4D Phase Contrast EPI for assessing 3D volumetric strain rate in the human brain over the cardiac cycle

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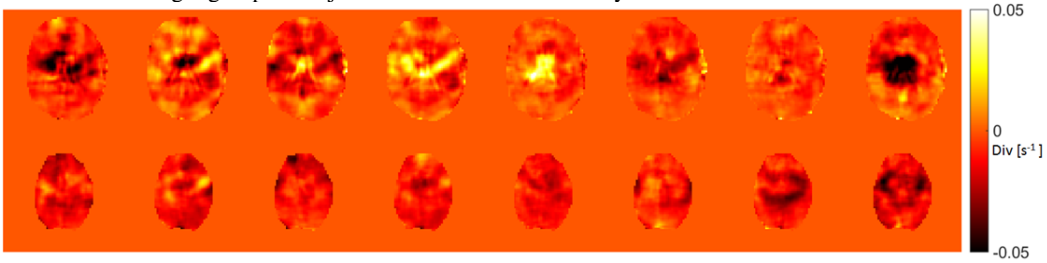
Background: Pulsation of the brain in synchrony with the cardiac cycle is an important physiological phenomenon since the resulting pulsatile volumetric strain is involved in the interstitial transport of metabolites and waste products. Non-invasive mapping of the volumetric strain over the cardiac cycle would provide a valuable tool for studying brain pulsation in relation to age and neurodegenerative diseases. Motion-sensitive MR sequences can detect the small pulsatile motion of the brain tissue [1,2,3,4]. However, mapping the volumetric strain (rate) over the entire brain and full cardiac cycle remains challenging as it requires measuring very small tissue displacements (or velocities) in three directions in a temporally resolved way for a relatively large volume. The aim of this study was to test the feasibility of mapping the cerebral volumetric strain rate with full coverage of the brain and cardiac cycle, by using a time resolved 3-dimensional velocity encoded phase contrast sequence.

Methods: Four volunteers (30±14, 2 males) were scanned on a 1.5T Philips Achieva MR scanner (Philips Healthcare) equipped with an 8-channel head coil. A 3D segmented EPI sequence was used, which yields high SNR and temporal resolution thanks to its high SNR-efficiency [5]. Two-point velocity encoding was done in each orthogonal direction with a V_{enc} of 0.3 cm/s, which was chosen based on the results from ref [3]. Other sequence parameters were: FOV: 192x192x99 mm; resolution: 3x3x3 mm³; TR/TE: 37/30; bandwidth: 2645 Hz; EPI factor: 21; Averages: 2; acquired temporal resolution: 74 ms/frame; scan time approx. 3x4 min for 60 beats/min. Retrospective cardiac triggering was achieved using a pulse oximeter on the finger, which lags ~0.5 cardiac cycle behind. Noise measurements were obtained by an acquisition without RF and gradient readout to sample the noise. The 3-dimensional flow vector field **v** was calculated from the phase data for 23 points of the cardiac cycle. The divergence of the flow vector field was calculated as a measure of the volumetric strain rate. Regions of interest (ROI) were selected anterior (95 pixels) and posterior (64 pixels) to the ventricles in three transversal slices per volunteer. The time evolution in these regions was calculated by averaging the volumetric strain rate over these ROIs to mitigate noise-induced effects. To remove static background errors, it was assumed that the time integral of div(**v**) over one cardiac cycle has to vanish due to the periodicity of the process [6].

Results: Figure 1 shows a series of volumetric strain rate images. In the inferior slices (top row), most activity is present in the inner brain regions, while the superior slice (bottom row) shows more divergence in the periphery. Figure 2 shows the minimum and maximum peak volumetric strain rates for a posterior and anterior ROI, in slices at three different locations with a spatial separation of 15 mm. Positive strain rates represent expansion, whereas negative values represent compression. The largest events are happening in the highest slice with peak volumetric strain rates of $(1.4\pm0.7)\cdot10^{-2}$ s^{-1} and $-(1.6\pm1.1)\cdot10^{-2}$ s^{-1}. The difference in volumetric strain rates between the different slices was, although quite large, not significant (P=0.15 (n=4)). At the arrival of the arterial pressure wave, a strong expansive component was observed throughout the brain, followed by a weaker relaxation process. The strain rate maps indicate that the magnitude of the pulsation is stronger in inferior slices (slice 14) than in superior slices (slice 25).

Discussion: The overall shape of the strain rate curves (data not shown) was consistent with the findings presented in [3]. However, the amplitudes of the effect presented in this work are larger by a factor of approximately 5. This might be related to differences in acquisition techniques, but requires further research and validation. The major contribution to volumetric strain stems from the feet-head axis, which is in agreement with previous findings [1,3]. The strain rate maps indicate that the strain rate is largest in the center of the brain and decreases towards the periphery. This can be explained by the fact that most major arterial vessels are concentrated in that region, so that their pulsation is subject to geometric attenuation, similar to waves emanating from a point source. However, the most cranial slices tended to show higher strain rates. Anterior ROIs show a compression at the end of the cardiac cycle (relative to the peripheral pulse oximeter), while posterior ROIs expand. This may be related to the Monroe-Kelly principle, stating that the total volume within the skull is constant, but this needs to be confirmed in a larger group of subjects and a more detailed analysis.



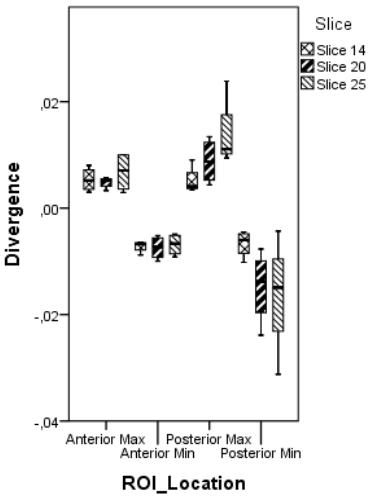


Figure1 (left) Divergence of the measured velocity field for (top row) an inferior slice (at the level of the basal ganglia) and (bottom row) for a superior slice, 27 mm above the basal ganglia. Only every third point in the cardiac cycle is shown. Positive values indicate expansive motion, whereas negative values represent compression. Note that the majority of the pulsation in the inferior slice occurs in the slice center, where the big arteries are, while the superior slice shows most activity around the periphery.

Figure2 (right) Comparison between the divergence measured in a posterior and anterior ROI in three different slices. Overall, the most compression and expansion is observed in the posterior regions, as well as in the more superior slices. Note that central regions are not taken into account due to the presence of cerebrospinal fluid.

Conclusions: This feasibility study showed for the first time that the 3D PCA with very low V_{enc} can be utilized to quantify volumetric strain rate. Though the shape of the strain rate curves were similar as in previous studies using different techniques, the magnitude was much larger, requiring direct comparison and validation before using this technique as a tool for studying neurodegenerative diseases and ageing.

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