Whitening of colored noise in PROPELLER using iterative regularized PICO reconstruction

Jyh-Miin Lin[1], Andrew Patterson[2], Hing-Chiu Chang[3], Tzu-Chao Chuang[4], Hsiao-Wen Chung[5], Jonathan H. Gillard[1], and Martin J. Graves[2]

[1]Department of Radiolgoy, University of Cambridge, Cambridge, Cambridgeshire, United Kingdom, [2]Cambridge University Hospitals NHS Foundation Trust, Cambridge, United Kingdom, [3]Brain Imaging and Analysis Center, Duke University Medical Center, NC, United States, [4]Department of Electrical Engineering, National Sun Yat-sen University, Kaohsiung, Taiwan, Taiwan, [5]Department of Electrical Engineering, National Taiwan University, Taiwan, Taiwan

Target Audience: Scientists studying PROPELLER MRI

Purpose

MR images acquired using the periodically rotated overlapping parallel lines with enhanced reconstruction (PROPELLER) technique are known to exhibit colored noise pattern due to two reasons. First, overlapped central k-space acquisitions generate uneven noise power spectra, which is higher in high-k region and vice versa. Second, angular under-sampling leads to wedge shaped missing data in k-space. This study examines the colored noise pattern in PROPELLER imaging using theory, simulations, and experiments, and its whitening using an iterative reconstruction method named the Pseudo-Inverse as COnstraint (PICO) approach.

Methods

The noise pattern in a PROPELLER scan was examined theoretically using the concept of Cramér-Rao lower bound (CRLB), followed by Monte Carlo simulation with 100 realizations to verify the findings. Phantom and human experiments (ethically approved) were performed on a 1.5T system (MR450, GE Healthcare, Waukesha, WI, USA) using a 8-channel head coil. T2-weighted PROPELLER fast spin-echo images (TR/TE = 2500/85.5, echo-spacing = 6.8 ms, ETL = blade width = 24, receiver bandwidth = ±125 kHz. FOV = 26cm, 512x512 matrix, 12 slices) were obtained from eight healthy subjects (3 males, mean age 26). Images were acquired with 6 to 20 blades evenly distributed across π, corresponding to total scanning times from 25 to 55s, respectively. Susceptibility-weighted PROPELLER processing gradient-echo images (384×384, TR/TE=67/40) were acquired from two healthy subjects.

The blade data underwent reconstruction using conventional density compensation (DC) and PICO, both with in-plane motion correction. The PICO algorithm is derived from the split-Bregman method, with a dual-loop iteration where the multi-coil data are combined before undergoing the regularization procedure. PICO further integrates the linearized Bregman iteration to minimize discrepancy between the acquired data and the estimated image and a regularization to smooth the image while preserving the edges via minimization of total variation. [1]

For the experimental data, noise measurements were achieved in both the image and the k-space domains using the subtraction method with multiple acquisitions. [2] Overall reconstruction quality was evaluated using the structural similarity index (SSIM). [3]

Results

CRLB shown in Fig.1**a** suggests higher noise in peripheral k-space, which is confirmed by simulation (Fig.1**b**) and phantom results (Fig.1**c**). Colored noise from DC reconstruction becomes largely whitened by PICO as shown in the noise power spectra (lower row in Figs.1**b** & 1**c**). Fig.2**a** compares the phantom images and noise power spectra at different under-sampling factors, where PICO is seen to spread the noise distribution to the wedge-shaped missing data region in the k-space, leading to better image quality in Fig.2**b**. The SSIM results from PICO consistently demonstrate superior quality to DC (Fig.2**c**). Human images also show reduced streak artifacts on the T2-weighted PROPELLER images (Fig.3) and reduced noise on susceptibility-weighted PROPELLER processing images for PICO compared with DC reconstruction (Fig.4).

Discussions

To date, the currently established quality assurance procedure [4] does not consider the colored noise pattern as found in PROPELLER MR images. Effects of colored noise, although subtle and are hence never investigated before, may affect image quality in an undesirable manner. In our study, both theory and simulation confirm the colored noise behavior in the k-space for PROPELLER imaging. It is further demonstrated that iterative reconstruction such as PICO used in this study is able to help whitening the noise distribution in the k-space, which is particularly important for noisy data to attempt for better visual perception (Fig.4). In addition, PICO also fills in the missing data in angularly under-sampled PROPELLER scans, such that the streak artifacts are reduced (Fig.3). The consequent improvement in image quality is reflected in the increased SSIM index, where PICO is shown to outperform DC throughout all under-sampling factors. The python source code of PICO can be downloaded from https://github.com/jyhmiinlin/pynufft.

Conclusion

The results from our study involving theory, simulation, and experiments on phantom and human subjects suggest that MR images acquired using the PROPELLER k-space trajectory should benefit from PICO reconstruction by whitening the colored noise pattern, which may help broadening its use for motion-insensitive scans.

References

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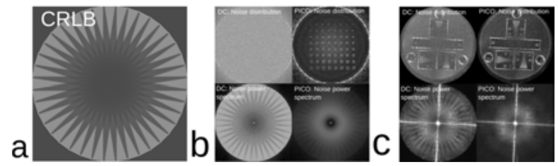

Figure 1. (**a**) Colored noise pattern in PROPELLER illustrated by CRLB in the k-space. Simulation (**b**) and phantom experiment (**c**) showing noise distribution in the image space (upper row) and k-space noise power spectra (lower row) using DC (left column) and PICO (right column). PICO substantially reduces noise power in the high-k region.

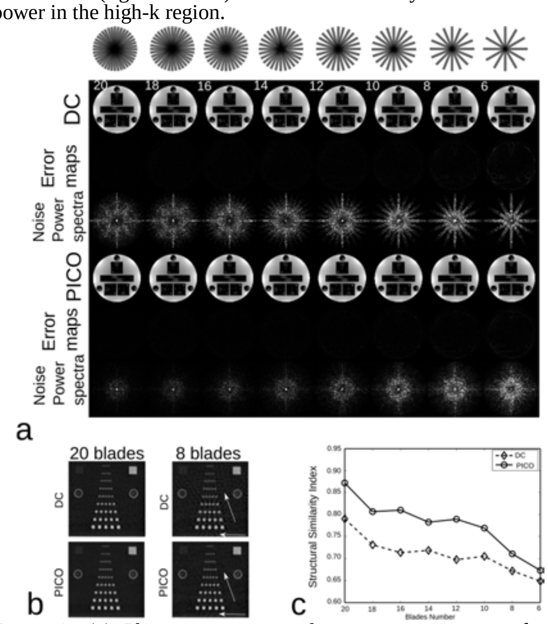

Figure 2. (**a**) Phantom images and noise power spectra for PROPELLER reconstructed using DC and PICO at various angular under-sampling factors (k-space coverage in top row), showing generally improved noise reduction by PICO. (**b**) Images of the resolution phantom showing reduction of streak artifacts by PICO. (**c**) PICO also shows consistently higher structural similarity index than DC for all under-sampling factors.

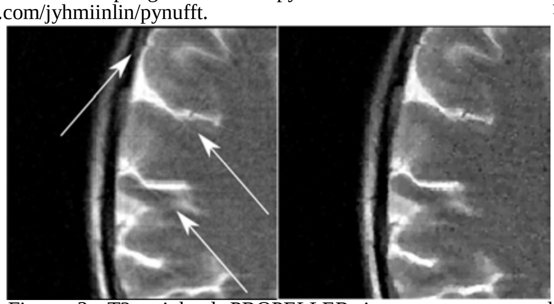

Figure 3. T2-weighted PROPELLER images reconstructed using DC (left) and PICO (right), with magnified view showing reduced streak artifacts near CSF-cortex boundaries (white arrows) using PICO.

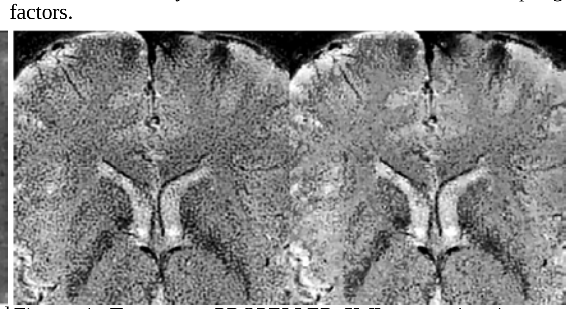

Figure 4. Transverse PROPELLER-SWI processing images obtained using DC (left) and PICO (right), showing reduced noise in PICO-reconstructed SWI processing image.