3D SPARKLING for accelerated ex vivo T2*-weighted MRI with compressed sensing

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Synopsis

In the last decade, compressed sensing (CS) has been successfully used in MRI to reduce the acquisition time. Recently, we have proposed a new optimization-driven algorithm to design optimal sampling patterns for CSMRI, called SPARKLING for Spreading Projection Algorithm for Rapid K-space sampLING. This method yields significantly higher image quality compared to standard geometrical patterns such as radial or spiral trajectories, while allowing very high acceleration factors up to 20 for T2*-weighted *in vivo* 2D high-resolution imaging of the brain. In this communication, we introduce an extension of the SPARKLING method for 3D imaging that allows to achieve an isotropic resolution of 600 µm in just 45 seconds for T2*-weighted *ex vivo* brain imaging at 7 Tesla. Compared to current acceleration techniques, our approach achieves similar imaging quality while being 20 times faster.

Introduction

The design of optimal sampling trajectories for MRI in the context of compressed sensing may allow to further reduce MR scan time [1]. In [2], we have presented and applied the SPARKLING method based on the theoretical work of [3]. Using these optimized sampling patterns in 2D, high-resolution T2*-weighted *in vivo* brain images were rapidly acquired and presented enhanced image quality compared to spiral imaging. Here, we extend the SPARKLING method to 3D by using either a stack-of-SPARKLING strategy or fully 3D SPARKLING trajectories.

Materials and Methods

- **SPARKLING trajectories**

First, a regular stack-of-SPARKLING (SOS) is considered by stacking an identical 2D SPARKLING trajectory along the third direction (see **Fig.1(a)**).

Second, a z-variable-density SOS can be used to obtain a fully 3D variable density by changing the target density according to the plane's altitude k_z. Given a 3D density $\rho \in R^{N\times N\times N_z}$, a trajectory at altitude k_z will be generated with the density: $\rho_{2D}(k_z) = \frac{\rho(:,:,k_z)}{\int \rho(:,:,k_z)}$. In addition, once the number of shots in the central plane $n(0)$ is chosen, the mass of each plane can be adapted to the plane density by reducing the number of shots as k_z increases: $n(kz) = n(0)\frac{\int \rho(:,:,k_z)}{\int \rho(:,:,0)}$. **Fig.1(b)** illustrates such a z-variable-density stack-of-SPARKLING composed of 11 planes for an isotropic density (defined on a 3D ball).

Finally, a fully 3D SPARKLING trajectory was obtained by extending the algorithm presented in [3] to 3D. **Fig.1(c)** displays a fully 3D SPARKLING for 100 shots.

We compared these three SPARKLING strategies to a Cartesian iPAT4 acquisition (GRAPPA), a 3D radial trajectory [4] and Poisson Disk sampling acquired along lines in the 3rd direction as presented in [5].

- **Acquisitions**

3D prospective acquisitions were performed on an *ex vivo* baboon brain at 7 Tesla (Siemens Healthineers MR scanner, Erlangen, Germany) with a 1Tx/32Rx head coil (Nova Medical, MA, USA) and a 3D GRE sequence. The maximum gradient amplitude and slew rate were 40 mT/m and 200 T/m/s, respectively. The imaging parameters were set as follows: TR=40ms, TE=20ms, FA=15°, Tobs=15.36ms, BW=200kHz. The targeted resolution was 600µm isotropic for a field-of-view of 200x200x140mm^3.

- **Reconstructions**

Images (320x320x224) were reconstructed by minimizing a classical CS parallel imaging regularized criterion balancing the trade-off between data consistency and l_1-based sparsity in the wavelet domain.

Results

First, the different 3D SPARKLING strategies were compared for an isotropic resolution of 0.6 mm. Regular SOS, z-variable-density SOS and fully 3D SPARKLING trajectories were acquired for an acquisition time of 2 min 40 s (4000 shots). A Cartesian iPAT4 scan (TA=14 min 31 s) was also performed and will be considered as the reference image. Results in transversal, coronal and sagittal planes are displayed in **(Fig.2)**, where each column corresponds to a different sampling method. The image quality in the accelerated SPARKLING acquisitions is well preserved especially in the tree cerebellum. The fully 3D SPARKLING results appear slightly more blurry that the SOS techniques. Regular and z-variable-density SOS yield similar image quality as is corroborated by the SSIM scores measured on an axial slice taking the iPAT4 image as reference.

Second, 3D SPARKLING trajectories were compared to 3D radial and Poisson disk sampling strategies for a very short acquisition time of 45 seconds. Here, a z-variable-density SOS was used for SPARKLING acquisitions since it yielded better image quality among the previously tested 3D SPARKLING strategies. Moreover, a standard GRAPPA-accelerated Cartesian scan was performed for an iPAT4 as reference. Results are displayed in **(Fig.3)** for coronal, sagittal, axial planes and a magnified central region of the axial image, where each column displays a different strategy. Among all 45-second scans, the SPARKLING method presents the best image quality (see tree cerebellum typically). These visual observations are corroborated by SSIM scores, calculated for a central axial slice with the iPAT4 image as reference.

Discussion and Conclusions

In this work, we proposed to use the SPARKLING strategy to accelerate the scan time of high resolution 3D acquisitions. Among the three studied approaches of 3D SPARKLING, it was observed that the z-variable-density SOS was the most promising.

The proposed method allowed to divide the acquisition time by a factor of 20 (compared to the iPAT4 scan), while maintaining very good image quality. Moreover, we compared SPARKLING to other 3D methods such as 3D radial and the Poisson-disk-lines, for the same acquisition time of 45s. The proposed method performed significantly better than these two techniques which both appear very blurry, because of the inefficiency of their sampling lines which are too few at this acceleration rate to produce correct images. These results may be of interest for susceptibility-weighted imaging [6].

Acknowledgements

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References

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Figures

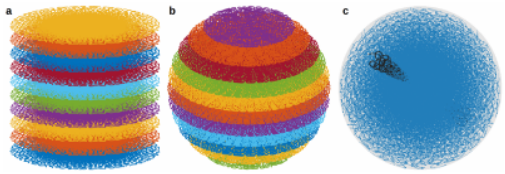

Figure 1: 3D SPARKLING trajectories. **(a)**, Regular Stack-of-SPARKLING: stack of 10 identical 2D SPARKLING trajectories filling a cylinder. **(b)**, z-variable-density stack-of-SPARKLING displaying 11 planes filling a ball. **(c)**, fully 3D SPARKLING trajectory composed of 100 shots. One shot is highlighted in black.

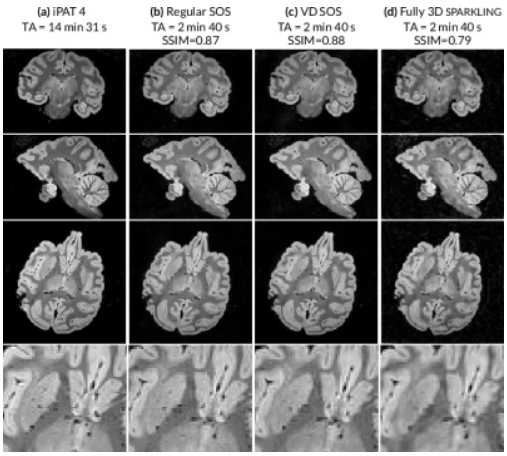

Figure 2: 0.6 mm isotropic *ex vivo* results comparing different SPARKLING strategies. Column **(a)**: iPAT 4 (GRAPPA) acquisition lasting TA = 14 min 31 s. Column (**b**): regular stack-of-SPARKLING (SOS) results for an acquisition time of TA = 2 min 40 s. Column **(c)**: z-variable-density SOS for an acquisition time of TA = 2 min 40 s. Column **(d)**: fully 3D SPARKLING for an acquisition time of TA =2 min 40 s. SSIM scores with the iPAT4 image as reference were computed in an axial slice. FOV was 200x200x140 mm^3.

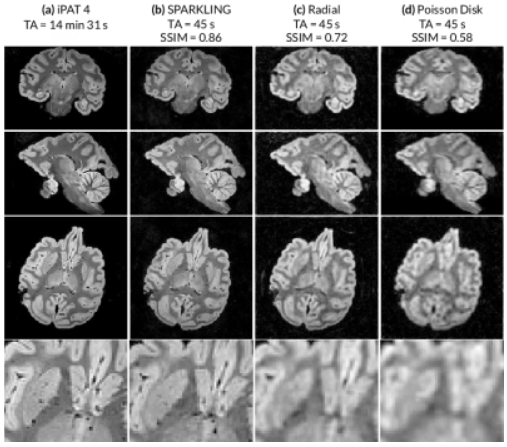

Figure 3: 0.6 mm isotropic *ex vivo* results comparing **(a)** an iPAT4 (GRAPPA) acquisition with acquisition time TA = 14 min 31 s, **(b)** 3D SPARKLING (VD SOS), **(c)** 3D radial and **(d)** a 3D Poisson disk lines sampling. The trajectories used in **(b-c-d)** were composed of 1140 shots, corresponding to an acquisition time of TA = 45 s. SSIM scores with the iPAT4 image as reference were computed in an axial slice. FOV was 200x200x140 mm^3.