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Demonstration of periventricular brain motion during a Valsalva maneuver: description of technique, evaluation in healthy volunteers and first results in hydrocephalic patients

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Abstract There has long been a need for a sensitive and predictive parameter in the evaluation of hydrocephalic patients. Our goal was to assess ventricular response to a Valsalva maneuver as a potential method of studying patients with hydrocephalus. Twenty-five healthy volunteers and 5 patients with communicating hydrocephalus were examined with an axial and 10 volunteers with an axial, coronal and sagittal true fast imaging steady precession (FISP) sequence in a 1.5-T clinical MR scanner (TR 4.8 ms, TE 2.3 ms, flip angle 70°, slice thickness 5 mm, field of view 330 mm, 3 slices). Images were assessed both as dynamic images in cine mode and by measuring lateral ventricular size over time. All volunteers showed marked periventricular brain motion. The lateral ventricular area was reduced under the Valsalva maneuver by an average of 18% (SD 7) in healthy volunteers, while remaining practically constant in the patient group. Differences were statistically significant with a $p < 0.0001$. The Valsalva maneuver leads to periventricular brain motion, which can be consistently detected by a true FISP sequence. Our method proved to be an easy and reliable method with a capacity to identify hydrocephalic patients.

Keywords Brain · Hydrocephalus · Brain · Ventricles · MR · Cine study · MR · Motion studies

Introduction

Hydrocephalus can be viewed as a balance disorder in the production and absorption of cerebrospinal fluid (CSF) leading to the accumulation of CSF within the central nervous system (CNS). The degree of dilatation of the CSF pathways and the extent of damage to the CNS may, however, vary considerably. There has been an on-going discussion on possible predictive parameters and more refined imaging grading systems in hydrocephalic patients.

In the classical theory, hydrocephalus is usually the result of impaired CSF absorption either through blockage of CSF flow or through obstruction of the CSF absorption sites such as the arachnoid villi or the lymphatic channels. As the intracerebral pressure (ICP) increases, new pathways of CSF absorption may be opened and a new equilibrium may result leading to compensated hydrocephalus [1, 2, 3]. In a more recent theory, Greitz et al. suggested that CSF may not be absorbed through the arachnoid granulations, but rather through cerebral capillaries, thus proposing the concepts of reduced arterial pulsation hydrocephalus and venous congestion hydrocephalus [4, 5,6]. Both the classical model and the model of impaired cerebral capillary absorption have advantages in explain-

ing the distinctive features of hydrocephalus as an entity.

A multitude of MR imaging parameters have been tested to aid in distinguishing between ventricular enlargement as a result of hydrocephalus as opposed to white matter atrophy and to moreover allow for a more sophisticated differentiation between compensated and non-compensated hydrocephalus. Among these were measurements of the ventricular angle, the bicaudate index, the Evans ratio, the mamillopontine distance and the assessment of an increased signal loss in the third and fourth ventricle as a result of hyperdynamic CSF flow [7, 8, 9, 10]. Phase contrast studies have been performed to more precisely judge the CSF flow characteristic in the third and fourth ventricles and in the foramina [11, 12, 13].

However, to the best of our knowledge, no imaging method has thus far assessed the elasticity of the periventricular brain parenchyma and lateral ventricular motion under provocative maneuvers such as the Valsalva maneuver. This may prove to be a relevant factor in distinguishing between compensated and uncompensated hydrocephalus and moreover aid in diagnosis, since restricted motion suggests decompensation in the equilibrium of CSF flow dynamics. Moreover, the assessment of supraventricular brain motion under a provocative maneuver might aid in the evaluation of CSF shunt patency. We therefore intended to establish a reliable and easy-to-perform technique to assess motion in the lateral ventricles in response to a Valsalva maneuver in healthy volunteers and in hydrocephalic patients.

Materials and methods

We assessed 25 healthy volunteers and 5 patients with clinically decompensated normal pressure hydrocephalus in a 1.5-T clinical MR imaging scanner (Magnetom Vision, Siemens, Erlangen, Germany). All patients were scheduled for regular MR imaging as part of their routine work-up and all had a clear-cut clinical symptomatology consistent with communicating hydrocephalus. Additional examination time amounted to fewer than 5 min; no contrast media had to be administered. Since MR imaging was performed for an accepted clinical indication and the study itself was considered acceptable for patient care, institutional review board approval was not required. Informed consent was obtained from all patients and volunteers after the nature of the procedure had been explained.

Prior to the MR examination, both patients and volunteers were instructed in how to perform a Valsalva maneuver and demonstrated their ability to do so. They were subsequently examined with an axial true fast imaging steady precession (FISP) sequence with the following parameters: TR 4.8 ms; TE 2.3 ms; flip angle 70°; slice thickness 5 mm; distance factor 0.5; field of view 330 mm; 3 slices. The lowest slice was positioned at the level of the anterior to posterior commissure line (AC–PC line) Time of acquisition was 3 s for each measurement. Measurements were repeated 15 times without an inter-scan interval. Both patients and volunteers were asked to perform a Valsalva maneuver from measurement 4 to measurement 10.

We additionally assessed 10 volunteers in a coronal and sagittal slice orientation with the same parameter settings. In the coronal sections the most posterior slice was positioned at the level of the aqueduct and followed its outline. In the sagittal sections the median slice was positioned following the outline of the cerebral falx.

All images were evaluated in a cine mode. Moreover, the size of both the right and the left ventricle was assessed over time at the level of the uppermost slice. An irregular region of interest was drawn around each lateral ventricle and the area was calculated by the MR system software. In order to achieve a better comparability, the first three measurements were averaged and set as 1.00. All the following measurement values were assessed relative to this average resting value; however, absolute quantifications were also performed. For statistical analysis, a Wilcoxon rank test was applied.

Results

We examined the brains of 25 healthy volunteers (20 men and 5 women; mean age 34 years) and 5 patients with symptomatic communicating hydrocephalus (4 men and 1 woman; mean age 47 years) with the axial true FISP sequence during the Valsalva maneuver. Two volunteers (1 man and 1 woman) had to be excluded from the study due to head motion.

Pronounced ventricular movement was observed in all healthy volunteers (compare movie no. 1 and Fig. 1). The size of the lateral ventricle was significantly reduced under the Valsalva maneuver by an average of 18% (standard deviation 7). A ratio between the highest value without and the lowest value during Valsalva showed an average of 27% (standard deviation 7). The difference between the measurements before as compared with the measurements during the Valsalva maneuver was statistically significant with a $p < 0.0001$ in the Wilcoxon test. In order to exclude simple head motion as the mechanism of the observed effect, ten volunteers were evaluated in axial, coronal, and sagittal planes. The effect of a pronounced reduction of ventricular size during the Valsalva maneuver could be discerned in all three planes. No statistically significant differences were observed in relative ventricular size over time in the axial, coronal, and sagittal planes.

Figure 2 shows the time course of the change in size of the right and left lateral ventricles, respectively, in our volunteers. In order to correct for different ventricular sizes, the average value of the three initial measurements was set as 1.00 and all other measurements were plotted as relative to this value. A response to the Valsalva maneuver was noted in the very next measurement after initiation of the maneuver. A plateau phase was reached after the third measurement under Valsalva and a prompt return to baseline was seen immediately after the Valsalva maneuver was terminated.

Figure 3 demonstrates the time course of the size change in the right and left lateral ventricles in the pa-

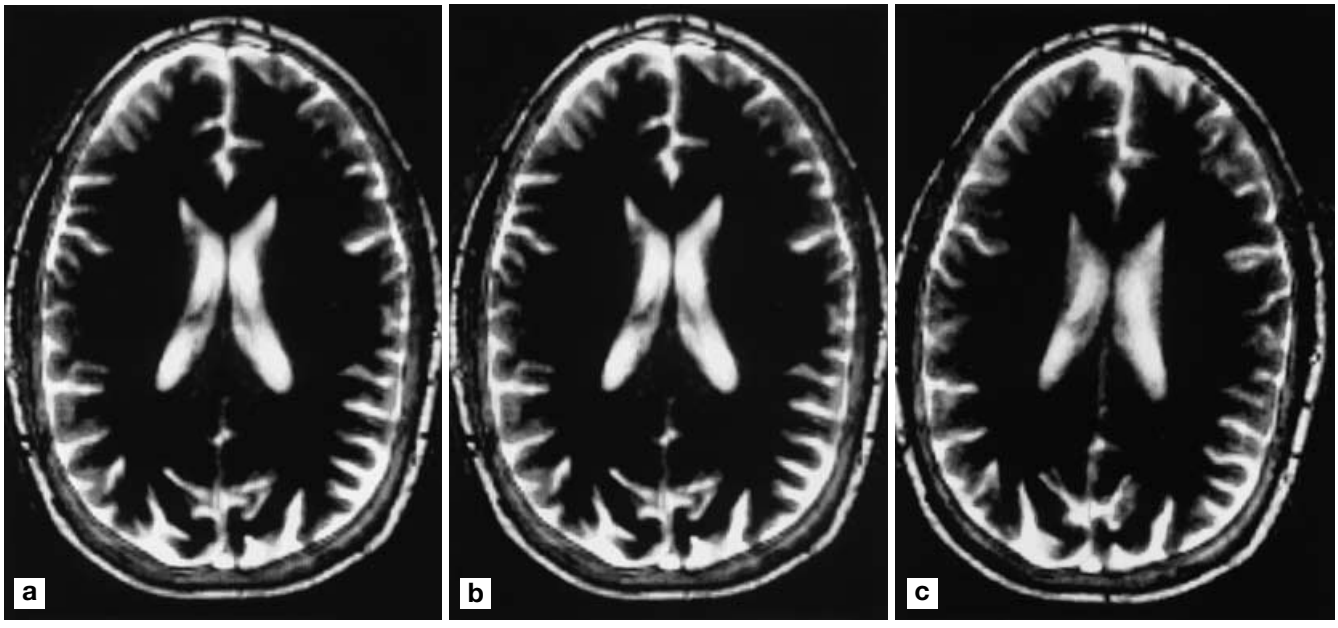

Fig. 1 a–c Axial true fast imaging steady precession (FISP) sequence in a healthy male volunteer. The lateral ventricular area is reduced during Valsalva maneuver with motion of the ventricular wall being inward and downward. Ventricular wall motion is best appreciated in the cine mode **a** before Valsalva maneuver, **b** beginning Valsalva maneuver, and **c** during Valsalva maneuver

tient group. No significant changes in relative ventricular size were discerned during the Valsalva maneuver. The average relative ventricular size was 100 % (standard deviation 3). Moreover, virtually no ventricular movement was noted in the cine mode in the patient group (compare movie no. 2 and Fig. 4). Figure 5 demonstrates the average time course of the relative change in size of the left and right ventricles in the patient group as compared with healthy volunteers. Differences between the two groups were statistically significant in the Wilcoxon test ($p < 0.0001$).

Discussion

Cerebrospinal fluid flow dynamics have long been an area of keen interest in the research of hydrocephalus. Physiological CSF flow is most likely the result of pulsatile movements created by the choroid plexus and the subarachnoid portions of the cerebral arteries [5, 14]. Other theories suggest a possible hydrostatic pressure gradient between the site of CSF formation and absorption [15]. In normal physiological states it is estimated that approximately 20 % of CSF bulk flow enters the spinal subarachnoid space before being recirculated and absorbed in the cerebral subarachnoid space [16].

In our study we asked patients and volunteers to perform a Valsalva maneuver, while an MR sequence with high temporal resolution was performed at the level of the ventricles. We noted a significant reduction of the area of the lateral ventricles in all healthy volunteers during the Valsalva maneuver. In a Valsalva maneuver, the intrathoracic pressure is sharply increased. Subsequently, the central venous pressure rises leading to a short-term venous congestion in the jugular veins; thus, a pressure shift in the cerebral compartments is achieved with an increase in cerebral parenchymal volume and a concomitant decrease in cerebral CSF spaces. A previous study performed in 1981 assessed CSF pressure changes invasively through a frontal burrhole and a lumbar puncture. This study showed a sharp increase in CSF pressure in response to the Valsalva maneuver. This increase equaled approximately 60 % of the central venous pressure range and amounted to approximately 20 mm Hg. Both lumbar and cerebral CSF pressure measurements showed almost identical increases [17]. A more recent study using phase-contrast MR imaging showed that deep-inspiratory and deep-expiratory breath-holding leads to a significant decrease in blood flow and velocity, which amounted to approximately 30 % in the superior sagittal sinus [18]. Moreover, another study demonstrated that vascular compliance was altered in patients with normal pressure hydrocephalus as compared with healthy volunteers [19].

The most likely pathway of the CSF shift in our experimental setting appears to be toward the nerve root pouches. In five volunteers, we examined signal intensity changes and changes in the angulation of the nerve root pouches in the lumbar spinal canal under the Valsalva maneuver with the same axial sequence used in

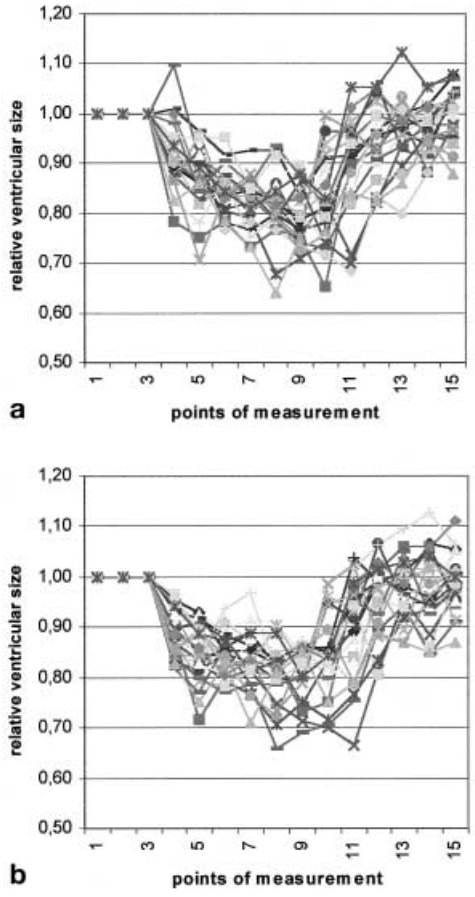

Fig. 2 Evaluation of the area of **a** the right and **b** left lateral ventricle under Valsalva maneuver (measurements 4–10) in healthy volunteers. The lateral ventricular area is significantly reduced under the Valsalva maneuver

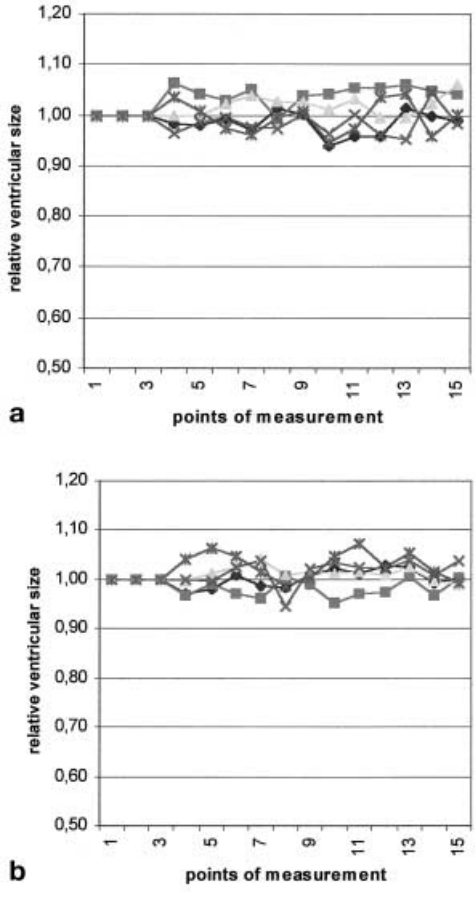

Fig. 3 Evaluation of the area of **a** the right and **b** left lateral ventricle under Valsalva maneuver (measurements 4–10) in patients with communicating hydrocephalus. No significant motion is discerned under the Valsalva maneuver

the assessment of periventricular brain motion. A widening of the foraminal pouches with CSF flow into the recess could be demonstrated in all volunteers (unpublished observation). We believe, therefore, that the most likely mechanism for our observed effect is a shift of CSF from the cerebral inner CSF spaces toward the subarachnoid spaces of the spinal canal in response to the pressure changes induced by the Valsalva maneuver.

One of the most obvious clinical applications of our technique is in the diagnostic assessment of hydrocephalic patients. Even with advanced MR technology it can be difficult to differentiate between atrophy of the white matter leading to ex-vacuo widening of the inner CSF spaces and hydrocephalic ventricular enlargement; however, since this differentiation has a decisive impact on the patient's further therapeutic course, all efforts should be made to obtain as thorough a diagnosis as possible.

Many authors have demonstrated the value of cardiac-gated measurement of CSF flow, especially in the aqueductal structures [11, 12, 13, 20, 21, 22, 23]. Moreover, some authors have assessed infratentorial brain motion in response to systolic contraction of the heart, also with an ECG-gated technique [24, 25]; however, these techniques are much more time-consuming and difficult to perform. They moreover do not assess the brain's elasticity, which most likely represents a cause for the increased CSF flow turbulences [7, 8]. This reduction in the brain's compliance to pressure changes may eventually turn out to play an important role in the generation of the symptomatology of communicating hydrocephalus.

In our study we examined five patients with communicating hydrocephalus. All patients were thoroughly instructed about the performance of the Valsalva maneuver before the examination and demonstrated that they understood the instructions and were able to perform the maneuver themselves; however, no significant motion of the lateral ventricles was observed in the patient group during the Valsalva maneuver. The differ-

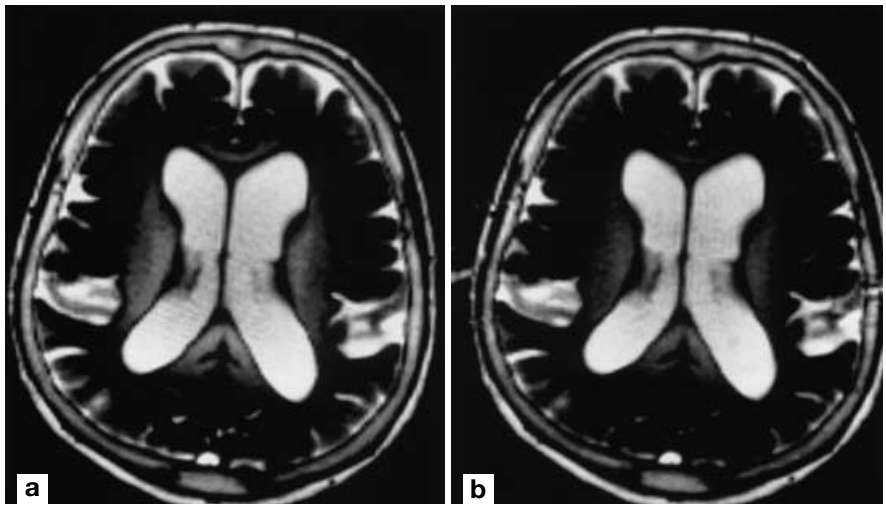

Fig. 4a, b Axial true-FISP sequence in a male patient with normal pressure hydrocephalus. No periventricular brain motion is noted

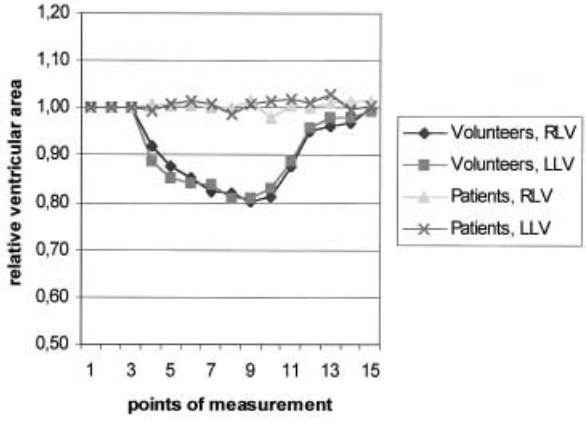

Fig. 5 Time curve of the mean relative area of the right and left lateral ventricle under Valsalva maneuver. A significant difference is observed between volunteers and patients with communicating hydrocephalus. Movie 1: axial true-FISP sequence in a healthy 32-year-old male volunteer without and with Valsalva maneuver. Pronounced periventricular brain movement is noted. Movie 2: axial true-FISP sequence in a 52-year-old male patient with normal pressure hydrocephalus. Periventricular brain movement is markedly reduced when compared with healthy volunteers

ences between the patient group and the group of healthy volunteers were statistically significant ($p < 0.0001$).

Ventricular movement in our group of healthy volunteers could be easily assessed either in the cine mode or by measuring the area of the lateral ventricles with respect to time. For the assessment of the lateral ventricular area, a manual segmentation technique was chosen in order to keep the methodology simple; thus, both the measurement itself and the post-processing can be easily performed with a routine clinical scanner.

In addition to evaluating the lateral ventricular area over time in the axial plane, we also assessed it in the coronal and sagittal planes in ten volunteers. There were no statistically significant differences between the relative size changes in the three planes; thus, there must be true periventricular brain motion, since gross head movement as the basis of the observed effect is essentially ruled out.

Our technique may have several important implications for the radiological diagnosis of hydrocephalus. Larger patient groups are needed in order to evaluate whether quantification of ventricular motion in response to the Valsalva maneuver may aid in determining the prognosis of hydrocephalic patients after CSF shunting. Loss of ventricular motion may prove to be an early indicator of decompensation of the CSF equilibrium and also prove to be an indicator for response to therapy. Moreover, our method may also prove to be useful in the evaluation of CSF shunt patency.

In summary, we describe an easy and reliable method for assessing the motion of the lateral ventricles during the Valsalva maneuver. First results in patients with decompensated communicating hydrocephalus point toward the utility of the method in identifying patients with this disease entity. Further studies are needed to show the method's possible implications in the evaluation of CSF shunt patency and as a possible predictive parameter in the diagnostic assessment of hydrocephalic patients.

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