Medical Engineering and Physics 38 (2016) 477–484

Contents lists available at ScienceDirect

Medical Engineering and Physics

journal homepage: www.elsevier.com/locate/medengphy

Non-invasive estimation of static and pulsatile intracranial pressure from transcranial acoustic signals

Alexandra Levinsky[a], Surik Papyan[a], Guy Weinberg[a], Trond Stadheim[b], Per Kristian Eide[c,d,*]

[a] Head Sense Inc., Netanya, Israel
[b] dPCom Inc, Oslo, Norway
[c] Department of Neurosurgery, Oslo University Hospital, Rikshospitalet, PB 4950 Nydalen, 0424 Oslo, Norway
[d] Faculty of Medicine, University of Oslo, Oslo, Norway

ARTICLE INFO

Article history:
Received 20 August 2015
Revised 12 February 2016
Accepted 16 February 2016

Keywords:
Brain injury
Intracranial pressure
Non-invasive
Transcranial acoustic signals
Prediction

ABSTRACT

The aim of the present study was to examine whether a method for estimation of non-invasive ICP (nICP) from transcranial acoustic (TCA) signals mixed with head-generated sounds estimate the static and pulsatile invasive ICP (iICP). For that purpose, simultaneous iICP and mixed TCA signals were obtained from patients undergoing continuous iICP monitoring as part of clinical management. The ear probe placed in the right outer ear channel sent a TCA signal with fixed frequency (621 Hz) that was picked up by the left ear probe along with acoustic signals generated by the intracranial compartment. Based on a mathematical model of the association between mixed TCA and iICP, the static and pulsatile nICP values were determined. Total 39 patients were included in the study; the total number of observations for prediction of static and pulsatile iICP were 5789 and 6791, respectively. The results demonstrated a good agreement between iICP/nICP observations, with mean difference of 0.39 mmHg and 0.53 mmHg for static and pulsatile ICP, respectively. In summary, in this cohort of patients, mixed TCA signals estimated the static and pulsatile iICP with rather good accuracy. Further studies are required to validate whether mixed TCA signals may become useful for measurement of nICP.

1. Introduction

Invasive monitoring of intracranial pressure (iICP) has an important role in the surveillance and diagnostics of patients with brain injury of various causes [1]. However, iICP monitoring requires placement of a device within the scull and into the brain parenchyma, which imposes a risk of severe complications (bleeds and infection) in 1–2% of patients [2]. Given the important role of iICP monitoring in neuro-medicine, it is highly desired to find methods for non-invasive monitoring of ICP (nICP).

The physiological methods previously advocated for nICP monitoring can be divided into two groups; those that utilize properties of the structures within the cranium to derive nICP and those that infer nICP based on the extra-cranial organs that are anatomically connected to the intracranial compartment [3]. So far, no method has been accurate enough to justify its clinical use [4].

In the present study, we applied transcranial acoustic (TCA) signals for estimation of static and pulsatile iICP. The TCA signals were sent from an ear-bud like device placed in the right outer ear channel and were picked up along with head-generated acoustic signals by an ear-bud like device placed in the left outer ear channel. Based on a mathematical model of the association between mixed TCA and iICP signals, the information within the mixed TCA signals were used to estimate the static and pulsatile iICP. The aim of the present study was to validate the use of this approach.

2. Materials and methods

2.1. Study design and ethical approval

The aim of this study was to validate whether alterations in transcranial TCA signals mixed with head-generated acoustic

Abbreviations: AUC, area under curve; CI, confidence interval; CSF, cerebrospinal fluid; iICP, invasive intracranial pressure; nICP, non-invasive intracranial pressure; MWA, mean ICP wave amplitude; ROC, Receiver Operating Characteristics; TCA, transcranial acoustic.

* Corresponding author at: Department of Neurosurgery, Oslo University Hospital – Rikshospitalet, PB 4950 Nydalen, 0424 Oslo, Norway. Tel.: +47 23074300; fax +47 23074310.

E-mail addresses: alexandra@head-sense-med.com (A. Levinsky), surik@head-sense-med.com (S. Papyan), guy@head-sense-med.com (G. Weinberg), trs@dpcom.com (T. Stadheim), p.k.eide@medisin.uio.no, peide@ous-hf.no (P.K. Eide).

http://dx.doi.org/10.1016/j.medengphy.2016.02.009
1350-4533/

signals predict the static and pulsatile ICP measured by invasive methods. For this purpose, we developed a mathematical model of association between iICP and mixed TCA signals based on simultaneous measurements of iICP/mixed TCA signals from a set of patients (i.e. Training Group). In turn, the model was applied to the mixed TCA signals of another set of patients to establish the predictive value of mixed TCA signals with regard to static and pulsatile iICP scores (i.e. Validation Group).

The Regional Ethics Committee, REK South-East (2014/126) and Oslo University Hospital (2014/1019) approved the study. Inclusion was by written and oral informed consent, either by the patient herself/himself or by the closest family member.

2.2. Patient cohort

The study enrolled patients admitted to the Department of Neurosurgery, Oslo University Hospital – Rikshospitalet, from July 2014 to December 2014 in whom continuous iICP monitoring was indicated as part of their clinical management. Inclusion criteria were willingness from patients and/or relatives to participate. The clinical conditions in the patient cohort included 25 patients undergoing iICP monitoring as part of surveillance for subarachnoid hemorrhage, and 14 patients undergoing iICP monitoring as part of diagnostic assessment of either hydrocephalus ($n = 10$) or idiopathic intracranial hypertension ($n = 4$). Exclusion criteria were conditions in outer ear channel, making placement of an ear probe dangerous to the patient. ICP levels were not used as an enrollment or exclusion criterion. Inclusion in the study did not influence patient management.

2.3. Monitoring and analysis of transcranial acoustic (TCA) signals

For monitoring of mixed TCA signals, we used the HeadSense MD© (Netanya, Israel) monitor, which comprises a headset with transmitting and receiving sensors, connected to a user interface. An earphone placed in the subjects right outer ear channel contains a speaker for generating an acoustic signal of ~68 dB at a fixed frequency (621 Hz; Test Signal), and an earphone placed in the left outer ear channel contains the microphone that picks up the TCA signal after its propagation through the cranium, as well as acoustic signals generated within the intracranial compartment (created by e.g. cerebral hemodynamics and respiration). The combination of the acoustic Test Signal and the body generated acoustic signals are referred to as the mixed TCA signals.

First, we shortly describe the rationale behind the usage of the TCA signal (HeadSense algorithm©) (for overview see Fig. 1). The energy of the generated Test Signal (621 Hz) passing through the cranium decreases due to attenuation caused by absorption in the different materials of the intracranial compartment (i.e. brain tissue, cerebrospinal fluid (CSF), blood and blood vessels). The acoustic wave attenuation factor (α) depends on various physical parameters such as density, viscosity, elasticity as shown in the following formula;

$$\alpha = \frac{\omega^2}{2\rho c^3}\left[\frac{4}{3}\eta + \xi + \chi\left(\frac{1}{C_v} - \frac{1}{C_\rho}\right)\right] \quad (1)$$

where ρ – density of the intracranial compartment; c – speed of a sound; ω – circular frequency of a sound wave ($w = 2\pi f$); η and ξ – factor of shift and volume viscosity, respectively; χ – coefficient of the thermal conductivity; C_ρ and C_v – the heat capacity of medium at a constant pressure and volume, respectively.

However, in fluids, the factors playing most significant role are the shift and volume viscosity (η and ξ). Hence, we can approximate the acoustic wave attenuation factor (Eq. (1)) to the following expression:

$$\alpha = \frac{\omega^2}{2\rho c^3}\left(\frac{4}{3}\eta + \xi\right) \quad (2)$$

It can be derived from Eq. (2) that the density of the intracranial compartment, ρ, is inversely proportional to the attenuation factor α. Based on Monro–Kelli doctrine [5], since the cerebral cavity has a constant volume composed of the volumes of brain tissue, blood (arterial and venous) and CSF, the increase of volume in one of these components as a result of hemorrhage, brain edema or addition of solid intracranial masses such as tumor growth causes rise in the total brain mass, consequently, the density of the intracranial compartment (ρ) and the ICP increase while the attenuation factor α decreases. Applying the same principle, the lower the ICP and ρ, the higher the attenuation factor α. Consequently, the ICP level is correlated to the measured attenuation factor α.

Second, with regard to the method used for analysis of the mixed TCA signals, the recorded acoustic signal is processed in real-time: the algorithm takes every 6 s of the signal (i.e. 6-s time window), processes it for 2 s in parallel with the recordings of the next 6 s and displays the calculated non-invasive ICP (nICP) value representing mean nICP of the previous 6-s time window.

In the first step, the captured signal is filtered from external noise applying Wavelet Packet Decomposition filtering, with 'coif2' mother wavelet, based on thresholding. Then the acoustic signal is split to different frequency bands corresponding to: blood flow (0–15 Hz, 0–25 Hz, 0–45 Hz, 0–75 Hz), breathing processes (150–180 Hz) and test signal (621 ± 3 Hz), which are represented both in time domain and by applying Short Time Fourier Transformation (STFT) in time-frequency domain. The extracted signals (bands) are processed to calculate their amplitudes, energy and energy spectral density content. The nICP value is derived from the developed regression model composed of weighted linear summation of the

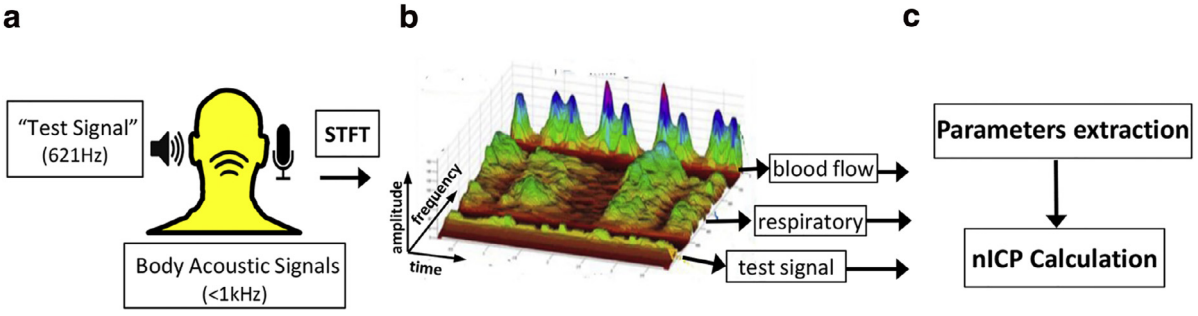

Fig. 1. Overview of methodology for measurements of mixed TCA signals used in the present study. (a) An earphone placed in the right outer ear channel gives a Test Signal with a fixed frequency (621 Hz), while an earphone placed in the left outer ear picks up the Test signal and the Body acoustic signals (<1 kHz) created by such as the cerebral hemodynamics and respiratory cycle. (b) The mixed TCA signals are analyzed both in the time and time-frequency domains by applying Short Time Fourier Transformation (STFT). Hence, the mixed TCA signals are split into frequency bands. (c) Finally, parameters are extracted from the frequency bands for nICP calculation.