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Non-invasive measurement of intracranial compliance using cine MRI in normal pressure hydrocephalus

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Summary

The aim of this study is to clarify biophysics of normal pressure hydrocephalus (NPH) based on non-invasive intracranial compliance measurement using magnetic resonance imaging (MRI). Patients with NPH after subarachnoid hemorrhage (NPH group, n = 5), brain atrophy or asymptomatic ventricular dilation (VD group, n = 5), and healthy volunteers (control group, n = 12) were included in this study. Net blood flow (bilateral internal carotid and vertebral arteries, and jugular veins) and cerebrospinal fluid (CSF) flow in subarachnoid space at the C2 level of cervical vertebra were measured using phase-contrast cine MRI. CSF pressure gradient and intracranial volume changes during a cardiac cycle were calculated based on Alperin's method. Compliance index (Ci = delta V/delta P) was obtained from the maximum pressure gradient and volume changes. Pressure volume response (PVR) was measured in the NPH group during a shunt operation. Ci in the NPH group was the lowest among the three studies groups. No difference was found between the control and VD groups. There was a linear correlation between Ci and PVR. In conclusion, intracranial compliance can be determined by cine MRI non-invasively. It is well known that NPH has relatively low intracranial compliance, this non-invasive method can be used for the diagnosis of NPH.

Keywords: Intracranial compliance; elastance; MRI; normal pressure hydrocephalus; cerebrospinal fluid flow dynamics.

Introduction

The diagnosis of normal pressure hydrocephalus (NPH) continues to be difficult in some cases and many diagnostic examinations have been attempted. However, in electing NPH patients for shunt surgery, there remains no unambiguously useful and non-invasive examinations which are easily performed or widely accepted in medical centers.

Intracranial compliance is one of the most important parameters to estimate the compensatory capacity of the cranial cavity in patients with various intracrainal pathologies. It has been reported that the intracranial compliance was relatively low in NPH [4, 8]. We have already shown that cerebrospinal fluid (CSF) flow dynamics on magnetic resonance imaging (MRI) was affected by changes of intracranial compliance [5–7, 9].

In the present study, we directly measured intracranial compliance as compliance index (Ci) non-invasively using cine MRI based on Alperin's method [1], and studies the biophysis by analyzing the changes of Ci in these patients.

Materials and methods

Compliance index

The compliance index (Ci) was calculated from the ratio of intracranial volume change to craniospinal CSF pressure gradient change during a cardiac cycle with retrospective cardiac gated phase-contrast (PC) cine MRI [1]. We set the vertical slice plane at the dense (C2) level against the cerebrospinal axis (Fig. 1a and b), and obtained velocity-mapped phase images (32 cardiac phases) with different velocity encoding gradients for CSF flow, cord motion and transcranial blood flow respectively (Fig. 1c and d). Measurements were done by using a gradient echo pulse sequence (T1-FFE) with shortest echo time, 20 degrees flip angle, 3 mm slice thickness, 2 signals averaged, 150×120 mm^2 rectangular field of view, and 256×256 or 256×128 acquisition matrix on a 1.5T MR system (Gyroscan ACS II; Philips). The velocity-encoding value for the CSF flow measurement was $\pm$15 cm/sec in patients suspected of having NPH, and $\pm$10 cm/sec in the others. The velocity-encoding value for measuring blood flow was $\pm$90 cm/sec.

To obtain the net transcranial flow, we measured the flow (or displacement) during a cardiac cycle, CSF flow [$V_c(t)$], displacement of cord [$V_s(t)$], arterial inflow (the sum of both internal carotid arteries and vertebral arteries) [$V_a(t)$] and venous outflow (the sum of both

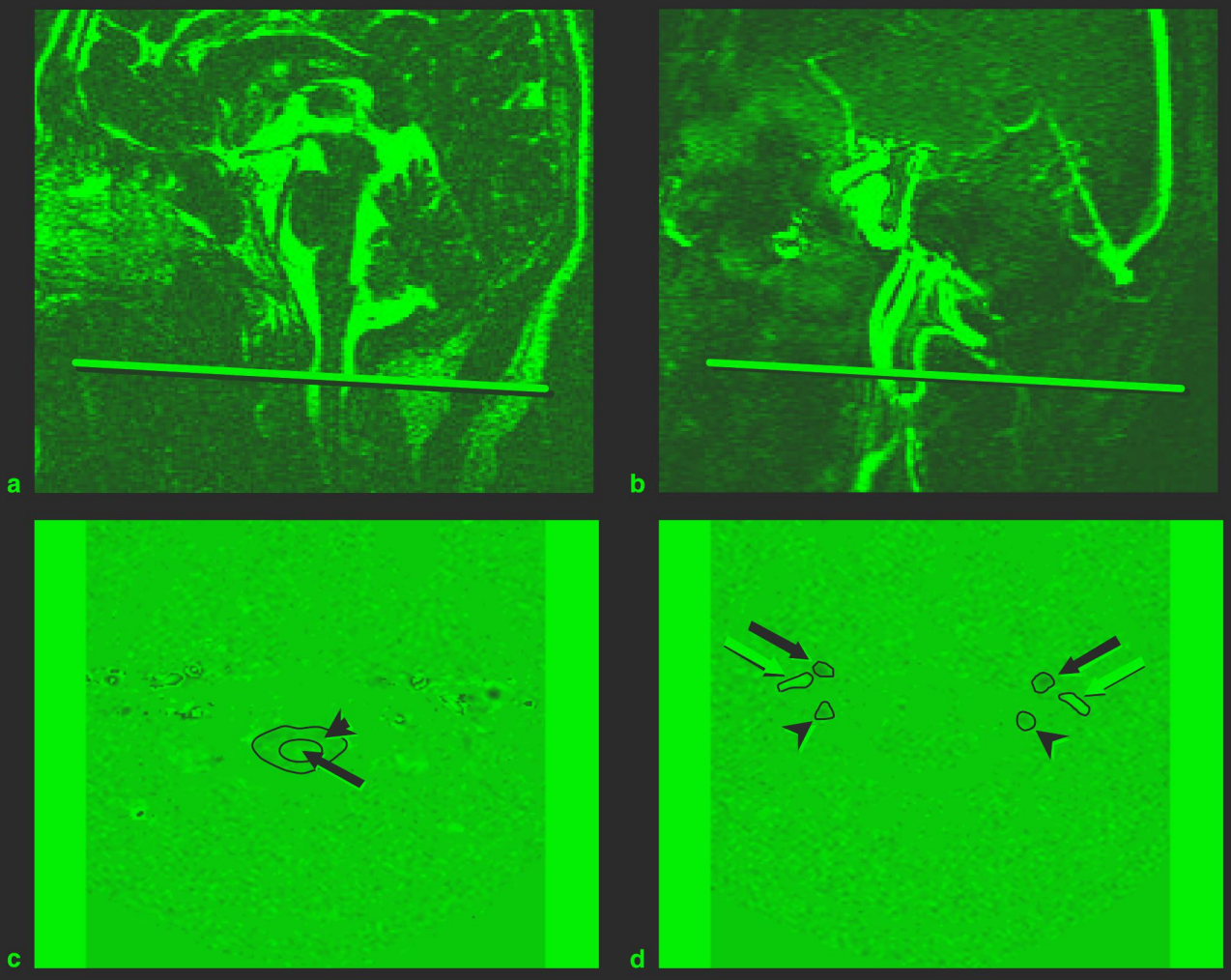

Fig. 1. Slice planes of MRI for CSF flow (a) and vascular flow (b) were set at the C2 level of cervical vertebra. Region of interest (*ROI*) on velocity-mapped phase images with different velocity encoding gradients for CSF flow (white arrow head) and cord motion (white arrow) (c) as well as for transcranial blood flow (white arrows: internal carotid artery, black arrows: jugular veins, white arrow heads: vertebral arteries) (d) were shown

internal jugular veins) [$V_v(t)$]. Firstly, we corrected the baseline offset due to eddy currents by a subtraction process. Secondly, to match the difference in inflow and outflow capacity to the cranium in a cardiac cycle, the flow wave of the venous outflow was scaled down and the net transcranial flow (intracranial volume change) [$V_n(t)$] in each cardiac phase was calculated using the equation:

$$V_n(t) = [V_a(t) - V_v(t) - V_c(t) - V_s(t)]\Delta t$$

And then, we determined the craniospinal CSF pressure gradient change [$\square P(t)$] during the cardiac cycle, which was calculated from the above measured CSF flow velocity using a simplified Navier-Stokes equation [11]:

$$\nabla P = \frac{\partial P}{\partial z} = -\rho\frac{\partial w}{\partial t} + \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2}\right)$$

where x, y, and z are coordinates, and z-direction is a canal axis. P and w are the pressure and the axial velocity, and ρ and μ are the fluid density (CSF: 1.0007 g/cm^3) and viscosity (CSF: 1.1 cP), respectively.

Finally, Ci was obtained from dividing the peak-to-peak intracranial volume change by the peak-to-peak CSF pressure gradient change.

Clinical subjects

Ci analysis was performed in patients with NPH after subarachnoid hemorrhage (n = 5), asymptomatic ventricular dilation or brain atrophy (VD, n = 5), and healthy volunteers (control group, n = 12).

During the shunt operations, intracranial pressure (ICP) and pulse pressure of the ICP pulse wave in the lateral ventricle were recorded (n = 4). Pressure-volume response (PVR) was determined as the ICP changes after a bolus injection of saline (1–5 ml) into the lateral ventricle, as an invasive measure of compliance [5]. $PaCO_2$ was kept within a normal range during the measurements (38.2 $\pm$ 3.6 mmHg). Relationship between the PVR and Ci was investigated.

The purpose and procedures of all our investigations were fully explained to all patients, and the studies were performed only after obtaining informed consent from each patient.

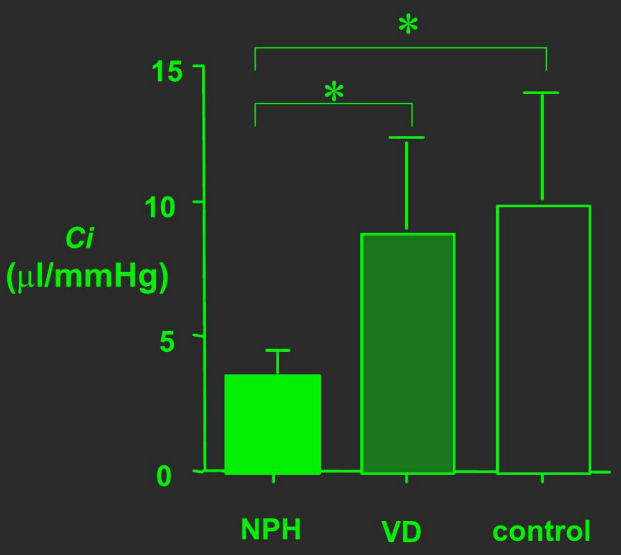

Fig. 2. Compliance index (*Ci*) of each group. Ci of the NPH group is significantly smaller than those of VD and control groups

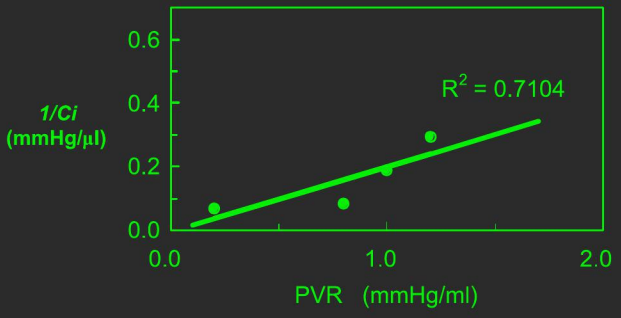

Fig. 3. Relationship between 1/Ci and PVR. There was a linear correlation between 1/Ci and PVR

Results

The Ci obtained with MRI was significantly smaller in the NPH group (mean ± SD: 3.52 ± 0.78 μl/mmHg) than those in the control (9.80 ± 4.04 μl/mmHg) and VD (8.77 ± 3.38 μl/mmHg) groups. There was no significant difference in the Ci between the VD and control groups (Fig. 2). There was a positive linear correlation between the reciprocal of Ci and the PVR (Fig. 3).

Discussion

Intracranial compliance is one of the most important parameters to understand the intracranial condition of patients with various intracrainal pathologies. Especially in cases with no abnormal findings using conventional imaging techniques (CT or MRI), such as diffuse brain swelling or slit ventricle syndrome. Therefore, intracranial compliance can be very useful for determining therapeutic strategies and evaluating the effects of treatments. In genereal, the intracranial compliance is determined by measurement the change in intracranial pressure (ICP) after intrathecal or intraventricular infusion of saline (pressure volume response, PVR). However, this procedure is invasive and has some risks of infection or other complications, and therefore it is not widely accepted. In the present study, we could directly measure intracranial compliance non-invasively (Ci) using cine MRI based on Alperin's method [1]. Significant corrections between Ci and PVR suggests Ci is accurate and reliable. And Ci may become a very important clinical index for estimating intracranial condition non-invasively.

In many trials CSF flow dynamics were measured by using MRI to evaluate the changes in intracranial conditions in normal-pressure hydrocephalus (NPH) [2, 4–7, 9, 10]. However, the diagnosis of NPH based on the CSF flow study using MRI has not been established yet. The most reliable test could the infusion test for evaluating intracranial compliance and out flow resistance of craniospinal cavity, or the tap-test (analyze symptoms after withdrawal of CSF) [3], nevertheless both are invasive. In the present study, we showed that patients with NPH had significantly lower Ci, which meant that compensatory capacity decreased. This corresponds with the other reports that NPH has low compliance [4–6, 8]. Analysis of Ci may be useful for more accurate diagnosis of NPH. Although further investigation is needed, CSF flow study including Ci using MRI promises to become an essential component of preoperative examination.

Conclusion

Ci (compliance index) analysis measured by phase contrast cine MRI enables the determination of intracranial state and dynamics precisely and non-invasively. Ci of patients with NPH was significantly lower than that of healthy controls or patients with asymptomatic brain atrophy. Ci may become one of useful indices for the diagnosis of NPH.

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