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Analysis of Intracranial Pressure Waveform During Infusion Test

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Summary

An analysis of intracranial pressure (ICP), based on an examination of the temporary correlation between the changes in amplitude of the pulse wave and the mean ICP level, is presented. The paper contains a discussion of the preliminary results of the method when applied to the analysis of ICP as monitored during infusion tests in a group of 24 children. Infusion of a certain volume of CSF is a good example of an uncompensated volume process, introduced externally into the intracranial space. Results allow an interpretation of the short term correlation coefficient RAP (correlation coefficient between ICP and variations of the amplitude of fundamental component of the pulse wave AMP), as a steady state index. According to this interpretation, the presented analysis enables the observation of a loss of equilibrium during the test. Other phenomena can also be observed, for instance a recovery to equilibrium after the test, nonlinearities of amplitude-pressure relationship, vasomotor reflexes etc.

Keywords: Hydrocephalus; intracranial pressure; wave-form; infusion test; computerized analysis.

Introduction

The general aim of this work is an examination of the correlation between rapid changes of certain parameters of the ICP signal, monitored during an infusion test. The dynamic relationship between these temporary parameters may include additional information to that obtained by standard techniques of calculating intracranial space model parameters, such as those introduced by Marmarou[4], Sliwka[6, 7] or Avezaat[1].

External infusion of CSF represents undoubtedly an uncompensated volume process, thus an interpretation of certain calculated parameters such as the factors of the steady state of the cerebrospinal system, could have been illustrated clearly. This was the second aim of the work presented: to discuss the meaning of monitored parameters in cases where the patient's state and observed intracranial processes are much better defined and controlled than in continuous monitoring of ICP, as described in our other works[2, 3].

It should also be emphasized that, due to the size of the patient sample used, the results cannot be treated as being statistically significant. However, the authors feel that a larger sample may produce results of some significance in the diagnosis of infantile hydrocephalus. The authors hope that such an approach would be valuable and they will be able to present larger studies soon. The presented material may be treated as an illustration of the computerized method of ICP analysis, as applied to infusion tests.

The material included in this paper was presented at the International Symposium on Intercranial Hypertension in Clinical Practice, Warsaw, September 1986.

Material and Method

Twenty four children ranging in age from 1 to 14 years, with symptoms of hydrocephalus (*e.g.* enlarged head circumference, as observed in CT scans, enlarged ventricular system and/or neurological symptoms of increased ICP) were examined using the infusion test in the Neurosurgery Clinic of the Child's Health Centre. The clinical aim of the examination was the determination as to whether a shunting device should be implanted.

The tests were performed according to a scheme introduced by the Neurosurgical Clinic of the Medical Research Centre, Polish Academy of Sciences. The test consists of a fast phase with a high infusion rate of 5 ml/min, lasting 1 min or until ICP reaches 20 mmHg, and then the slow phase of 1 ml/min infusion rate, continuing until the cerebrospinal system reaches a new equilibrium state. This procedure was introduced in order to minimize the total volume load and improve the reliability of the calculated parameter of the cerebrospinal space model[5, 6]. It should be stressed that the scheme of infusion does not influence the interpretation of results wich are being described.

Patients were anaesthetised using N_2O/O_2 and halotane (0.2 vol%) mixture.

ICP was monitored using a lumbar catheter, tied through a standard manometer line to a Hewlett Packard 1280C pressure transducer and HP monitor (the cut-off frequency of the entire hydraulic line was greater then 12 Hz). The analogue output of the monitor provided the input ICP signal to the custom computer system, constructed in the Warsaw University of Technology and developed in cooperation with the Department of Anaesthesiology of the Child's Health Centre.

A detailed description of the method of ICP analysis is included in[2, 3]; only a brief revue will be presented here: ICP is sampled with a frequency five times higher than an actual heart rate, and then the spectral density function of a fragment of the signal, containing from 6 to 12 heart evolutions, is calculated. This allows the calculation of the individual ICP componant powers and minimizes the errors produced by the components interference. Such errors could be respectively large, if the direct calculation of the pulse wave amplitude from the signal, as proposed in the works[1] or[7], were applied for a short-term analysis of the ICP[2]. It should be stressed, that both of the methods (*i.e.* direct and by spectral-analysis) contain a form of filtration of the signal to remove the influence of the other components on the pulse amplitude, but in the case of spectral analysis the filtration is much more selective and, moreover, allows an analysis of all the components of ICP—not only the pulse wave[2, 3].

The analysis is repeated every one or two heart beats (depending on the programmed parameters), and with every new spectrum of the current signal the three sequences of the temporal parameters: mean ICP level, amplitude of fundamental component of pulse wave and its frequency (*i.e.* heart rate) are updated with the new elements, calculated by means of the interpolation algorithm[3], on the basis of the power spectrum shape. Once the sequences contains 256 elements—after the artifacts extraction and the matched filtration of amplitude sequence, performed in order to extract its variations, evoked by the changes of heart rate—the linear regression between the sequences of temporal amplitudes and mean pressure levels is calculated. The slope of the regression line, as well as the correlation coefficient and the other listed parameters, are calculated and stored in special buffers in the form of time trends.

All of the described operations are performed continuously, during monitoring of the ICP signal, with the maximum rate of 1.5 min. The scheme of the algorithm, written in a pseudopascal notation, is presented in Table 2. Each loop of the calculation of the next set of final parameters (outer), contains a special routine for ICP signal recognition and matching of the sampling frequency to the current heart rate—to avoid a faulty interpretation in cases when the signal is measured improperly.

All parameters treated as time trends, form new signals, which can be analysed, correlated to each others and interpreted:

— mean ICP value (ICP),

— root mean square value of slow waves of ICP (rmsICP). This represents the effective power of all components slower than the respiratory wave but faster than the current period of analysis (1.5 min in this case),

— amplitude of fundamental component of pulse wave (AMP),

— root mean square of AMP (rmsAMP),

— heart rate (calculated as the frequency of the fundamental component of pulse wave HR),

— amplitude of respiratory wave (Abrth),

— correlation coefficient between ICP and variations of AMP, (RAP), registered within the 1.5 min period,

— slope of the linear regression line between the set of AMP and ICP from one 1.5 min period (AMP/p).

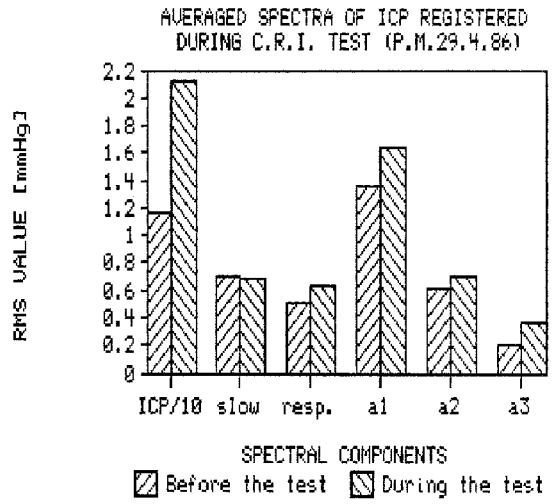

Fig. 1. Averaged spectrum of ICP from the period before and during the test. *Slow*—slow waves; *Resp.*—respiratory component, I, II, II—the first, second and third harmonic components of pulse wave respectively. Note that content of higher harmonic components did not change during elevation of mean ICP, which was equal 13 mmHg before and 23 mmHg during infusion

On the basis of the sets of AMP and ICP from the whole period of the analysis (typically about 1 hour), the so called static amplitude-pressure (stAMP/p) characteristic may be calculated, as well as the static relationship between rmsAMP and rmsICP (rmsAMP/rmsICP).

The calculation of the amplitude of fundamental component of the pulse wave, instead of the peak to peak value of the signal from one heart evolution, seems to be the biggest innovation in this method. Therefore it should be commented more precisely:

As proved in the works of Avezaat and Eijndhoven[1], the peak to peak value of the pulse wave (CSFPP) is determined by three factors: the blood flow into the arterial part of the cerebrospinal vessels, the outflow an the elastance of the system. All these factors may vary independently, but only one is analysed during the infusion test[1, 5] namely the cerebrospinal system elastance, or elastivity. It can be measured on the basis of the slope of the CSFPP/ICP characteristic. In the presented method, only the fundamental component of the pulse wave is taken into account, and not the full CSFPP value. But, as observed in this group of cases, the correlation coefficient (static) between sets of ICP and AMP from the whole test, was high (0.95 mean). Strong changes of the shape of the ICP pulse wave during the test were not observed in all cases (see Fig. 2, where an example of the analysis of the harmonic distortion of the pulse wave before and during the test is shown). This provided the basis for an assumption, *i.e.* that the fundamental component of the pulse wave accurately reflects the variations of the CSFPP during the test. The slope of AMP/p may differ from the slope of CSFPP/ICP—it depends on the shape of pulse wave in each individual case, but from the point of view of the analysis of variations of amplitude-pressure relationship during the test, it deserves satisfactory and accurate results.

Results

The typical trends of analysed parameters are presented on Figs. 2–6, as well as examples of stAMP/p

Table 1

No.	Definition	Mean	S. dev	Corr.
1.	Slope of static AMP-p characteristic	0.290	0.079	$r_{14}=0.89$
2.	Staticcorrelation coeff. between AMP and ICP stRAP	0.91	0.29	
3.	AMP/p on elevation of ICP	0.596	0.512	
4.	Slope of rmsAMP/rmsICP charact.	0.276	0.116	
5.	Decrease of hr (beats/min)	13	8	
6.	Slope of static AMP/p characteristic calculated as $(AMP_b-AMP_t)/(ICP_b-ICP_t)$; index b denotes parameters before the test, index t-parameters from stabilized phase of test.	0.30	0.432	$r_{16}=0.82$

Table 2. *Scheme of Program of ICP Processing, Written in Pseudopascal Notation.* $\{a\}$, $\{p\}$, $\{f_{hr}\}$ are sequence of temporary values of amplitude of fundamental component of pulse wave, current ICP level and heart rate respectively

```
Program ICP processing;
VAR
break: BOOLEAN {interrupt};
k: INTEGER {index of sequences};
a, p, fhr: ARRAY {1 ... 512} OF REAL;

BEGIN
Initialization (all parameters);
REPEAT
Signal recognition and finding the proper sampling frequency;
k:=0;
REPEAT
Fast Fourier Transform of ICP samples;
Interpolation;
Calculation of a[k], p[k], fhr[k];
k:=k+1
UNTIL k=256
Automatic artifacts extractions from a, p, fhr;
Matched filtering of a;
Linear regression between a and p;
Calculation of other parameters
UNTIL break;
End.
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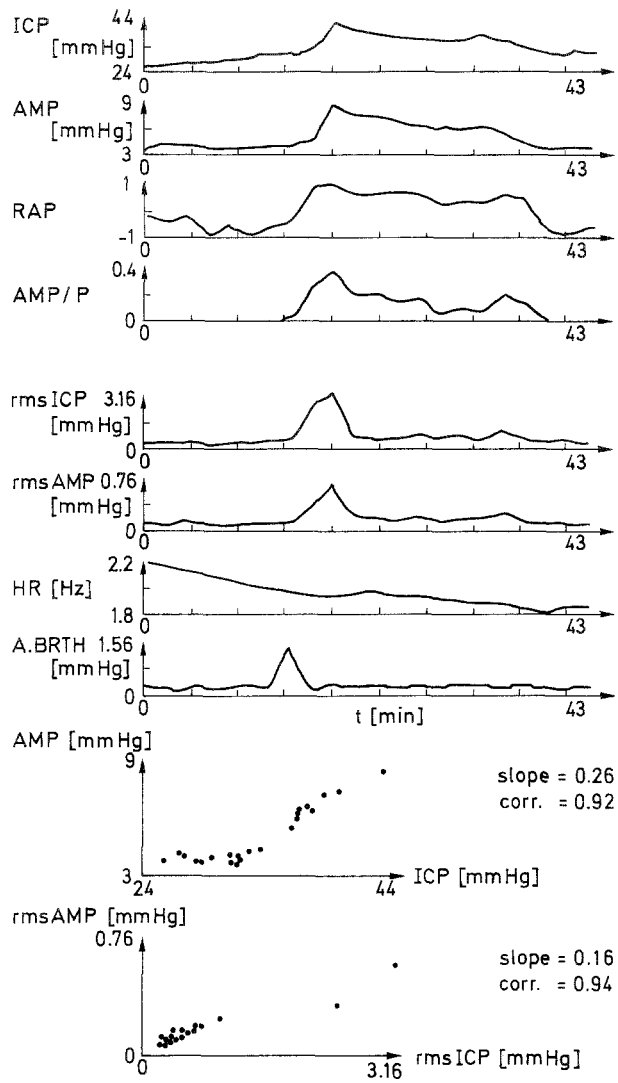

Fig. 2. Trends of analysed parameters, registered during the test, (boy, 4 years old, qualified to implantation of shunting device—note increased level of opening pressure). Static below. Symbols of x and y axes are explained in text

and rmsAMP/rmsICP relationships. The averaged values of measured parameters are listed in Table 1.

The strong heterogenity of presented trends should be stressed, however some common features were noticed:

1. The correlation coefficient between the mean ICP and AMP (the so called static correlation coefficient—stRAP) is high with a mean of 0.91 and a standard deviation of 0.29. Some patterns of nonlinearity of the AMP/p characteristic can be observed, especially near the limits of the pressure ranges, registered during the tests (see Figs. 2 and 5a).

2. The correlation coefficient between the rmsAMP and rmsICP also remains high (with a mean of 0.755 and standard deviation of 0.279) but is statistically lower than the stRAP.

3. The high correlation coefficient between the slopes of stAMP/p and rmsAMP/rmsICP regression lines was observed. But standard deviation of the slope of rmsAMP/rmsICP is higher than stAMP/p and the correlation coefficient between rmsAMP and rmsICP

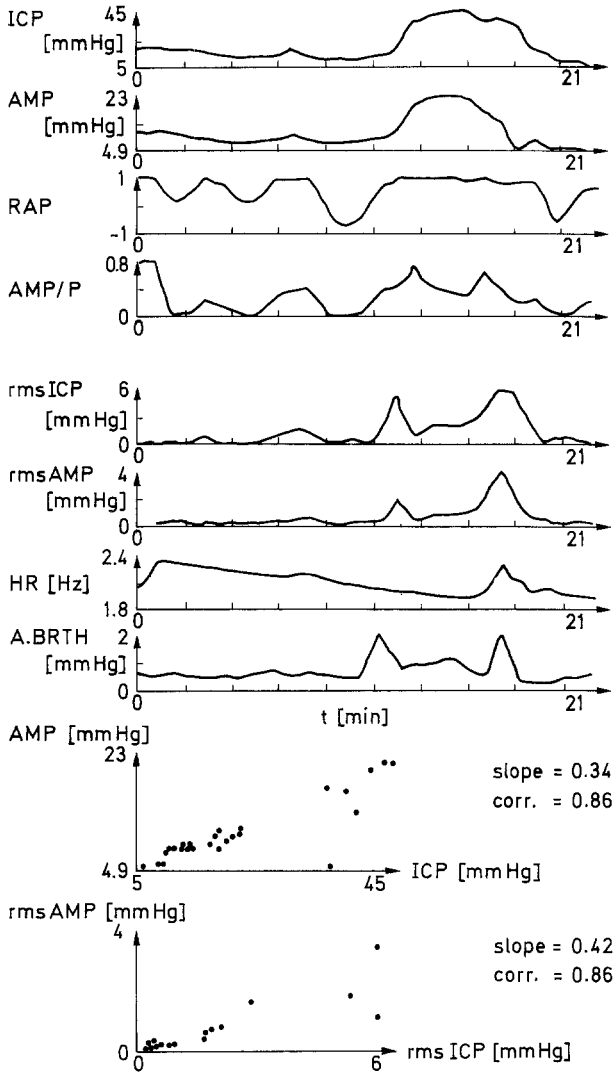

Fig. 3. Trends of analysed parameters and static characteristics in 7 years old girl, qualified for implantation of shunting device (high level of RCSF). Note high RAP before and during the test and rapid increase of HR after the test

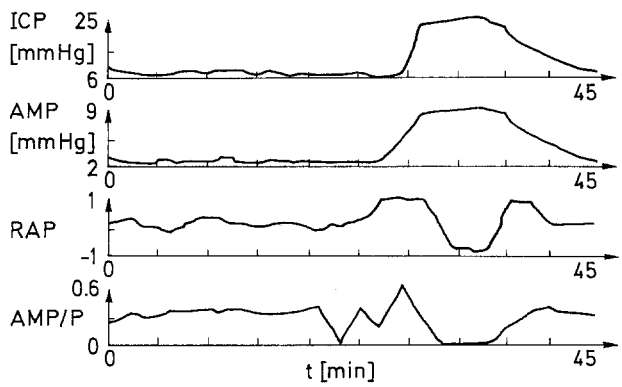

Fig. 4. Trends of analysed parameters (boy, 3 years, RCSF about 20 mmHg/ml/min). Note negative correlation (RAP) during ICP increased

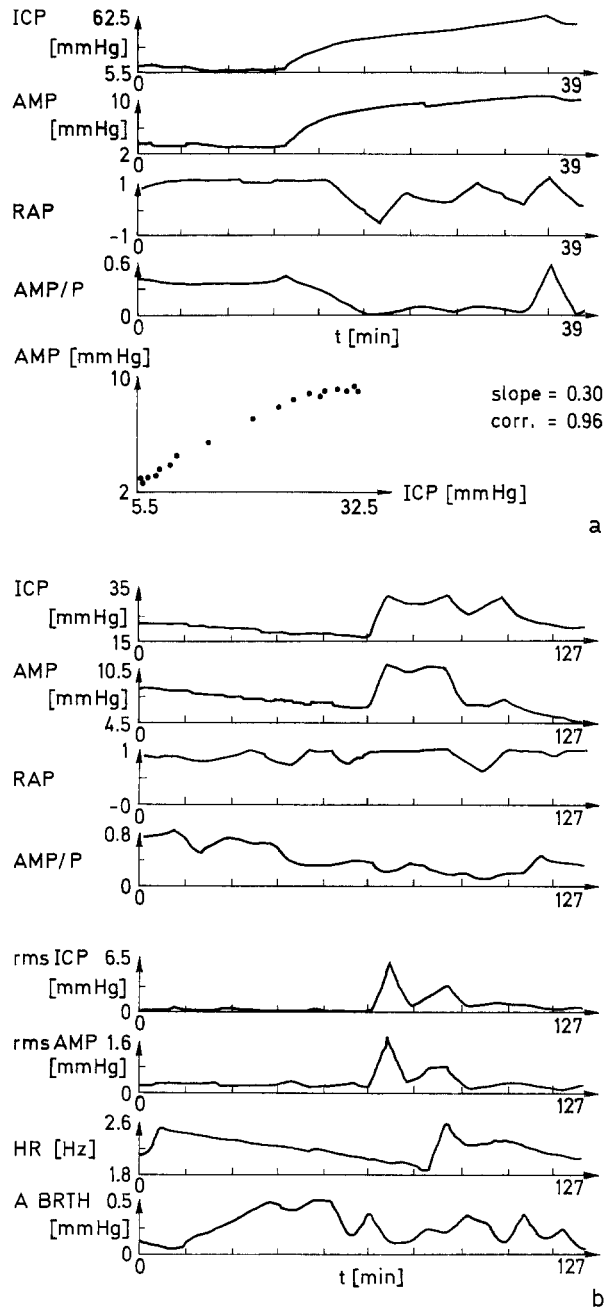

Fig. 5a, b. Examples of analysed parameters, where high RAP level before the test was detected. Decreasing of RAP during ICP increased and AMP/p static characteristic with the upper brakpoint, above which it becomes flatter, was found in case a). Note strong increase of HR after infusion in case b)

is significantly lower than stRAP (0.75 and 0.91 respectively).

4. The presented group can be divided to two classes with respect to trends of RAP:—The first group contains all cases with a low RAP (close to zero or slightly negative) before infusion and a high RAP (close to one)

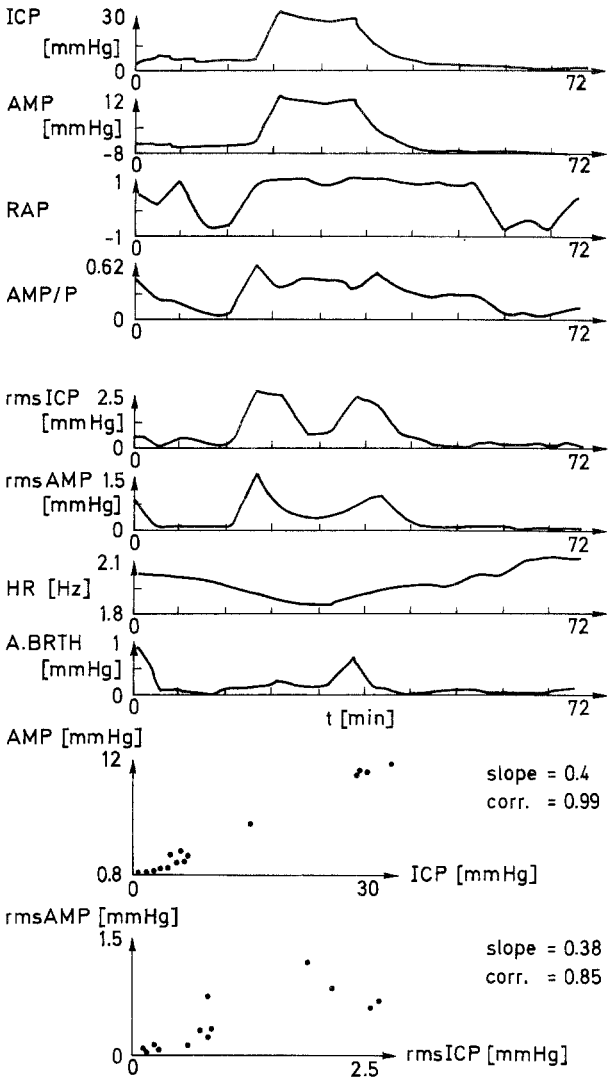

Fig. 6. Test in 5 years old boy with increased RCSF level. Note, that infusion started after RAP reached level near 0—it means after recovery to steady state, disturbed by induction, and long period of increased RAP after the test

during infusion (see Figs. 2 and 3). After infusion, when the ICP recovers to the baseline level, RAP also decreases to near zero, but with a considerably long delay in some cases (compare Figs. 2 and 3).—The second group is characterised by the RAP remaining close to 1 before infusion and then decreasing during infusion-typically in the slow phase of the test, following a sharp elevation of the ICP level. Eight cases from the tested group can be assigned to this class (see Figs. 4 and 5a, the case from Fig. 5b can be classified neither to the first nor to the second of these groups).

5. The slope of the short-term regression line between the amplitude of the pulse wave and the mean ICP level (AMP/p) considered as a time-trend, shows a strong time-dependancy. Usually the short-term amplitude-pressure characteristic is steeper during the steady state (see Figs. 2, 3, 4).

6. It should be stressed, that there was no correlation found between the short-term slope of AMP/p characteristic, measured during the elevation of ICP within the test, and the slope of the static AMP/p characteristic. The value of AMP/p during the elevation of ICP is significantly greater than that of stAMP/p (the mean value of AMP/p on the rising edge of ICP = 0.6, and the equivalent value for stAMP/p = 0.29).

7. In almost all cases the heart rate decreased gradually throughout the whole test (about 13 beats per minute on average), see Figs. 2, 3, 6. In many cases a rapid increase of heart activity was noticed during the fall of ICP after the infusion.

Discussion

In the presented group, 16 children qualified for the implantation of the shunting device, on the basis of increased resistance of CSF outflow (above 13 mmHg/ml min^{-1}), and/or considerably increased level of opening pressure (above 10 mmHg). The results of the described analysis were considered only as additional information of not well established clinical meaning. Some possible relationships between the patient's state and the analysed parameters should be evaluated carefully, on a statistically significant group of cases. Hence the phenomena discussed below may only stand to illustrate the processes observed during the filling of the cerebrospinal space with a certain extra volume.

The initial interpretation of the RAP, made following the continuous analysis ICP after operations for tumours of the fossa posterior, as an index of the steady state of the cerebrospinal system[2], seems to be validated by all 15 cases, which can be classified into the first of the above mentioned groups. In a stable system, correlation between the changes of AMP and ICP is low, thus the RAP in steady state is close to 0. In this state all the changes of intracranial volume seem to be compensated by compression of the vessel bed—and, as Avezaat suggested[1], in this state the Monroe-Kelly doctrine holds. This steady state lasts until an uncompensated volume process, introduced internally or externally, appears. "Uncompensated" in this case describes such a strong volume excitation, that the total volume of the cerebrospinal space cannot remain constant[1]. The constant infusion of an extra volume into the intracranial system can be undoubtedly interpreted as such a process—it forces the RAP close to 1 for the

period, until the new equilibrium state is obtained. This interpretation of the RAP as the steady state index is important in two practical aspects in infusion tests: for determining the moment when the system reaches steady state after induction (see Fig. 3, where the ICP level, increased during induction, was falling gradually to about 10 mmHg, when the RAP decreased to negative values, pointing to the restoration of equilibrium) and when the system recovers to the steady state after the test. Time delay between the recovery of the ICP level to the baseline after the infusion and recovery of the RAP to 0, seems to be an important guide to the compensation ability of the examined system, however this hypothesis needs more investigations in future.

Due to this hypothesis, the system presented on Fig. 2 should have had better compensation ability than the one on Fig. 6 (it should be noticed, that in the second case considerably higher resistance of CSF absorption and AMP/p slope during the rapid phase of the test were observed).

The paradoxical decrease of RAP during the test in 8 cases can not be definitely interpreted yet. It can be only remarked that in these cases, strong, uncorrelated waves appeared in both the ICP and in the AMP signals, in spite of this the mean ICP and the mean AMP remained well correlated. Vasomotor reflexes could be pointed to as a source of such waves—they can be classified to B waves, which, according to many authors, are commonly observed in hydrocephalic patients[6, 8]. A similar phenomenon was observed during the long term analysis of ICP, particularly when symptoms of increased ICP, due to the development of a brain oedema, occurred (encephalitis, head injuries, and postoperative complications after the removal of tumours[2, 3]). It is likely that due to the increase of the ICP above a certain critical level, maximal vasodilatation occurs to maintain the cerebral perfusion on a satisfactory level. Hypothetically, this is the edge of a pressure range, where the autoregulation of CBF holds. Lowering of the heart rate and increase of the systemic pressure form symptoms of Cushing's response in these cases. Rapid increase of HR, as a response to the decrease of the ICP after the test can be easily observed, even in cases classified into the first of the mentioned groups-see Figs. 3, 5, and 6.

The big difference between the slope of the static and dynamic AMP-p characteristics suggests that these two parameters have different deductable meanings. Variations of AMP/p inform not only on the elastic properties of the cerebrospinal system, but also on some dynamic compensation processes evoked by vasomotor reflexes and the heterogenity of the exhaustion of the compensatory volume in the intracranial space. The influences of all these phenomena overlap each other and affect observed variations of the AMP/p.

Conclusions

The correlation coefficient between the rapid variations of the fundamental component of the pulse wave and the mean ICP level (RAP), interpreted as a steady state index, can be used as an indicator of the equilibrium state before and during recovery to the steady state after the test.

A high RAP value before the test with a resulting decrease after elevation of the ICP level, seems to be typical for cases in which an increase in ICP in the test evokes strong vasomotor reflexes for avoidance of a decrease of cerebral perfusion.

Decreases in HR during the test were noticed, as well as a high correlation between the slopes of static AMP-p and rmsAMP-rmsICP characteristics.

The amplitude of the respiratory wave seems to be a good index of depth of anaesthesia during the test.

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