Flexible Dynamic Phantoms for Evaluating MRI Data Sampling and Reconstruction Methods

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Purpose: Dynamic numeric phantoms have been widely used to simulate organ motion during MRI scans. The approach involves fabricating data directly in k-space, offering arbitrary spatial and temporal resolution, but typically with objects made up of ellipses and rectangles [1-3]. More realistic phantoms have been built from cine MRI, tagged MRI and CT results [4-6]. Our work is motivated by our need for a vocal tract phantom to test new data sampling and reconstruction methods. We present a method for generating polygon-based dynamic numeric phantoms that enables arbitrary rigid/non-rigid motions with any spatial and temporal resolution. Our approach uses dynamic time warping (DTW) [7-8] and polygon-support Fourier transform [9].

Methods & Results:

PHANTOM CONSTRUCTION: Phantom construction is illustrated in Fig. 1, using tongue motion rest – tip – retraction – rest as the example. The steps are as follows: (a) Manually Draw Boundaries and use complex-numbers to capture control points for boundaries of all relevant postures (e.g. rest, tip, and retraction (back)); (b) Spatially Smooth the Boundaries while increasing the number of boundary points (e.g., using piecewise cubic Hermite interpolation); (c) Temporally Align Boundaries by applying apply DTW pairwise to the sets of boundary points, aligning a later posture to its previous state (e.g. R–T–B–R). (d) Temporally Interpolate Boundaries (3X interpolation is illustrated); (e) Synthesize k-space Data: by dividing up each object into a set of polygons, and using the analytical formulation for the Fourier transform of a polygon [9].

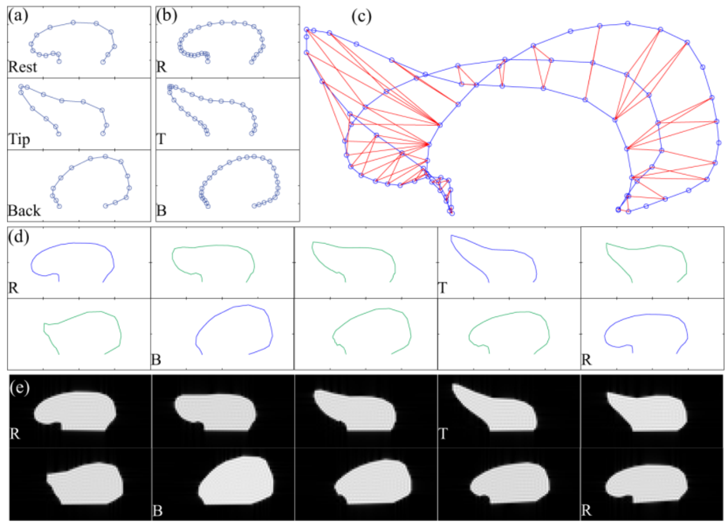

Figure 1. (a) Boundaries of three tongue postures; (b) interpolated tongue boundaries; (c) pairwise alignment results from DTW; (d) 3X temporal interpolation in green; (e) image reconstruction of data from polygon-support FT.

VOCAL TRACT PHANTOM: A vocal tract phantom was constructed using the steps above. Boundaries were drawn from a 2D real-time MRI [10] movie, with 20×20 cm^2 FOV, 2.4×2.4 mm^2 spatial resolution, and 78 ms temporal resolution, reconstructed at 23.8 fps. The phantom was composed of two closed contours, the lower jaw including the tongue, and "everything else". The lower jaw/tongue and the soft palate were segmented from each temporal frame, other boundaries were fixed. We added bivariate Gaussian noise during to the synthesized k-space data.

EXPERIMENTS: We used the phantom to test 2DFT and spiral sequences. Fig. 2 illustrates the (a) ground truth and (b) sliding window reconstruction for 2DFT, and the (c) ground truth and (d) sliding window reconstruction for 2D spiral sequence described above. All figures were at the same time frame. Data inconsistency (motion) artifacts are identified by arrows.

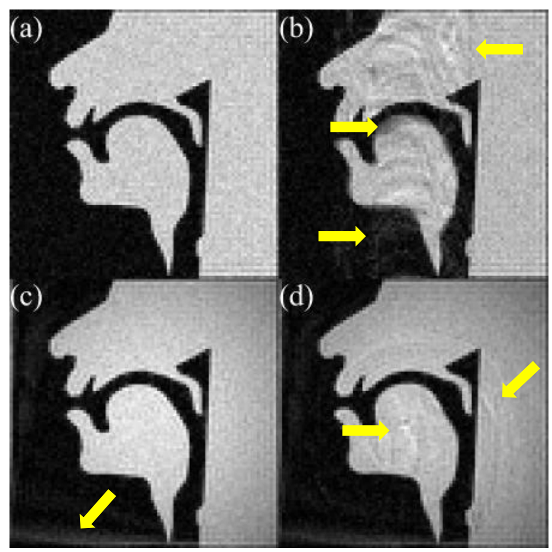

Figure 2. (a) 2DFT ground truth; (b) 2DFT sliding window reconstruction; (c) spiral ground truth; (d) spiral sliding window reconstruction. Arrows point out the expected imaging artifacts.

Discussion: The proposed vocal tract phantom successfully synthesizes the k-space data of complex-shaped object, with arbitrary spatial and temporal resolution (not shown). Other dynamic phantoms (e.g. cardiac short-axis, sagittal knee during flexion) can be generated following the same procedure.

Our test cases involved three boundaries that are very different in shape. The algorithm performed well. Some boundary points in the tongue tip and back were not aligned well, and this occurred when DTW created many-to-one mappings and we forced a one-to-one mapping. This can be improved in general by manually generating more intermediate contours.

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