Simulation of Temporal Resolution for Non-Cartesian K-Space Sampling Strategies to Trace Fast Dynamic Changes of Helium-3 Spin Density

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Motivation

The increase of the temporal resolution has been for many years one of the issues in MRI method development. In biomedical MRI this aspect is essentially important in fields such as blood flow measurement, tissue perfusion, or dynamic imaging of lung ventilation with hyper- or thermally polarized gases. There are two basic strategies of temporal resolution enhancement in MRI. The first implies hardware acceleration methods such as increasing gradient slew rate with different boosters, using ultra-fast sequences as /EPI or increasing number of channels for parallel imaging. However, these methods meet their limitation both due to safety reasons (gradients stimulation restrictions) and sufficient increasing of costs for system manufacturing and maintains. The second way is known to be the using of non-cartesian schemes of k-space sampling such as radial or spiral. The aim of employing these schemes is optimizing a gradient switching and reducing a total number of NMR signals acquisitions required to cover whole k-space. The mentioned schemes, however, require special image reconstruction techniques with re-gridding to Cartesian matrix for subsequent Fourier transformation, compensation of the inhomogeneous filling of the k-space and correction of deviation between theoretical and really generated gradient waveforms. The combination of these factors causes certain artefacts in resulted image. The situation becomes even more complicated when using "sliding-window" technique in connection with non-cartesian k-space trajectories by sampling only every other k-space line for each new image frame [Salerno]. The real temporal resolution of such schemes, taking into account the reconstruction artefacts caused by a variation of the MR signal intensity during k-space filling, therefore requires special theoretical and experimental proof.

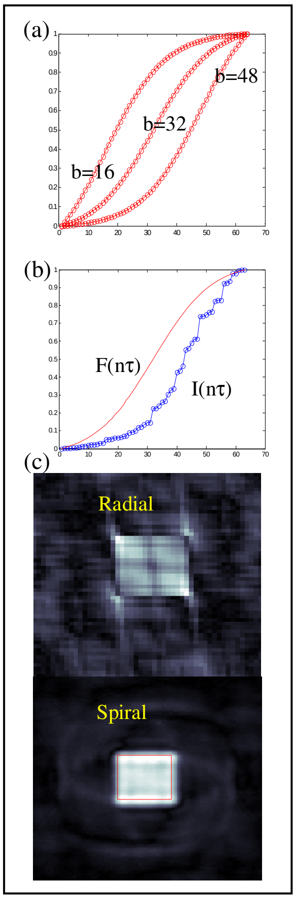

Fig 1(a) Spin density modulation function F(nτ), (b) Following the F(nτ) by reconstructed image intensity integral.
(c) Final reconstruction of homogeneous rectangular area encoded with radial and spiral interleave trajectories.

Method

To examine the time resolving effectiveness of different MRI data acquisition strategies under conditions of dynamic imaging as a model, numerical simulations were performed. The generated initial spin density matrix was affected by the temporal modulation of intensity. As an modulation model a Fermi function (F-function) with discrete steps τ_d was used $F(n\,\tau_d)=(1+exp\text{-}(\,k\,\tau_d\,\text{-}b)/a)^{-1}$ (Fig.1a) with n=1..N, the number of time steps. This function describes well the curve found for wash-in dynamic MRI of hyperpolarized ^{3}He [Lehmann] in lungs. By variation of parameters **a** and **b** the speed of transition regime as well as transition starting point can be adjusted respectively. Such a model can for instance with the certain approximation describe the inhalation phase of lungs ventilation imaged with hyperpolarized ^{3}He. In simulations, the phantoms of various shapes with spin density temporarily modulated by function $F(n\,\tau_d)$, were encoded using radial and spiral k-space scan schemes with different interleave modes for each scheme. The amount of individual radial or spiral k-space lines was set to be N. Because the reconstruction of images was done using sliding-window method, the series of N images were generated for each set of modulation function parameters. The calculated integral intensity curve $I(n\,\tau_d)$ of reconstructed images allows finding out the ability of each scanning scheme to reproduce the shape of spin density modulation function $F(n\,\tau_d)$. The deviation between these two curves can be, therefore, considered as reliable measure of "real" temporal resolution. Additional interest represents the case of "instant jump" type of spin density dynamic i.e. the case when the whole process of changing of spin density occurs within time period shorter than requires for scanning a single k-space line. This situation was also simulated using the described above types of k-space sampling and image reconstruction schemes.

Results and conclusions

The well known disadvantage of the Cartesian k-space encoding for measuring fast dynamically changing spin density is that the integral intensity of image are mainly determined by a single line which goes through k-space origin. Therefore, following the fast dynamic variation of spin density is only possible by decreasing the amount of acquired higher order k-space lines with corresponding loses in spatial resolution information.

This problem is avoided in interleaved non-cartesian sampling schemes. The large advantage is that any acquisition line in radial and spiral method includes the k-space origin point that allows avoiding the strong contrast losses even if essential part of k-space is sampled at minimal values of spin density. In general the simulation results shows that the integral intensity curve obtained by sliding-window reconstruction method with radial o spiral scanning of k-space reproduces roughly the shape of integral of spin density modulation curve (Fig 1b). A difference between spin density modulation curve $F(n\,\tau_d)$ and reconstructed spin density $I(n\,\tau_d)$ can be minimized by using interleaving schemes of radial k-space trajectories, whereas for preserving of the imaging structure is more effective in the case of non-interleaving trajectories. The spiral interleaving and non-interleaving schemes under certain conditions may be a good compromise when preserving both components of imaging information (i.e contrast and resolution) is equally important. On the other hand, the radial scan strategy may allows more robust implementing of partial acquisition and reconstruction methods based on k-space segmentation or «compressed sensing» [Lustig] which may provide the much higher «real» temporal resolution in the case of «instant changes» of spatial information and contrast of spin density in comparison with sliding-window methods.

In conclusion, the optimal strategy of k-space sampling is strongly depended on the specific form of spin density function variation and the choice of the specific one must be considered individually depending on the particular experiment purposes. In consequence, the k-space acquisition strategy should be optimized for the particular biomedical question to be examined.

Acknowledgements

This study was supported by the "German Research Council" grants # FOR 474 and SCHR 687/5. Further financial support by Mainz Universities "Forschungsfonds" and MAIFOR programmes is appreciated.

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