Z-Variable-density Stack of 2D SPARKLING for Isotropic High Resolution T_2^* MRI at 7 Tesla

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1. Introduction

In the last decade, compressed sensing (CS) has been successfully used in Magnetic Resonance Imaging (MRI) to reduce the acquisition time. Recently, we have proposed a new optimization-driven algorithm to design optimal non-Cartesian sampling patterns for CS-MRI, called SPARKLING for Spreading Projection Algorithm for Rapid K-space sampLING. This method has a few advantages over standard trajectories such as radial lines or spirals: i) it allows to sample the k-space data along any arbitrary density while the other two are restricted to radial densities and ii) it allows to achieve a higher image quality for a given scan time. Here, we introduce an extension of the SPARKLING method for 3D imaging that allows to achieve an isotropic resolution of 600 μm in only 45 seconds for T2*-weighted ex vivo brain imaging at 7 Tesla over a field-of-view of $200 \times 200 \times 140$ mm^3.

2. An optimization-based design of k-space trajectories

SPARKLING: **S**preading **P**rojection **A**lgorithm for **R**apid **K**-space samp**LING**.
Combining sampling efficiency to compressing sensing [1], the proposed approach seeks to comply with two criteria for optimal sampling [2, 3]:

(i) **Controlled variable density**: low frequencies should be sampled more densely.
(ii) **Locally uniform coverage**: to avoid large gaps and clusters of samples.

This is achieved by minimizing the distance between a target density π and a sampling trajectory $\mathbf{k}$, **under the hardware constraints** on maximum gradient amplitude $G_{\max}$ and slew rate $S_{\max}$:

$$\min_{\mathbf{k}\in\mathcal{Q}_p} dist(\rho,\nu(\mathbf{k})) = \min_{\mathbf{k}\in\mathcal{Q}_p} \frac{1}{2}\|h \star (\nu(\mathbf{k})-\rho)\|_2^2$$

where h is a continuous interpolation kernel, $\nu(\mathbf{k})$ is the measure supported by the curve $\mathbf{k}$ (see [3, p. 2052]) and $\mathcal{Q}_p$ is the set of admissible curves respecting the aforementioned constraints. The distance can be conveniently rewritten by expanding the ℓ_2-norm into:

$$\min_{\mathbf{k}\in\mathcal{Q}_p} \underbrace{\frac{1}{p}\sum_{i=1}^{p}\int_\Omega H(x-\mathbf{k}[i])\rho(x)\,dx}_{F_{\rm a}(\mathbf{k})} - \underbrace{\frac{1}{2p^2}\sum_{1\le i,j\le p} H(\mathbf{k}[i]-\mathbf{k}[j])}_{F_{\rm r}(\mathbf{k})}$$

where the Fourier transform $\hat{H}$ of H is equal to $|\hat{h}|^2$. Here, we used the Euclidean distance $H(x) = \|x\|_2$ [4, 3]. The non-convex energy $F = F_{\rm a} - F_{\rm r}$ contains an attractive term $F_{\rm a}$ and a repulsive term F_r and can be locally minimized using a projected gradient descent: $\mathbf{k}_{t+1} = \Pi_{\mathcal{Q}_p}(\mathbf{k}_t - \beta_t \nabla F(\mathbf{k}_t))$.

3. Assessing SPARKLING

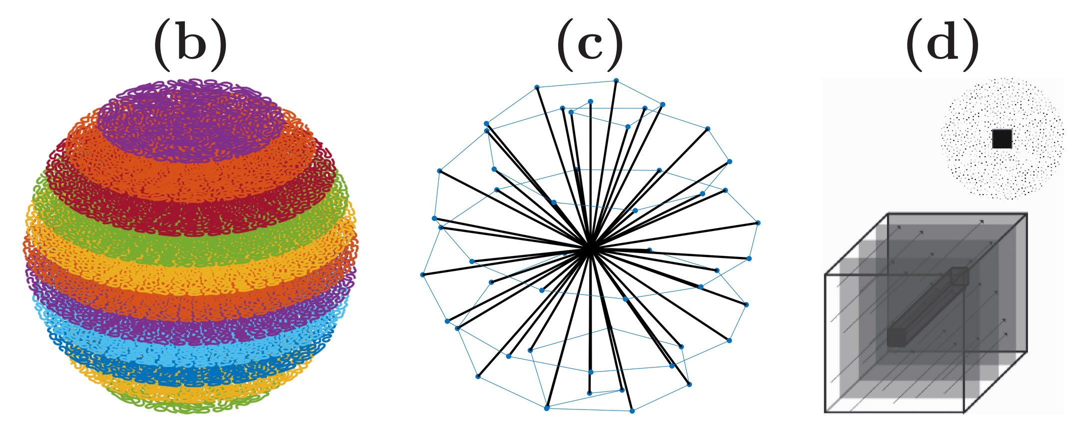
Comparison between:

(a) iPAT-4 GRAPPA as ground truth (parallel imaging);

(b) z-variable density stack of 2D SPARKLING (z-vd SOS) trajectories [6];

(c) 3D Radial trajectories [7];

(d) 3D Poisson disk sampling introduced by Lustig et al [8].

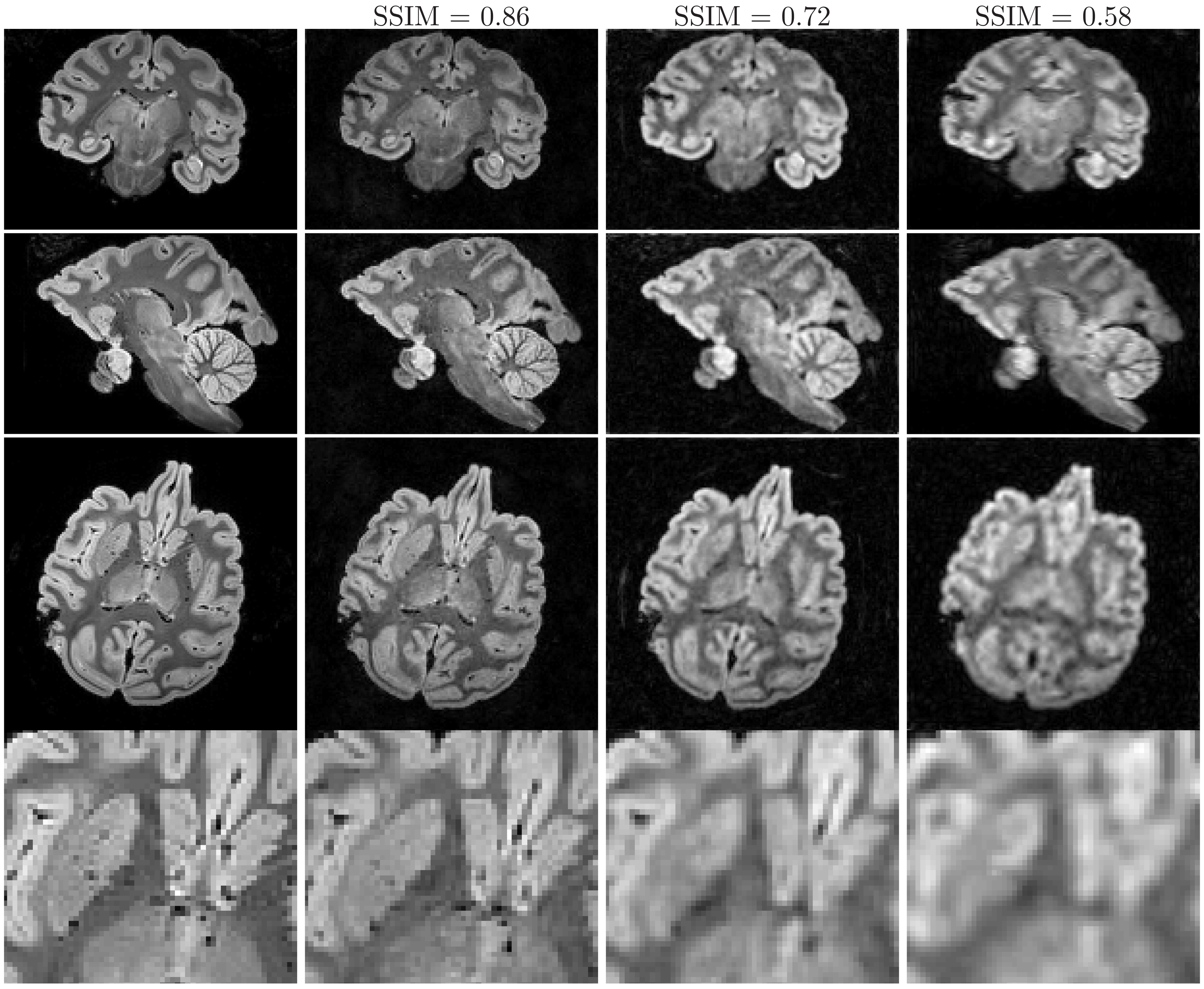


4. Acquisition and reconstruction

- 7T system (Siemens Healthineers, Erlangen, Germany), 1Tx/32Rx head coil (Nova Medical, Wilmington, MA, USA). $G_{\max} = 40$ mT/m, $S_{\max} = 200$ T/m/s.
- 3D T_2^*-weighted GRE sequence
- Matrix: 320×320×224, Resol.: 600μm iso.
- TR/TE=40/20 ms, Tobs=15.36 ms, FA=15°.
- Reconstruction: A self-calibrating nonlinear algorithm minimizing a CS-SENSE criterion in the wavelet domain was adapted to non-Cartesian samples using the GPU-NUFFT [5].

5. Results: prospective *ex vivo* baboon brain imaging at 7 Tesla

(a) iPAT 4	**(b)** z-vd SOS	**(c)** 3D Radial	**(d)** 3D Poisson Disk
TA = 14 min 31 s	TA = 45 s	TA = 45 s	TA = 45 s
	SSIM = 0.86	SSIM = 0.72	SSIM = 0.58



7. References

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6. Conclusions

Here, we demonstrated the *ex vivo* superiority of the proposed zvd-SOS-SPARKLING sampling over 3D radial 3D Poisson-disk approaches. Although accelerated by a factor of 70, SPARKLING acquisitions were able to preserve fine structural details and proved to be more robust to system imperfections. Most interestingly, our method can adapt to any sampling density, observation window, MR weighting and hardware specifications.

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