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Blood flow assessment in cerebral arteries with 4D flow magnetic resonance imaging

An automatic atlas-based approach

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Abstract
Background: Disturbed blood flow to the brain has been associated with several neurological diseases, from stroke and vascular diseases to Alzheimer's and cognitive decline. To determine the cerebral arterial blood flow distribution, measurements are needed in both distal and proximal arteries.
4D flow MRI makes it possible to obtain blood flow velocities from a volume covering the entire brain in one single scan. This facilitates more extensive flow investigations, since flow rate assessment in specific arteries can be done during post-processing. The flow rate assessment is still rather laborious and time consuming, especially if the number of arteries of interest is high. In addition, the quality of the measurements relies heavily on the expertise of the investigator.
The aim of this thesis was to develop and evaluate an automatic post-processing tool for 4D flow MRI that identifies the main cerebral arteries and calculates their blood flow rate with minimal manual input. Atlas-based labeling of brain tissue is common in toolboxes for analysis of neuroimaging-data, and we hypothesized that a similar approach would be suitable for arterial labeling. We also wanted to investigate how to best separate the arterial lumen from background for calculation of blood flow.
Methods: An automatic atlas-based arterial identification method (AAIM) for flow assessment was developed. With atlas-based labeling, voxels are labeled based on their spatial location in MNI-space, a stereotactic coordinate system commonly used for neuroimaging analysis. To evaluate the feasibility of this approach, a probabilistic atlas was created from a set of angiographic images derived from 4D flow MRI. Included arteries were the anterior (ACA), middle (MCA) and posterior (PCA) cerebral arteries, as well as the internal carotid (ICA), vertebral (VA), basilar (BA) and posterior communicating (PCoA) arteries. To identify the arteries in an angiographic image, a vascular skeleton where each branch represented an arterial segment was extracted and labeled according to the atlas. Labeling accuracy of the AAIM was evaluated by visual inspection.
Next, the labeling method was adapted for flow measurements by pre-defining desired regions within the atlas. Automatic flow measurements were then compared to measurements at manually identified locations. During the development process, arterial identification was evaluated on four patient cohorts, with and without vascular disease. Finally, three methods for flow quantification using 4D flow MRI: k-means clustering; global thresholding; and local thresholding, were evaluated against a standard reference method.
Results: The labeling accuracy on group level was between 96% and 87% for all studies, and close to 100% for ICA and BA. Short arteries (PCoA) and arteries with large individual anatomical variation (VA) were the most challenging. Blood flow measurements at automatically identified locations were highly correlated (r=0.99) with manually positioned measurements, and difference in mean flow was negligible. Both global and local thresholding out-performed k-means clustering, since the threshold value could be optimized to produce a mean difference of zero compared to reference. The local thresholding had the best concordance with the reference method (p=0.009, F-test) and was the only method that did not have a significant correlation between flow difference and flow rate. In summary, with a local threshold of 20%, ICC was 0.97 and the flow rate difference was -0.04 ± 15.1 ml/min, n=308.
Conclusion: This thesis work demonstrated that atlas-based labeling was suitable for identification of cerebral arteries, enabling automated processing and flow assessment in 4D flow MRI. Furthermore, the proposed flow rate quantification algorithm reduced some of the most important shortcomings associated with previous methods. This new platform for automatic 4D flow MRI data analysis fills a gap needed for efficient in vivo investigations of arterial blood flow distribution to the entire vascular tree of the brain, and should have important applications to practical use in neurological diseases.

Keywords
Circle of Willis, 4D flow MRI, Cerebral arteries, Vascular disease, Stroke, Automatic labeling, Probabilistic atlas, Cerebral blood flow, Neuroimaging, Magnetic Resonance Imaging

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