

A comparison between the transfer function of ABP to ICP and compensatory reserve index in TBI

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Abstract

Background The transfer functions which map the arterial blood pressure to the intracranial pressure and the compensatory reserve index have been investigated by various groups to evaluate the brain compliance of patients with traumatic brain injury. The focus of this study has been to assess the capability of both the above mentioned methods to monitor the intracranial compliance in patients suffering from brain swelling.

Materials and methods Clinical data was collected from sixteen traumatic brain injury patients and split into 4 min segments. For each segment, both the magnitude of the empirical transfer function at the fundamental cardiac frequency and the compensatory reserve index were extracted.

Findings The mean values of the compensatory reserve index and the magnitude of the transfer function which scored higher than 0.7 and 0.1 respectively were recorded for all patients suffering from brain swelling. By comparing the histogram of the magnitude of the transfer function

at the fundamental cardiac frequency with the histogram of the compensatory reserve index for all patients, a positive correlation between the mean values and a negative correlation among their variances were observed. The linear correlation between the mean values was estimated at $r=0.82$ ($p<0.0001$).

Conclusions These observations suggest that to evaluate the intracranial compensatory reserve, the magnitude of 0.1 could be a useful threshold for the transfer function at the fundamental cardiac frequency.

Keywords Arterial blood pressure (ABP) · Compensatory reserve index (RAP) · Transfer function · Intracranial pressure (ICP) · Traumatic brain injury (TBI)

Introduction

Head injuries are important causes of disability and death in people of all ages. In the neurointensive care of patients with traumatic brain injury or other cerebrovascular diseases such as stroke or subarachnoid hemorrhage, a principal objective is to minimize the risk of secondary injury. Intracranial hypertension or brain swelling which can follow severe traumatic brain injury are life threatening complications which can cause serious permanent damage to the brain and even lead to death. This is due to the fact that the brain is enclosed in a non-expanding cavity and swelling leads to an increased pressure which at high levels can initiate cerebral ischemia or cause structural damage to brain tissues. If such incidents of brain swelling could be better predicted, the treatment of secondary injury could be made more selective and provide better overall results. Today, brain swelling is mainly monitored by measuring the intracranial pressure (ICP) and the cerebral perfusion

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pressure (CPP) which is defined as the difference between the mean arterial pressure (MAP) and ICP. However, clinical experiences show that the monitored data cannot give enough information regarding the intracranial regulatory processes. 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, sometimes several times a day, and in most instances require the patient to be transported. Several investigations have attempted to find a solution to the demand of reliable and continuous brain monitoring and as a result different concepts have been proposed and applied to this area. In the time domain, the pressure–volume curve and the term “compensatory reserve” which have been introduced by Langeftt et al. [5] and Lofgren et al. [6] are foundations of many studies. More recently much attention has been paid to the volume–pressure compensatory reserve index (RAP) which determines the level of linear correlation between the amplitude of the ICP wave (AMP) and the mean of ICP (ICP_{mean}) [2–4]. The RAP index is not able to define the steepness of the volume–pressure curve as is done by the pressure–volume index (PVI) [7], but it is able to classify the volume–pressure curve into three distinct regions corresponding to: good pressure–volume compensatory reserve, poor pressure–volume compensatory reserve and deranged cerebrovascular reactivity [4]. A RAP coefficient close to 0 indicates an asynchrony between the simultaneous changes in AMP and ICP_{mean} and hence it implies a good compensatory reserve. A RAP index around 1

indicates that the changes in AMP and ICP_{mean} are synchronized and is therefore the indicator of a poor compensatory reserve. In the frequency domain, the study of the pulse transmission between ABP and ICP has a long history [8]. In this approach the brain is modeled as a dynamic system with ABP wave as the input and ICP wave as the output. The idea behind this method is that any change in the transfer function between input and output is indicative of a change in the system itself. Piper and his group defined four different curves for the magnitude of the transfer function (MTF), and classified them into two classes of low and high ICP [8]. According to their observations, elevated ICP was associated to the larger MTF at the fundamental cardiac frequency. This study is an attempt to utilize the above mentioned time and frequency domain methods to explore their potentials to monitor the brain swelling in TBI patients. During this study, patients were clinically classified according to their injury type and later on divided into two groups corresponding to with and without brain swelling.

Materials and methods

Clinical data was collected from sixteen patients admitted to the Neurointensive Care Unit at Sahlgrenska University Hospital in Gothenburg, Sweden. The underlying intracranial pathology for each patient was classified according to the clinical information which is summarized in Table 1. Five patients had brain swelling and four of them underwent decompressive craniectomy surgery to give the brain more

Table 1 Clinical profile of studied group

Patient	Age/sex	CT classification	Mechanism of injury	Surgical treatment	Data length (h)
1	41F	Contusion	Fall	Evacuation of contusion	13
2	26M	DAI	TA	–	24
3	60F	SAH	–	–	26
4	66F	EDH, CCF	Fall	Evacuation of EDH, Embolization	168
5	42M	SDH, Contusion, Brain swelling	WA	Evacuation of SDH and contusion, Craniectomy	43
6	51M	–	Fall	–	342
7	65M	SDH	Fall	Evacuation of SDH	23
8	56F	SAH	–	–	70
9	20F	DAI, Contusion, Brain swelling	Fall	–	193
10	55M	Contusion, Brain swelling	Fall	Evacuation of contusion, Craniectomy	306
11	38M	DAI	TA	–	29
12	69F	SDH, Contusion	–	Evacuation of SDH and contusion	376
13	21M	EDH, Brain Swelling	TA	Evacuation of EDH, Craniectomy	12
14	36M	Brain Swelling	TA	Craniectomy	18
15	50M	SAH, DAI, Contusion	TA	–	306
16	18F	SDH	Fall	Evacuation of SDH	175

CCF carotid cavernous fistula, DAI diffuse axonal injury, EDH epidural hematoma, SAH subarachnoidal hematoma, SDH subdural hematoma, TA traffic accident, WA work accident

space to swell and compensate for the high intracranial pressure. ICP was monitored continuously using either a parenchymal fiber optic pressure transducer (ICP express, Codman) or a ventricular catheter (Medtronic). A Datex-Ohmeda S/5 critical care monitor collected both ICP and ABP measurements. These signals were collected from an S/5 network, using S5-collecting software at the sampling rate of 300 Hz and stored on CD-ROM.

The 300 Hz sampled data was downsampled to 30 Hz. The entire data for each patient was broken up into 4 min segments. In case of craniectomy, only the recorded data before craniectomy was used. Length of data for each patient can be seen in Table 1. Both ABP and ICP segments were first smoothed by a Blackman-Tukey window and then using a 4096 point FFT transformed to the frequency domain (frequency resolution 0.007 Hz). The fundamental frequency (F_C) of the cardiac components for each segment was estimated using a search algorithm to find the bin with the highest magnitude value in ABP. Although the amplitude of the fundamental component appears to be resilient to noise, a small error in estimation of the fundamental frequency will turn to the large deviations in higher harmonics. Therefore, to compensate for the effect of noise and make a robust estimation of the fundamental frequency and its magnitude, a quadratic function was fitted to the magnitude of ABP at the frequency range of $f=[F_C -0.3 \text{ Hz}; F_C +0.3 \text{ Hz}]$. The desired quadratic function was linearly modeled as

$$\mathbf{X} = \mathbf{H}\boldsymbol{\theta} + \mathbf{W}$$

where \mathbf{X} is the vector of magnitudes, \mathbf{H} is a known observation matrix dependent on f , $\boldsymbol{\theta}$ is a vector containing curve parameters to be estimated and \mathbf{W} is the unknown

noise. The least square (LS) estimation of $\boldsymbol{\theta}$ was simply found using:

$$\boldsymbol{\theta} = (\mathbf{H}^T \mathbf{H})^{-1} \mathbf{H}^T \mathbf{X}$$

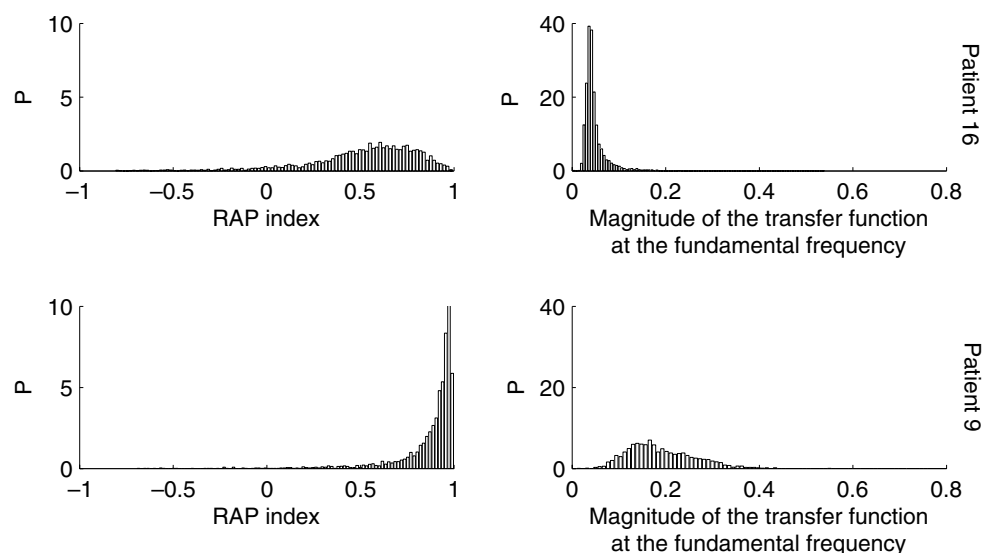
Knowing the curve parameter, the maximum of the quadratic function and the respective frequency were used as an updated estimation for the fundamental frequency and its magnitude in ABP. Fitting another quadratic function to the magnitude of ICP around the estimated fundamental frequency, the magnitude of ICP was found and subsequently MTF at the fundamental frequency was calculated as the ratio between the ICP and ABP magnitudes.

In the next step the amplitude of ICP was calculated using a time domain method which measures the peak-to-peak value of ICP waveform directly from the time domain samples. ICP beats were detected for each ICP segment employing an automatic pressure waveform components detector algorithm [1]. AMP and ICP_{mean} were extracted for each beat, averaged over a 6 s interval and subsequently used to calculate the RAP index of each segment by determining the linear correlation between them.

Results

Histograms of MTF and RAP coefficients were plotted for each of the sixteen patients. It was recognized that whenever MTF has a sharp and concentrated distribution around small values, the RAP index shows a broad and smooth distribution stretched from the values close to 1 toward -1 . In a similar way, the wider distribution of MTF, extended toward the larger values, was observed for the sharp and concentrated distribution of the RAP index around 1. The

Fig. 1 Histograms of MTF and RAP coefficients are shown for patient 16 (*top panels*) and patient 9 (*bottom panels*). In *top panels* MTF has a sharp and concentrated distribution below 0.1, while RAP index indicates a smooth distribution between -0.3 and 1. The opposite situation can be recognized in bottom panels. The wider distribution of MTF extended between 0.005 and 0.4 is observed for the sharp and concentrated distribution of RAP index around 1



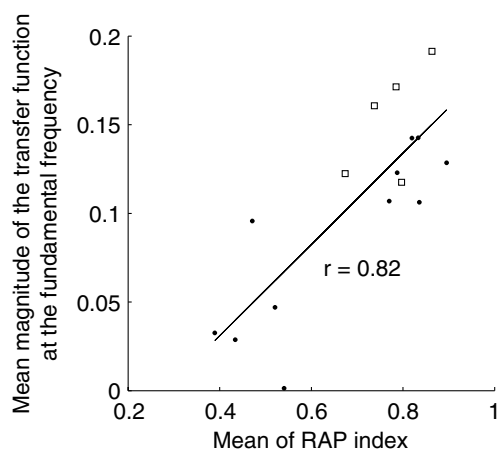


Fig. 2 Mean of MTF versus mean of RAP index. Patients with brain swelling are highlighted by the *square marks*. For mean RAP index less than 0.7, mean of MTF below 0.1 is observed, while for mean RAP index greater than 0.7, mean MTF above 0.1 is the most probable. Note that all brain swelling patients are positioned in the region with the high mean values for both MTF and RAP coefficient case of concentrated MTF can be seen in the top panels of Fig. 1, which show the distributions of MTF and RAP coefficients from patient 16. The bottom panels of Fig. 1, represent the case of concentrated RAP index and are from patient 9 (who was a patient with brain swelling.).

The mean value of MTF versus the mean value of RAP coefficients are shown in Fig. 2. A linear correlation of $r=0.82$

($p<0.0001$) has been estimated to be exist between these values. For a RAP index scored lower than 0.7, MTF below 0.1 are most probable while for the larger values of RAP index, MTF values larger than 0.1 are observed. In this figure patients who suffered from brain swelling have been marked with squares. Note how all these values are concentrated in the right side of the window with high mean values of both MTF and RAP coefficient, with three of them having the largest mean values of MTF. Although five members of the non-brain swelling patients have low mean values concentrated in the left side of the window, the other six show mean values of MTF and RAP coefficient above 0.7 and 0.1 respectively, which could be suggestive of a poor pressure–volume compensatory reserve in these patients. However, there is no clinical proof of brain swelling for this group.

Figure 3 represents the box plot of MTF and RAP coefficients over only 1 h time segment for two groups of patients with and without brain swelling (left and right panels respectively). In this part of study, only the data from five patients without brain swelling who had the least amount of MTF and RAP index (see Fig. 2) were used. For patients with brain swelling who had decompressive craniectomy, MTF and RAP index were extracted just before the surgery. As observed in the left panels, all the patients with brain swelling had the median of RAP index above 0.8 and the median of MTF above 0.13, with the

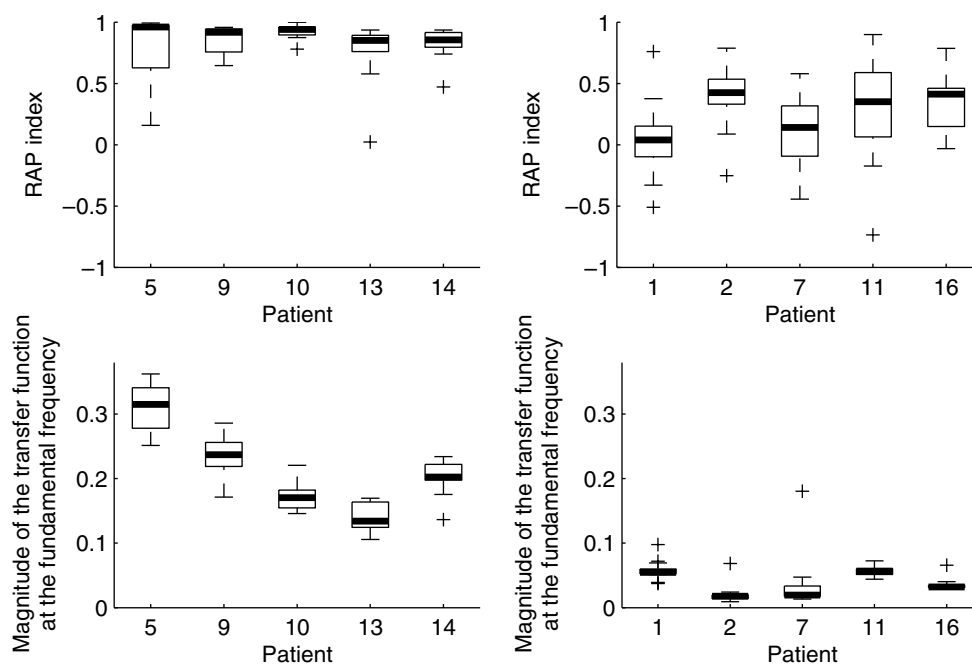


Fig. 3 Boxplot of MTF and RAP coefficients for two groups of swelling and non-swelling brain patients over 1 h time segment. Each box has lines at the lower quartile, median (*highlighted line within the box*), and upper quartile values. The *lines extending from each end of the box* are whiskers to show the extent of the rest of the data. The data shown with + are outliers with values beyond the ends of the whiskers. In patients with brain swelling RAP index and MTF show

the median above 0.8 and 0.13 consequently and even the range of MTF is positioned above 0.1 (*left panels*). Note how concentrated the RAP coefficients are (except patient no. 5). Patient without brain swelling have median of RAP index and MTF below 0.5 and 0.1 respectively (*right panels*). Rap index has a broad range of values while MTF is completely concentrated

range of MTF spread above 0.1. However, comparing the box plot of RAP index with the box plot of MTF, it can be recognized that even though all the five patients have a similar median of RAP index, MTF is quite different. For example, both patient 5 and patient 10 have a median RAP index around 0.95, while they have the completely different medians and ranges for MTF. This dissimilarity might be due to the fact that during RAP index calculation, AMP and ICP_{mean} are normalized to their standard deviations within the individual time segment (here 4 min time segment) and therefore there is not any reference to compare the amount of the changes in AMP and ICP_{mean} , and consequently RAP index, over the different time intervals. On the other hand, RAP index just indicates the synchronization degree among AMP and ICP_{mean} and does not care about their actual values. Therefore, it is possible to have the same RAP index for two different time segments, while ICP and AMP are not the same. In such cases depending on the simultaneous changes in ABP waveform, MTF may change. Coming back to the right panels which refer to the patients without brain swelling, all patients show the median and range of MTF below 0.1 and the median of RAP below 0.5. Note how RAP coefficients are distributed over a wide range, while MTF parameters are completely concentrated.

Discussion

Both MTF and RAP coefficients could experience large variations during a short time interval. Today, the only way to use the information conveyed by RAP coefficients is averaging over a reasonable time window, which means one RAP coefficient by itself does not provide any reliable evaluation of the pressure–volume compensatory reserve. Furthermore, the raw Fast Fourier Transform is not a consistent estimation of the spectrum either. Under this circumstance, it is not possible to find a way to directly describe the underlying connection between each RAP coefficient and the corresponding MTF. However, the above observations suggest that highly correlated changes occur in both the distributions of MTF and RAP coefficients as the brain working point moves along the pressure–volume curve. The positive correlation between the mean values of MTF and RAP coefficients, which emphasizes the increase in the magnitude of the transfer function of ABP to ICP at the fundamental cardiac frequency during the poor compensatory reserve state of the brain, is in complete agreement with previous findings [8]. Furthermore, the negative correlation among the variances of MTF and RAP index seems promising for evaluation of brain compliance by relying more on the parameter with less variability.

Assuming a threshold of 0.7 for RAP index to describe the intracranial states as a good or poor compensatory reserve, the

current data suggests the magnitude of 0.1 as the corresponding threshold for MTF at the fundamental cardiac frequency. However, consideration of the contribution of higher harmonics and their relationship to the fundamental component might provide more information regarding the brain compliance.

Conclusions

It is obvious that both RAP index and MTF are the results of a heavy data reduction which can lead to the loss of a significant part of the information contained in the ICP waveform. A reliable evaluation of the intracranial compliance requires more features to be found, extracted and included. The transfer function of ABP to ICP in conjunction with time has an intrinsic ability to compare the ICP waveform with a reference such as ABP to provide a detailed sort of information regarding the amount and rate of changes in each component and even specify the relationship between different components to take the advantage of ICP waveform study. Considering this capability besides the results of current study, the transfer function of ABP to ICP seems promising to provide a multi-dimensional feature space to evaluate brain compliance.

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Conflict of interest statement We declare that we have no conflict of interest.

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