Ultra-high resolution 3D upper airway MRI with compressed sensing and parallel imaging

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Introduction: 3D MR imaging of the vocal tract during sustained sound production provides valuable insight into the shaping and modeling of vocal articulation [1]. Recently, high spatial resolution 3D imaging of vocal tract shaping (with no repetitions of the same sound) was demonstrated [2] by utilizing compressed sensing MRI [3] with a single channel receive coil. When imaging with multiple channel receive coil, the benefit of combining compressed sensing (CS) and parallel imaging has been demonstrated by several research groups [4,5]. In this abstract, we propose a highly accelerated, short scan time, high spatial resolution 3D imaging technique, which adopts the phase constrained (PC) CS methodology and parallel imaging.

Methods: (*Experimental Setup*) Experiments were performed on a GE 3.0 T scanner with an 8-channel neurovascular receive coil array (the 4 superior elements were used for reconstruction). The readout direction (k_x) was superior-inferior (S-I). A gradient echo sequence was used with TE = 2.3ms, TR = 5.0ms, flip angle = 10°, NEX = 1, resolution = 1.33 x 1.33 x 1.33 mm^3, and FOV = 20 x 24 x 8 cm^3. A fully sampled dataset was acquired when one trained subject held their mouth open for 54 seconds. The 180 k_y and 60 k_z encodes were used to fully cover 3D k-space. The undersampling of (k_y,k_z) was based on 1) full sampling of low-spatial frequencies and 2) random undersampling of the remaining high-spatial frequencies. Prospective accelerated acquisitions were performed during sustained production of English consonants /ʃ/ and /r/. The scan time for 6x, 8x, and 10x acquisitions were 9.0, 6.8, and 5.4 seconds, respectively.

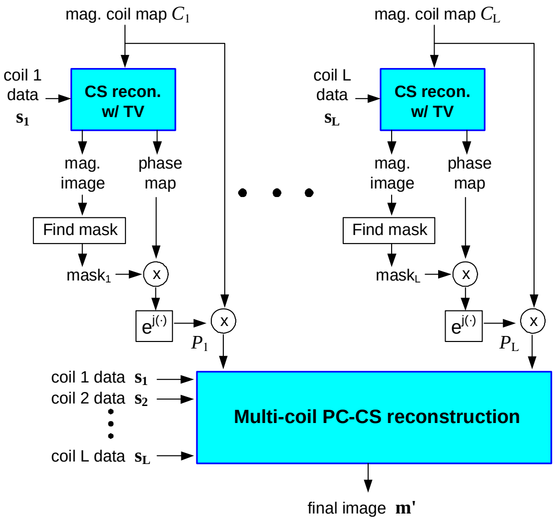

Figure 1. *Flowchart of the proposed reconstruction.*

$$f(\mathbf{m}) = \sum_{l=1}^{L} \left\| \mathbf{s}_l - \Phi P_l C_l \mathbf{m} \right\|_2^2 + \lambda_{\mathrm{TV}} \left\| \Psi_{\mathrm{F}} \mathbf{m} \right\|_1 + \lambda_{\mathrm{w}} \left\| \Psi_{\mathrm{w}} \mathbf{m} \right\|_1 \quad \text{Eq.(1)}$$

(*Image Reconstruction*) Data were first inverse-Fourier transformed (IFT) along k_x. At each x position, reconstruction was performed in 2D planar section. Figure 1 describes our two-stage iterative reconstruction. In the first stage, high-resolution phase map was estimated using CS reconstruction for each coil element. This can be effective at capturing rapidly varying phases in the air-tissue boundaries, where rapid phase variation is expected due to large susceptibility difference between air and tissue. Its incorporation into a PC-CS optimization leads to increased sparsity of the transform coefficients of the final solution [3]. In the second stage, multi-coil PC-CS reconstruction was performed by minimizing the convex function in Eq. (1). Here, $\mathbf{s}_l$ is the data vector for the l^{th} coil element, Φ is the Fourier encoding matrix, P_l is a diagonal matrix containing the phase estimate, C_l is a diagonal matrix containing coil intensity map, and $\mathbf{m}$ is the unknown image estimate. λ_{TV} and λ_{w} are regularization parameters for total variation and l_1-norm of wavelet transform, respectively. Their values were chosen after visual inspection of reconstructed images representing a broad range of the values from retrospective studies. 3D visualizations of the tongue shape were constructed by manually segmenting the tongue in coronal slices from each dataset, stacking the segmented slices, and generating a 3D volume rendering using the vol3d.m Matlab function.

Results and Discussion: Reconstruction results from retrospectively undersampled data (not shown) indicated that 6x and 8x produced little or no air-tissue boundary errors but 10x produced significant boundary errors in the airway and lateral sides of the tongue. Figure 2 contains mid-sagittal images and their corresponding 3D visualization of tongue shapes for /ʃ/ and /r/ sounds from prospectively acquired 8x data. The degree of the tongue grooving is clearly seen for sibilant fricative /ʃ/ (black arrow in (c)). The /r/ sound characterizes a complex geometry of the tongue shape (e.g., large volume of the sublingual cavity (white arrow in (d)) and cupping of the frontal tongue (red arrow in (d))). The use of 1.33mm isotropic resolution allows for sufficiently resolving the narrowing of the vocal tract between the tongue blade and alveolar ridge (white arrow in (a)).

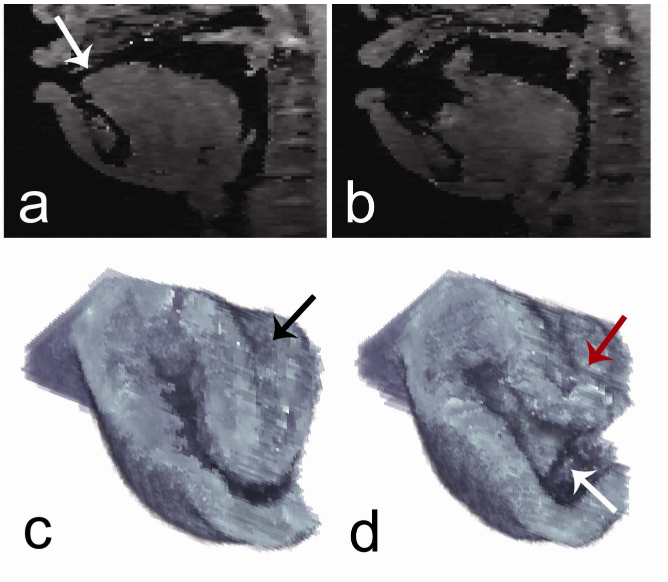

Figure 2. *Mid-sagittal image for (a) /ʃ/ and (b) /r/ and their corresponding 3D tongue shape for (c) /ʃ/ and (d) /r/.*

Conclusion: The proposed reconstruction can produce a clear depiction of 3D vocal tract shaping with 1.33x1.33x1.33mm^3 resolution during a 7-sec sustained sound without repetition. It adopts a phase-constrained CS combined with multi-coil data and improves the depiction of air-tissue boundaries, which are the features of interest in speech production research. It is computationally intensive because it requires L+1 iterative reconstructions as shown in Fig. 1, where L is the number of coils.

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References: [1] Narayanan et al., J. Acoust. Soc. Am., 1995;98(3): 1325-1347, [2] Kim et al., ISMRM, 2008, p2003, [3] Lustig et al., MRM, 2007;58:1182-1195, [4] King, ISMRM, 2008, p1488, [5] Marinelli et al., ISMRM, 2008, p1484.