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Detecting pulsatile motion of blood vessels in Real-Time MRI

T.v.d. Ohe[1,2,*] V. Telezki[3,4,5,*] S. Hofer[5] P. Dechent[6] M. Uecker[3,4,7] M. Bähr[5] S. Luther[1,2,8,9] U. Parlitz[1,2,9]

***Abstract*—We present a modular approach to analyse vascular pulsatile motion based on real-time MR imaging data. To analyse this pulsatile motion blood vessels are detected frame-wise using intensity threshold determination in combination with edge detection and outlier filter functions. The detected vessels found in consecutive frames are assigned to one another according to their relative position within the frame. This approach allows us to restrict the region of interest (ROI) to only contain individual blood vessels and to use these ROIs for further analysis.**

***Index Terms*—real-time MRI, vessel detection**

Arterial pulsations (1; 2; 3) and respiration (4) are thought to be the driving forces behind the bulk flow of cerebrospinal fluid (CSF), which is believed to play a crucial role in the brain's waste disposal processes (5; 6; 7). Investigating the dynamics and potential impact of heartbeat and breathing on CSF flow necessitates a method for measuring the pulsatile motion of blood vessels. Ultrasound measurement is a clinically established method for measuring such pulsations, offering significantly higher temporal resolution than MRI-based methods. However, it is limited to measuring selected vessels at a time and is subject to variability based on the angle of measurement and the expertise of the operator. Additionally, traditional ultrasound pulsation measurements assume circular cross sections of the measured vessels (8). Time resolved phase contrast MRI (4D PC-MRI) has also been used to quantify vascular streaming and pulsation (9; 10). This method relies on combining information from many heart cycles and therefore requires the assumption of a periodic heartbeat. In addition, some 4D PC-MRI acquisition parameters need to be specified before the acquisition to account for the highest expected flow velocities. A wrong choice leads to loss in image quality or velocity aliasing artifacts. So far, neither ultrasound nor the emerging 4D MRI techniques have been able to robustly characterize the dynamics of the small intracranial vessels relevant to the waste clearing system. Our initial strategy is to robustly validate the pulsatile movements of the larger extracranial vessels using real-time MRI data. In the future, we plan to extend this analysis to investigate the dynamics in small intracranial vessels. To this extent, we have developed a pipeline for automated detection and analysis of the pulsatile vascular wall motion recorded with real-time MRI (11; 12) (3T Siemens Prisma fit).

1. Max Planck Institute for Dynamics and Self-Organization, Göttingen, Germany
2. Institute for the Dynamics of Complex Systems, University of Göttingen, Göttingen, Germany
3. Cluster of Excellence Multiscale Bioimaging: from Molecular Machines to Networks of Excitable Cells (MBExC2067), University of Göttingen, Göttingen, Germany
4. Department of Interventional and Diagnostic Radiology, University Medical Center Göttingen, Göttingen, Germany
5. Department of Neurology, University Medical Center Göttingen, Göttingen, Germany
6. Department of Cognitive Neurology, University Medical Center Göttingen, Göttingen, Germany
7. Institute of Biomedical Imaging, TU Graz, Austria
8. Institute of Pharmacology and Toxicology, University Medical Center Göttingen, Göttingen, Germany
9. German Center for Cardiovascular Research (DZHK e.V., partner site Niedersachsen), Göttingen, Germany
* T.v.d. Ohe and V. Telezki contributed equally to this work.

After approval from the local ethics committee, high spatial ($0.8 \times 0.8 \times 6\mathrm{mm}^3$) and temporal (25 images per second) resolution real-time MRI data was acquired in a healthy volunteer. The plane of imaging was chosen by experienced operators to be orthogonal to the internal carotid artery, directly above its bifurcation point (see Fig. 1, left). The total measurement time was 1 minute, resulting in 1500 images, under free breathing and without any physiological gating.

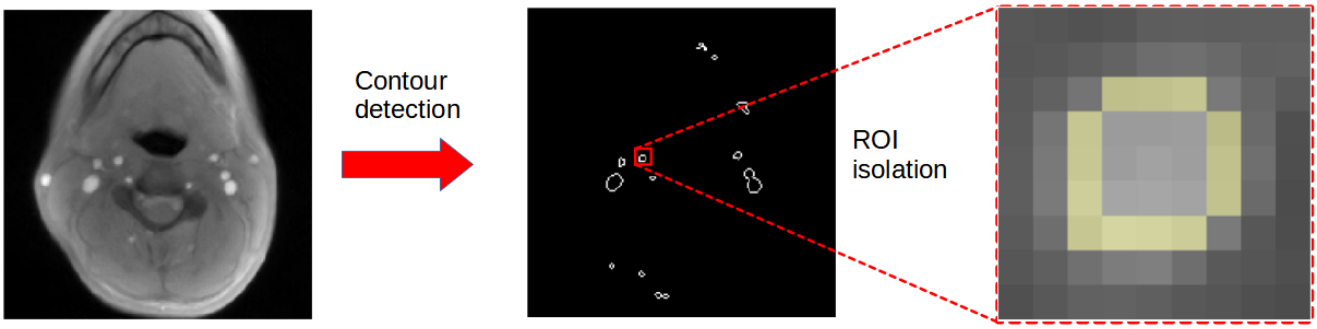

Fig. 1: Illustration of analysis pipeline. Left: single exemplary frame of MRI data in axial orientation. Center: detected contours following procedure in (see step 1). Right: ROI of single detected vessel contour. The yellow pixels depict the detected contour.

The analysis pipeline uses a modular design. In the following, we specify its basic structure and main components and demonstrate this analysis pipeline on a single data set.

1) After binarizing the image by applying a selected intensity threshold, we use a border-detection algorithm to detect contours (13). To identify contours not related to blood vessels, we apply two filter functions. The first function filters by size using an upper and a lower bound (here 5 and 500 times the area of a pixel). The second filter function calculates the ratio of the maximum horizontal (vertical) diameter of the contour and the length of the corresponding horizontal (vertical) edge of the smallest rectangle along the pixel grid which contains the contour. If one of these ratios (horizontal or vertical) is below a certain threshold (here: 0.5), we assume that this contour does not describe a blood vessel and exclude this outlier from further analysis.
   As a result, we obtain the boundaries of the smallest rectangle that contains the detected contour describing blood vessels. This rectangle is set as the region of interest (ROI) for each contour. This process is illustrated in Fig. 1. We repeat these steps for each frame.
2) To analyse the pulsatile vascular motion over time, the in step 1) detected contours are tracked over multiple frames. Accordingly, we compare a contour to all detected contours within the preceding five frames and check if their ROIs overlap. If the ROIs overlap, we assume that these ROIs contain the same blood vessel and they are therefore grouped together.
3) Finally, we characterize the pulsatile motion over time. For each group of ROIs, the smallest common area containing all ROIs is defined. This results in a time series of images showing an isolated blood vessel. We then calculate the total intensity of each image. The resulting time series is used as an approximation for the changing area of the vessel over time, assuming that the brightness of each pixel indicates whether the pixel belongs to the vessel or not. An example of the resulting time series and its spectral analysis is shown in Fig. 2. In this example, the spectral analysis shows two dominant contributions to the pulsatile motion which correspond well to expected, physiological breathing and heart rates.

Our approach neither requires a strictly periodic pulsatile motion nor do we make assumptions about the shape of the cross-sections of the vessels of interest. In contrast to 4D PC-MRI, we do not need to estimate the flow velocity in a vessel of our choice before measurement, which allows us to analyze multiple vessels with potentially vastly different flow velocities simultaneously.

The here presented pipeline allows us to automatically detect blood vessels within real-time MR images. The pipeline performs well even if the blood vessel is not detected or classified correctly within every frame of the video due to noise or motion events like swallowing. The pipeline allows us to analyse multiple comparable distinct blood vessels within the same MRI time series simultaneously. The modular design

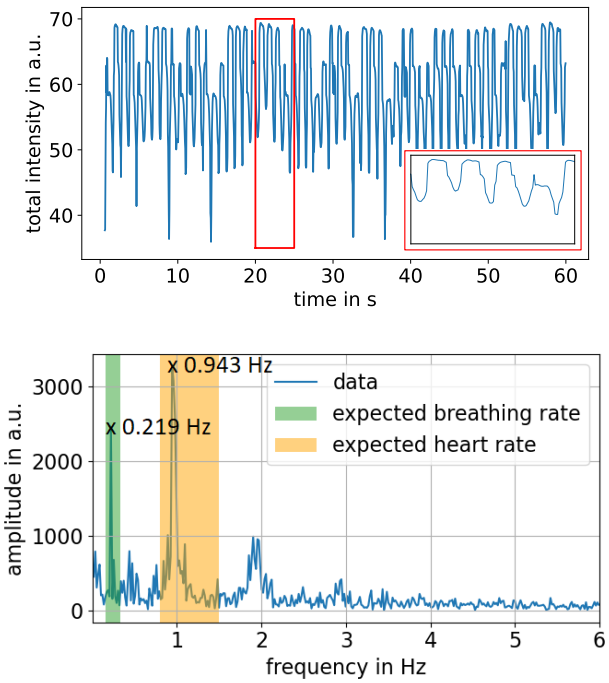

Fig. 2: Extracted data from a pulsating blood vessel. Top: total intensity of the extracted ROI as a function of time. The red box in the bottom right shows the part of the graph within the other red box in more detail. Bottom: its frequency spectrum, where the green area indicates the normal physiological range of human breathing rates (14) and the yellow area indicates the normal physiological range of human heart rates (15). The two highest peaks are marked with crosses.

of the pipeline makes it adaptable by allowing to replace or supplement any of its components. In the future development of the algorithm, it is planned to address the following limitations:

- The threshold in the first step is adjusted manually and should be replaced by an automatic procedure.
- On the tested data set the algorithm continuously detects the vessels of interest. However, in principle it is possible that a vessel is not detected over a period of five frames. This would result in the algorithm identifying the vessel as a separate vessel once it is detected again in the following frames.
- Contours that are close to each other can be incorrectly identified as the same contour.
- The integrated intensity computed in the last step of the analysis pipeline depends not only on the size of the vessel, but also on the velocity of blood flow within it. To separate both components a more detailed analysis of intensity profiles is required.

In future applications, the dominant modes of the resulting spectral analysis can be compared with other physiological recordings (ECG, SpO2, respiratory belt) to improve our understanding of vascular dynamics. In addition, the appli-

cation of this analysis to specific patient cohorts, such as patients with cardiac arrhythmias, can provide information about the dynamics of the blood vessels during arrhythmia in spontaneous breathing. A more challenging task will be the application to much smaller intracranial vessels to study their dynamics and their direct impact on the waste-clearing system.

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