

Proceedings Article

Relaxation-induced stimulated emission depletion (ReSTED) magnetic particle imaging

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Abstract

Stimulated emission depletion (STED), widely used in fluorescence microscopy with a key donut-shaped PSF, is rarely applied to other biomedical imaging. Magnetic particle imaging (MPI), a non-ionizing technique for detecting magnetic nanoparticles, has Gaussian PSF (from field-free line/FFL harmonic signals) with limited resolution. The imaginary part of a point source's harmonic signal in MPI can form a donut-shaped PSF. Based on difference of Gaussian (DoG) theory, subtracting this donut PSF from Gaussian PSF yields a STED PSF with 3–4x higher resolution. In human brain FFL-MPI simulation, STED acquired donut-PSF projected signals, and super-resolution images were reconstructed via 1D deconvolution, filtered backprojection, or Richardson–Lucy with total-variation regularization.

1. Introduction

MPI is an *in vivo*, non-ionizing imaging modality proposed in 2001 and experimentally validated in 2005 [1]. FFL-based MPI scanners use gradient selection fields for SPIO signal localization but suffer from low resolution (1–10 mm) in large-bore/brain-sized devices due to

non-sharp Langevin magnetization derivatives. STED microscopy, developed by Hell *et al.* [2], uses a donut-shaped focal spot to break the diffraction limit, advancing imaging from the “micron” to “nano” scale. This work introduces STED's donut point spread function (PSF) into MPI. In collinear FFL-excitation-receiver setups, the relaxation time of SPIO particles decreases with selec-

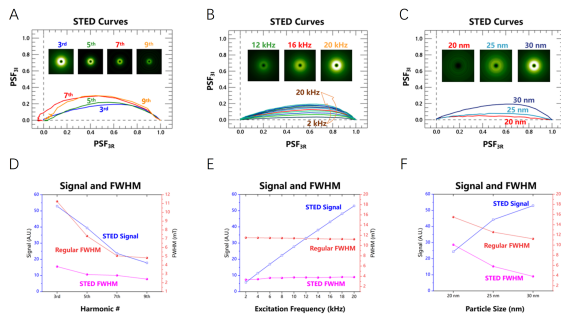


Figure 1: STED curves from simulation. A and D, Higher harmonics generate smaller donut PSFs but lower signals. B and E, higher excitation frequency enhances signal without altering FWHM or image resolution. C and F, Larger magnetic nanoparticles exhibit stronger signals and smaller donut PSFs (smaller FWHM).

tion gradient intensity causing harmonic signal phase lag [3]. Rotating these harmonic complex signals to null the imaginary part at the FFL center generates a donut PSF, and subtracting it from the regular Gaussian PSF enhances MPI resolution.

II. Simulations and Experiments

In terms of magnetization dynamics, we conducted experiments via rotational Brownian dynamics simulations using the Landau-Lifshitz-Gilbert (LLG) equation, under experimental conditions involving 1000 single-domain magnetite nanoparticles (with diameters ranging from 20 to 55 nm and excitation frequencies of 2 to 20 kHz).

In terms of Donut PSF experiments, we conducted experiments in an FFL-based MPI scanner. The selection gradient field forming the FFL was 3 mT/mm. The excitation field amplitude was 10 mT at a frequency of 25 kHz. The FOV was 20 mm×20 mm. The point source and letter phantoms (“BUAA”) were filled with Perimag (Micromod Partikeltechnologie GmbH, Germany), with an iron concentration of 8.5 mg/mL. Gaussian and donut-shaped PSFs were derived from the 3rd harmonic STED curve of the point-source phantom. Richardson-Lucy with Total Variation (RLTV) was used to reconstruct STED-PSF-based images using a low regularization with 150 iterations.

III. Results and discussion

Figure 1 simulation results show PSF performance trends: higher harmonic STED curves reduce donut PSF size but lower signal, with the 3rd harmonic optimal (Figure 1A and D); increasing excitation frequency boosts signal but does not improve resolution (Figure 1B and

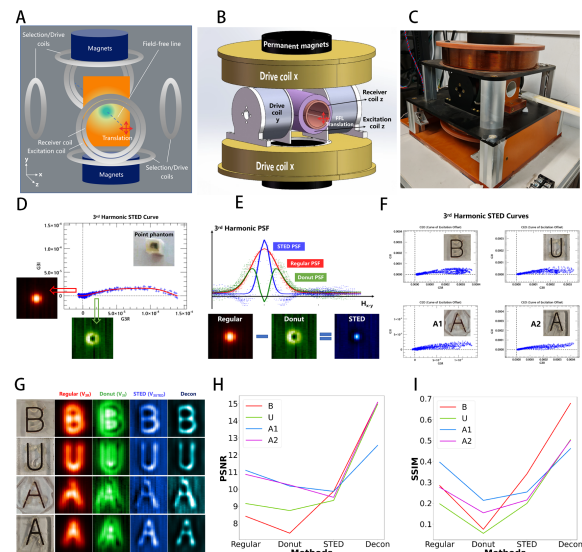


Figure 2: STED-MPI scanner with FFL 2D-translation and reconstructed images. A, The main components of a STED-MPI scanner that requires coaxial FFL, excitation, and receiver. B, Drive coils push the parallel movement of the FFL and generate projected 2D images. C, Photograph of the STED-MPI scanner. D, The 3rd harmonic STED curve of a point-source phantom. E, A 3rd harmonic STED PSF can be derived by subtracting the donut-shaped PSF from the regular PSF. F, The 3rd harmonic reconstructed curves of the letter phantoms. G, Reconstructed images of the letter phantoms.

E); larger nanoparticles (30 nm) yield smaller donut PSFs and stronger signals (Figure 1C and F).

Figure 2 shows the 3rd harmonic STED curve of a point-source phantom. The real part was a regular Lorentzian curve, and the imaginary part was a donut-shaped PSF after a certain rotation angle (Figure 2D). The STED deconvolution method shows the highest peak signal-to-noise ratio (PSNR) (Figure 2H), and the greatest structural similarity index measure (SSIM) (Figure 2I).

In conclusion, STED-MPI not only avoids artifacts associated with system matrix methods, but also simplifies reconstruction via Gaussian PSF deconvolution that is compatible with Fourier transform and filtered backprojection.

Acknowledgments

This work was supported in part by the National Natural Science Foundation of China under Grant No. 82227802, 62471370, and 62471320, and in part by the Key Project of Liaoning Provincial Department of Science and Technology under Grant No. 2022JH1/10500004.

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