Time efficient and robust perfusion measurement using Walsh-reordered time encoded pCASL

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Target audience: Researchers and clinicians interested in new acquisition techniques and developments of ASL

Purpose: Hadamard time-encoded pCASL (TE pCASL)[1,2] offers the possibility to combine the superior SNR of pCASL with the feasibility to acquire data at different inflow times. In a classical TE pCASL experiment, *N* images are acquired to resolve *N-1* time points. It is important to note that in this scheme all *N* images are needed for correct decoding. In other words, if one or more of the *N* images are corrupted, e.g. by motion or premature termination of the measurement, erroneous or incomplete decoding can be the consequence and render the complete dataset useless. To overcome this limitation we propose a new acquisition scheme that consists of an extended, Walsh-ordered Hadamard matrix. In contrast to the classic scheme, this approach permits reconstruction of perfusion data already after two, instead of *N,* image acquisitions. Therefore, perfusion data can be reconstructed at a very early stage of the measurement and the robustness against complete data loss by motion or by premature termination of the experiment is significantly increased.

Methods:

Encoding matrix: The new encoding matrix is generated in two steps. First, the Walsh-ordered form of a classical *N*x*N* Hadamard matrix $\mathbf{H}$ is constructed by reordering the rows according to their sequency, which is defined, as the half number of zero crossings (i.e. changes from label to control). Second, the resulting matrix $\mathbf{H}^+$ is then row wise interleaved with the matrix $\mathbf{H}^- = -\mathbf{H}^+$. The *n*-th row of the resulting 2*N*x*N* matrix $\boldsymbol{H}^{\pm}$ has then the form $(\mathbf{H}^+_{1,n}, \mathbf{H}^-_{1,n}, \dots, \mathbf{H}^+_{N,n}, \mathbf{H}^-_{N,n})^T$ (fig. 1a). $\mathbf{H}^{\pm}$ is then used for encoding.

Reconstruction: As recently proposed[3], two or more images corresponding to single subboli can be added to yield an image corresponding to a longer virtual subbolus. Several different subbolus lengths (SBLs) and post labeling delays (PLDs) can be generated this way. When using a classical Hadamard matrix for encoding all *N* encoded images have to be acquired for this, even though fewer images are necessary for the longer virtual subboli.

The proposed encoding scheme, on the other hand, begins with the acquisition of the images necessary to reconstruct the longer virtual subboli. That means, that their reconstruction is possible already from the second image acquisition on. The more images are acquired, the shorter become the virtual subboli and the more PLDs can be reconstructed (fig 1 a & b).

When looking at the PLDs, the sequency ordering of $\mathbf{H}^+$ already yields a time efficient acquisition scheme for the shorter PLDs. $\mathbf{H}^-$, being mirror-symmetric to $\mathbf{H}^+$, complements this by yielding same time efficiency for the longer PLDs. Therefore, using $\mathbf{H}^{\pm}$ for encoding results in a time-optimized acquisition for short and long PLDs. Furthermore, it allows the reconstruction of up to *N* subboli ("real" and virtual), instead of *N*-1in the classic case.

Testing: The images resulting from the 11 virtual subboli are compared to the images resulting from 11 classical pCASL measurements, where in each the BL and PLD is set to the SBL and PLD of the respective virtual subbolus. An analogous method was recently used to test classical TE pCASL[2].

Imaging: A 16x8 Walsh-ordered Hadamard matrix with a SBL of 350 ms and a PLD of 200 ms was used for the labeling. This results in up to 8 inflow times between 200 and 2650 ms. The labeling plane was positioned at the height of the C3 vertebrum. Two FOCI pulses at 1200 ms and 2520 ms were used for background suppression. Since $\mathbf{H}^+$ and $\mathbf{H}^-$ can be regarded as independent measurements and each allows the reconstruction of all virtual subboli, the resulting images of both are used for averaging.

Three healthy male volunteers (age 27-43) were scanned at 3T (Skyra, SIEMENS Healthcare) using a 16-channel head coil.

For the readout a segmented 3D GRASE readout[4] was used (24 slices, 4 segments, resolution 2x2x5 mm^3(interpolated), TA: 5:52 min, TR 5.5 s, TE 19 ms).

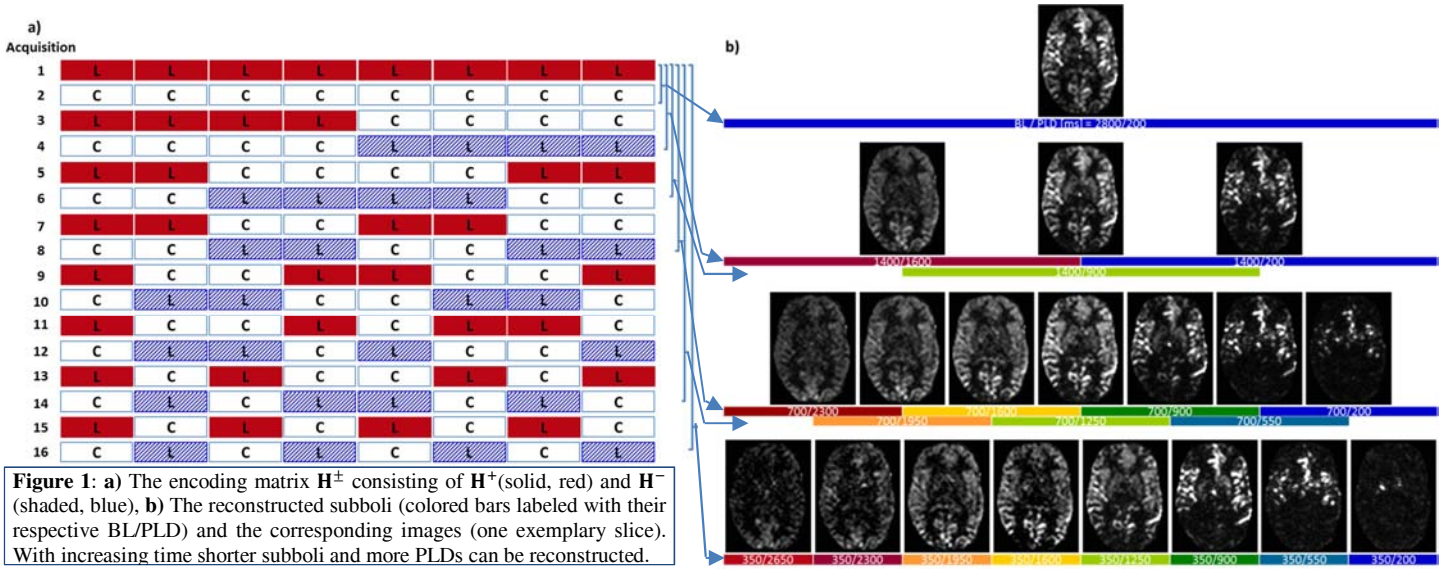

Figure 1: **a)** The encoding matrix $\mathbf{H}^{\pm}$ consisting of $\mathbf{H}^+$(solid, red) and $\mathbf{H}^-$ (shaded, blue), **b)** The reconstructed subboli (colored bars labeled with their respective BL/PLD) and the corresponding images (one exemplary slice). With increasing time shorter subboli and more PLDs can be reconstructed.

Results and Discussion: From the proposed acquisition scheme all predicted virtual subboli could be successfully reconstructed and the expected bolus dynamics became clearly visible (fig 1 a & b). After 2, 4, 6, 8, 14, and 16 acquisitions a total of 1, 3, 4, 8, 11 and 19 SBL/PLD combinations were obtained.

The pCASL multi-TI experiment agrees well with the results and confirms the correct reconstruction by the Walsh-ordered Hadamard approach.

$\mathbf{H}^+$ and $\mathbf{H}^-$ could be used as independent measurements for averaging, which is anyway necessary in most ASL measurements to obtain sufficient SNR. Thus, measuring 2*N* instead of *N* images means no additional time penalty.

The risk of total loss of information due to image corruption was highly reduced, because perfusion weighted data can be obtained beginning with the second image acquisition and even with an incomplete set of images. Furthermore, the concept of virtual subboli offers the flexibility to vary BL and PLD in postprocessing and the proposed Walsh-ordered Hadamard matrix even optimizes the time efficiency of this concept.

Conclusion: The Walsh-Hadamard approach provides a time-efficient and robust image acquisition strategy. Especially in the clinical setup with agitated patients, as in Alzheimer disease or stroke, this is a crucial criterion. Furthermore, it offers the flexibility of choosing the BL and the PLD in the postprocessing. These features render this approach especially suitable for the clinical use.

References:1) Guenther, M.: Proc Intl Soc Mag Reson Med 15,no 380, (2007), 2) Dai, W. et al.: *Magn Reson Med* 69(4), 1014-22 (2013), 3) Guenther, M: Professoral thesis, 177-93, Heidelberg (2007) 4) Guenther, M et al.: *Magn Reson Med* 54, 491-8 (2005)