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Single Pulse Analysis of Intracranial Pressure for a Hydrocephalus Implant*

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***Abstract*— The intracranial pressure (ICP) waveform contains important diagnostic information. Changes in ICP are associated with changes of the pulse waveform. This change has explicitly been observed in 13 infusion tests by analyzing 100 Hz ICP data. An algorithm is proposed which automatically extracts the pulse waves and categorizes them into predefined patterns. A developed algorithm determined 88 %±8 % (mean ± SD) of all classified pulse waves correctly on predefined patterns. This algorithm has low computational cost and is independent of a pressure drift in the sensor by using only the relationship between special waveform characteristics. Hence, it could be implemented on a microcontroller of a future electromechanic hydrocephalus shunt system to control the drainage of cerebrospinal fluid (CSF).**

I. Introduction

The intracranial volume consists of brain parenchyma, blood and cerebrospinal fluid (CSF). If blood- or CSF-volume increases due to pathophysiological processes, the intracranial pressure (ICP) increases as well because of the rigidity of the skull. The ratio of change in volume to change in ICP is termed "intracranial compliance". The characteristic intracranial pulse waveform with its different peaks and notches (P-wave) is caused by the closing and opening of the heart valves and by the reflections of the blood pressure wave (s. Figure 1).

Due to the advances in sensor development, it is nowadays possible to measure ICP with a sampling frequency of 100 Hz and more. This gives the opportunity to analyze the ICP waveform in detail. A single pulse within the ICP wave can consist of up to five peaks P_i. Exact morphology (size, extent etc.) and number of these peaks vary from patient to patient and depend on individual physiological parameters (s. Figure 2 for a wave example). However, first three peaks (P_1-P_3) are generally leading and determine the main waveform. It might enable physicians to deduce a more integral diagnosis of increased cerebrovascular pathophysiology or decreased intracranial compensatory reserve as it is the case in hydrocephalus.

Since the 1990s, ICP research has been focused on the so-called single pulse analysis. Pulse analysis includes the pulse detection followed by the waveform analysis of each extracted wave. Aboy et al. [2] developed an algorithm to determine the period of a wave without any electrocardiogram support. To determine the different existing waveforms, Contant et al. [3] observed the waveform changes due to increased ICP in patients with a severe head trauma. Morgalla et al. [4] evaluated parameters like amplitude, min, max and slope to analyze the waveform and Hu et al. [5] developed an integrative approach describing the waveform by the amplitude of the peaks, the temporal distance between them and relationships like the rise time of a peak. The group of these parameters is called "Morphological Clustering and Analysis of Intracranial Pressure Metric group", or short MOCAIP Metric group. Research has in recent years focused on automated learning of different waveforms [6]. Further research has been done, to automatically assign determined features of a waveform to a high or low ICP for example with dynamic time warping by Cuesta-Frau et al. [7].

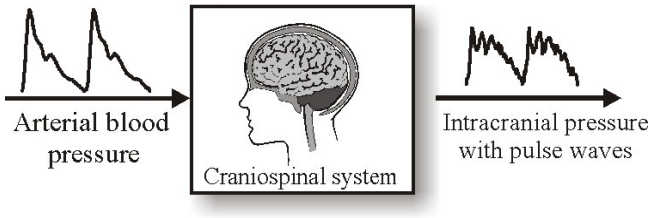

Figure 1. Arterial pressure influences intracranial pressure, [1].

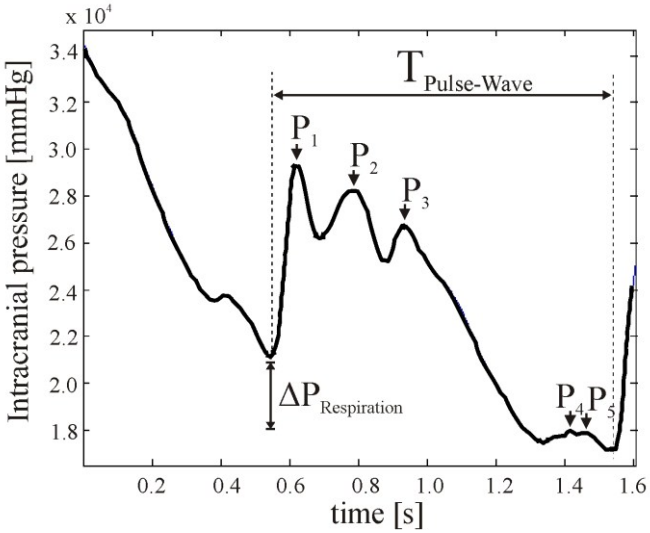

Figure 2. A typical single pulse waveform due to heartbeat

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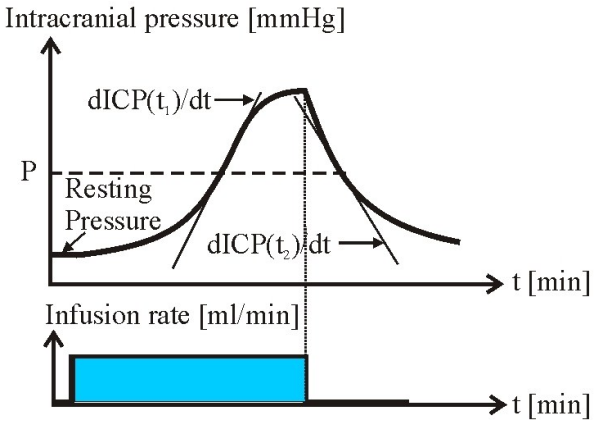

Figure 3. Principle of a dynamic infusion test

In this work, an algorithm is proposed which automatically extracts each single pulse in the ICP signal and categorizes them into one of five predefined waveform patterns in order to determine the patient's state. The main distinction of this algorithm is that it works with few computations only and independently of a possible drift of the pressure sensor by using only relationships of pressure amplitudes. This development enables the algorithm to work later on a low cost microcontroller of an electromechanical implant.

This future electromechanical implant, which is still under development, is supposed to drain cerebrospinal fluid into another body compartment, whenever the pressure is too high or the compliance too low for the patient.

The proposed algorithm was already partly described by Krause et al. [8]. In this paper, all steps necessary for the algorithm will be explained in detail followed by extended results including also the consideration of cerebrospinal fluid parameters.

II. Medical Background Concerning Infusion Tests

To verify suspected diagnosis of hydrocephalus, an invasive procedure called "infusion test" to determine the CSF-dynamics can be performed. One option is inserting liquid at a constant rate into the cranium (into brain ventricles) and recording the pressure rise and fall after the infusion ended, which is called "dynamic infusion test" (s. Figure 3). The intracranial compliance C can be calculated from a dynamic infusion test as follows:

$$C(ICP) = I_{\inf} \cdot \left(\frac{dICP(t_1)}{dt} + \frac{dICP(t_2)}{dt} \right)^{-1} \quad (1)$$

with $dICP(t_1)/dt$ and $dICP(t_2)/dt$ being the pressure gradients in the rising and falling arms of the infusion test, is the infusion rate applied during the rising arm of the infusion test.

III. Materials

13 infusion tests of suspected idiopathic normal pressure hydrocephalus patients with an infusion rate of 3 ml/min have been evaluated. The intracranial pressure was measured at 100 Hz with a tip catheter connected to the Datalogger (Raumedic AG, Germany), a multimodal neuromonitor. The change in waveform patterns during the infusion tests has been visually analyzed and recorded in order to judge the performance of the algorithm.

IV. Algorithm

In the following, the three crucial parts of our single pulse analysis algorithm will be explained (s. Figure 4). In the first part, the pulse beat is extracted, which is needed for the second part to extract each single wave. The third part finally decides to which waveform pattern the single waves can be assigned to. Relative thresholds have been determined by optimization on a set of training infusion tests with a step size of ±0.125. A 5.12 s window of ICP data has been chosen as trade-off between computation time and exact pulse beat extraction.

A. Pulse beat extraction

The pulse beat has been determined by an algorithm similar to Aboy et al. [2]. To eliminate outliers in measurements a median filter with a length of five samples has been used.

Then the following lowpassfilter with the transfer function $H(z^{-1})$ has been used foreward and backward to have zero phase delay and eliminate measurement noise:

$$H(z^{-1}) = \frac{1}{3}(1 + z^{-1} + z^{-2}) \quad (2)$$

There is no need for a high pass filter because the respiratory waves are much slower than the pulse waves. The pulse time has been determined by comparing the maximum values of adjacent clustered data units U_i of 16 samples. If the maximum value of one unit is higher than the values of their neighbors' units, then the maximum of the P-wave has been found:

$$\max(U_{i-1}) < \max(U_i) < \max(U_{i+1}) \quad (3)$$

with i being the time index. With these data units, a signal with a heart frequency of up to 187.5 beats per minute can be analyzed. Again the median was calculated over a 5.12 s window to obtain the correct pulse time.

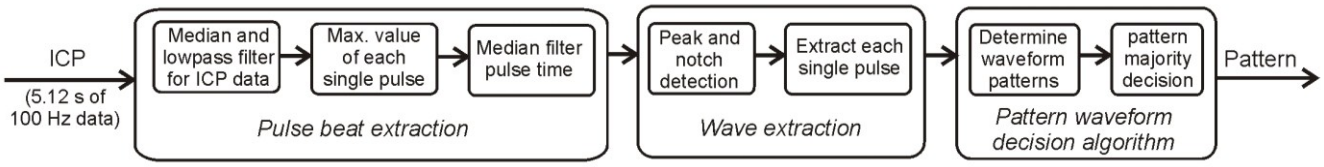

Figure 4. Entire algorithm to determine the waveform pattern from ICP measurements

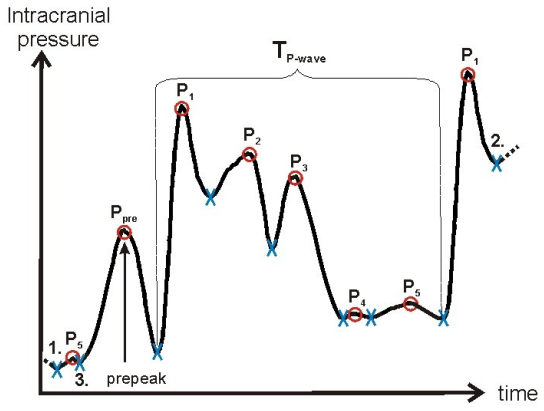

Figure 5. Determined peaks and notches in an ICP window and numbered elimination of notches according to the steps in the algorithm (circle=peak, cross=notch)

B. *Wave extraction*

An ICP pulse wave consists of one primary peak P_1 that is caused by arterial pressure due to the heart beat, and then possibly one or more peaks caused by reflections of the pulse wave and venous reaction, as can be seen in Figure 5. The primary peak does not have to be the highest peak. In order to extract exactly one wave, the time window has to be longer than one single wave. To determine the peaks and notches in this window, a comparison with the neighboring non-clustered samples was made.

Subsequently, the algorithm aims at reducing the window size in such a way that it contains only the wave starting from the notch before P_1 until the notch after the last existing peak P_i, in this example displayed in Figure 5 it is P_5. This was done by the following three steps. The effect can be followed by the numbered discarded notches in Figure 5.

1. Discard all notches at the beginning after which the following peak was not high enough (in relation to the P-wave amplitude).
2. Discard all notches at the end of the wave, which are too high (in relation to the minimal pressure of the wave).
3. To eliminate occasionally occurring prepeaks, discard the notch n_i before the first peak, if the following notch after this peak is too small in relation to the notch n_i.

C. *Waveform Pattern Decision Algorithm*

By analyzing infusion tests, 5 different waveform patterns have been identified changing from the first to the fifth pattern with increasing pressure and hence decreasing compliance (s. Figure 6).

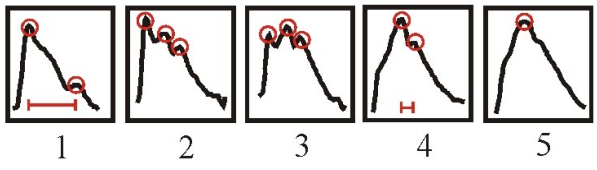

Figure 6. Predefined waveform patterns for the decision algorithm correlating with the patient's state of compliance

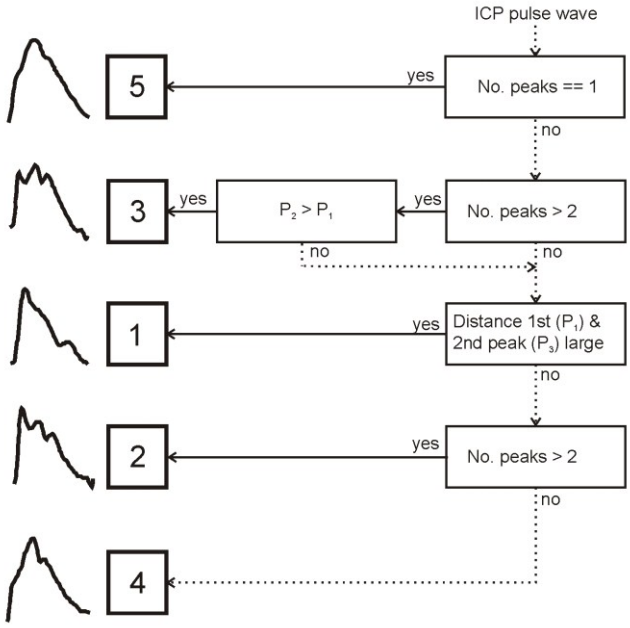

Figure 7. Developed pattern decision algorithm

After having identified all peaks and notches belonging to the P-wave as described in the subsection before, the following aim was to categorize the wave and therefore draw conclusion about the patient's state. The algorithm developed (s. Figure 7) makes it possible to decide between patterns by only few comparisons. Key features are the number of peaks, their relative height amongst and their spatial distance between them. Thresholds were chosen to be powers of 2. This enables the microcontroller to perform fast multiplications by shifting bits.

All waves in a window of 5.12 s were categorized and the valid pattern was determined by a majority decision of all found patterns. If the number of occurring patterns was the same, no pattern was determined for this window.

V. RESULTS

A. *Identified patterns*

As already mentioned, five different patterns have been identified by studying infusion tests (s. Figure 6). This is quite similar to the finding of Contant et al. [3] except that in this paper, one more pattern (pattern 4) was determined. Not all patients developed all kind of waveforms during the infusion test. Some started already with pattern 2 and some never developed pattern 4 and 5. Most of the time, patterns 1 to 5 appeared in the numerical order but one patient for example did have pattern 4 and constantly the highest P-wave amplitude of all infusion tests.

One special kind of wave has rarely been observed in some patients. This special wave was characterized by a high prepeak in front of P_1 and a low notch after this prepeak (s. Figure 5). In literature, this kind of prepreak has not been explained yet and was thus discarded.

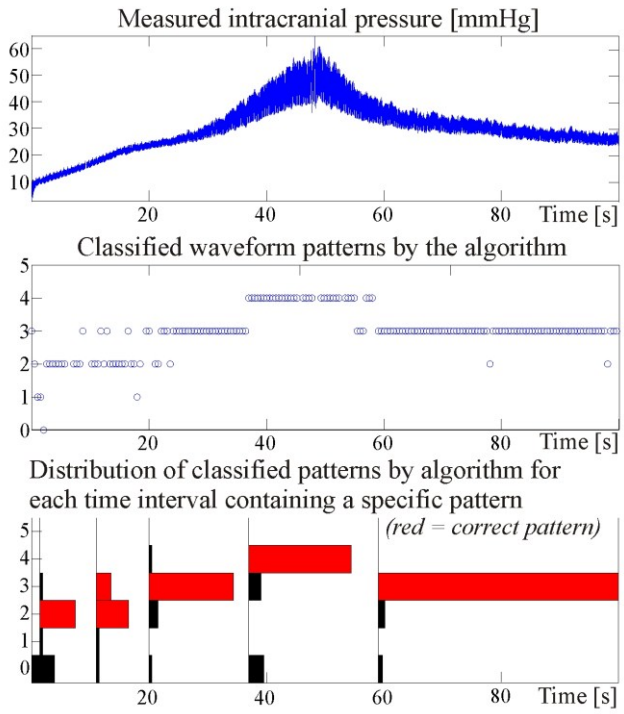

Figure 8. Evaluated infusion test of one patient serving as an illustrative example

B. *Recognition of patterns by the algorithm*

The algorithm has been tested on the 13 infusion tests and was compared to visual judgement. Figure 8 shows the result of one infusion test as example. The first plot shows the recorded intracranial pressure over time, in the second plot each circle is the output of the algorithm concerning the determined pattern number. If no pattern could be classified, the algorithm outputs the value zero. The last plot shows the distribution of the determined patterns of the algorithm for each time slot, where the pattern has been visually judged as constant with the visually determined pattern in red. Hence if there is only a red bar, the algorithm has been categorized the pattern correctly all the time. Overall, the algorithm determined the right pattern with 88 %±8 % (mean ± SD) using only classifiable patterns (90 %).

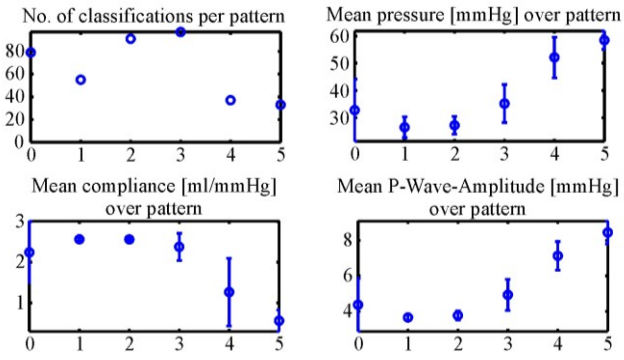

Figure 9. Dynamic cerebrospinal fluid parameters over classified waveform patterns (1 to 5) of one patient

C. *Relationship of Patterns to dynamic cerebrospinal fluid parameters*

For each measuring value of the dynamic infusion test, the compliance has been calculated and ordered by the classified patterns. The same was done for the mean pressure and the P-wave amplitude. Figure 9 shows the result of one infusion test. The patterns identified by the algorithm correlate with the mean pressure, the compliance and the P-wave amplitude for this infusion test with significant correlation of 0.8 – 0.9.

VI. Conclusion and Outlook

A P-wave categorization algorithm has been developed, which can be easily implemented on a microcontroller. This algorithm can automatically identify and categorize the P-wave. The algorithm is independent on pressure drift and might thus be suitable for a future hydrocephalus implant which recognizes intracranial condition over a long time and drains cerebrospinal fluid whenever necessary.

The next step is to identify whether the patterns correlate with the well-being of a patient and with dynamic cerebrospinal fluid parameters all the time. It is also left to evaluate, if the pattern waveform is independent of the heartbeat rate.

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