Ultra-fast variable density spiral imaging technique using multiscale CORNOL reconstruction

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TARGET AUDIENCE: Researchers and clinicians interested in ultra-fast MR data acquisition

PURPOSE: Variable-density spiral (VDS) trajectory gains increasing interest due to its fast kspace traversal speed and nearly incoherent undersampling artifacts (1,2) that can be removed by proper nonlinear reconstruction (3,4). However, suppression of some large-scale artifact can conflict with fine-scale image structure preservation and thus degrades the image quality. To solve the problem, a multiscale reconstruction based on recently developed CORNOL (coherence regularization with a nonlocal operator) (5) was proposed in this study. Multiscale CORNOL decouples artifact suppression and structure preservation by iteratively performing CORNOL with different scales of smoothness constraint, so that the aforementioned conflict can be avoided. The simulation and *in vivo* VDS experiment demonstrate that this method can effectively suppress artifacts while preserving image details at high sampling reduction factors.

METHODS: Unlike most nonlinear reconstruction methods that usually impose only a single-scale smoothness constraint, multiscale CORNOL imposes smoothness constraints with different spatial scales. Based on the original CORNOL (5), the cost function of multiscale CORNOL can be formulated as:

$$\bar{\mathbf{u}}_k^{\alpha} = \arg\min_{\bar{\mathbf{u}}}\left\{\left\|\mathbf{A}\bar{\mathbf{u}}-\bar{\mathbf{f}}\right\|_2^2 + \alpha J_{CORNOL}^{h_k}(\bar{\mathbf{u}})\right\}$$

where $\mathbf{A}$ is the encoding matrix, $\bar{\mathbf{u}}$ is the desired image, $\bar{\mathbf{f}}$ is the under-sampled data, α is the regularization parameter, h_k is the scale of smoothness constraint at k-th iteration and h_0 is the initial scale. $J_{CORNOL}^{h_k}(\bar{\mathbf{u}})=\sum_{i\in\Omega}\left\langle \vec{\phi}_i(h_k), |\nabla u_i|^2\right\rangle$ is the original CORNOL regularization function at scale h_k with nonlocal operator $\vec{\phi}_i(h_k)$. Since CORNOL imposes smoothness constraint within structures detected by the nonlocal operator (5), the scale of its smoothness constraint is determined by the scale of nonlocal operator. Thus, to impose constraint at different scales, multiscale CORNOL uses the following scale-varying nonlocal operator: $\vec{\phi}_i(h)=\{\phi_{ij}(h)\},\ \ \phi_{ij}(h)=\frac{1}{W_i}\exp(-\frac{\|p(i)-p(j)\|_2^2}{h^2}),\ \text{with } h_k = 2^{-k}h_0$,

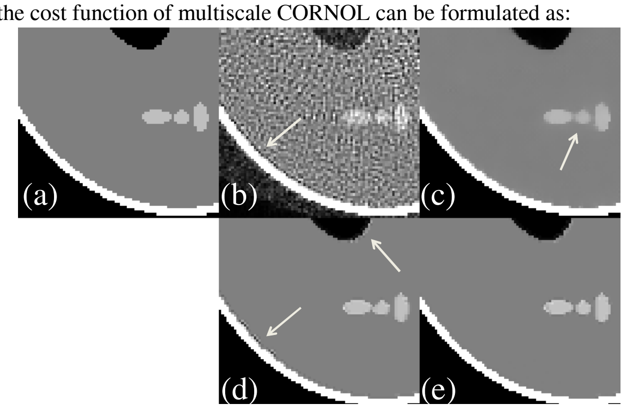

Fig.1 Simulation results with a reduction factor of 5. (a) True image; (b) CG-SENSE; (c) TV; (d) CORNOL; (e) multiscale CORNOL.

where $p(i)$ and $p(j)$ are patches centered at pixel i and j, j is a pixel within the neighborhood of i, W_i is the sum of all ϕ_{ij}. Initially, a large scale h_0 is used for aliasing artifact suppression. Then, the scale is dyadically reduced to ensure structure preservation. A Shepp-Logan phantom and an 8-channel phased array coil were used for numerical simulation. A spin-echo VDS sequence was used to acquire *in vivo* brain images on a Philips 3T scanner (Achieva, Philips, Best, The Netherlands) using 8-channel coil with: TR = 2500 ms, TE = 80 ms, flip angle = 90°, FOV = 220 mm×220 mm, and image matrix = 256×256, the VDS alpha was set to 3. A reduction factor of 5 was used for both experiments.

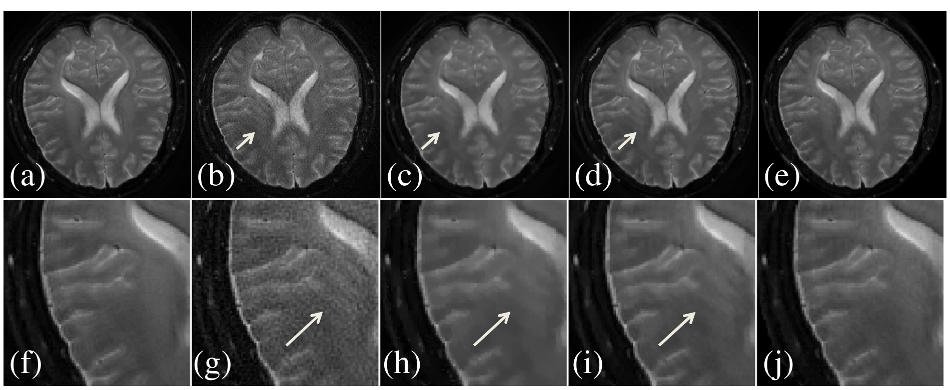

Fig.2: In vivo data reconstruction results with R=5. (a) sum-of-squares image; (b) CG-SENSE; (c) TV; (d) CORNOL; (e) multiscale CORNOL; (f), (g), (h), (i) and (j) show the zoomed-in part of (a) ,(b), (c), (d) and (e), respectively.

RESULTS AND DISCUSSION: Fig. 1 compares the VDS sampled phantom simulation results of CG-SENSE, Total Variation (TV), CORNOL and multiscale CORNOL. The CG-SENSE image shows amplified noise and ring artifacts (pointed to by the arrow in Fig. 1(b)). TV removes both ring artifact and noise, but blurs small structures (pointed to by the arrow in Fig. 1(c)). Although CORNOL shows sharper structure, it exhibits residual ring artifact (pointed to by the arrows in Fig. 1(d)). In contrast, multiscale CORNOL effectively removes ring artifact while preserving the structure well (Fig. 1(e)). Fig. 2 compares the *in vivo* VDS imaging results. CG-SENSE, TV and CORNOL images all show some residual aliasing artifact (pointed to by the arrows in Fig. 2). Besides, TV image is considerably blurred (Fig. 2 (c) and (h)). In comparison the multiscale CORNOL image is free of aliasing artifact and shows sharp details that are close to the sum-of-squares image.

CONCLUSION: A multiscale CORNOL reconstruction was proposed to circumvent the conflict between large-scale artifact suppression and fine-scale structure perseveration in nonlinear VDS reconstruction. The numerical simulation and *in vivo* VDS experiments results demonstrate that this method can effectively suppress large-scale artifact without losing image details at high reduction factors.

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