

# ESPreSSo: A Compressed Sensing partial k-space acquisition and reconstruction

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**Purpose:** A combined PET/MR system offers the possibility to perform motion correction (MC) of PET data by means of an additional MR acquisition<sup>1</sup>. In order to keep the additional sequence workload low, the acceleration of the MR acquisition is substantial for the implementation of a clinically feasible MC setup. Compressed Sensing (CS) strategies offer the most promising acceleration factors. Using a variable-density Poisson disc (VDPD) subsampling, one can gain high acceleration factors, but at the expense of a degraded image quality, especially with respect to edge sharpness, due to highly undersampled high frequency components, leading to loss of tissue boundary integrity which is crucial for an accurate MC. To compensate for this problem, high frequencies should be sampled denser. This could be achieved by reducing the allowed k-space sampling region to a smaller subset. In this work we propose a new undersampling scheme, called ESPReSSo (comprEessed Sensing PaRtial SubSampling), and show how this constraint is incorporated into a CS reconstruction using a projection-onto convex sets (POCS).

**Theory:** As well-known from Partial Fourier (PF), one can benefit from the conjugate symmetry of the k-space  $v(-k) = v^*(k)$  for acquisition acceleration. The missing data can then be reconstructed via a POCS algorithm<sup>2</sup>. We make use of this property by incorporation into the CS acquisition and reconstruction algorithm.

**Acquisition:** To achieve a sampling region reduction and to still ensure a random k-space sampling, the VDPD subsampling is confined to a smaller region, see Fig. 1. Similar to PF, we avoid symmetry ambiguity by restricting the sampling region reduction only along one phase encoding direction. If  $N_s$  denotes the samples along one phase encoding direction, then the reduced region is given by  $1 \leq k \leq \gamma N_s$  with  $\gamma$  being the compression factor. Since an initial low frequency estimate is essential for the CS reconstruction, we allow the fully sampled region in the k-space center to exceed across the border  $\gamma N_s$ .

**Reconstruction:** The CS reconstruction algorithm uses a FOcal Underdetermined System Solver (FOCUSS) as proposed by<sup>3</sup>. We try to find the optimal multichannel image  $\rho$  out of the acquired k-space samples  $\mathbf{v}$ . Therefore the underlying optimization problem is

$$\text{find } \rho = \Psi^{-1}(\mathbf{W} \circ \mathbf{q}), \text{ where } \min_{\mathbf{q}} \|\mathbf{q}\|_F, \text{ s. t. } \|\mathbf{v} - \Phi \circ \mathbf{F}(\Psi(\mathbf{W} \circ \mathbf{q}))\|_F \leq \epsilon, (\mathbf{G} - \mathbf{1}) \circ \mathbf{W} \circ \mathbf{q} = \mathbf{0} \quad (1)$$

$$\text{and } \Omega_1: \arg(\rho), \Omega_2: \mathbf{F}^{-1}[\mathbf{F}(\rho) \circ (\mathbf{1} - \Phi) + \mathbf{v} \circ \Phi] \quad (2)$$

where  $\mathbf{W}$  denotes the weighting matrix of the affine scaling transformation,  $\mathbf{F}$  is the Fourier transform operator,

$\Psi$  is a sparsifying transformation operator and  $\mathbf{G}$  is a channel correlation matrix, as proposed in<sup>4</sup>.  $\Phi$  is the extracted subsampling mask,  $\Omega_1$  and  $\Omega_2$  describe the two convex optimization sets for the POCS reconstruction. The cost function of eqn. (1) is solved iteratively by means of a conjugate gradient (CG) method. At the end of each FOCUSS iteration step, the POCS updates the estimated output image  $\rho$  following eqn. (2). A functional overview of the reconstruction process is given in Fig. 2.

**Materials & Methods:** Transversal *in-vivo* datasets were acquired on a 3T scanner (Biograph mMR, Siemens), using a FLASH sequence with a flip angle of 10°, TR = 6.04 ms, TE = 3 ms, bandwidth = 300 Hz/px, voxel size = 0.89 x 0.89 x 3 mm and 32 slices. The ESPReSSo mask is created online on the scanner obeying the VDPD property in the reduced k-space area. For comparison, we acquired image series containing 1x,  $N_x$  and  $N_x$ -ESPreSSo ( $N = 2, \dots, 10$ ) accelerated images in one breath-hold, with 45s sequence duration for the 1x accelerated acquisition. The images were evaluated pairwise with the 1x accelerated image as reference using the Mean Structural Similarity (MSSIM)<sup>5</sup> quality measure. In order to appreciate subjective image quality, images were inspected and rated by two radiologists blinded for the reconstruction method.

**Results & Conclusions:** The 4x-ESPreSSo image from Fig. 3c) has a sharper delineation compared to Fig.3b) and hence smaller structures like vessel boundaries of the portal and hepatic veins or aorta (marked by arrows), can be visualized.

On the other hand, this comes at cost of worse contrast due to reduced SNR. It can be seen from Fig. 3d) that for nearly all acceleration factors (except for 4x), the ESPReSSo algorithm shows a better performance regarding the MSSIM than a VDPD subsampling. For accelerations up to a factor of 4, which can be regarded as clinical feasible with diagnostic performance, both radiologists decided in favor of the ESPReSSo images. For higher accelerations the decision mainly depends on the diagnostic need: If sharp contours are of interest, then the ESPReSSo images should be favored, while soft tissue contrasts can be better visualized in the non-ESPreSSo images. In conclusion, in a MC setup the ESPReSSo sequence with the proposed reconstruction algorithm could also be used for diagnostic purposes with reasonable expenditure of examination time.

**References:** [1] Würslin, JNM, 2013, 54(3):464-71; [2] Lindskog, JMR, 1991, 92:126; [3] Gorodnitsky and Rao, IEEE Trans. Signal Processing, 1997, 45(3):600-16; [4] Lustig, MRM, 2010, 64:457-71; [5] Wang, IEEE Trans. Signal Processing, 2004, 13(4):1-14

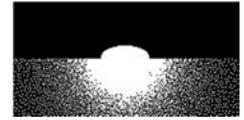


Fig. 1: 4x accelerated ESPReSSo mask

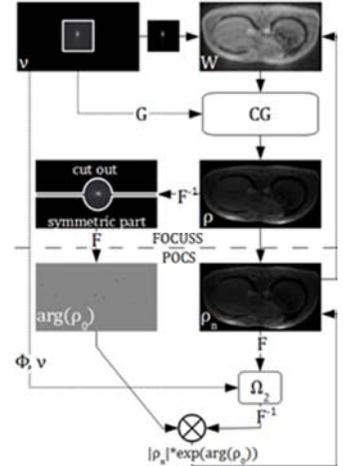


Fig. 2: Reconstruction process of ESPReSSo images

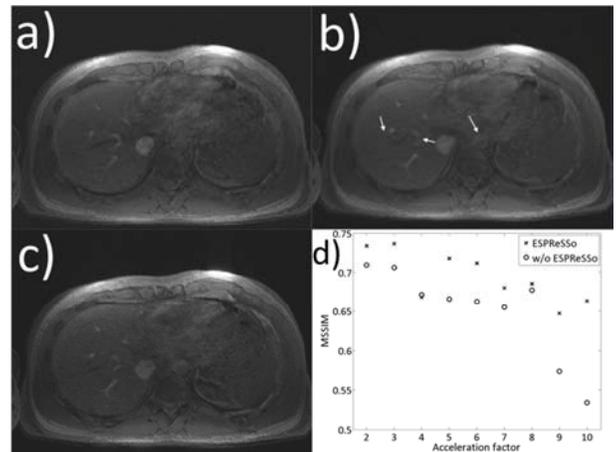


Fig. 3: Transversal liver slice of a) 1x, b) 4x, c) 4x-ESPreSSo, accelerated acquisition. d) MSSIM of all acceleration factors