Assessment of Respiration- and Cardiac-Related Flow Patterns of Cerebro-Spinal Fluid Using Balanced Steady-State Free Precession and Breathing-ECG Synchronization

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Introduction. Assessment of Cerebro-Spinal Fluid (CSF) dynamics is a challenging task, because peak velocities are slow (few centimeters per second) and the motion is not caused by heartbeat only but also by respiration phase. Slow flow reduces the signal enhancement due to inflow effect in MR imaging, thus standard flow-sensitive spoiled gradient echo sequences suffer from low signal-to-noise ratio because of the saturation of the spins, the dependence on cardiac and respiratory phase introduces the need for a double gating if accurate measurement is required. In this work, a flow-sensitive double-gated cine balanced Steady State Free Precession (bSSFP) sequence is presented, together with a Breathing-Electrocardiogram Synchronization SYstem (identified with the acronym BESSY) that provides visual feedback to the examined subject forcing a breathing pattern that always spans the same number of heartbeats.

Materials and Methods.

A) Flow-sensitive bSSFP Sequence. A standard bSSFP scheme was made flow-sensitive in the through-slice direction by adding two bipolar gradients after the Slice Selection gradient. The slice rephasing gradient is introduced as an offset in one of the two lobes, so that at echo time the zeroth moment of the slice selection gradient is zero and the first moment is different than zero. The same bipolar gradient (shown in green in Fig.1) is "paired", i.e. run twice on two adjacent *k-space* lines, to reduce the amplitude of induced eddy currents as shown in [1], then the same lines are scanned with inverted amplitude of the bipolar gradient (shown in red in the same Figure), to provide higher motion sensitivity and compensation for offset phases. After image reconstruction, the phase images corresponding to the different bipolar gradients are subtracted, so that the final phase of a pixel containing a moving structure is $\varphi = \gamma(M_{1,1} - M_{1,2})v$, where γ is the gyromagnetic ratio, $M_{1,1}$ and $M_{1,2}$ are the first moments at echo times, and v is the velocity. The sequence was run continuously, retrospectively updating the phase encoding pair at every gating signal received.

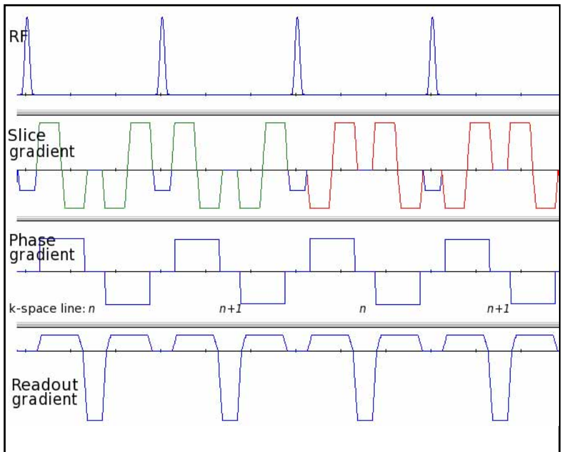

Figure 1 – Sequence scheme (RF pulses and gradients).

B) Breathing-Ecg Synchronization SYstem (BESSY). This system consists in an electrocardiogram (ECG) monitor, an analog to digital converter (ADC), a personal computer and a projector. The ECG signal was fed into the computer through the ADC, and a Java (Sun Microsystems, CA) program analyzed it in real-time and gave as output a desired breathing pattern continuously adapted to a user-selectable number of heart periods. The breathing pattern was modelled on a real human breathing waveform recorded in rest conditions. The desired breathing pattern was shown to the subject through the projector as a progress bar, and the subject was instructed to breathe in when the bar was rising and breathe out when it was falling.

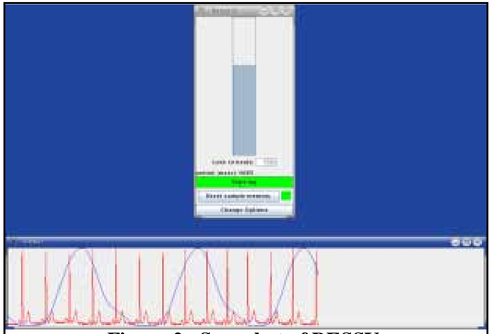

Figure 2 –Snapshot of BESSY.

C) Measurement protocol. Flow measurements were performed on a 1.5T whole-body MR imaging system (Magnetom Avanto, Siemens Medical Solutions, Erlangen, Germany), with TR=12ms and scanning four *k-space* lines per phase, corresponding to a $Venc = \pi / \gamma \Delta M = 3.8\text{cm/s}$ and a time resolution of 96ms. A scan of the spine was performed at the level of the C3 vertebra, with an in-plane resolution of 0.86x0.86mm^2. A Region of Interest (ROI) was selected in the frontal part of the spine, to restrict analysis to a region with homogeneous flow (Fig. 3). Mean value of the voxels in the phase images were obtained for each respiratory and cardiac phase, the result was then converted from degrees to cm/s.

Results. Preliminary results confirmed the hypothesis of double dependency of the velocity from heart and breathing phase. Figure 3 shows the measured velocities due to heartbeat in the different respiratory phases. Figure 4 shows calculated velocity due to breathing in the five measured respiratory phases, obtained by taking the mean velocity of the first and last cardiac phases, where the contribution due to heartbeat is supposed to be minimum.

Discussion. Flow-sensitive bSSFP was proven to be useful for the assessment of CSF flow velocities, because its characteristic T_2/T_1 weighting gives a very high signal-to-noise ratio for this tissue, and it does not suffer from saturation effects. "Pairing" reduced eddy currents effects, and made slow flow accurately measurable. The breathing and ECG synchronization system made possible the quantitative measurement of contributions to CSF flow due to breathing and heartbeat in reasonable scan times (around 5 minutes per slice).

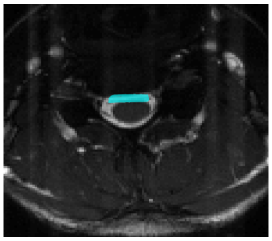

Figure 3 – Magnitude image with selected ROI.

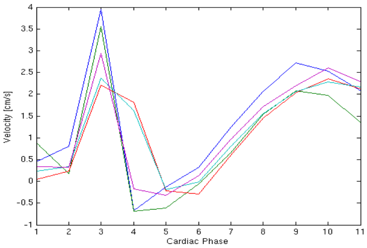

Figure 4 – Flow patterns due to cardiac pulsations in different respiratory phases.

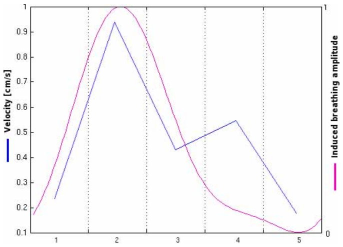

Figure 5 – Calculated breathing-induced flow (blue) and breathing pattern (pink).

References.

[1] Bieri O *et al.*, Magn Reson Med. 2005 Jul;54(1):129-37