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Spectral analysis of intracranial pressure: Is it helpful in the assessment of shunt functioning in-vivo?

Dong-Joo Kim[a,b,*], Hakseung Kim[a], Eun-Jin Jeong[a], Hack-Jin Lee[a], Marek Czosnyka[b], Yunsik Son[a], Byung-Jo Kim[c], Zofia Czosnyka[b]

[a] Department of Brain and Cognitive Engineering, Korea University, Seoul, South Korea
[b] Department of Neurosurgery, Addenbrooke's Hospital, University of Cambridge, Cambridge, United Kingdom
[c] Department of Neurology, Korea University College of Medicine, Seoul, South Korea

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ABSTRACT

Objective: Shunt failure is common in hydrocephalic patients. The cerebrospinal fluid (CSF) infusion test enables the assessment of CSF absorption capacity, which is represented by the resistance to CSF outflow (R_{OUT}) However, shunt failure may not only affect the CSF absorption capacity but also the intracranial compliance or compensatory properties. Spectral analysis of the ICP signal obtained during the infusion test may enable the comprehensive assessment of the overall deterioration caused by shunt failure.
Material and methods: A total of 121 hydrocephalic shunted patients underwent the infusion test with continuous intracranial pressure (ICP) and arterial blood pressure (ABP) recording. The maximum amplitudes of three major frequency bandwidths (0.2–2.6, 2.6–4.0 and 4.0–15 Hz, respectively) were calculated from the ICP. Statistical analyses were conducted to identify factors significantly associated with shunt failure, to construct an index (i.e., the shunt response parameter, SRP) for detecting shunt failure, and to define thresholds for R_{OUT} and SRP.
Results: The R_{OUT} threshold for detecting shunt failure was 7.59 mmHg/ml/min, and this threshold showed an accuracy of 82.64%. All spectral parameters were found to be significantly associated with shunt patency ($p < 0.05$). The SRP exhibited significantly better accuracy than R_{OUT} in detecting shunt failure (91.74%).
Conclusion: The hydrodynamic assessment of shunted patients enhanced by spectral analysis during the infusion test detected shunt failure with high accuracy. Although further validation is needed, the SRP exhibited promising results.

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1. Introduction

It is believed that hydrocephalus is at least partially caused by disturbed cerebrospinal fluid (CSF) dynamics. The treatment of hydrocephalus has greatly improved following the invention of an implantable shunt [1]. The shunt relieves the symptoms of hydrocephalus by removing excess CSF from the brain and stabilizing the intracranial pressure (ICP).

However, not all patients exhibit positive reactions to shunt insertion. Infection, obstruction and under- or over-drainage are well-known complications. Furthermore, seizures, visual loss, subdural hematoma, slit ventricle syndrome and low ICP syndrome may develop if a shunt malfunction is left untreated [2,3]. Frequent symptom relapse and high revision rates are also major risks that cause subsequent complications [4–6], and the average failure rates of these shunts have been reported to be as high as 31.3% at the first year [7] and 50% within five years [8]. Therefore, the timely detection and application of interventions for shunt malfunction are important tasks in the treatment of shunted patients.

Clinical evaluation, physical examination and neuroimaging are considered the basic modalities in the detection of shunt malfunction [9,10]. However, the diagnosis of shunt malfunction can be difficult, particularly when the patient presents less acute symptoms [9,11]. The CSF infusion test offers valuable information on

Abbreviations: ABP, arterial blood pressure; CSF, cerebrospinal fluid; ICP, intracranial pressure; R_{OUT}, resistance to cerebrospinal fluid outflow; SRP, shunt response parameter.

* Corresponding author at: Departments of Brain and Cognitive Engineering, Korea University, Anam-dong, Seongbuk-gu, ASI|KR|KS013|SEOUL, Seoul 136-713, South Korea. Tel.: +82 2 3290 5929; Fax: +82 2 3290 3970.
E-mail address: dongjookim@gmail.com (D.-J. Kim).

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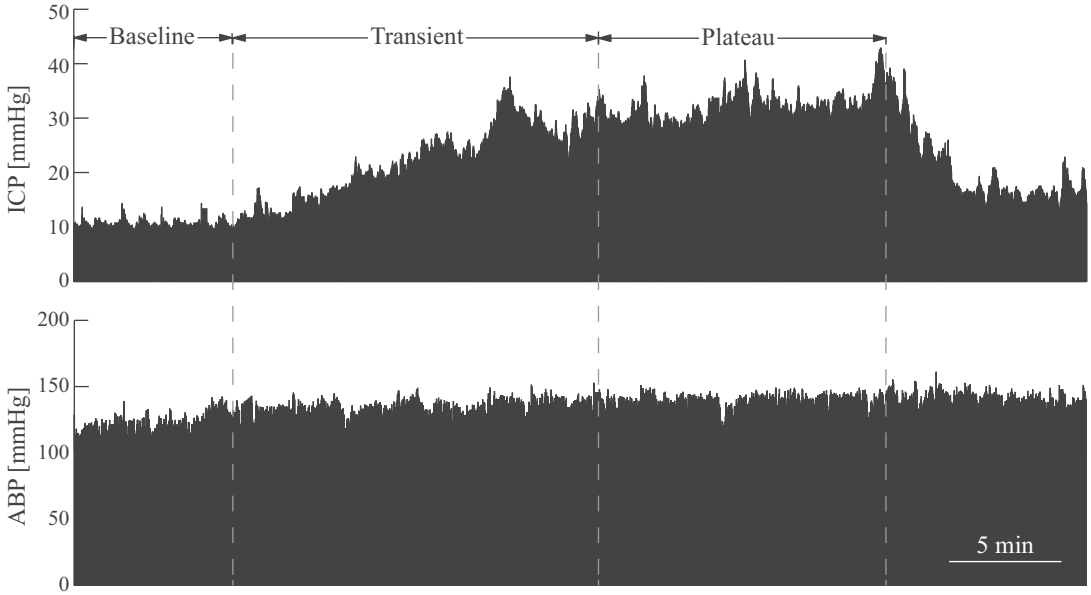

Fig. 1. Segmentation of continuous ICP data obtained during an infusion test. Baseline = stable, baseline phase before the injection of mock CSF; Transient = transient phase during the injection of mock CSF including the characteristic rise of the ICP; Plateau = plateau phase representing the achievement of the balance between CSF absorption and infusion.

the CSF dynamics and thus enables a more accurate diagnosis of shunt functionality.

The infusion test allows for assessment of the CSF dynamics of the patient [12]. A functioning shunt diverts CSF elsewhere into the body cavities and thus mitigates the compromised absorptive ability of hydrocephalic patients. In other words, shunt malfunctions can manifest as the malabsorption of CSF, which is detectable via the infusion test [8,13–16]. Because the hydrodynamic characteristics of commonly used shunts are known, the abnormal increases in CSF pressure during infusion tests indicating shunt malfunction can easily be identified [13]. Other hydrodynamic parameters derived from the infusion tests, such as the resistance to CSF outflow (R_{OUT}) and the conductance of CSF outflow (C_{OUT}), are also used to detect shunt malfunction in some institutes [8,14]. However, there is no widely accepted R_{OUT} (or C_{OUT}) threshold that can be used as a suitable indicator of shunt failure.

The assessment of CSF dynamics via infusion tests provides a valuable insight into abnormalities of CSF reabsorption capacity. However, the repeated need for shunt revision despite readjustments may indicate the necessity for an additional study on the pathologic changes caused by hydrocephalus.

An R_{OUT} threshold of 12 mmHg/ml/min has been considered to indicate disturbed CSF dynamics in non-shunted subjects. A recent meta-analysis study thoroughly reviewed the existing literatures regarding the threshold value of R_{OUT} for the prediction of shunt responsiveness and concluded that R_{OUT} = 12 mmHg/ml/min is the most suitable value [17]. The present study aimed to determine whether this R_{OUT} threshold for shunt responsiveness could also be used as the threshold for detecting shunt failure. Although the insertion of a shunt induces a significant decrease in R_{OUT} [18], the failure of a shunt system may increase the R_{OUT} level to greater than 12 mmHg/ml/min. If this is not the case, statistical analysis may enable the identification of a new R_{OUT} threshold for detecting shunt failure. Furthermore, there is evidence that the shunt insertion and its functional state affect intracranial compliance [19], and the CSF pulse pressure waveform is known to be closely related to cerebrospinal compensatory properties [20]. Therefore, spectral analyses of continuous ICP waveforms were conducted within the bandwidth of 0.2–15 Hz, as the behavior of the derived parameters during the infusion test may provide further insights into the pathophysiology of shunt failure. The spectral parameters were also used to devise a model that may accurately predict shunt malfunction.

2. Material and methods

2.1. Subjects

Continuous ICP recordings acquired during the CSF infusion tests of 121 patients who were admitted to Addenbrroke's Hospital (Cambridge, UK) during the period from 2004 to 2008 were investigated. All subjects had normal pressure hydrocephalus and underwent ventriculoperitoneal shunt surgery (Strata valve, Medtronic, Minnesota, U.S) prior to the infusion test. The subjects were classified as having functioning shunts or malfunctioning shunts by the attending neurosurgeon based on physiological and neuroimaging examinations aided by infusion tests. The interpretation of the results of the infusion tests followed the methods proposed by the UK Shunt Evaluation Laboratory, Cambridge, UK [13]. The recordings consisted of regular routine clinical assessments of CSF dynamics and were therefore exempted from the requirement of institutional review board approval. The anonymized clinical infusion test data were analyzed retrospectively as a part of a routine clinical audit.

2.2. Infusion test and data acquisition

The infusion test was performed with a shunt prechamber. Two 25-gauge hypodermic needles were used for the pressure measurement and the CSF infusion. A pressure transducer and an infusion pump (Simonsen & Will, Sidcup, UK) were connected to the needles. The baseline ICP was measured for the first 10 min during the test, and mock CSF was then infused at a rate of 1.0 or 1.5 ml/min. The tests were prematurely aborted if the ICP reached 40 mmHg. The arterial blood pressure signal was noninvasively acquired using a Finapres device (Finapres 2300, Ohmeda, Englewood, CO).

A digital converter (DT 2814, Data Translation, Marlboro, MA, USA) processed raw analogue into digital signals. The on-line data acquisition during the infusion tests was performed using ICM+

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