Improving the spatial resolution and SNR of rat brain T2-weighted MR images: application of a super-resolution method

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Purpose: MRI spatial resolution is inherently limited by the strength of the B0 magnetic field, SNR consideration and scanning time. When coupled to optimal acquisition strategies, post-processing methods such as super-resolution (SR) can be used to improve MR images with few modifications of the classic protocols and in reasonable scanning times[1]. They have proved to improve the trade-off between scanning time, spatial resolution and SNR[2,3]. We focus on isotropic volume reconstruction and propose a super-resolution methodology to improve the spatial resolution and SNR of rat brain MR images.

Methods: We propose to perform a high-resolution (HR) isotropic reconstruction from three orthogonal anisotropic low-resolution (LR) volumes of a rat brain. Acquisitions were performed on a horizontal 4.7T MRI Bruker Biospec using a receiver quadrature surface coil shaped and sized for the rat brain (Rapid Biomed). Three orientations were successively acquired at a voxel size of 0.1x0.1x0.5mm^3 for a total acquisition time of 40 minutes (Figures 1 (a)-(c)). Sequences used were 2D multi-slices (no gap) RARE sequences (turbo factor = 8; 50 kHz bandwidth) with T2-weighted image contrast (72.9ms TE, TR > 5.7 ms depending on the maximum number of slices necessary to cover the brain). In these scans, the TR was assumed long enough to reach the full recovery of longitudinal magnetization. Volumes are subsequently bias corrected and denoised using N4[4] and SUSAN[5]. An additional nearly isotropic scan is performed (0.1x0.1x0.2mm^3) as a reference in 31 minutes (Figure 1 (d)) using 3D turboRARE sequence (turbo factor = 8; 21 kHz bandwidth) with T2-weighted image contrast (108.6 TE; 900ms TR). It is also denoised using SUSAN for comparison as shown in Figure 1 (e). SR methods rely on an acquisition model that allows to link the observations (LR acquisitions) to an ideal HR isotropic volume that we aim to reconstruct. The model takes into account 3 main parameters:

<u>Blur modeling</u>: The point-spread function (PSF) of the imaging system, defined by the operator B. In our model, the PSF is modeled by a separable 3D Gaussian filter. The Gaussian variance is empirically set equal to the pixel spacing in the in-plane dimensions, and so that the full width at half maximum equals the slice thickness in the through-plane dimension.

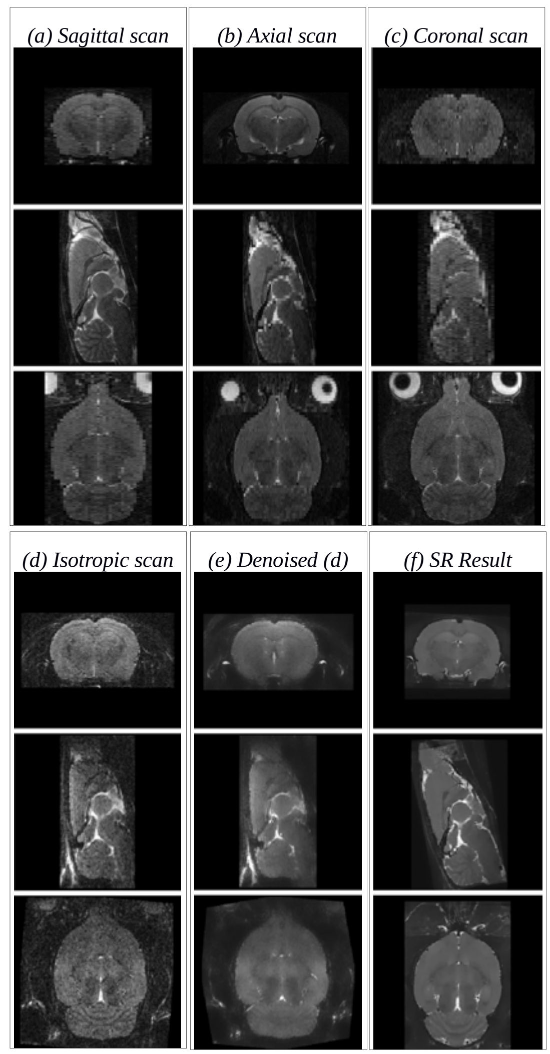
<u>Geometric transformation</u>: The geometric transformation between the LR acquisitions is defined by the operator G. It compensates both the choice of the acquisition orientation and the motion that might have occurred between acquisitions. It is computed by successively registering the observations in similar spatial configurations.

<u>Down-sampling</u>: The operator D defines the down-sampling operation required to match the desired resolution of the HR volume to the resolution of the observations.

<u>Global model</u>: Following the previously defined operators, the acquisition model can be expressed as : $Y_k = DBG_k(X) + n$ for $k = \{1, \dots, N\}$, where n is an additive zero mean Gaussian noise, Y_k the k-th observation and X the HR volume to be estimated. This model needs to be inverted to estimate X. This is an ill-posed problem so no analytic solution can be derived from it. The estimation of X is thus performed through an iterative optimization procedure of the following cost function:

$$X = arg\min_X \sum_{k=1}^{N} \|Y_k - DBG_k(X)\|^2 + \alpha R(X)$$

Here, α balances the influence of the regularization term $R(X)$ and the data fidelity term. The regularization is needed to constraint the solution and facilitates the convergence towards a satisfactory estimation. A tri-lateral total-variation regularizer is used for its efficient noise reduction and its ability to produce images with sharp edges.



Results and Discussion: Fig. 1 (f) illustrates both the SNR and resolution improvements when compared to the reference and the LR images. The reference acquisition shows a high level of noise and would not be exploitable in practice, and the denoised version does not reveal similar details and contrast as the SR reconstruction. To reach the targeted spatial resolution with reasonable SNR in a single acquisition scan, only 3D acquisitions can be considered. Due to large impact of TR values on the total acquisition time, 3D acquisitions induce some limitations in the choice of parameter values used for image contrast compared to 2D acquisition. This illustrates the difficulty to acquire high quality (contrast and signal) high-resolution data. In this study, 3 orthogonal scans are acquired to perform SR reconstruction because it optimizes the k-space sampling. Other acquisition protocols using more than 3 LR acquisitions have been proposed[5] and could be investigated in this context. Finally, the LR scans have a through-plane to in-plane ratio of 5. This ratio balances the overall required acquisition time and the final reconstruction quality, and its optimal value will probably depend on the application.

Conclusion: SR proves to be efficient to enhance the spatial resolution and SNR of rat brain data. Significant voxel size reduction induces a diminution of the partial volume effect, and in turn an in-plane resolution improvement. SR allows to produce volumes that would require prohibitive acquisition times in practice. Moreover, the T2-weighthed contrast can be further improved. The few modifications required on classical protocols and the reasonable overall acquisition time make it a realistic post-acquisition approach. Several post-processing processes such as registration, segmentation could be improved by using reconstructed HR volumes.

References: **[1]** E Van Reeth et al. "Super-resolution in magnetic resonance imaging: a review", Concepts in Magn Res Part A, 2012; **[2]** E Van Reeth et al. "Isotropic reconstruction of a 4-D thoracic sequence using super-resolution". Magn Res Med, 2014; **[3]** NJ Tustison et al. "N4ITK: improved N3 bias correction" IEEE Trans Med Imaging, 2010 **[4]** SM Smith and JM Brady "SUSAN: a new approach to low level image processing" Inter Jour Computer Vision, 1997; **[5]** RZ Shilling "Sampling strategies for super-resolution in multi-slice MRI", IEEE ICIP 2008