclude about normal and abnormal values of mean wave amplitude (TS.MeanWavedP) in children, but some information is provided. In all cases No. 1–3 and 5 and 6 with intracranial hypertension and successful outcome after surgery, mean wave amplitude (TS.MeanWavedP) was above 5 mm Hg, including variable fluctuations above 5 mm Hg. In case No. 3, the ophthalmologist verified the disappearance of the papilledema after surgery. In adult cases with normal pressure hydrocephalus, a good outcome after surgery was consistently found when the mean wave amplitude (TS.MeanWavedP) was above 5 mm Hg; however, the outcome was bad in those with values below 4 mm Hg [unpubl. results]. In case No. 4 with mean wave amplitude (TS.MeanWavedP) values below 4–5 mm Hg, no change in symptoms was observed after shunt revisions. In this case, intracranial hypotension was suspected.

Conclusions

The present cases demonstrate that information about both the steady and pulsatile components of ICP can be derived from a new method of processing continuous ICP signals. In 5 patients with intracranial hypertension and successful outcome after surgery, mean wave amplitude (TS.MeanWavedP) values were variably above 5 mm Hg. Further studies are required to determine the predictive value of mean wave amplitude (TS.MeanWavedP) values for outcome after surgery in pediatric cases with intracranial hypertension.

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