Phase-Contrast Magnetic Resonance Imaging Measurements of Cerebral Autoregulation With a Breath-Hold Challenge
A Feasibility Study

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Background and Purpose—Vasomotor reactivity (VMR) testing can identify patients with hemodynamically critical cerebrovascular disease. The use of VMR has been limited by the invasiveness of most of the available methods and of acetazolamide as VMR stimulus. In the present study, we evaluated a completely noninvasive VMR approach by combining quantitative phase-contrast magnetic resonance imaging (MRI) with a breath-hold challenge.

Methods—Volume flow rates in the right and left internal carotid artery (ICA), basilar artery (BA), superior sagittal sinus, and sinus rectus were measured on 2-dimensional phase-contrast MR angiograms (MRAs) with a temporal resolution of 4.3 seconds. In 20 healthy control subjects, the VMR was assessed during 2 consecutive 30-second periods of breath-holding.

Results—A flow increase on breath-holding of 66% was found for the left ICA (240±54 mL/min to 398±120 mL/min; P<0.01), 59% for the right ICA (253±98 mL/min to 402±159 mL/min; P<0.01), 71% for the BA (107±48 mL/min to 184±79 mL/min; P<0.01), 62% for the superior sagittal sinus (232±75 mL/min to 375±130 mL/min; P<0.01), and 65% for the sinus rectus (77±30 mL/min to 127±38 mL/min; P<0.01). The coefficient of variation for the total volume flow increase in the brain feeding arteries (ICAs and BA) between the first and the second breath-holds was 18%.

Conclusion—The combination of MRA phase-contrast volume flow measurements and a breath-holding challenge allows for a fast, completely noninvasive, and reproducible assessment of VMR. (Stroke. 2004;35:1350-1354.)

Key Words: cerebral blood flow ■ vasomotor reactivity ■ cerebrovascular circulation ■ magnetic resonance imaging ■ cerebral veins

Vasomotor reactivity (VMR), ie, vasodilatory response of the cerebral resistance vessels, has been demonstrated to be of prognostic importance in cerebrovascular disease.1,2 Thus far, the use of VMR has been limited by the invasiveness of most of the available methods and of acetazolamide as VMR stimulus. Firstly, the methods to monitor cerebral hemodynamics, such as positron emission tomography (PET) and single photon emission computed tomography (SPECT), use (ionizing) radiation or administration of intravenous contrast agents.3–4 Secondly, the most frequently used VMR stimuli require the intravenous administration of acetazolamide or a carbon dioxide (CO2) challenge with a CO2 mask.5–7 However, simple breath-holding has also been proposed as a noninvasive alternative.8–9 Currently, noninvasive methods to monitor cerebral hemodynamics are transcranial doppler (TCD) sonography and phase-contrast magnetic resonance imaging (MRI).

With phase-contrast MRI, absolute volume flow and changes in volume flow can be obtained. Resting phase-contrast volume flow measurements have been used to evaluate cerebral hemodynamic impairment in patients with obstructive disease of the internal carotid artery (ICA) or posterior circulation,10–12 arteriovenous malformations,13,14 and the evaluation of vascular interventions, such as bypass surgery,15,16 or carotid endarterectomy.17 Recently, in vivo studies have demonstrated the reproducibility of phase-contrast volume flow measurements in rest and volume flow increase on an acetazolamide challenge.18,19 Thus far, no studies evaluated the amount and reproducibility of the volume flow increase in the arteries in the neck on a breath-hold challenge. Current abdominal and cardiac MRI scan protocols frequently use breath-holding periods of 15 to 30 seconds to decrease respiratory motion artifacts. Therefore, breath-holding combined with MRI volume flow measurements may be added to existing scan protocols to measure VMR noninvasively.

In the present study, we evaluated with quantitative phase-contrast MRI the volume flow increase on a 30-second breath-hold challenge. The relative and absolute change in volume flow and reproducibility were assessed for the left and right ICAs, the basilar artery (BA), and dural venous sinus flow (sinus rectus, superior sagittal sinus).
Materials and Methods

MRI

MRI was performed on a 1.5-T whole-body system (Gyrosan ACS-NT; Philips Medical Systems). On the basis of a localized MR angiography (MRA) slab in the sagittal plane, a 2-dimensional phase-contrast slice was positioned at the level of the skull base to measure the volume flow in the ICAs, the BA, the sinus rectus, and the superior sagittal sinus (Figure 1). The MRA volume flow measurements in the present study are derived from a previously developed and optimized protocol (nontriggered; repetition time [TR], 16 ms; echo time [TE], 9 ms; flip angle, 7.5°; slice thickness, 5 mm; field of view, 250×250 mm; matrix size, 256×256; 8 averages; velocity sensitivity, 150 cm/s).20,21 A series of 80 dynamics was acquired with a 4.3-second temporal resolution per dynamic leading to a scan time of 5 minutes 44 seconds. Two periods of breath-holding, each with a 30-second duration (7 dynamics), were performed during the series of dynamics. The interval between the 2 breath-holding periods was 1 minute long. Breath-holding was started after a normal inspiration to avoid artificially lowering of the cerebral perfusion after a deep inspiration (Valsalva effect).22 Adequate breath-holding during the 30-second period was monitored by a pressure sensor under a respiratory band located at the abdomen. To restrain bulk motion, subjects were stabilized using foam pads and a head strap.

Subjects and Data Analyses

Twenty healthy young volunteers (age range 22 to 32 years; 10 females, 10 males) were imaged using this protocol. Subjects gave informed written consent before participating. The study protocol was approved by the institutional review board.

On an independent workstation, quantitative flow values and maximum flow velocities were calculated in the ICAs, BA, sinus rectus, and superior sagittal sinus by integrating across manually drawn regions of interest that enclosed the vessel lumen closely (Figure 1). Resting volume flow and maximum flow velocity values were obtained by averaging over 5 dynamics before the first breath-holding period and 5 dynamics between the 2 breath-holding periods. Volume flow and maximum flow velocity during the first and second breath-holding periods were obtained by averaging the flow values of 2 dynamics obtained 25.8 to 34.4 seconds after the beginning of the breath-hold challenges. To determine the average percent increase in flow volume and velocity, the response of the first and the second breath-holding period was averaged before calculating a group response. The breath-holding index (BHI), a quotient of percentage volume flow or flow velocity increase and time of breath holding, was calculated based on the mean time from the start of breath-holding (30.1 seconds) for these 2 dynamics.

Statistical Analysis

Quantitative volume flow and flow velocity was expressed as mean±SD. Differences in volume flow between the rest and the breath-holding period and differences in volume flow and reactivity between the first and the second breath-holds were analyzed with the Student t test for 2 related samples. In all tests, P<0.05 was considered statistically significant.

Reproducibility of the increase in volume flow on a breath-hold challenge was analyzed according to the method of Bland and Altman.23 With the difference between the volume flow increase for the first and the second breath-holding period, the standard deviation of the difference (SDD) was calculated. The SDD is a measure of the repeatability of the method. The 95% limits of agreement were calculated (ie, the mean difference±1.96×SDD). The coefficient of variation was calculated (ie, the SDD given as a percentage of the mean cerebral blood flow).

Results

Figure 2 shows the arterial and venous volume flow in rest and during 2 30-second breath-holding periods for an average subject. For the right and left ICAs, BA, sinus rectus, and superior sagittal sinus, an increase in volume flow was found during breath-holding, which returned to baseline flow values soon after the breath-holding period.

In Figure 3a, the average (n=20 subjects) baseline volume flow and volume flow during breath-holding are shown in mL/min (mean, SD) for the right ICA, left ICA, BA, sinus rectus, and superior sagittal sinus. The flow increase on breath-holding was 59% for the right ICA (253±98 mL/min to 402±159 mL/min; P<0.01), 66% for the left ICA (240±54 mL/min to 398±120 mL/min; P<0.01), 71% for the BA (107±48 mL/min to 184±79 mL/min; P<0.01), 65% for the sinus rectus (77±30 mL/min to 127±38 mL/min; P<0.01), and 62% for the superior sagittal sinus (232±75 mL/min to 375±130 mL/min; P<0.01). The BHI for the volume flow increase was 1.96 for the right ICA, 2.19 for the left ICA, 2.35 for the right BA, 2.16 for the sinus rectus, and 2.06 for the superior sagittal sinus.

In Figure 3b, the maximum flow velocity and maximum flow velocity during breath-holding are shown in centimeters per second (mean, SD) for the right and left ICAs, BA, sinus rectus, and superior sagittal sinus. The flow velocity increase on breath-holding was 48% for the right ICA (28±10 cm/sec to 42±14 cm/sec; P<0.001), 53% for the left ICA (28±11 cm/sec to 43±21 cm/sec; P<0.01), 47% for the BA (24±13 cm/sec to 35±20 cm/sec; P<0.01), 41% for the sinus rectus (19±7 cm/sec to 26±9 cm/sec; P<0.01), and 75% (19±9 cm/sec to 33±15 cm/sec; P<0.01) for the superior sagittal sinus. The BHI for the flow velocity increase was 1.59 for the right ICA, 1.76 for the left ICA, 1.56 for the BA, 1.36 for the sinus rectus, and 2.49 for the superior sagittal sinus.

No significant difference in baseline volume flow between the first and the second breath-hold was found for the right ICA (248 mL/min versus 231 mL/min), the left ICA (254 mL/min versus 252 mL/min), the BA (109 mL/min versus 105 mL/min), the sinus rectus (73 mL/min versus 80 mL/min), and the superior sagittal sinus (234 mL/min versus 229 mL/min). Furthermore, no significant difference in volume flow increase between the first and the second breath-holding period was found. The coefficient of variation of the volume flow increase between the first and the second breath-hold
was 33% for the right ICA, 30% for the left ICA, 25% for the BA, 34% for the sinus rectus, and 30% for the superior sagittal sinus. The coefficient of variation for the total volume flow increase in the brain feeding arteries (ICAs and BA) was 18%.

**Discussion**

In the present study, we show the absolute volume flow increase, relative volume flow increase, and reproducibility of noninvasive VMR measurements with phase-contrast MRI in combination with a breath-hold challenge. Optimal angulation of the 2-dimensional phase-contrast MRI scan allowed simultaneous assessment of the change in volume flow of the right and left ICAs, BA, sinus rectus, and superior sagittal sinus.

A 384 mL/min (64%) increase in total volume flow was found of the brain feeding arteries on breath-holding. In previous phase-contrast MRA studies, an acetazolamide challenge resulted in 278 mL/min (46%) and 300 mL/min increase in total volume flow. Furthermore, in a color Doppler study, a volume flow increase of 215 mL/min (50%) was found for an acetazolamide challenge and 163 mL/min (47%) for a CO₂ challenge. We found a significant volume flow increase for the sinus rectus and the superior sagittal sinus. These findings are in agreement with the tight coupling between arterial and venous flow to prevent elevation of intracranial pressure.

The increase in ICA flow velocity of 50% is in agreement with the 40% to 45% increase in arterial flow velocity found with breath-holding techniques and the 50% to 60% increase in flow velocity found with TCD and CO₂ challenges. A 47% flow velocity increase was found in the BA in our study compared with a 54% increase previously found for...
activation were in agreement with literature values.\textsuperscript{28}

The coefficient of variation for the volume flow increase in the brain feeding arteries between the first and the second breath-hold was 18% compared with a coefficient of variation of 28% found in a previous phase-contrast study with an intravenous acetazolamide injection.\textsuperscript{18} The average time between the first and the second measurement was 15 days in the study of Spilt et al compared with a 1-minute interval in our study. Therefore, the minimal effect of physiological flow variations may have caused the higher reproducibility of our VMR study. Furthermore, the reactivity after acetazolamide was assessed with a single phase-contrast MRA scan of 36 seconds,\textsuperscript{18} instead of continuous monitoring of the volume flow. Although previous TCD studies reported a better reproducibility compared with MRI-based methods, the presented method has several potential advantages for clinical studies. Firstly, phase-contrast flow measurements combined with a breath-hold challenge can be added to existing MRI protocols. Secondly, in addition to reactivity measurements absolute values of the total volume flow (mL/min) are obtained. Total volume flow may be useful as a general measure of cerebral hemodynamic status in patients with generalized cerebrovascular diseases\textsuperscript{31} or potentially in patients with (vascular) dementia.

Our results show a higher increase in flow velocity in the superior sagittal sinus (75%) compared with the flow velocity increase of the ICAs (50%) and BA (47%). This finding is in agreement with a previous study, in which a higher increase in velocity of the sphenoparietal sinus was found compared with the velocity increase in the middle cerebral artery.\textsuperscript{28} In the present study, no significant difference was found in volume flow increase in the superior sagittal sinus compared with the ICAs and BA. This difference in response between the flow velocity and volume flow of the arteries and veins can be explained by a diameter increase of the major brain feeding arteries and a not extensible venous caliber of the superior sagittal sinus.\textsuperscript{25,28} An arterial vasodilatation results in relatively lower increase in flow velocity. The advantage of MRA phase-contrast volume flow measurements above flow velocity-based (cm/sec) techniques is the integration of flow velocity over the cross-sectional vessel area, which will reflect more closely the change in cerebral blood flow at the tissue level.\textsuperscript{24} The difference in total volume flow between the arteries and veins in the present study can be explained by the veins in which no flow measurements were performed, such as the veins draining directly in the left and right transverse sinuses.

In conclusion, MRA phase-contrast volume flow measurements with a breath-hold challenge allow for complete noninvasive and reproducible assessment of cerebrovascular reactivity. The breath-hold challenge is already used for other purposes (artifact reduction) in daily MRI scan protocols. Furthermore, volume flow phase-contrast MRI scans reflect the change in cerebral blood flow independent of arterial vasodilatation. When added to existing MRI scan protocols, phase-contrast MRI may increase the availability of the valuable prognostic information provided by VMR in patients with hemodynamically critical cerebrovascular disease.

References


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