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Clinical commentary

Evaluating the effect of hydrocephalus cause on the manner of changes in the effective parameters and clinical symptoms of the disease

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ABSTRACT

In the present study, the heads of 11 normal subjects and 21 patients affected by hydrocephalus due to three different causes were simulated using fluid–structure interaction (FSI). To validate the results, the calculated diagram of CSF velocity in aqueduct of Sylvius (AS) was compared with the similar velocity diagram measured using Cine PC-MRI for the same subject. After ensuring the agreement of results, other outputs such as CSF pressure were calculated non-invasively using FSI. The intracranial pressure and CSF pressure in AS and behind the optic nerve sheath were in patients 5–5.3 times the value in normal subjects and the ventricular system volume in patients was 10.2–11.1 times the value in normal subjects. However, the difference between the coefficient of variation and the maximum value of pressure and volume in different types of hydrocephalus was small. Furthermore, the difference between CSF stroke volumes in various types of hydrocephalus patients was less than 4.4%. Results showed that the intensity of clinical symptoms was similar in patients with similar CSF pressure and the cause of the hydrocephalus disease didn't have any significant effect on the intensity of patients' clinical symptoms and the manner of changes in effective parameters on disease. It was also found that the relation of CSF pressure and volume was 16.7% greater in patients with non-communicating hydrocephalus than in patients with communicating hydrocephalus. These results enhance the insight into hydrocephalus bio-mechanism and can help to choose the proper treatment method for hydrocephalus patients.

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1. Introduction

The imbalance between formation and absorption of cerebrospinal fluid (CSF) or disorder in CSF flow pathway leads to fluid accumulation in head [1,2], which in turn raises the CSF volume in head and results finally in hydrocephalus disease. Hydrocephalus is classified into two types: non-communicating hydrocephalus (NCH) and communicating hydrocephalus (CH) [2]. The hydrocephalus due to disorder in CSF flow pathway is usually called NCH and CH is mainly caused by disorder in CSF absorption into blood circulation in the sagittal sinus [3]. Of course, there are other definitions and classifications for this disease.

It has always been an area of interest to researchers to get more insight into the manner of changes in parameters affecting the hydrocephalus disease. Some previous studies investigated hence the manner of changes in the hydrodynamic parameters of CSF flow in hydrocephalus patients comparing to normal subjects [4,5]. Some studies – in addition to investigating the effective parameters on CSF – took the blood-CSF interaction for evaluation of the hydrocephalus patients' conditions into considerations [6,7]. Some other studies investigated the effectiveness of cerebral shunting and endoscopic third ventriculostomy in treatment of hydrocephalus patients by comparing the parameters affecting the disease [8–10]. In two recent studies by Gholampour et al., the manner of changes in the hydrodynamic parameters of CSF flow in hydrocephalus patients was investigated before and during the patients' treatment process [11,12]. Although the hydrocephalus patients' conditions were compared to those of normal subjects in previous studies, none of them studied the manner of changes in effective parameters on disease in the various types of hydrocephalus and it is not yet clear if the cause of hydrocephalus affects the manner of changes in patients' clinical symptoms and the disease progression. Therefore the present study dealt with this matter which can help the treating physician to choose the proper treatment strategy for hydrocephalus patients.

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2. Method

2.1. Patients and MRI assessment

11 normal subjects with the average age of 26 ± 2.7 years and 21 hydrocephalus patients with the average age of 22 ± 5.7 years were recruited for this research. Table 1 shows the body mass index (BMI) and heart rate of cases. Aqueductal stenosis and tumor or obstruction in CSF flow pathway are the most common causes of NCH [13]. The study population consisted of 6 hydrocephalus patients with aqueductal stenosis (group A), 5 hydrocephalus patients with mesencephalic tumors (group B), 10 idiopathic CH patients (group C) and 11 normal subjects. The clinical symptoms in patients of group A included: sleepiness (3 patients), nausea and vomiting (3 patients), headache (4 patients), seizures (5 patients), cognitive difficulties (4 patients), papilledema (1 patient), balance and gait disturbances (6 patients), urinary incontinence (2 patients). The clinical symptoms of patients of group B were: gait disturbance (3 patients), headache (3 patients), hemiparesis (5 patients), upward gaze paresis (2 patients) and nausea and vomiting (4 patients). The clinical symptoms of group C included: gait disturbance (10 patients), papilledema (1 patient), urinary incontinence (4 patients), mental impairment (7 patients), nausea and vomiting (8 patients) and headache (3 patients).

The head Cine PC-MRI images of 32 subjects were produced (Fig. 1a). In Cine PC-MRI method, the fluid flow velocities are encoded by phase and finally the velocity of fluid is measured in in vivo conditions [14]. In fact, this method creates a signal contrast between stationary and flowing nuclei through making the phase of the transverse magnetization sensitive to the motion velocity [15].

The protocol and details of MRI were similar to those of previous studies [14,15]. The first Cine PC-MRI output was DICOM files of subjects' head, which was used to produce the head points cloud and to measure the dimensions and volumes of head substructures. The second Cine PC-MRI output was the CSF velocity diagram in subjects' aqueduct of Sylvius (AS) (between the third and fourth ventricles). This second Cine PC-MRI output which is obtained non-invasively is no unique index for evaluation of hydrocephalus patients' conditions based on the recent study findings which revealed that there is a very small difference between the maximum velocities in patients and normal subjects and there is a very high range of maximum velocity variability and dispersion in various cases [11]. It is therefore necessary to investigate the CSF pressure exerted on the inner and outer surfaces of brain.

The CSF pressure, however, cannot be measured by MRI [7]. In this study the CSF pressure in 32 subjects was calculated using fluid–structure interaction (FSI) method following the 3D modelling of head (Fig. 1b) in similar conditions.

2.2. Computational analysis

FSI is a fluid–structure interaction technique based on computer modelling for calculation of hydrodynamic parameters of fluid and biomechanical parameters of the solid part [16]. In hydrocephalus disease, both phases of fluid (CSF) and solid (brain) are effective and hence in analysis of this disease, it is not appropriate to use the numerical analysis methods like Computational fluid dynamics (CFD), which investigate only the hydrodynamic parameters of fluid and cannot include the effect of solid part in calculations, or finite element method (FEM), which investigates only the effect of the solid part. Therefore, the FSI method was used in this research for CSF pressure calculation.

Numerical simulations such as FSI technique are generally time consuming – the present study took 4 years to be completed – however they have high accuracy and are also non-invasive [17]. Based on the FSI technique, Eqs. (1) and (2) were considered as the governing equations of brain tissue and CSF, respectively:

$$\frac{\partial \tau^{s}_{ij}}{\partial x_j} = \rho^s \frac{\partial^2 d^s_i}{\partial t^2} \tag{1}$$

$$\rho^f \frac{\partial u_i}{\partial t} + \rho^f \left(u_j - \frac{\partial d^f_j}{\partial t} \right) \frac{\partial u_i}{\partial x_j} = \frac{\partial \tau^f_{ij}}{\partial x_j}, \quad \frac{1}{\beta}\frac{\partial p}{\partial t} + \frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

where τ^s_{ij} and τ^f_{ij} are the Cauchy stress tensors of the brain and CSF, ρ^s and ρ^f are the density of the brain and CSF, d^s and d^f are the displacements of brain and CSF in FSI boundaries (interfaces between CSF and brain) and u_i, β and P are the CSF velocity, bulk coefficient and CSF pressure, respectively [12].

The complementary information about FSI equations and the equations governing the boundary between CSF and surfaces of brain tissue (FSI boundaries) can be found in the study by Zhang et al. [18]. Assuming the brain tissue as a viscoelastic material is one of the advantages of this study. Although this assumption has the best agreement with the real properties of brain tissue, none of the previous FSI studies applied it. The same material properties as in the recent study by Gholampour et al. were used for brain tissue and CSF [11]. Furthermore, the CSF flow rate function was considered as the input flow in lateral ventricles and as the output flows in sagittal sinus and spinal cord. The amplitude of the flow rate functions in input and outputs was 0.34 ml, 0.17 ml, respectively [2]. The frequency and the movement pattern of input and output flow rate functions were similar to those of the blood flow rate function.

Grid independence studies show the error between the fine and medium meshes for all cases is less than 4.2%.

Table 1
Details of the properties of patients, volume of head's substructures and CSF pressures. The units of Heart rate, volumes and pressure are beat/min, ml and Pa, respectively. The values in rows 4–8 are given in Mean ± SD. BMI: body mass index.

Parameters	Cases			
	Normal subjects	NCH with Aqueductal stenosis (Group A)	NCH with Mesencephalic tumor (Group B)	Idiopathic CH (Group C)
Number of subjects	11	6	5	10
BMI	24.3	21.4	31.0	27.1
Heart rate	76.8	73.5	77.2	72.4
CSF pressure in AS	540.8 ± 32	2855.5 ± 337	2814.2 ± 295	2787.8 ± 306
CSF pressure in ONS	563.4 ± 35	2870.4 ± 338	2827.1 ± 296	2803.9 ± 307
ICP	571.0 ± 34	2892.1 ± 338	2835.7 ± 295	2829.9 ± 307
Ventricles volume	26.3 ± 1.8	281.4 ± 14.8	291.1 ± 14.5	267.5 ± 15.9
Brain volume	1207.1 ± 81	1077.2 ± 61	1069.1 ± 53	1086.0 ± 57

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