A Multi-parameters Fusion Model for Non-invasive Detection of Intracranial Pressure

Zhong Ji, Xu Liu

Abstract—**On the basis of discussing the limitation of a single intracranial pressure non-invasive detection method in clinical application, the feasibility of the measurement and analysis model is investigated based on multi-parameters organic integration facing to intracranial pressure non-invasive measurement. Then the sensitivity analysis for the relation between the detected parameters and the change of intracranial pressure will be done. Finally, a synthesized non-invasive evaluation frame for intracranial pressure measurement with disease-adaptive model choice will be realized. By this way, a new idea is provided for the realization of the non-invasive measurement of intracranial pressure and its clinical application, which will be of significance for improving the clinical feasibility and monitoring accuracy of intracranial pressure non-invasive measuring methods.**

I. Introduction

Intracranial hypertension is a major cause of secondary brain injury and its extent and duration have been proved to be associated with survival rate, permanent dysfunction, especially when the intracranial volume-pressure curve reaches a critical point. As long as the intracranial volume has a little change in that point, it will lead to a sharp increase in intracranial pressure, then aggravate brain shift and herniation, even central failure crisis. Intracranial pressure (ICP) is a vitally important monitoring variable , which is the base to prevent and control intracranial hypertension and to determine the treatment programs. Besides it also provides an objective way to evaluate the success of treatment. However, A lot of hospitals do not perform ICP monitoring, as clinical measurement of ICP is highly invasive with the risk of infection and needs professionals to operate and interpret clinical data[1]. Another reason is the invasive ICP monitoring is very expensive.

The literature [2] reviewed 93 literatures from 1985 to 2009 on ICP monitoring and pointed out that although ICP monitoring had been well-accepted because of its clinical application value, the clinical application of invasive ICP monitoring was limited to certain neurosurgical ICU and some specialist hospitals, it couldn't be applied to general hospitals, emergency rooms, outpatient department and accident scene. In China, the invasive method and devices for ICP monitoring have been used less even in many clinical neurosurgery departments with relatively good conditions of class 3-A hospitals. Therefore, non-invasive ICP monitoring, analysis methods and equipments could provide a better choice and are of great significance to make better use of the clinical value of ICP monitoring.

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II. Non-invasive ICP Detection Methods

Non-invasive ICP measurement technique for newborns and infants was first reported in 1966. However, the method was used based on the unclosed fontanelle of an infant, and was not applicable for older children and adults[3]. In the past few decades, a considerable number of researchers tried to develop non-invasive detection technologies of ICP and these methods have a common point that some parameters, which are obtained easily and related to the changing of ICP, are used to estimate ICP non-invasively. But so far, these studies are far away from the wide application in clinical practice, and the reasons could be summed up as follows:

A. Flash Visual Evoked Potential Method

Flash visual evoked potential (FVEP) method is based on the relationship between the changes of ICP and the evoked potential of the second negative wave (N2) in FVEP waveforms to achieve non-invasive detection of ICP. This method had been studied since 1986[4,5], and there have been FVEP-based non-invasive ICP devices to be used in clinical[6]. But there are the following main problems for FVEP used in non-invasive ICP monitoring: individual differences, stability of wave type and repeatability are not good enough. Moreover, FVEP is very sensitive to anesthetics, so operators should pay attention to the state of physiological and pharmacological state while monitoring ICP. In addition the current findings in found literatures are based on the linear relationship between N2 wave latency and changes of ICP, however, the critical point in intracranial volume - pressure curve should be a turning point, and the relation between N2 wave and changes of ICP is linear before the critical point and should be a power function after that point[7].

B. Transcranial Doppler Method

Transcranial Doppler (TCD) method is used to study the fluctuations of cerebral blood flow, and ICP is mainly the pressure from the cardiac cycle fluctuations and cerebral blood flow fluctuations caused by respiratory motion, and the waveform is made up of the pulse wave and respiratory wave. Therefore, fluctuations of ICP are closely related to the wave theory of cerebral blood flow which TCD studies[8,9]. However, there is not a well-recognized formula to quantify the ICP values non-invasively with TCD, and only the relationship model between the hemodynamic parameters and ICP have been proposed in literatures, which cannot provide accurate quantitative measurements of ICP.

Other non-invasive methods for ICP measuring, such as CT and MRI method, bioelectric impedance technology, near infrared spectrum, Intraocular pressure method, tympanic membrane displacement, anterior fontanel pressure method, mathematical model method, are also reported to be used in non-invasive detection of ICP[10,11,12]. But all of these methods realize the indirect measurement of ICP non-invasively by using a single method to find a relation between some detectable parameters and the changes of ICP. However, different intracranial non-invasive detection methods have themselves' application scope, and changes of ICP are the comprehensive characterizations caused by different factors. Therefore, it is very difficult to get accurate values of ICP non-invasively by only one method or a few parameters. In accordance with the provisions of the American Association for Advancement of Medical Instrumentation (AAMI), ICP monitoring instruments should be able to continuously output in the range of 0-100mmHg with a accuracy ± 2mmHg within in 0-20mmHg range, and the maximum error is 10% for over 20mmHg, while most existing methods are far behind the AAMI standard[13]. According to the 130 literatures between 1783 and 2011 years, the literature [14] summarized the advantages and disadvantages and the scopes of clinical application of the invasive and non-invasive methods for ICP monitoring, and pointed out that the accuracy and stability with non-invasive methods for ICP measuring could not be guaranteed due to individual differences, the applicable non-invasive ICP detection devices in clinical were also very rare, and there was still not an effective alternative to invasive detection methods in clinical application.

III. A MULTI-PARAMETERS FUSION MODEL NON-INVASIVE DETECTION OF ICP

A. *Multi-parameters Model*

There are different types of ICP hypertension, such as acute, subacute, and chronic types. Owing to subacute and chronic ICP increasing are relatively slow, and self-adjusting process has great significance on the non-invasive measurement results of ICP, it is difficult to guarantee clinical detection precision for ICP measurement. For acute type of ICP increasing, the development of illness is fast, the signs and symptoms caused by increased ICP are serious and vital signs (blood pressure, respiration, pulse and body temperature) change drastically, the changing process from physiology to pathology has little effect on the results of ICP detection. According to its characteristics, a multi-parameters model of ICP non-invasive detection could be constructed.

The realization of the ICP non-invasive detection is to find the pathological, physiological and biomechanical parameters related to the ICP change, and these parameters could be measured with non-invasive methods. Just shown in figure 1, the input information of the model includes patient's vital signs and pathological parameters, and the pathological parameters include the information related to the changes of ICP, which could be obtained by different ICP non-invasive detection methods, such as the evoked potential of FVEP, hemodynamic parameters of middle cerebral artery (MCA), changes of bioelectrical impedance and its change rate and biomechanical parameters of brain aorta. Clinical information database also collects the patients' value of invasive ICP at the same time. Signal database also records and saves the signal waveforms of invasive ICP changes. Clinical information database records information of patients and related cases with ICP hypertension. It not only provides a common data for the following establishment of the non-invasive comprehensive assessment framework of ICP, but also provides data reflecting individual differences.

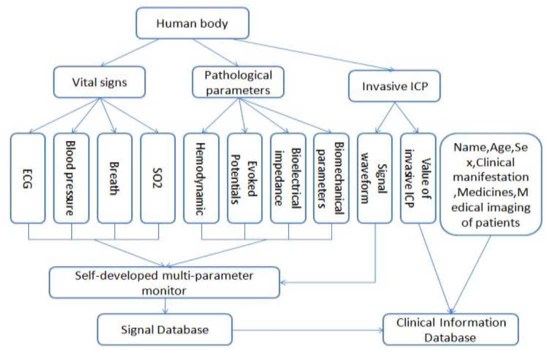

Figure 1. Non-invasive detection of ICP multi-parameter database of patients

According to the database information shown in figure 1, non-invasive comprehensive evaluation framework and model should include all the pathophysiological factors and individual factors. The non-invasive ICP integrated assessment framework model based on multi-parameters fusion for different diseases has been constructed as formula (1):

$$V_{nICP}(t, Diseases) = F(t, ABP, Disease, feature\ parameters, \cdots) + \Delta_s \quad (1)$$

Where V_{nICP} is a non-invasive measurement value of ICP, and its selection of calculation model is related to the 'Diseases' which cause the changes of patients' ICP; F is a nonlinear function of the relationship between V_{nICP} and detected parameters, and it depends on many interrelated factors, such as time, arterial blood pressure (ABP), cerebrospinal fluid compliance, cerebrovascular auto-regulation state, individual patient-related factors (e.g., sex, age), various pathological characteristic parameters recorded in the signal database; Δ_s is the system error which is affected by a series of factors, such as individual differences, hardware system, model structure simplified process, the error of the input parameters themselves, etc, which will be compensated based on the changing rule of the experiment results.

B. *Parameter Sensitivity Analysis*

The increasing of input messages in the model will inevitably make the model structure more complex, therefore based on the constructed ICP clinical database shown in figure 1, from the perspective of pathology and biomechanics, considering the different clinical manifestation causing the increasing of ICP, studying the relationships between biomechanical and physiological parameters and the changes of ICP, then the model could be trained according to the simultaneously recorded invasive ICP detection values, and the sensitivity analysis is further studied to find the relevancy between the changes of feature parameters and changes of ICP. By this way, the feature parameters with small relevancy could be found and removed from the model to reduce the model complexity. Ultimately the different pathophysiological parameters with increased ICP and biomechanical parameters could be organically integrated and applied comprehensively to improve the clinical application accuracy for comprehensive assessment of non-invasive ICP.

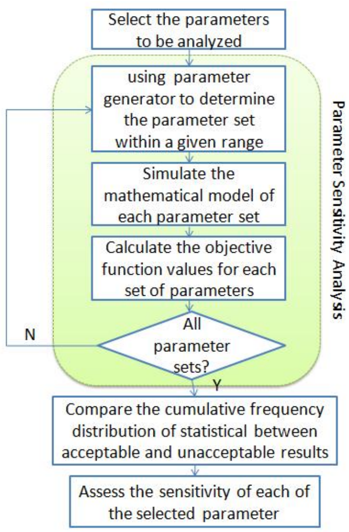

Figure 2. Sensitivity analysis of the parameters in the model for non-invasive measurement of ICP

The flow diagram of sensitivity analysis of the parameters in the multi-parameters fusion model for non-invasive measurement of ICP is shown in figure 2. According to formula (1), the non-invasive ICP integrated assessment framework model, the sensitivity analysis model of parameters could be established as follows:

$$\frac{d}{dt}S_{ij} = \sum_{l}\frac{\partial F_i}{\partial x_l}S_{lj} + \frac{\partial F_i}{\partial p_j}. \quad (2)$$

Where x_l is the l^{th} disease causing ICP increased; p_j represents the j^{th} parameter associated with increased ICP; F_i is the nonlinear function shown in formula (1) in the situation of the i^{th} disease, and $S_{ij} = \frac{\partial x_i}{\partial p_j}$ denotes the sensitivity of the j^{th} parameter for ICP increased corresponding to the i^{th} disease. In formula (2), the influence of system error Δ_s is ignored for simplifying the model.

With this model, the correlation among a clinical diagnosis, physiological and pathological parameters, and non-invasive measuring values of ICP can be established. By training the model with the invasive ICP detection values, the associated weight of each physiological and pathological parameter could be determined and assessed. Finally, the small correlation characteristic parameters could be ignored, and the integrated complexity of the model could be simplified.

C. Multi- methods Integrated in a Same Platform

Based on the multi-parameters fusion model for ICP non-invasive measuring, the non-invasive synthesized monitoring and analyzing system for ICP has been constructed by using the principle of virtual instrument and system integration, software technology and measurement technology of medical signals. On the same instrument platform, this system realizes deep integration and comprehensive application of parameters that are related with the increased ICP, and improves the precision and accuracy of non-invasive detection for ICP and thus makes it have a more extensive clinical adaptability. Figure 3 is a non-invasive detection equipment of ICP that based on the model. In the equipment, the parameters, such as the potential of N2 wave in FVEP waveform, cerebral hemodynamic parameters, etc, obtained by FVEP method and TCD method have been integrated with the model. While in clinical application, the patient's information, like gender, age, clinical diagnosis, blood pressure, etc, will also be input into the patient's database as a part of input parameters of the model.

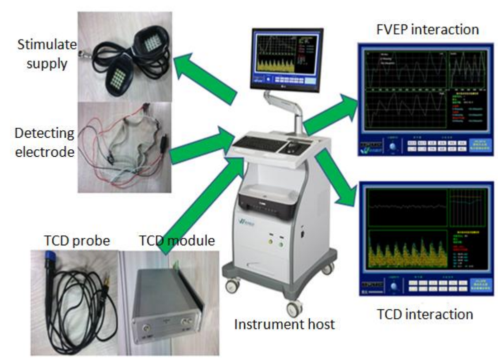

Figure 3. Multi-parameter fusion equipment for non-invasive detection of ICP

The equipment has been used in Daping hospital to test its feasibility for non-invasive detection of ICP in clinical application. 50 cases are included, ages range from 18 to 80 years old, with an average age of 51.08 years old, of which 34 cases are male and 16 cases are female.

The symptoms related are 18 cases of patients with cerebral hemorrhage, 15 cases of patients with hydrocephalus, 5 cases of patients with arachnoid cyst, 7 cases of patients with cerebral contusion, and 5 cases of patients with anterior communicating artery aneurysm.

The test and analysis results are:

(1) The correlation analysis using non-invasive detection values of ICP obtained by this equipment and invasive values of ICP obtained by ventricle puncture shows a linear correlation between the two (as shown in figure 4), the correlation coefficient $r = 0.931 > 0.9$, and it means there is a significant correlation between the two kinds of data and they are interchangeable.

(2) To compare the differences between non-invasive detection values and invasive detection values of ICP, t-test

for paired data is needed. Taking the significant level α =0.05, the value of T is calculated as 0.0705, then check T threshold value table, get T_{49} (0.05) = 2.0102, so T <T_{49} (0.05), which shows there is no significant difference. That is, non-invasive detection values of ICP obtained by this equipment can replace invasive values of ICP in clinical application.

(3) The average relative error (as shown in figure 5) between non-invasive detection values of ICP obtained by this equipment and invasive detection of ICP is 8.2763% <10%, which shows there is enough accuracy for this equipment used in clinical.

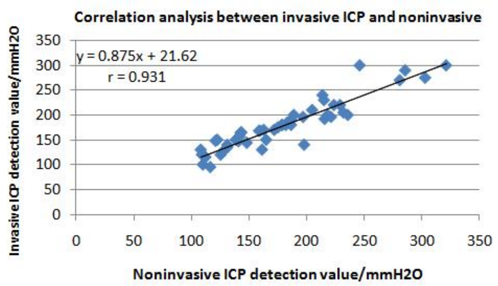

Figure 4. The correlation analysis between the ICP values obtained with invasive and non-invasive equipments

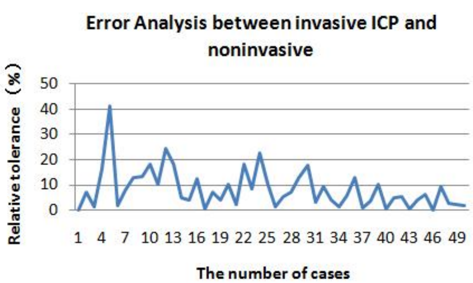

Figure 5. Relative error between the ICP values obtained with invasive and non-invasive equipments

IV. CONCLUSIONS

The study of non-invasive measuring methods for ICP is the need of clinical application. The disadvantages, like infection, hernia, low ICP and complex operations etc., associated with invasive methods for ICP measuring, can be avoided effectively by applying non-invasive detection methods and devices for ICP in clinical. At the same time, the non-invasive methods can reduce the suffering of patients, and there is no risk of intracranial infection. It is of an important significance to realize a technology and devices which are accurate, convenient, cheap and dynamic, and improve the clinical adaptability of ICP non-invasive detection methods. The non-invasive detection method and device for ICP based on the multi-parameters fusion model provide an alternative way in clinical application.

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