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# Carotid artery flow as determined by real-time phase-contrast flow MRI and neurovascular ultrasound: A comparative study of healthy subjects

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ABSTRACT

*Background:* The assessment of carotid artery flow by neurovascular ultrasound (nvUS) can be complemented by real-time phase-contrast (RT-PC) flow MRI which apart from quantitative flow parameters offers velocity distributions across the entire vessel lumen.

*Materials and methods:* The feasibility and diagnostic potential of RT-PC flow MRI was evaluated in 20 healthy volunteers in comparison to conventional nvUS. RT-PC flow MRI at 40 ms temporal resolution and 0.8 mm in-plane resolution resulted in velocity maps with low phase noise and high spatiotemporal accuracy by exploiting respective advances of a recent nonlinear inverse model-based reconstruction. Peak-systolic velocities (PSV), end-diastolic velocities (EDV), flow volumes and comprehensive velocity profiles were determined in the common, internal and external carotid artery on both sides.

*Results:* Flow characteristics such as pulsatility and individual abnormalities shown on nvUS could be reproduced and visualized in detail by RT-PC flow MRI. PSV to EDV differences revealed good agreement between both techniques, mean PSV and EDV were significantly lower and flow volumes were higher for MRI.

*Conclusion:* Our findings suggest that RT-PC flow MRI adds to clinical diagnostics, e.g. by alterations of dynamic velocity distributions in patients with carotid stenosis. Lower PSV and EDV values than for nvUS mainly reflect the longer MRI acquisition time which attenuates short peak velocities, while higher flow volumes benefit from a proper assessment of the true vessel lumen.

## 1. Introduction

The carotid arteries are the major supplier of cerebral blood flow to the human brain. Their most frequent pathologic changes are due to arteriosclerosis, causing focal narrowing (stenosis) of the vessel lumen. These stenoses can remain asymptomatic for many years, but may also lead to severe ischemic strokes in case of acute occlusion or arterio-arterial thromboembolism [1]. In fact, up to 20% of all ischemic strokes are caused by carotid artery stenosis with increasing incidence with age and contribute to a significant socio-economic burden [2,3].

Neurovascular ultrasound (nvUS) represents the most important dynamic imaging technique for the investigation of blood flow velocities and volumes in brain-supplying arteries. The technique relies on the frequency shift of ultrasound beams reflected by blood cells, which

*Abbreviations:* B-mode, brightness-mode; CCA, common carotid artery; ECA, external carotid artery; EDV, end-diastolic velocity; FLASH, fast low-angle shot; ICA, internal carotid artery; nvUS, neurovascular ultrasound; PSV, peak-systolic velocity; RT-PC, real-time phase-contrast; SD, standard deviation; VENC, velocity-encoding gradient

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correlates to their velocity. Stenosis can be graded and controlled by repeated examinations [4,5]. Although well established in clinical practice, nvUS only visualizes the dynamics of the blood stream within a single small sample volume. The method is therefore limited in the evaluation of spatial flow patterns across the vessel. Furthermore, the technique is dependent on the examiners experience and is limited by anatomical variations of patients (e.g. short neck, obesity).

In contrast, phase-contrast (PC) flow MRI techniques of the carotid arteries not only quantify velocities and volumes, but further delineate the detailed distribution of through-plane velocities across the true vessel lumen [6–8] or even provide access to three-dimensional flow characteristics [9]. Unfortunately, these studies relied on ECG-synchronized flow MRI acquisitions which merge data from multiple heartbeats and therefore bear the risk of losing relevant information by averaging incoherent ("chaotic") MRI phases from non-periodic heartbeats. Such limitations become even more relevant in situations of turbulent-like flow, either due to presence of a bifurcation or a stenosis. To resolve this dilemma, real-time PC (RT-PC) flow MRI emerges as a promising alternative in general. However, various technical developments during the past 15 years [10–13] offer only insufficient spatial resolution to allow for a meaningful evaluation of the carotid arteries. In contrast, this work exploits velocity maps with excellent spatio-temporal acuity, high velocity-to-noise ratio and almost noiseless floor of zero-flow regions which is obtained by a recent model-based RT-PC flow MRI reconstruction technique [14,15]. The method provides 0.8 mm in-plane resolution and 40 ms temporal resolution for through-plane flow studies of the carotid arteries – without ECG synchronization and during free breathing. It emerged from the preceding development of a real-time MRI technique at 20 ms resolution [16] and subsequent extensions toward RT-PC flow MRI [17–19] with applications to major heart vessels [20], peripheral veins [21] or cerebrospinal fluid [22].

Model-based RT-PC flow MRI bears the potential to accompany and possibly extend the diagnostics in patients with pathologic changes of brain-supplying arteries in a standardized manner. The general aim is to evaluate the velocity profiles within the carotid arteries and to assess their diagnostic potential for clinical routine, e.g. for etiologic stroke workup. As a first step, this pilot study compared measurements of healthy subjects by RT-PC flow MRI and nvUS as performed according to medical standards.

## 2. Material and methods

The following subsections describe the selection of subjects, technical aspects of the applied real-time phase-contrast flow MRI method, the use of nvUS for studying carotid arteries, and details of the statistical analysis.

### 2.1. Subjects

In this prospective, single center pilot study, 20 volunteers without known illness underwent RT-PC flow MRI and nvUS of the carotid arteries. Blood pressure and heart rate were measured before the nvUS examination. RT-PC flow MRI was performed afterwards within a period of one to two hours. The study was approved by the ethics committee of the University Medicine Göttingen (11/8/16) and all subjects gave written informed consent. This study was in consent with the Declaration of Helsinki.

### 2.2. Real-time phase-contrast flow MRI

MRI examinations were performed at 3 T (Prisma Fit, Siemens Healthineer, Erlangen, Germany) with use of a 64-channel head-neck array coil. RT-PC flow MRI was based on a highly undersampled radial fast low-angle shot (FLASH) sequence with asymmetric echoes and sequential flow encoding [19] in combination with an advanced model-based reconstruction technique described in [14,15]. In contrast to all conventional approaches for velocity mapping, which rely on the pixel-wise phase difference between two separately reconstructed images with differential velocity encoding, the model-based reconstruction jointly estimates one anatomic image, one PC velocity map, and all coil sensitivity maps directly from the two raw datasets. Assuming the same magnitude image and the same coil sensitivities for each pair ($l$ = 1,2) of flow-encoded datasets, the PC flow MRI signal model emerges as

$$y_{j,l}(t) = \int \rho(\vec{x}) \bullet e^{z(\vec{x})\cdot S_l} \bullet c_j(\vec{x}) \bullet e^{i\vec{k_l}(t)\vec{x}} d\vec{x} \text{ with } j \in [1, N],\ l \in [1,2]$$

$\rho$ is the anatomic image shared by the two flow-encoding acquisitions (indices $S_1 = 0$ and $S_2 = 1$), $z$ denotes the velocity map which contains the phase differences $\Delta\phi$ in its imaginary part, while the real part is constrained to be zero, $c_j$ are the sensitivity maps of the $j$ rf coils, and $\vec{k_l}(t)$ is the radial k-space trajectory of the $l^{th}$ acquisition. The unknowns $\rho$, $z$, and $c_j$ in this nonlinear inverse problem are estimated by the iteratively regularized Gauss-Newton method which exploits the temporal continuity of serial acquisitions by a suitable regularization to a

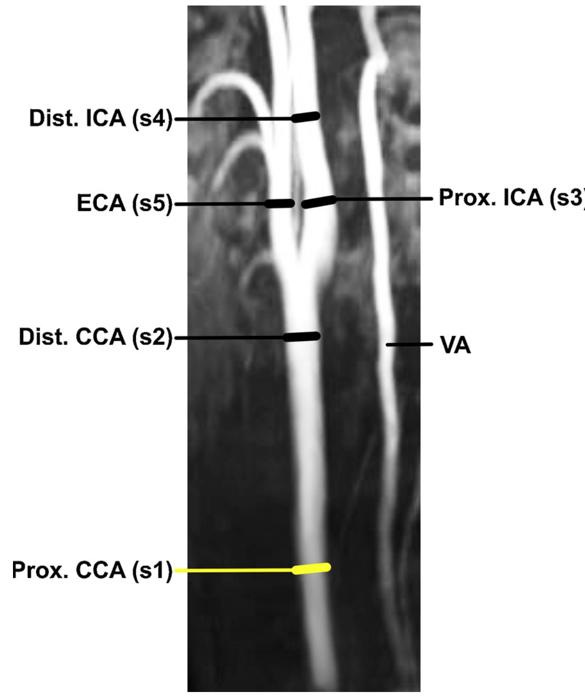


**Fig. 1.** MR angiogram indicating locations s1 to s5 for flow measurements in the common carotid artery (CCA), internal carotid artery (ICA) and external carotid artery (ECA): s1 = 36 mm proximal to the beginning of the carotid sinus, s2 = 12 mm proximal to the carotid sinus, s3 and s5 = 12 mm distal to the carotid bifurcation, and s4 = at the angle of the jaw. VA = vertebral artery.

**Table 1**
Characteristics of subjects (n = 20).

| Parameter | |
|---|---|
| Age (years) | 27.7 ± 3.9 |
| Sex (male, %) | 12 (60) |
| Heart rate ($min^{-1}$) | 73 ± 9 |
| Systolic blood pressure (mm Hg) | 126 ± 12.5 |
| Diastolic blood pressure (mm Hg) | 75 ± 8 |
| Weight (kg) | 74.1 ± 10.4 |
| Height (cm) | 176.5 ± 8.7 |
| BMI | 23.7 ± 2.5 |
| Smoking (n, %) | 4 (20) |
| Other CVRF (n) | 1[a] |

Values are given as mean ± standard deviation; BMI: body mass index; CVRF: cardio-vascular risk factors.
[a] Diabetes mellitus type 1.