Field-corrected Dynamic Imaging of the Velopharyngeal Musculature During Swallow

C. A. Conway[1], Y. Song[2], D. P. Kuehn[1,2], and B. P. Sutton[1]

[1]Bioengineering, University of Illinois at Urbana-Champaign, Urbana, Illinois, United States, [2]Speech and Hearing Science, University of Illinois at Urbana-Champaign, Urbana, Illinois, United States

Introduction Real time dynamic MRI imaging of the mouth and throat is especially difficult because magnetic susceptibility distortions both limit the data acquisition readouts and change as the air-spaces change shape. We have combined new and existing methods into a toolbox, consisting of pulse sequences, reconstruction algorithms, and processing algorithms, to allow non-invasive study of velopharyngeal travel with very high temporal resolution without requiring repetition of the motion. Evaluation of swallowing function in patients, including those having had cancer operations or with neurological disorders, usually involves the use of endoscopy, nasopharyngoscopy, or X-ray fluoroscopy. The first two methods are invasive, may interfere with normal anatomical function, and cannot show the movement of underlying soft-tissue. X-ray fluoroscopy exposes the patient to ionizing radiation and still provides poor contrast in soft-tissue areas. MRI, on the other hand, is a great tool for soft-tissue imaging, but historically low temporal resolution (~700 ms) [1] and significant magnetic susceptibility in this region has kept it from replacing the methods above in routine clinical use. Here we demonstrate an acquisition method with 13.2 frames per second (FPS) true temporal resolution and a reconstruction method producing intermediate images with 33 ms spacing (30 FPS) and 61-76 ms temporal blur without the use of contrast agents or partial image acquisition across repeats; important because motions may vary considerably between swallows.

Materials and Methods Imaging was performed with a custom multi-shot spiral FLASH sequence with regional saturation for a reduced field of view (FOV) on a Siemens Magnetom Allegra 3 T head-only scanner with birdcage headcoil. The sequence was run with 10 ms TR, 1.3 ms TE, flip angle 8°, 8 mm slice thickness, 120 mm FOV, 64x64 matrix, and 512 repeats in 38.8 seconds. A 120 mm axial saturation pulse was aligned to saturate everything from the top of the skull down to the top of the hard palette. Another 120 mm sagittal saturation pulse covered the region from the back of the skull to the spinal column. The saturation pulses were played out once per image (every 6 interleaves). The readout time for each interleaf was 5.57 ms and the voxel size was 1.9x1.9x8 mm. Healthy subjects were scanned in accordance with an IRB-approved protocol. The subjects were scanned in the supine position and instructed to dry swallow at a normal pace repeatedly when they heard the sequence begin. Subjects typically completed five to six swallows during the scanning. The image phase could be used as a field map for each reconstructed image because the magnetic susceptibility induced field inhomogeneity was not large enough to cause substantial phase wrapping during the short 1.3 ms TE. Field-corrected image reconstruction was performed using time-segmented conjugate phase reconstruction [2] to reduce the blurring inherent in spiral readouts in the presence of field inhomogeneity. Each image consisted of interleaves collected over six TR periods. Due to the use of a sliding window reconstruction scheme [3], the true temporal resolution was 76 ms for intermediate images whose interleaves spanned the two saturation pulses and 61 ms for those that didn't. A reconstruction frame rate of 30 frames per second was specified and groups of 6 sequential interleaves (intermediate images) were chosen which most closely aligned to the desired regular 33.3 ms spacing. The resulting images have an average true temporal resolution of 72.2 ms and are spaced 33.3±4.7 ms apart. To increase temporal accuracy, sequence timings were simulated in the manufacturer-supplied simulation environment and absolute timings were recorded for each interleaf relative to the start of the acquisition. This technique assured accurate frame timing for each of the 512 images. Additionally, during sequence acquisition, data was recorded from an infant respiratory bellows attached around the neck to track laryngeal motion. Trigger pulses generated by the scanner sequence were recorded along with the bellows waveforms to aid in accurate alignment of the data to the real-time MRI movie.

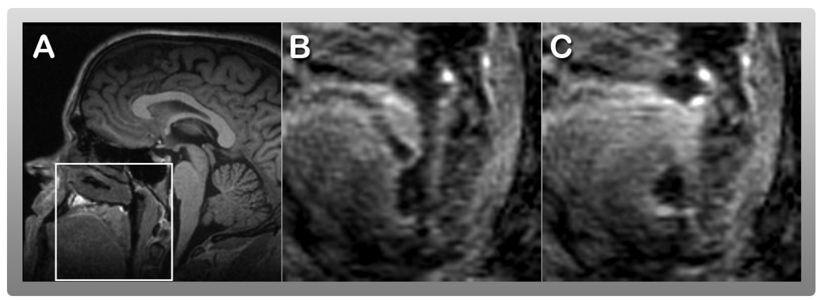

Figure 1. **(a)** T1-weighted anatomical scan. **(b)** Real-time MRI images with reduced FOV (outlined in **a**) of a bolus being transferred from oral to pharyngeal stage and **(c)** initial contact of the velum (soft palate) with the posterior pharyngeal wall.

Results and Discussion Figure 1 shows two frames from the real-time dynamic MRI sequence. The tongue, hard palate, soft palate, and pharynx are visible and well resolved. Field correction was shown to refocus soft tissue signal blurred by magnetic susceptibility, especially at air-tissue interfaces. The acquisition frame rate of 13.2 FPS is significantly better than a previous speech production study at 8-9 FPS [4] and much faster than previous MRI swallowing studies at 7 [5] and 1.4 FPS [1]. Reducing the FOV allowed for faster imaging speed while maintaining spatial resolution similar to that achieved by Narayanan et al. (2004). Our sliding window reconstruction at 30 FPS was also slightly faster than previous studies at 20-24 FPS [4]. Higher temporal resolution allowed us to distinguish finer-grained steps in the swallowing process such as initial contact between the tongue and velum and velum to posterior pharyngeal wall closure, which may occur in as little as 100ms. Motion artifact was minimal as compared to Anagnostara et al. (2001) due to short spiral readouts. By addressing the distortion due to magnetic susceptibility we were able to visualize soft tissue surfaces without the need for additional contrast from liquid boluses [1] or Gadolinium-based contrast agents [5]. The bellows waveforms showed a large degree of consistency across swallows, demonstrating their ability to augment motion tracking of the larynx; something which is only partially visible in the FOV of our head-only scanner.

Conclusion Previous swallowing studies have lauded MRI's ability to visualize soft tissue non-invasively, but limitations on temporal resolution have kept it from seriously challenging X-ray fluoroscopy and endoscopy as standard methods for evaluation of swallowing function. Our approach advances the frame rate and image quality from a dynamic MRI examination, bringing it within clinically relevant rates, while remaining non-invasive, providing superior contrast, and avoiding exposure to ionizing radiation.

References [1] Hartl et al. *Dysphagia* (2003) vol. 18 (4) pp. 255-62, [2] Noll et al. *Magnetic resonance in medicine* (1992) vol. 25 (2) pp. 319-33, [3] A. Bernstein et al. Handbook of MRI Pulse Sequences. (2004) Elsevier Academic Press, [4] Narayanan et al. *J Acoust Soc Am* (2004) vol. 115 (4) pp. 1771-6, [5] Anagnostara et al. *Journal of Magnetic Resonance Imaging* (2001) vol. 14 (2) pp. 194-9