Anesthesiology
1999; 90:1546–50

Phase-contrast MRI Measurement of Systolic Cerebrospinal Fluid Peak Velocity ($CSFV_{Peak}$) in the Aqueduct of Sylvius

A Noninvasive Tool for Measurement of Cerebral Capacity

Christian Kolbitsch, M.D., Michael Schocke, M.D.,† Ingo H. Lorenz, M.D.,* Christian Kremser, Ph.D.,† Fritz Zschiegner,* Karl P. Pfeiffer, Ph.D.,‡ Stephan Felber, M.D.,§ Franz Aichner, M.D.,§ Christoph Hörmann, M.D.,‖ Arnulf Benzer, M.D.‖*

Background: **Cerebrospinal fluid (CSF) outflow to intra- and extracranial subarachnoid spaces caused by arterial inflow to the brain predominantly compensates systolic increases in cerebral blood volume. Phase-contrast magnetic resonance imaging is a new tool for noninvasive assessment of CSF displacement by measuring CSF peak velocity ($CSFV_{Peak}$). The authors tested this new tool in an experimental human model of increased intracranial pressure and reduced cerebral capacity by means of continuous positive airway pressure (CPAP) breathing.**

Methods: **The authors investigated systolic $CSFV_{Peak}$ in the aqueduct of Sylvius in 11 awake, normocapnic (end-tidal carbon dioxide [ET_{CO_2}] = 40 mmHg) volunteers without CPAP and at two different CPAP levels (6 and 12 cm H_2O) by means of electroencephalography-gated phase–contrast magnetic resonance imaging.**

Results: **Administration of 6 cm H_2O CPAP did not change systolic $CSFV_{Peak}$ (−4.9 ± 2.8 cm/s *vs.* control: −5.1 ± 2.7 cm/s), whereas 12 cm H_2O CPAP significantly reduced systolic $CSFV_{Peak}$ (−4.0 ± 1.8 cm/s *vs.* control: −5.1 ± 2.7 cm/s; $P < 0.05$).**

Conclusions: **These findings in awake volunteers show that monitoring $CSFV_{Peak}$ in the aqueduct of Sylvius is a sensitive method for detecting even minor impairment of cerebral capacity caused by experimentally induced increases in intracranial pressure. (Key words: Cerebral reserve; cerebrospinal fluid circulation; cerebrospinal fluid outflow resistance; human model of experimentally increased intracranial pressure.)**

* Department of Anesthesia and Intensive Care Medicine.

† Department of Magnetic Resonance Imaging.

‡ Professor, Institute of Biostatistics and Documentation.

§ Professor, Department of Magnetic Resonance Imaging.

‖ Professor, Department of Anesthesia and Intensive Care Medicine.

Received from Departments of Anesthesia and Intensive Care, and Magnetic Resonance Imaging, and the Institute of Biostatistics and Documentation, The Leopold-Franzens University of Innsbruck, Innsbruck, Austria. Submitted for publication September 22, 1998. Accepted for publication January 19, 1999. Support was provided solely from institutional and/or departmental sources.

Address reprint requests to Dr. Kolbitsch: Department of Anesthesia and Intensive Care Medicine, The Leopold-Franzens University of Innsbruck, Anichstrasse 35, A-6020 Innsbruck, Austria. Address electronic mail to: christian.kolbitsch@uibk.ac.at

SYSTOLIC changes in cerebral blood volume have been shown to cause compensatory cerebrospinal fluid (CSF) displacement to intra- and extracranial subarachnoidal spaces, so there is no net accumulation of intracranial fluid (blood plus CSF) over an average cardiac cycle.[1] This intracranial reserve or capacity prevents increases in intracranial pressure beyond physiologic limits.

Monitoring CSF displacement to intra- and extracranial subarachnoidal spaces could be a new means for investigating physiology, pathophysiology, and effect of drugs on intracranial capacity and, subsequently, intracranial pressure. A noninvasive *in vivo* assessment of CSF circulation in terms of CSF flow and systolic CSF peak velocity ($CSFV_{Peak}$) has recently become available with cardiac-gated phase-contrast magnetic resonance imaging (MRI; see Appendix 1).[2–4]

To test the practicability of this method for monitoring impaired intracranial capacity we measured systolic $CSFV_{Peak}$ in the aqueduct of Sylvius by means of phase-contrast MRI in a human model of experimentally increased intracranial pressure, which was achieved by continuous positive airway pressure (CPAP).

Methods

After obtaining the approval of the local University Ethics Committee and written informed consent, 11 healthy awake men underwent three consecutive MRI measurements of $CSFV_{Peak}$ in the aqueduct of Sylvius. Wearing a tightly fitting face mask the volunteers

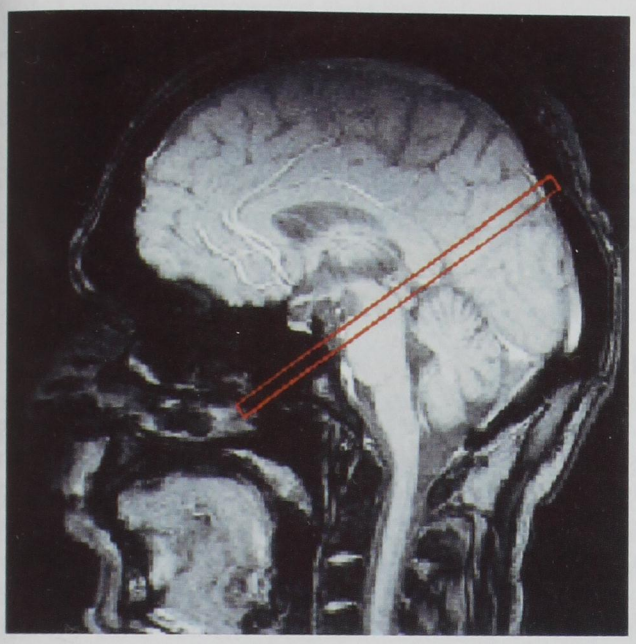

Fig. 1. The examination plane for the phase–contrast magnetic resonance imaging perpendicular to the aqueduct of Sylvius is indicated on the Scout image.

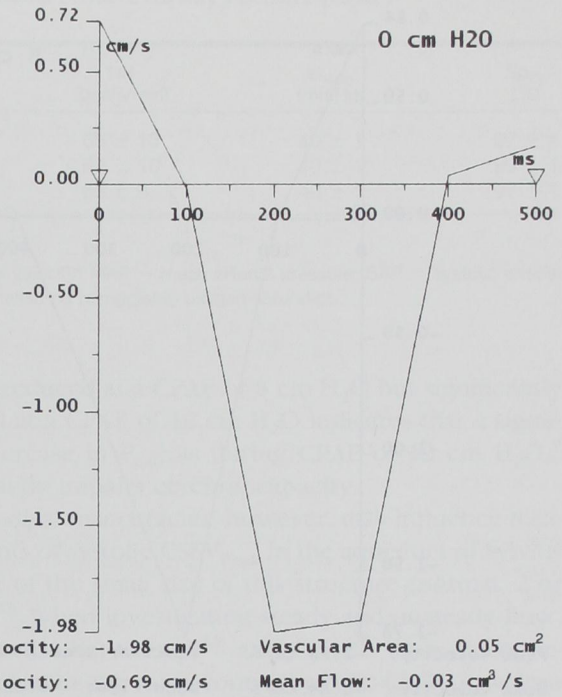

Fig. 3. Systolic cerebrospinal fluid (CSF) peak velocity tracing during control (0 cm H_2O). The vertical scale is given in centimeters/secoond and the horizontal scale is given in milliseconds. The negative deflections represent craniocaudal systolic CSF flow.

breathed without CPAP and subsequently with 6 and 12 cm H_2O CPAP at normocapnia (end-tidal carbon dioxide concentration [ET_{CO_2}) = 40 mmHg). Before taking the readings a minimum of 5 min for stabilization at each level was allowed. A high-flow CPAP device (CF-800: Draeger; Luebeck, Germany) was used to apply a CPAP of 6 and 12 cm H_2O at 21% oxygen in a randomized order. All airway pressure measurements were taken directly from the face mask. Flow adjustments provided an inspiratory and expiratory pressure swing of no more than 1 cm H_2O. The volunteers were trained to breathe at a constant ET_{CO_2} (40 mmHg) supported by voice command when necessary.

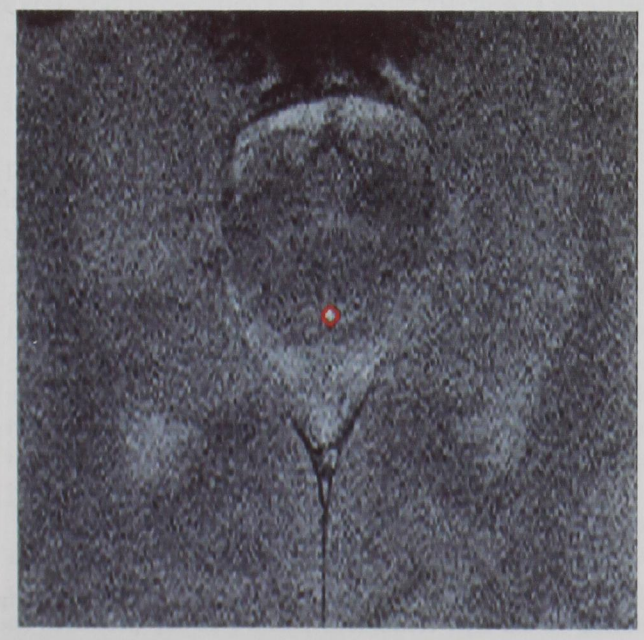

Fig. 2. On the source image for the phase–contrast flow measurement, the region of interest for quantitative evaluation shows the aqueduct in the red circle.

ET_{CO_2}, noninvasive blood pressure (systolic arterial pressure and mean arterial pressure), and pulsoxymetrically measured hemoglobin-oxygen saturation (Sp_{O_2}) were monitored during the investigative period (Odam / Mag-Life/Bruker, Wissembourg, France).

Measurements of systolic $CSFV_{Peak}$ in the aqueduct of Sylvius were performed on a 1.5 Tesla whole-body scanner (Magnetom VISION; Siemens, Erlangen, Germany) using a standard circular polarized head coil. A two-dimensional gradient echo sequence (2D-FISP) (repitition time [TR] = 100 ms, echo time [TE] = 12 ms, α = 10°, acquisition matrix = 256 × 512, field of view [FOV] = 160 mm) with flow velocity encoding in slice-select direction was used. For this high-resolution axial technique, which is sensitive to through-plan flow, the

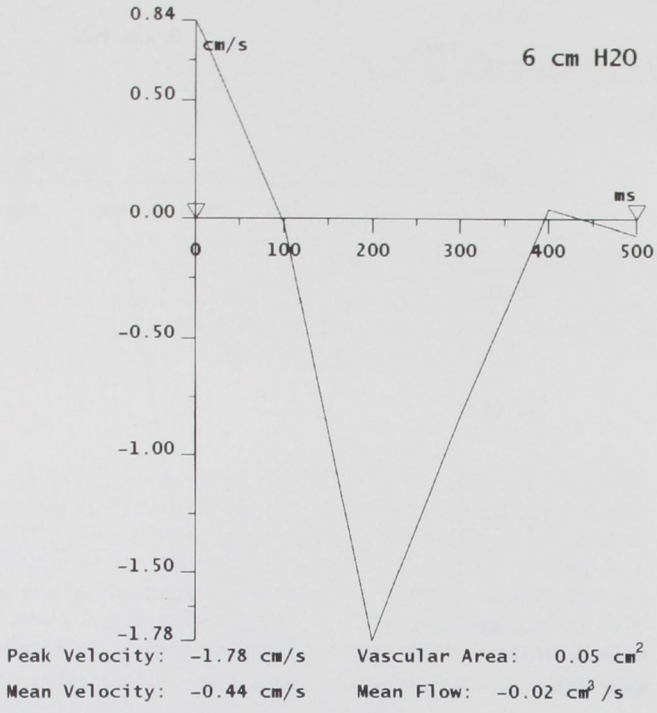

Fig. 4. Systolic cerebrospinal fluid (CSF) peak velocity tracing at 6 cm H_2O continuous positive airway pressure. The vertical scale is given in centimeters/second and the horizontal scale is given in milliseconds. The negative deflections represent craniocaudal systolic CSF flow.

maximum detectable flow velocity was 20 cm/s. Electrocardiography triggering was used for prospective gating of the acquisition. The disadvantage of prospective gating, however, is that the acquisition is stopped within approximately 200 ms of the next R wave for accurate detection of the next trigger. Thus, the diastolic phase particularly is not evaluated.[5] Cardiac gating produced a series of phase-contrast images at different cardiac phases. From these phase-contrast images a blinded investigator measured the systolic $CSFV_{Peak}$ in the aqueduct of Sylvius using region-of-interest measurements (figs. 1 and 2).

Statistical Analysis

Data are presented as the mean ± SD. Analysis of variance for repeated measurements and the Student *t* test for paired samples were used for data analysis, with Bonferroni correction for multiple testing. A $P < 0.05$ was considered statistically significant.

Results

All volunteers (n = 11, aged 33 ± 7 yr) completed the study without complications. At a CPAP level of 6 cm H_2O the systolic $CSFV_{Peak}$ remained unchanged, whereas at a CPAP of 12 cm H_2O the systolic $CSFV_{Peak}$ decreased significantly ($P < 0.05$) (figs. 3–5).

At a CPAP of 12 cm H_2O mean arterial blood pressure increased significantly, whereas systolic arterial pressure, heart rate, Sp_{O_2} and ET_{CO_2} concentration remained unchanged, regardless of the applied CPAP level (table 1).

Discussion

The results of our study show that, when measuring systolic $CSFV_{Peak}$ in the aqueduct of Sylvius in an experimental human model of increased intracranial pressure, phase-contrast, MRI is a reliable method for detecting changes in cerebral capacity.

With regard to CSF circulation, the inflow of arterial blood during cardiac systole increases the intracranial volume and is compensated by immediate venous egress and CSF displacement to the spinal canal,[6] whereas the cephalocaudal displacement of brain at the foramen magnum[7] contributes only a little to this volume compensation. Recent MRI studies using phase-contrast technique have shown a pulsatile CSF flow in a to-and-fro

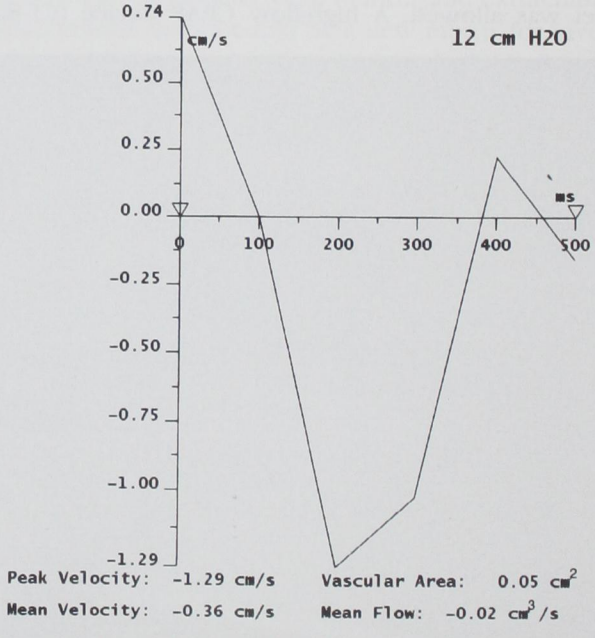

Fig. 5. Systolic cerebrospinal fluid (CSF) peak velocity tracing during 12 cm H_2O continuous positive airway pressure. The vertical scale is given in centimeters/second and the horizontal scale is given in milliseconds. The negative deflections represent craniocaudal systolic CSF flow.

Table 1. Systolic Cerebrospinal Fluid Peak Velocity ($CSFV_{Peak}$) during Continuous Positive Airway Pressure (CPAP) Breathing in Volunteers

CPAP (cmH_2O)	$CSFV_{Peak}$ (cm/s)	MAP (mmHg)	SAP (mmHg)	HR (beats/min)	ET_{CO_2} (mmHg)	Sp_{O_2} (%)
0	−5.1 ± 2.7	88 ± 11	127 ± 14	65 ± 13	40 ± 1	97 ± 1
6	−4.9 ± 2.8	91 ± 10	129 ± 14	64 ± 10	40 ± 1	96 ± 1
12	−4.0 ± 1.8*	93 ± 10*	132 ± 12	65 ± 9	40 ± 1	97 ± 1

Values are mean ± SD.

CPAP = continuous positive airway pressure; $CSFV_{Peak}$ = systolic cerebrospinal fluid peak velocity; MAP = mean arterial pressure; SAP = systolic arterial pressure; HR = heart rate; ET_{CO_2} = endtidal CO_2 concentration; Sp_{O_2} = pulsoxymetrically measured hemoglobin oxygen saturation.

* Significant ($P < 0.05$).

manner in the aqueduct of Sylvius and the cervical subarachnoid space.[8]

The systolic increase in cerebral blood volume, displacing CSF caudally across the foramen magnum, occurs slightly earlier than CSF egress from the third to the fourth ventricle. However, both locations (*e.g.*, cervical subarachnoid space and aqueduct of Sylvius) show similar CSF flow velocity profiles.[8] Assuming a negligible change in the cross sectional area of both locations during systole, changes in CSF flow must cause corresponding changes in $CSFV_{Peak}$. Therefore, we measured the $CSFV_{Peak}$ in the aqueduct of Sylvius to assess systolic CSF displacement, which predominantly determines the cerebral capacity or intracranial reserve for accommodating increased systolic cerebral blood volume.

We used CPAP breathing for experimentally increasing extra- and intracranial CSF pressure, because a small but significant increase in lumbar CSF pressure (P_{csf}; 7 *vs.* 11 mmHg) has been previously reported in volunteers during CPAP breathing.[9]

The intrathoracic transmission rate of positive airway pressure depends on lung and chest wall compliance[10] and is reported to be approximately 50% in young volunteers. Three main routes for pressure transmission from the thoracoabdominal cavity to the CSF compartment have been described, namely the jugular veins,[11] numerous non-valved anastomoses between the epidural and vertebral veins and the veins of the thoracoabdominal cavity,[12] and the intervertebral foramina.[13] In humans and animals, however, the percentage contribution of each route to changes in P_{csf} has not yet been precisely determined.

Independent of the route of pressure transmission, any increase in P_{csf} increases outflow resistance for systolic craniocaudal CSF displacement. Consequently, slowing of craniocaudal CSF flow, which reduces cerebral capacity, should decrease $CSFV_{Peak}$ in the aqueduct of Sylvius.

Therefore, in the current study, finding $CSFV_{Peak}$ slightly reduced at a CPAP of 6 cm H_2O but significantly reduced at a CPAP of 12 cm H_2O indicates that a significant increase in P_{csf}, as during CPAP of 12 cm H_2O,[9] significantly impairs cerebral capacity.

Methodical inaccuracies, however, may influence measurements of systolic $CSFV_{Peak}$ in the aqueduct of Sylvius because of the small size of this structure (normal, 2 or 3 mm).[14] When investigating steady and unsteady flow, inaccuracies between 5[15] and 7.5%[16] have been described; but in our study control systolic $CSFV_{Peak}$ values (−5.1 ± 2.7 cm/s) were in good accordance with previously reported data (−2.0 to −5.2 cm/s).[5,17]

Arterial and venous (AV) waveform amplitudes in combination account for 56% of the variance of the CSF waveform amplitude at the C2–C3 disk level in healthy subjects.[6] A similar influence on the variance of aqueductal CSF waveform amplitudes, which has not been investigated in previous studies or in the current study, is, however, assumable and must therefore be regarded as another possible source of methodical inaccuracy. Furthermore, evaluation of diastolic CSF flow velocity profiles was not reliably possible because of prospective, instead of continuous, retrospective cardiac gating in our study.

In conclusion, in a human model of experimentally increased intracranial pressure by breathing at CPAP concentrations of 6 and 12 cm H_2O we found a significant reduction in $CSFV_{Peak}$ in the aqueduct of Sylvius at a CPAP of 12 cm H_2O. Decreased $CSFV_{Peak}$ indicates a slowing of CSF displacement to the spinal canal, which impairs cerebral capacity for accommodating increased cerebral blood volume. Measurement of $CSFV_{Peak}$ in the aqueduct of Sylvius by means of phase-contrast MRI is a promising noninvasive method, which may prove useful in neuroanesthesiologic research.

The authors thank those volunteers at Innsbruck University Hospital whose participation made this study possible.

Appendix

MR signal sensitivity to motion has first been described by Hahn *et al.*[18]

When protons move in a magnetic field gradient, they exhibit a change in precession angle (so-called phase shift) related to their velocity along the gradient direction. The total phase shift of a proton thereby increases quadratically with time. In phase-contrast MRI this quadratic phase evolution, in combination with special flow velocity encoding gradients, is used to discriminate moving from stationary protons. For quantification of flow velocity, the phase of the MR signal from a baseline measurement is subtracted from that of a measurement made sensitive to flow velocity by the use of velocity encoding gradients.

Usually, two-dimensional gradient echo sequences are used for quantitative flow velocity measurements in which the direction of the velocity encoding gradients are chosen according to the direction of the measured flow. In the current study a two-dimensional fast imaging with steady state precession (2D-FISP) sequence from the commercially available flow quantification package implemented in the Magnetom VISION system (Siemens) was used.

For quantitative velocity measurements of pulsatile CSF flow cardiac gating is necessary. In prospective electrocardiographic gating, which was used in the current study, the acquisition is stopped within approximately 200 ms of the next R wave to enable the accurate detection of the next trigger. Thus, the diastolic phase in particular is not evaluated.

References

1. Alperin N, Vikingstad EM, Gomez-Anson B, Levin DN: Hemodynamically independednt analysis of cerebrospinal fluid and brain motion observed with dynamic phase contrast MRI. Magn Reson Med 1996; 35:741–54

2. Feinberg DA, Mark AS: Human brain motion and cerebrospinal fluid circulation demonstrated with MR velocity imaging. Radiology 1987; 163:793–9

3. Mark AS, Feinberg DA, Brant-Zawadzki MN: Changes in size and magnetic resonance signal intensity of the cerebral CSF spaces during the cardiac cycle as studied by gated, high-resolution magnetic resonance imaging. Invest Radiol 1987; 22:290–7

4. Feinberg DA: Modern concepts of brain motion and cerebrospinal fluid flow (editorial; comment). Radiology 1992; 185:630–2

5. Nitz WR, Bradley WG Jr, Wantanabe AS, Lee RR, Burgoyne B, O'Sullivan RM, Herbst MD: Flow dynamics of cerebrospinal fluid: Assessment with phase-contrast velocity MR imaging performed with retrospective cardiac gating. Radiology 1992; 183:395–405

6. Bhadelia RA, Bogdan AR, Kaplan RF, Wolpert SM: Cerebrospinal fluid pulsation amplitude and its quantitative relationship to cerebral blood flow pulsations: A phase-contrast MR flow imaging study. Neuroradiology 1997; 39:258–64

7. Poncelet BP, Wedeen VJ, Weisskof RM, Cohne MS: Brain parenchyma motion: Measurement with cine echo-planar MR imaging (see comments). Radiology 1992; 185:645–51

8. Enzmann DR, Pelc NJ: Normal flow patterns of intracranial and spinal cerebrospinal fluid defined with phase-contrast cine MR imaging. Radiology 1991; 178:467–74

9. Hormann C, Mohsenipour I, Gottardis M, Benzer A: Response of cerebrospinal fluid pressure to continuous positive airway pressure in volunteers. Anesth Analg 1998; 78:54–7

10. Chapin JC, Downs JB, Douglas ME, Murphy EJ, Ruiz BC: Lung expansion airway pressure transmission and positive end-expiratory pressure. Arch Surg 1979; 114:1193–7

11. Luce JM, Huseby JS, Kirk W, Butler J: Mechanism by which positive end-expiratory pressure increases cerebrospinal fluid pressure in dogs. J Appl Physiol 1982; 52:231–5

12. Batson OV: The function of the vertebral veins and their role in the spread of metastases. Ann Surg 1940; 112:138–49

13. Hamilton WF, Woodbury HT: Arterial, cerebrospinal and venous pressures in man during cough and strain. Am J Physiol 1944; 141: 42–50

14. Quencer RM, Post MJ, Hinks RS: Cine MR in the evaluation of normal and abnormal CSF flow: Intracranial and intraspinal studies. Neuroradiology 1990; 32:371–91

15. Ku DN, Biancheri CL, Pettigrew RI, Peifer JW, Markou CP, Engels H: Evaluation of magnetic resonance velocimetry for steady flow. J Biomech Eng 1990; 112:464–72

16. Frayne R, Steinman DA, Ethier CR, Rutt BK: Accuracy of MR phase contrast velocity measurement for unsteady flow. J Magn Reson Imaging 1995; 5:428–31

17. Henry-Feugeas MC, Idy-Peretti I, Blanchet B, Hassine D, Zannoli G, Schouman-Claeys E: Temporal and spatial assessment of normal cerebrospinal fluid dynamics with MR imaging. Magn Reson Imaging 1993; 11:1107–18

18. Hahn EL: Detection of sea-water motion by nuclear precession. J Geophys Res 1960; 65:776–7

19. von Schulthess GK, Higgins CB: Blood flow imaging with MR: Spin-phase phenomena. Radiology 1985; 157:687–95