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Normalized Power Transmission between ABP and ICP in TBI

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Abstract— **A new approach to study the pulse transmission between the cerebrovascular bed and the intracranial space is presented. In the proposed approach, the normalized power transmission between ABP and ICP has got the main attention rather than the actual power transmission. Evaluating the gain of the proposed transfer function at any single frequency can reveal how the percentage of contribution of that specific frequency component has been changed through the cerebrospinal system. The gain of the new transfer function at the fundamental cardiac frequency was utilized to evaluate the state of the brain in three TBI patients. Results were assessed using the reference evaluations achieved by a novel CT scan-based scoring scheme. In all three study cases, the gain of the transfer function showed a good capability to follow the trend of the CT scores and describe the brain state. Comparing the new transfer function with the traditional one and also the index of compensatory reserve, the proposed transfer function was found more informative about the state of the brain in the patients under study.**

I. INTRODUCTION

The prime aim in neurointensive care of traumatic brain injury (TBI) patients is to prevent and treat secondary brain injury. At the moment, the only reliable way to detect changes of the brain parenchyma is to perform computer assisted tomography (CT) or magnetic resonance imaging (MRI). These investigations give a momentary picture of the brain and often have to be repeated several times a day which means that the patient should be transported, repeatedly. Since high intracranial pressure (ICP) has been found to be an important cause of secondary brain injury, ICP monitoring has become a well-established practice in most neurointensive care units. Today the time average of the ICP signal is usually used in clinical practices to guide a cerebral perfusion pressure (CPP)-oriented protocol [6] or to evaluate the dynamic state of the brain. However, many researchers have belief in more valuable information, hidden in the ICP waveform, which is correlated to cerebral dynamics and can be used for early detection and monitoring the development of secondary injuries. Various investigation has been performed based on this shared sentiment, and many still are ongoing.

Applying system identification methods to ICP analysis goes back to 1980 when Portnoy and Chopp described the cerebrovascular system as a black box model [1]. In their model arterial blood pressure (ABP) was defined to be the main input to the system and ICP as the output response to that stimulus. The idea behind this type of investigation was that the intracranial compliance can have a frequency dependent nature [9]. In 1982, investigation by Portnoy and his colleagues showed that in case of low ICP in dogs, there exists an amplitude attenuation at the fundamental frequency, while during hypercapnia or intraventricular infusion the transfer function looks more flat in amplitude [5].

Employing similar methods, the existence of a positive correlation among the raised ICP and the amplitude of the first four cardiac harmonics in both the ICP waveform and transfer function was shown by Takizawa and co-workers [8]. This result is identical to the concept behind the index of compensatory reserve (RAP), where, a high correlation among the ICP wave pulse amplitude and the ICP level is expected in the case of low cerebral compliance [2]. About the same time Kasuga, who was studying cerebrovascular transmission in dogs, showed that the lower frequencies of the pulse wave are suppressed during transmission through the intracranial cavity [3]. Later, in 1990, Piper employed the system analysis method to study the cerebrovascular pressure transmission in 1500 ICP records, collected from 30 TBI patients [4]. According to his results, the elevated amplitude at the fundamental cardiac frequency was associated with raised ICP, while a low amplitude at that frequency was associated with ICP less than 15 mmHg. Recently a time-varying transfer function, which uses autoregressive moving average (ARMA) modeling, was applied by Zou and his colleagues to ICP and ABP signals collected from dogs [9]. Their investigations revealed an existence of a deep notch in the amplitude of the transfer function, centered at or close to the cardiac frequency for normal cases with normal ICP. This notch was suppressed when ICP was increased by a bolus injection. This is very similar to the results, reported by Portnoy in 1982 and Kasuga in 1987. They came to the conclusion that there may exist a pulsation absorber in intracranial system in animals for which the target frequency appears to be close to the cardiac frequency. The free movement of cerebrospinal fluid considered as one possible source for such an absorbing mechanism.

Although all the above mentioned studies emphasize on the amount of the amplification of the fundamental cardiac component as an important feature of the brain state, it is still unclear how this feature should be utilized. The gain of the transfer function could be the first option to come to mind, however its usability has been doubted due to several considerations. First, the transfer function by default assumes there exist a linear transmission from input to the output. Such assumption may not be valid when it comes to biosignal

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considerations, particularly in pathological circumstances [2]. Second, the pulsation of the ICP signal is damped by performing decompressive craniectomy surgery. This restricts the gain of the transfer function from being used in patients who have a greater need to be continuously monitored. In this study we introduced a new transfer function which measures the normalized power transmission between the ABP and ICP. The gain of the proposed transfer function can be used as a factor to find out how the percentage of contribution of one specific frequency component is changed through the cerebrospinal system. A novel scheme of CT scan scoring has been employed to provide a set of reliable references. The capability of the new transfer function to evaluate the state of the brain is assessed using the CT scan scores and is also compared to the performance of the traditional transfer function between ABP and ICP and the index of compensatory reserve.

II. Materials

A. Data acquisition

Clinical data was acquired from three subjects admitted to the Neurointensive Care Unit at Sahlgrenska University Hospital in Gothenburg, Sweden. Subject 1 was a 55-year-old male who had fallen from height of 4 meters. During sixteen consecutive days (some discontinuity was found between days 7 and 9), ICP and ABP measurements were collected by a Datex-Ohmeda S/5 critical care monitor at the sampling rate of 300Hz. Five CT scans have been performed on days 1, 8, 10, 13 and 14. Patient had a decompressive craniectomy surgery on day 8 to compensate for swelling and high ICP. Patient died on day 18.

Subject 2, a 50-year-old male, faced a head trauma as a result of a bicycle accident. Pressure signals were collected during twelve days. Four CT scans, on days 1, 2, 5 and 8, were available. High ICP was mainly treated using medications and draining out the cerebrovascular fluid through the ventriculostomy.

Finally, patient 3 was an unknown age male, who was subject to a head trauma in a motor vehicle accident. Patient monitored during nineteen days and seven CT scans performed on day 1, 3, 6, 8, 10, 11 and 14. A decompressive craniectomy was performed on day 3 due to the brain swelling and high ICP.

B. CT Scan Scoring

Each CT scan image was examined by an expert and scored based on Marshall CT scan scores, degree of visible compression in brain structure (i.e. brain stem), existence of hematoma (including epidural, subdural and subarachnoid), visibility of sulcal pattern and existence of contusion. The scoring was performed by the intention of evaluating the evolution of an individual over time and therefore should be regarded as a scoring system within patients rather than between them. All scores, except those based on Marshal CT scan classification, were determined based on comparison between all CT images captured from the individual and probably do not represent the identical phenomena in different patients.

Table I represents the scoring criteria that has been utilized in the CT scan scoring. As it can be recognized from the table, Marshall CT scores I to IV have been mapped to scores 0 to 3 respectively. Both degrees of compression and sulcal pattern visibility were defined to be in the range of 0 to 3, while absence or existence of hematoma or contusion was described by 0 and 1, respectively. In all cases, the higher the score is, the more severe state of brain is represented.

TABLE I
SCORING CRITERIA

Basis.	Score
Marshal CT scan scores	0-3
Degree of compression	0-3
Existence of hematoma	0-1
Sulcal pattern visibility	0-3
Existence of contusion	0-1

III. Methodology

The response of the cerebrospinal system to the pulsatile stimuli is usually studied through the transfer function between ABP and ICP, $H(\omega)$, which relates input and output signals by

$$Y(\omega) = H(\omega)U(\omega) \tag{1}$$

where $U(\omega)$ is the input to the cerebrospinal system (here ABP) and $Y(\omega)$ represents the system output (ICP). The magnitude of the identity in (1) can be rewritten as

$$\frac{|Y(\omega)|^2}{\sum_\omega |Y(\omega)|^2} = |H(\omega)|^2 \frac{\sum_\omega |U(\omega)|^2}{\sum_\omega |Y(\omega)|^2} \frac{|U(\omega)|^2}{\sum_\omega |U(\omega)|^2} \tag{2}$$

where $\frac{|U(\omega)|^2}{\sum_\omega |U(\omega)|^2}$ and $\frac{|Y(\omega)|^2}{\sum_\omega |Y(\omega)|^2}$ refer to the normalized power of the input and output signals on the specific frequency of ω, respectively. The first two terms, in the right hand side of (2) we define as

$$|F(\omega)|^2 \triangleq |H(\omega)|^2 \frac{\sum_\omega |U(\omega)|^2}{\sum_\omega |Y(\omega)|^2}. \tag{3}$$

By substituting (3) in (2), we obtain

$$\frac{|Y(\omega)|^2}{\sum_\omega |Y(\omega)|^2} = |F(\omega)|^2 \frac{|U(\omega)|^2}{\sum_\omega |U(\omega)|^2} \tag{4}$$

In the above equation $|F(\omega)| < 1$ simply means that the percentage of contribution of the frequency component of ω to the output signal spectrum has been suppressed by the system. In the same manner $|F(\omega)| > 1$ and $|F(\omega)| = 1$ will be, in order, informative of the amplified and equal percentage of contribution. According to what has been explained above, $|F(\omega)|$ can be regarded as the gain of a new transfer function that measures the normalized power transmission between input and output signals by

$$F(\omega) = \frac{\frac{Y(\omega)}{(\sum_\omega |Y(\omega)|^2)^{0.5}}}{\frac{U(\omega)}{(\sum_\omega |U(\omega)|^2)^{0.5}}} \tag{5}$$

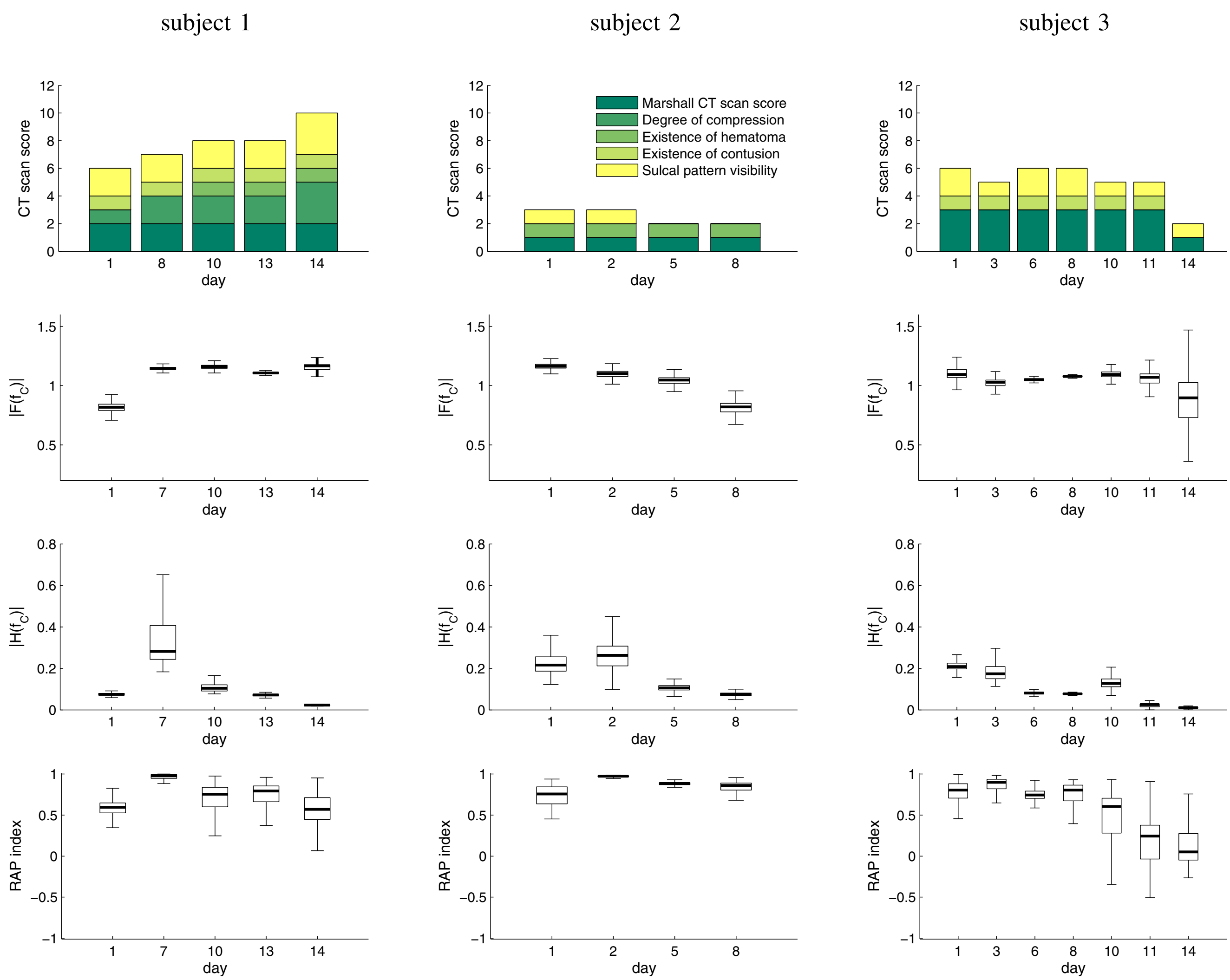

Fig. 1. Summary of the achieved result. Each column refers to one of the three subjects under study. *The first row:* represents the scores achieved by a novel CT scan evaluation scheme. Scoring is based on Marshall CT scan scores, degree of the visible compression in the brain structure, degree of the sulcal visibility and existence of hematoma and contusion. *The second row:* Boxplot of the gain of the proposed transfer function at the fundamental cardiac frequency. *The third row:* Boxplot of the gain of the traditional transfer function at the fundamental cardiac frequency. *The forth row:* Boxplot of the indices of compensatory reserve (RAP indices). Each box contains one hour data.

Note that $F(\omega)$ is a scaled version of $H(\omega)$ and contains all morphological characteristics of $H(\omega)$. An interesting aspect of this new transfer function is that the value at a particular frequency reveals if the transfer function at that point contains a peak or valley. This feature makes $F(\omega)$ an interesting candidate to study the cerebrospinal system at the fundamental cardiac frequency when patients experience different pathological circumstances.

In order to estimate $F(\omega)$, the frequency components of both ICP and ABP signals need to be calculated. The Discrete Fourier transform (DFT) is a traditional approach to the mentioned problem; however a signal decomposition method similar to that specified in [7] has been used in the current study. First the pressure signal is represented by

$$y_t \quad = \quad \tilde{y}_t + x_t \tag{6}$$

where y_t denotes the pressure signal and $\tilde{y}_t$ refers to the pulsation of the pressure signal due to respiratory or circulatory excitations. Here, x_t represents the remaining part including slow waves and the DC components. Later the effect of the DC component and also slow waves was removed through a filtering process. By this, we availed ourself of rewriting (6) as

$$\tilde{y}_t = \sum_{k=1}^{m} a_{k,t,r}\cos(\theta_{k,t}) - a_{k,t,i}\sin(\theta_{k,t}) \tag{7}$$

such that

$$\theta_{k,t} = mod_{2\pi}\{\theta_{k,t-1} + 2\pi f_{k,t} T_s\} \tag{8}$$

where $\theta_{k,t}$ denotes instantaneous phase, $f_{k,t}$ refers to instantaneous frequency and T_S is sampling time. The number of harmonics, denoted by m, is assumed to be known a priori. In this study, based on the spectrum analysis of the pressure signals, the following 20 different harmonics were used,

$$\mathbf{f} = [f_R,\ 2f_R,\ 3f_R,\ f_C-2f_R,\ f_C-f_R,\ f_C,\ f_C+f_R,\ 2f_C-f_R,\ 2f_C,\ 2f_C+f_R,\ 3f_C,\ 4f_C,\ 5f_C,\ 6f_C,\ 7f_C,\ 8f_C,\ 9f_C,\ 10f_C,\ 11f_C,\ 12f_C]^T \quad (9)$$

where f_R and f_C represent respiratory and cardiac rates, respectively. The involved parameters in (7) were estimated through recursive filtering by employing the Kalman filter.

IV. RESULTS

At the time of each available scored CT scan, one hour of the data was collected. In all cases, the data was collected before performing the CT scan. Although the aim was to use the data from the one hour window exactly prior to the CT imaging, it was not possible for all the CT scans. In one case (subject 1), no data on day 8 was available and therefore data from day 7 was utilized instead. The gains of the proposed transfer function, $F(\omega)$, and the traditional transfer function, $H(\omega)$, were estimated at the fundamental cardiac frequency. The indices of compensatory reserve (RAP indices) were estimated for each data record based on the algorithm described by [2].

Figure 1 summarizes the achieved results in 3 columns, each referring to one of the three subjects. The first row in the figure represents CT scan scores. Five different colors were used in order to illustrate the different parameters, contributed to the scoring scheme. The second row represents the box plots of the gains of the proposed transfer function, while the gains of the traditional transfer function are demonstrated in the third row. Boxplots are usually used to display differences between populations without making any assumptions of the underlying statistical distribution. Each box has lines at the lower quartile, median (highlighted line within the box), and upper quartile values. The lines extending from each end of the box are whiskers to show the extent of the rest of the data. Box plots of the RAP indices can be found in the last row.

In subject 1, the CT score on day 1 is evaluated to be around 6. This score shows tendency toward higher values over time, indicating an increasingly sever condition in brain. Despite a decompressive craniectomy on day 8, the CT score reaches to its highest level on day 14, mainly due to more visible compression in the brain structure and less visibility of sulcal pattern. For the same subject, the gains of the proposed transfer function were distributed around 0.8 on day 1. This can be regarded as the existence of a notch or valley in the transfer function between ABP and ICP at the fundamental cardiac frequency. On day 7, the transfer function shows a gain which is approximately 1.2. This simply means that ICP got a larger contribution from the fundamental cardiac component compared to ABP. Absence of the notch in the transfer function implies that the claimed pulsation absorber in the intracranial system did not work properly. Between days 7 and 13 the gain remains in values larger than 1 and on day 14, in spite of craniectomy, reaches to the highest level. The whole trend represents a good level of agreement with CT scan scores. In the third row, the gain of the traditional transfer function follows the similar trend as CT scores and gains of the proposed transfer function between days 1 and 7. However, on day 10 it shows a dramatic decrease due to the decompressive craniectomy. The traditional transfer function loses its usability after decompressive craniectomy, as the open skull acts like a damper. Although, the increase in RAP indices from day 1 to day 7 and their concentration around +1 on day 7 are in agreement with the CT scores, the tail of the trend does not match to the trend of the CT scores.

In subject 2, the CT scores imply an improvement in the state of the brain as they decrease over time. The same scenario can be seen in the gain of the proposed transfer function, where it evolves from value 1.2 on day 1 to 0.8 on day 8. The gain of 0.8 at the last day emphasizes on the suppressing of the fundamental cardiac component in the intracranial space and the presence of a notch in the transfer function. None of the other two plots show similar trend.

In subject 3, scores extracted from the CT scans introduce a more complex trend. The trend starts from score 6 on day 1 and experiences a small valley on day 3. However on days 6 and 8, trend goes back to the initial level. Finally on day 10 another fall appears in the trend which reaches to the minimum level of 2 on day 14. Looking at the gains of the proposed transfer function, a similar complexity can be recognized in the trend. Two valleys of the trend happened on days 3 and 14 which are in complete agreement with those in the trend of the CT scan scores. However compared to the trend of the CT scan scores, the second peak of this trend got a tendency toward right. In general an interesting level of similarity can be recognized in two trends. On day 14, existence of a notch in the transfer function can be recognized from the gain that is below 1. Due to the performed decompressive craniectomy on day 3, gains of the traditional transfer function in the third row are not reliable anymore. As it can be seen in the last plot, the evolution of the RAP indices do not follow the same pattern as the CT scan scores.

V. SUMMARY

In this paper, to evaluate the state of the brain in patients with TBI, a new transfer function has been proposed. The new transfer function is the traditional transfer function between ABP and ICP which has been scaled to the ratio between the power of the pulsation in ICP and that of ABP. Hence, the proposed transfer function does not show the actual gain in each frequency component. Instead it defines how the contribution of different frequencies in the pulsation of ABP are tuned by the cerebrospinal system to construct the specific waveform in ICP. As mentioned previously, existence of a notch in the fundamental cardiac frequency is claimed to be an important feature of an intact cerebrospinal system. Using the proposed transfer function, existence of this phenomenon can be examined through the evaluation of the transfer function gain at the fundamental cardiac frequency. This unique feature of the new transfer function reduces the complexity of the employed algorithms both in time and space and increases the comprehension of the cerebrospinal evolution over time.

To evaluate the performance of the proposed transfer function, its gain at the fundamental frequency was compared to the scores achieved by a CT scan-based evaluation of the patients. In all three study cases, an interesting level of agreement has been found between two sets of parameters. Comparing the result with those achieved from the traditional transfer function and also the index of compensatory reserve, the proposed transfer function was found to be more informative about the state of the brain in the mentioned group of patients. It was found to be a reliable parameter even after decompressive craniectomy, where the traditional transfer function usability fails due to the damping effect. To examine the true capability of the transfer function between normalized ABP and ICP to describe the brain state, further assessment with a larger population of patients will be needed.

REFERENCES

[1] M. Chopp and H.D. Portnoy. System analysis of intracranial pressure. comparison with volume-pressure test and csf-pulse amplitude analysis. *Journal of Neurosurgery*, 53(4):516–527, 1980.

[2] M. Czosnyka, P. Smielewski, I. Timofeev, A. Lavinio, E. Guazzo, P. Hutchinson, and J.D. Pickard. Intracranial pressure: More than a number. *Journal of Neurosurgical Focus*, 22(5):1–7, 2007.

[3] Y. Kasuga, H. Nagai, Y. Hasegwa, and M. Nitta. Transmission characterestics of pulse waves in intracranial cavity of dogs. *Journal of Neurosurgery*, 66(6):907–14, 1987.

[4] I.R. Piper, J.D. Miller, N.M. Dearden, J.R. Leggate, and I. Robertson. Systems analysis of cerebrovascular pressure transmission: an observational study in head-injured patients. *Journal of Neurosurgery*, 73:871–80, December 1990.

[5] H.D. Portnoy, M. Chopp, C. Branch, and M.B. Shannon. Cerebrospinal fluid pulse waveform as an indicator of cerebral autoregulation. *Journal of Neurosurgery*, 56(5):668–678, 1982.

[6] M.J. Rosner, S.D. Rosner, and A.H. Johnson. Cerebral perfusion pressure: management protocol and clinical results. *Journal of Neurosurgery*, 83:949–62, 1995.

[7] S. Shahsavari and T. McKelvey. Harmonics tracking of intracranial and arterial blood pressure. In *Proceedings of the 30th Annual International Conference of the IEEE*. Engineering in Medicine and Biology Society, 2008.

[8] H. Takizawa, T. Gabra-Sanders, and J.D. Miller. Changes in cerebrospinal fluid pulse wave spectrum associated with raised intracranial pressure. *Journal of Neurosurgery*, 20(3):355–61, 1987.

[9] R. Zou, E.H. Park, E. McCormack Kelly, M. Egnor, M.E. Wagshul, and J.R. Madsen. Intracranial pressure waves: characterization of a pulsation absorber with notch filter properties using systems analysis. *Journal of Neurosurgery: Pediatrics*, 2(1):83–94, 2008.