An Automatic Stopping Criterion for Iterative MRI Reconstructions

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Introduction: Image reconstructions from undersampled data such as in parallel imaging require the inversion of an ill-posed linear (or non-linear) system. In these cases the quality of the reconstructed image critically depends on the choice of the regularization. However, while small values of the regularization parameter cause substantial noise, large values still lead to visible undersampling artefacts. For some iterative methods the regularization parameter is controlled by the total number of iterations. Here, we propose an automatic stopping criterion which terminates the iteration as soon as all undersampling artefacts are fully removed.

Theory: Undersampling artefacts in the image domain correspond to missing data in k-space. Reconstruction methods try to infer this missing information from additional information like the encoding given by the coil sensitivities of multiple receiver coils in parallel imaging or the incorporation of various kinds of a priori knowledge. In general, the additional information is not sufficient to fully compensate for the missing data, so that the reconstructions need to be properly constrained. However, when choosing the regularization parameter too large, the empty positions in k-space are only partially filled which corresponds to residual artefacts in image space. In this work we estimate this effect by comparing the energy density of the inferred k-space positions to the energy density in the directly measured positions for some large region in k-space. In an image without undersampling artefacts both quantities should be equal. The iteration is stopped when this condition is reached.

Methods: Data from a parallel imaging acquisition of a human brain (3D FLASH; TR/TE = 10.6/4.2 ms, flip angle 17°; image matrix 256×162×224; reduction factor 6 = 3×2; 12 channels; 24×24 reference lines) was reconstructed with an iterative variant of the SENSE algorithm. Serial reconstructions reduced the regularization in each step by a factor of 1.5. The relation of the energy density for the measured positions in k-space to the energy density of the skipped positions was calculated for a circular ring in k-space excluding the fully sampled center. This quantity was compared to the visibility of undersampling artefacts in each image.

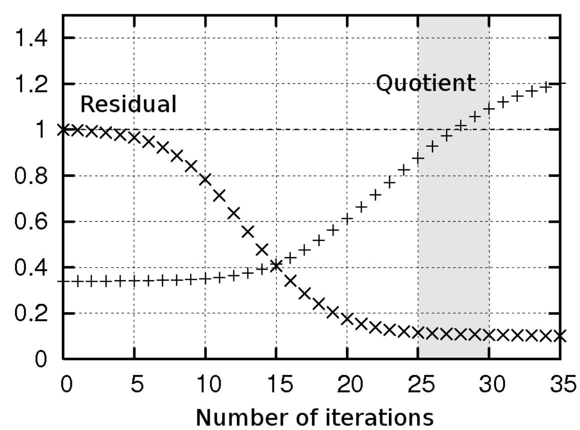
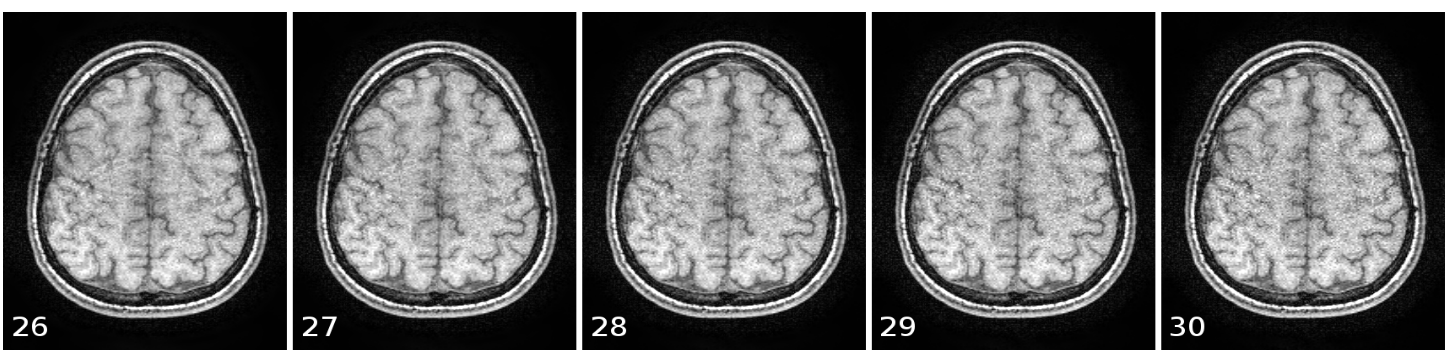


Figure 1: Quotient between the energy densities of the measured and skipped k-space positions (+) and corresponding residual (x) for an iterative SENSE-like reconstruction of a parallel imaging data set from a human brain with reduction factor 6=3×2.

Figure 2: Reconstructed images corresponding to the iteration steps in the grey area shown in Figure 1. The automatically chosen image is the one in step 28. Earlier images exhibit residual aliasing artefacts, while later images suffer from increasingly more noise.



Results and Discussion: Figures 1 and 2 demonstrate the energy density of the predicted k-space positions in relation to the energy density of the measured k-space and the resulting images, respectively. The final stopping index is given when the quotient of the energy densities becomes one. This condition is reached in iteration step number 28. In comparison with images belonging to neighboring steps ghosting artefacts are only visible for the images below the stopping index. Because the noise level is monotonously increasing in each iteration step, the first image without undersampling artefacts is a good choice for the final reconstruction and defines the stopping criterion. The choice of the regularization is a common problem to all parallel imaging algorithms. While the current approach is directly applicable to certain iterative methods, its adaptation to other methods is conceivable.