Aims and objectives

Flow measurements in the cerebral aqueduct are helpful adjuncts to clinical and morphological criteria in differentiating communicating normal pressure hydrocephalus from non-communicating obstructive hydrocephalus due to aqueductal stenosis. Quantification of cerebrospinal fluid (CSF) flow within the cerebral aqueduct can be quantified using phase contrast MRI (1, 2) utilizing the same principles as blood flow measurements in cardiac MR imaging. Several parameters like peak flow velocity, flow average or stroke volume can be determined. So far, this technique has not gained widespread acceptance mainly because of highly variable and inconsistent reference values in the literature (1, 3, 4) which makes comparison studies difficult to set up and interpret. The obtained values depend on different factors such as specific MR machine, field strength, sequence parameters, post processing software (5) as wells as patient age and gender (4). Hence, aqueductal flow measurement is still not used widely in clinical routine practice. We re-evaluated this method on a 3T MR scanner and investigated the influence of different parameters on healthy volunteers from the study group and a phantom to optimize scanning parameters and investigate necessary post-processing steps to obtain consistent and reliable flow parameters.
Methods and materials

A sagittal 3D T2 weighted T2w TSE sequence of the cranium was obtained for planning (Fig. 1). The phase contrast sequence, using cardiac triggering either via electrocardiogram or peripheral-pulse device, is then set strictly perpendicular (transversal) over the aqueduct. This sequence generates magnitude and phase images, in our case an anatomical magnitude image (FFE/M), a magnitude phase contrast image (PCA/M), and the phase of the phase contrast image (PCA/P) (Fig. 2). A processing software then calculates the flow parameters from the PCA/P image. Cardiac triggering allows the acquisition of several images per heartbeat relating to heart cycle, which determines the time resolution of a phase contrast sequence (Fig. 3). Flow velocity and the flow direction are encoded and presented in the PCA/P grayscale image. The setting of the direction of the velocity encoding parameter (VENC) defines the appearance of the signal on the PCA/P image. In a transversal acquisition plane the encoding of the flow direction is feet - head. Post-processing is done semi-automatically, only a region of interest (ROI) has to be manually defined. Different flow parameters are obtained: forward flow volume (ml), backward flow volume (ml), regurgitation fraction, absolute stroke volume (ml), mean flux (ml/sec), stroke distance (cm), mean velocity (cm/sec), peak velocity (cm/sec) and peak pressure gradient.

Various technical factors were then evaluated for their impact on the obtained flow parameters: anatomical positioning of the phase contrast sequence in the aqueduct, MR-sequence related factors (slice thickness, in-plane resolution, VENC) and post-processing related factors (size of manually placed ROI).

The accuracy for low flow rates and the impact of varying sequence parameters was studied in phantom studies. Physiological saline solution was pumped several times through a flexible tube of 1.5 mm diameter with an MR Injector. The flexible tube was placed between two phantom bottles (Fig. 4). Phase contrast measurements were obtained on a 3T scanner with an 8-channel head coil. For the phantom a non-ECG triggered phase contrast MR sequence with the following parameter was used: FOV 120 x 120 mm², acquisition voxel size 0.4 x 0.4 x 2.0 mm³, TR 17 ms, TE 10 ms, flip angle 15°, number of signal averages (NSA) 2, VENC 20 cm/sec, acquisition time 20 s. Each time one parameter was varied while the others were kept constant.
Fig. 1: High resolution 3D T2 weighted TSE sequence

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**Fig. 2:** Overview of all three image types of a transversal phase contrast measurement through the aqueduct. A) Anatomical magnitude image, (FFE/M), B) magnitude of the phase (PCA/M) and C) the phase image itself (PCA/P).

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**Fig. 3:** Overview of all heart phases of a phase contrast sequence. 12 images at different points in the heart cycle were acquired. During systole (images 1-6 and 12) the CSF appears dark on the PCA/P image because fluid flows from head to feet direction (backflow). During diastole CSF flows in the opposite direction (feet to head) and presents as a bright signal (forward flow).
**Fig. 4:** The flexible tube (red arrow) was placed between two phantom bottles (3l and 1l). The phase contrast sequence was planned perpendicular to the tube. The bright signal in the middle of the figures indicates the saline solution in the tube.
Results

The accuracy of a phase contrast MR measurement is adequate for the studied flow rates (0.1 - 0.5 ml/s), with a maximal undervaluation of 5-10 % in higher flows (Fig. 5). Slice thickness does not have a substantial influence on the measured flow parameters (Fig. 6). In-plane resolution on the other hand has a substantial impact on the mean and peak flow velocity, presumably due to partial volumes effects of larger flow with low velocity. The selected VENC should be the same as or slightly higher than the expected flow velocity in order to obtain higher signal in the phase image and to prevent phase aliasing. If the VENC is chosen too high the peak velocity is overestimated (Fig. 6) while the flow rate is less affected. Best results are obtained when the phase contrast sequence is optimized in slice thickness (max. 3 mm), in-plane resolution (# 0.5 x 0.5mm$^2$) and velocity encoding parameters (VENC; 24 cm/sec).

Slice placement (Fig.7) and ROI diameter (Fig. 8) have major influences on the measured flow values (Table 1). The slice should always be placed in the narrowest point of the stenosis und strictly rectangular to the aqueduct. Hence it is essential to include a planning high resolution 3D T2w TSE sequence for precise anatomical depiction. ROI diameter should enclose the aqueduct with as little surrounding tissue as possible. Our software required a minimum of 10 pixels to calculate reliable values.

Since the sequence used in the phantom experiment was not ECG-triggered, the influence of the number of acquired phases on flow parameters could not been studied. An optimal measurement would have highest possible spatial resolution (high in-plane resolution and thin slice) to minimize partial volume effects and highest temporal resolution (high number of heart phases).
Fig. 5: Constant sequence parameters with different flow rates. The flow rate was increased by 0.1 ml/s in four steps to 0.5 ml/s.

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Fig. 6: Constant flow rate (0.2 ml/s) with A) different slice thicknesses B) different in-plane resolution and C) with different VENCs.

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Fig. 7: Different slice positions along the aqueduct in phase contrast measurements

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Fig. 8: Different ROI sizes and corresponding flow curves.

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<th>ROI Superior</th>
<th>ROI Stenosis</th>
<th>ROI Inferior</th>
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Table 1

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Conclusion

CSF flow measurements have not been used extensively because reference values are highly dependent on MR hardware, sequence parameters, post-processing and patient population. Our research quantified the degree of influence of various sequence parameters, slice placement and ROI diameter on the obtained flow values. In addition, we showed that by keeping these variables constant reliable results can be obtained. A limitation of our study is the non-pulsatile phantom model. Pulsatile flow in patients may lead to larger deviations of flow parameters. In addition, acquisition time is limited in clinical practice, where a trade-off between best possible sequence parameters and acceptable acquisition time is required. However, once established, reliable values can be obtained if the listed variables are kept constant.

For interpretation the results should be best compared with normal values collected at one's own institute. A comparison with literature data is only possible to a limited extent due to a large number of other variables (MR device, field strength, MR sequence, evaluation software, etc.) (5, 6). The age and gender of the patients have a decisive influence on the flow values and should be taken into account in the interpretation of the results (4).
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References


