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Dynamic Magnetic Resonance Imaging of the Pharynx During Deglutition

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Abstract

Objectives—To utilize dynamic magnetic resonance imaging (dMRI) to visualize the pharynx and upper esophageal segment in normal, healthy controls.

Methods—A 3-T scanner with a 4-channel head coil and a dual-channel neck coil was employed to obtain hsMRI images of subjects swallowing liquids and pudding. Thirty sequential images were acquired over 3300ms for each swallow. Imaging was performed in the midsagittal and axial plane at the level of the oropharynx and pharyngoesophageal segment. Axial images were then analyzed for variables related to alterations in pharyngeal and UES area during swallowing as well as temporal measures related to these structures.

Results—All subjects tolerated the study protocol without complaint. Changes in pharyngeal wall luminal area and temporal measurements were consistent within and between subjects. Inter- and intra-rater reliability for the measurement tool was excellent.

Conclusions—dMRI of the swallow sequence is both feasible and reliable and may eventually compliment currently-used diagnostic modalities as it adds substantive information.

Keywords

Deglutition; Swallowing; Dynamic MRI; Dysphagia

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INTRODUCTION

Swallowing Disorders are common and have a significant health impact. Prevalence data vary; approximately one quarter of patients in an unselected primary care population presented with dysphagia.(1) In at-risk populations, these figures are significantly increased, including the elderly (~33%)(2) and patients following recent neurological insult (~41%).(3)

The impact of disordered swallowing is profound. In the acute setting, dysphagia is related to significantly increased cost and length of hospitalization for a wide variety of disorders. (4) In addition, dysphagia has been shown to have an independent, negative effect on anxiety, depression, and general health.(5) Unfortunately, despite the significance of the disorder, major gaps in our knowledge regarding the normal swallowing mechanism persist. Swallowing is complicated, involving multiple muscle groups, multiple cranial nerves, and most importantly, precise coordination. The complexities of the system and the anatomic position of the structures involved have largely confounded efforts to fully evaluate the entire swallow sequence. Current imaging techniques for swallowing, including videofluoroscopic evaluation of swallowing, flexible endoscopic evaluation of swallowing (FEES) and ultrasound of the oral cavity and oropharynx, (6–8) allow for assessment of different parts of the tongue base and pharyngeal constrictor region. However, each of these views is limited in that the tongue base and pharyngeal constrictors cannot be visualized in total, specifically the entire tongue base in the axial plane. Improved visualization of these structures is likely to significantly improve both the diagnostic process as well as therapeutic planning, and modalities providing such visualization are likely to be complimentary to currently available diagnostic tools. In that regard, we hypothesized that dMRI is likely to provide reliable visualization of these structures during the act of swallowing. In the current study, we sought to confirm feasibility of this modality in normal, healthy subjects to provide the framework for future investigation of aberrant swallow function.

METHODS

Subjects

The Institutional Review Board at the New York University School of Medicine approved the current study. Nineteen healthy subjects, ages 18–30 with no swallowing-related complaints were included. Exclusion criteria included any current or previous swallowing complaints, cranial neuropathy, or claustrophobia. Once eligibility was determined and informed consent obtained, an oral-motor examination was performed on all subjects by a licensed speech pathologist to assess cranial nerve and vocal tract functioning for isolated and rapidly repeated non-speech and speech tasks for the lips, tongue, palate and larynx. This was done to rule out abnormalities (particularly neurological) that would render the subject ineligible for the study. Subjects presenting with abnormal findings on this examination were excluded. All subjects were trained outside of the scanner on bolus delivery via syringe, as described in subsequent sections.

MRI Protocol

dmRI of swallowing was obtained in the supine position using a 3.0T scanner (Trio, Siemens Medical Solutions, Malvern, PA) with a 4-channel multichannel head coil, and a dual-channel neck coil. Turbo-FLASH sequence parameters were as follows: TR/TE 110/1.2 msec, slice thickness 10mm, matrix 80×192, FOV 217×260 mm, parallel acceleration factor 2 (GRAPPA). Thirty sequential images were acquired over 3300ms for each swallow. Imaging was performed in the axial plane at the level of the oropharynx and at the upper esophageal sphincter.

Swallowing Protocol

High protein boluses in the form of a protein drink (Nutrament, Novartis Medical Nutrition, Minneapolis, MN) or high protein pudding (Boost, Nestle Health Science, Highland Park, MI) was administered for optimal visualization on dmRI.

A technician adjacent to the scanner provided each subject with a 10cc syringe containing 5ml aliquots of each bolus. Scans were performed at both the C2 (mid-C2) and the UES (1.5 cm below esophageal inlet) levels, utilizing two bolus consistencies at each level. For each scanning level and consistency, subjects performed three identical swallows, resulting in a total of 12 swallows per subject for this experiment. Swallow initiation was cued by the technician running the scanner.

Data Acquisition and Statistical Methods

The dependent variables in the current investigation were 1) the duration of pharyngeal closure, 2) the excursion of the pharynx during closure, 3) the duration of UES opening, and 4) the maximal area of the UES during swallowing. All variables were examined as a function of bolus type. Sequential images were subjected to measurements of pharyngeal and UES area via ImageJ (National Institutes of Health) and reported as pixels. As shown in Figure 1, anatomic borders were plainly visible allowing for tracings. Area measurements were recorded for each frame of the swallow, starting from a point just prior to the arrival of the bolus until just after passage. Figure 2 demonstrates the hand-drawn tracing that is used to calculate the area during opening at the UES level. A similar measurement is made of the lumen at the C2 level just prior to the arrival of the bolus. Since the value of the area measurement at closure is zero, the area at this timepoint represents the excursion of the pharynx at that level. Temporal measures were calculated by manually counting the number of frames with a zero area value at C2 and, conversely, at the UES level, counting the frames with a non-zero area value. Figure 3 shows representative data contours for both the pharynx and UES. These are reported in milliseconds, calculated by multiplying the number of counted frames by 110 (3300 msec/30 frames).

Two independent examiners (one non-otolaryngologist and one speech language pathology Master's student) performed all measurements. Inter-examiner reliability was measured by randomly comparing the measurements obtained by each examiner for three subjects. Ten percent of all measures were reanalyzed by each examiner to measure intra-observer reliability. Examiners were trained on marking of swallow measures and demonstrated at

least 80% inter-judge and 85% intra-judge reliability prior to making measures for this study.

General estimating equation regression analysis employing PROC GENMOD (SAS v9.2) was employed to examine if the outcome variables of interest were significantly different between the two types of food, accounting for the within-subject correlations between the three trials. The consistency within subjects, reported as a correlation coefficient, for all experimental conditions was also examined. In addition, the consistency across subjects with regard to all dependent variables was determined qualitatively via standard deviation from the mean.

RESULTS

For all subjects, high-quality images were obtained with no artifact altering data acquisition. In addition, no adverse events were observed; all subjects tolerated supine bolus delivery and swallowing without aspiration. Inter- and intra-rater reliability for the measurements was found to be excellent.

Pharyngeal Measures

Complete closure of the pharynx was observed in all subjects for all swallows. Therefore, area measurements of the pharynx during the swallow were zero across all subjects. Qualitatively, there was a sinusoidal pattern of opening and closing of the pharynx at this level. As seen in Figure 2, just prior to bolus arrival, there is an increase in pharyngeal area, which likely is a result of furrowing of the tongue base and opening of the pharyngeal area to accommodate the upcoming bolus. This pattern was seen across all subjects, regardless of the bolus type. However, since there were generalized inconsistencies of pharyngeal movement in the pre-swallow, preparatory phase, precise alterations in the pharyngeal luminal area were problematic to calculate and were left out of the analysis.

The duration of closure at the C2 level across all subjects was 412.98 msec (SD=98.23) for liquid and 437.11 msec (SD=115.67) for pudding. On average, the closed time was 5.84% greater for pudding compared to liquid. This difference was not statistically significant ($p=0.61$). Intra-subject reliability as reported by correlation coefficient for the duration of pharyngeal closure for both liquid and pudding was 0.84 and 0.92, respectively.

UES Measures

As opposed to the pattern observed at the C2 level, the general pattern of movement qualitatively observed at the UES level is different, in that there is a clear and continuous opening and closing pattern (see Figure 2). This made area and temporal variables easier to calculate.

The area of the UES during maximal opening was 152.32 pixels (SD=38.67) for liquids and 160.77 pixels (SD=34.89) for pudding. This difference was not statistically significant ($p=0.16$). There was a high degree of consistency within subjects for this variable for both liquid and pudding boluses; the correlation coefficient was 0.94 for both. The duration of UES opening across subjects was 574.12 msec (SD=115.96) for liquid and 504.17 msec

(SD=78.10) for pudding. On average, the open time was 13.87% greater for liquid compared to pudding. This difference was statistically significant ($p=0.009$). However, intra-subject variability was slightly increased; correlation coefficients for liquid and pudding were 0.84 and 0.74, respectively

DISCUSSION

Despite decades of research focused on swallowing disorders, significant gaps in our basic knowledge of swallowing physiology persist, partly due to the complexity of the system, but largely due to limitations in evaluative tools. Despite advances in medical technology, the primary imaging modality for assessment of swallowing disorders remains a tool that was developed in the early 1900's-fluoroscopy. Although the spatial resolution has improved, the technology is inherently limited due to radiation exposure and the limited views obtained.

Because of these limitations, a significant amount of valuable information is lost during routine swallowing evaluations. Specifically, the area of the oropharynx, with its complex interaction between the tongue base and pharyngeal walls, remains problematic from an evaluative standpoint. Neither fluoroscopy nor flexible endoscopy evaluation of swallowing (FEES) examines this area comprehensively. Instead, videofluoroscopy allows for views of oral cavity, oropharynx, pharynx, larynx and cervical esophagus to view oropharyngeal and cervical esophageal swallow physiology in the lateral/sagittal as well as the anterior-posterior planes.(9) Tongue base posterior motion and contact to the pharyngeal wall can be viewed in the lateral plane, although symmetry and extent of tongue base contact from lateral to midline tongue cannot be viewed in the lateral/sagittal plane. Spatial resolution, however, is poor compared with other imaging techniques. In addition, fluoroscopy utilizes ionizing radiation, which limits the number of acquisitions possible. FEES provides views of the oropharynx, hypopharynx and larynx from above via nasendoscopy in the axial plane with improved resolution.(6, 10) However, the views are limited to before and after the swallow, due to the "white-out" period during the swallow. This "white-out" period occurs when the tongue base and pharyngeal wall contact the tip of the endoscope during the swallow, obscuring the view. Therefore, bolus movement through the pharynx and pharyngeal structural movement cannot be visualized.

Because of the limitations of these two primary modes of clinical swallow assessment, investigators have examined other potential modalities. Ultrasound provides views of the oral cavity in the lateral/sagittal and coronal planes.(8) However, the tongue base cannot be visualized. The lateral pharyngeal walls can be viewed in the coronal plane, but not in the lateral/sagittal or axial planes (7). In addition, resolution with ultrasound is poor. Computerized Tomography has been investigated and is promising because of the rapidity of the sequences and ability to image in multiple planes, but is significantly limited by radiation exposure.(11–13)

MR imaging of the swallow holds promise in that it can examine the swallow sequence in multiple planes with excellent spatial resolution without the use of ionizing radiation. However, imaging of the swallowing process with this modality has proven challenging due to the rapidity of the swallowing process, the presence of the large air column of the

aerodigestive tract and regional osseous structures, and, unlike the cardiac cycle, substantial variation across repeated swallows. Prior efforts at MR imaging of swallowing have made use of single-shot fast spin echo (SSFSE), (14, 15) true fast imaging with steady state precession (true-FISP), (16) and turbo-fast low angle shot (turbo-FLASH) imaging.(17, 18) Preliminary investigation in our laboratory led us to use turbo-FLASH imaging using a 3.0T magnet. Utilizing this technology, we were able to produce excellent image quality with a temporal resolution of 110ms, with good visualization of the tongue base and pharyngeal constrictors during swallowing in the axial and sagittal planes.(19)

In the current study, we expand on our previous work by demonstrating the inherent feasibility and reliability of the technique to characterize pharyngeal and UES movements in normal, healthy adults. Our data demonstrate that spatial and temporal measurements of pharyngeal wall movement can be reliably performed and shows a definable pattern at both the C2 and UES levels. For the large part, the area and temporal measures obtained were consistent within individuals across the three trials, with the possible exception of UES opening. It is not clear to us why there was poorer correlation of the UES data in this regard. It was noted that during many of the studies, subjects were swallowing air through the UES region along with the bolus (particularly with liquid). This has been noted previously.(13, 20) Perhaps the variation in the amount of air swallowed led to increased variability of this area measure at the UES level.

The data further demonstrate that there is a difference in temporal measures based on bolus consistency at the UES level, which has previously been demonstrated on videofluoroscopy. (21, 22) However, in contrast to previous studies, we demonstrated that liquid bolus caused a prolonged opening of the UES. This may occur due to fragmentation of the liquid bolus compared with the pudding bolus. Certainly, as mentioned, our observation during the study was that patients swallowed more air with liquid boluses than with pudding; this may have caused the increased fragmentation. The discrepancy between our results and previous studies, however, cannot be fully explained. Interestingly, we did not see significant differences between bolus types in the area measurement at the UES level.

At the C2 level, there were no significant differences in the temporal measures based upon bolus type. However, it is notable that in analyzing the pharyngeal movement, it is somewhat difficult to parse out movement that is occurring as a result of transmitted motion of the tongue base during the oral preparatory phase. This results in difficulty determining the exact point of initiation of the swallow in this view, resulting in some variability in the recordings of the data. This is likely to be better vetted through further post-hoc analysis of the swallow pattern at that level.

Regardless, our data are the first to suggest that dMRI is feasible and reproducible. It is not without limitation, however, and is likely to prove to be complimentary to current examination modalities, rather than replace them. At this point, dMRI is limited in temporal resolution and is not “real time”. The limitations inherent in the temporal resolution also do not allow for imaging in multiple planes simultaneously (thus limiting three dimensional reconstruction), though imaging can be done in any given single dimension. In addition, since it can only be done in the supine position, it is unclear that patients with significant

dysphagia will be able to tolerate it. However, it offers something that is not currently available with other modalities—a radiation-free ability to examine all the parts of the swallow in multiple planes with a high degree of resolution. Because we did not visualize aspiration on any of the subjects, we cannot comment on the value of this modality to evaluate for this problem.

CONCLUSIONS

In this study, we demonstrate methodology for performing and measuring swallowing movements of the pharyngeal structures using dynamic MRI in an axial plane. In performing these studies, we hope to characterize normal parameters for swallow analysis using this technology. These data may be used as a baseline for investigation of abnormal swallows in the future. This technique may prove useful particularly in the elderly dysphagic population, as well as allow for examination of swallowing pathophysiology in the setting of unilateral cortical stroke and treated head and neck cancer.

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References

1. Wilkins T, Gillies RA, Thomas AM, Wagner PJ. The prevalence of dysphagia in primary care patients: a HamesNet Research Network study. *Journal of the American Board of Family Medicine: JABFM*. 2007; 20(2):144–50. [PubMed: 17341750]
2. Roy N, Stemple J, Merrill RM, Thomas L. Dysphagia in the elderly: preliminary evidence of prevalence, risk factors, and socioemotional effects. *Annals of Otology, Rhinology & Laryngology*. 2007; 116(11):858–65.
3. Falsetti P, Acciai C, Palilla R, Bosi M, Carpinteri F, Zingarelli A, et al. Oropharyngeal dysphagia after stroke: incidence, diagnosis, and clinical predictors in patients admitted to a neurorehabilitation unit. *Journal of Stroke & Cerebrovascular Diseases*. 2009; 18(5):329–35. [PubMed: 19717014]
4. Altman KW, Yu G-P, Schaefer SD. Consequence of dysphagia in the hospitalized patient: impact on prognosis and hospital resources. *Archives of Otolaryngology -- Head & Neck Surgery*. 2010; 136(8):784–9. [PubMed: 20713754]
5. Eslick GD, Talley NJ. Dysphagia: epidemiology, risk factors and impact on quality of life--a population-based study. *Alimentary Pharmacology & Therapeutics*. 2008; 27(10):971–9. [PubMed: 18315591]
6. Aviv JE, Kim T, Thomson JE, Sunshine S, Kaplan S, Close LG. Fiberoptic endoscopic evaluation of swallowing with sensory testing (FEESST) in healthy controls. *Dysphagia*. 1998; 13(2):87–92. [PubMed: 9513302]
7. Miller JL, Watkin KL. Lateral pharyngeal wall motion during swallowing using real time ultrasound. *Dysphagia*. 1997; 12(3):125–32. [PubMed: 9190097]
8. Sonies BC, Parent LJ, Morrish K, Baum BJ. Durational aspects of the oral-pharyngeal phase of swallow in normal adults. *Dysphagia*. 1988; 3(1):1–10. [PubMed: 3073915]
9. Logemann, J., editor. *Evaluation and Treatment of Swallowing Disorders*. 2. Austin, TX: Pro-Ed; 1998.
10. Langmore SE, Schatz K, Olsen N. Fiberoptic endoscopic examination of swallowing safety: a new procedure. *Dysphagia*. 1988; 2(4):216–9. [PubMed: 3251697]

11. Takehara I, Chu J. Pharynx and oesophagus evaluation during the swallow using helical computerized tomography. *Disabil Rehabil.* 2004; 26(12):733–8. [PubMed: 15204496]
12. Poudereux P, Ergun GA, Lin S, Kahrilas PJ. Esophageal bolus transit imaged by ultrafast computerized tomography. *Gastroenterology.* 1996; 110(5):1422–8. [PubMed: 8613047]
13. Ergun GA, Kahrilas PJ, Lin S, Logemann JA, Harig JM. Shape, volume, and content of the deglutitive pharyngeal chamber imaged by ultrafast computerized tomography. *Gastroenterology.* 1993; 105(5):1396–403. [PubMed: 8224643]
14. Isogai S, Takehara Y, Isoda H, Kodaira N, Sakahara H, Kabasawa H, et al. Kinematic MRI using short TR fast recovery single shot fast spin echo (FRSSFSE). *Proceedings of the International Society of Magnetic Resonance in Medicine.* 2000:1120.
15. Hartl DM, Albiter M, Kolb F, Luboinski B, Sigal R. Morphologic parameters of normal swallowing events using single-shot fast spin echo dynamic MRI. *Dysphagia.* 2003; 18(4):255–62. [PubMed: 14571329]
16. Barkhausen J, Goyen M, von Winterfeld F, Lauenstein T, Arweiler-Harbeck D, Debatin JF. Visualization of swallowing using real-time TrueFISP MR fluoroscopy. *Eur Radiol.* 2002; 12(1): 129–33. [PubMed: 11868088]
17. Kitano H, Asada Y, Hayashi K, Inoue H, Kitajima K. The evaluation of dysphagia following radical surgery for oral and pharyngeal carcinomas by cine-magnetic resonance imaging (Cine-MRI). *Dysphagia.* 2002; 17(3):187–91. [PubMed: 12140643]
18. Suto Y, Kamba M, Kato T. Dynamic Analysis of the Pharynx during Swallowing Using Turbo-Flash Magnetic-Resonance-Imaging Combined with an Oral Positive Contrast Agent - a Preliminary-Study. *British Journal of Radiology.* 1995; 68(814):1099–102. [PubMed: 7496712]
19. Amin MR, Lazarus CL, Pai VM, Mulholland TP, Shepard T, Branski RC, et al. 3 Tesla turbo-FLASH magnetic resonance imaging of deglutition. *The Laryngoscope.* 2012; 122(4):860–4. [PubMed: 22253090]
20. Curtis DJ, Cruess DF, Dachman AH. Normal erect swallowing. Normal function and incidence of variations. *Investigative Radiology.* 1985; 20(7):717–26. [PubMed: 4066243]
21. Lazarus CL, Logemann JA, Rademaker AW, Kahrilas PJ, Pajak T, Lazar R, et al. Effects of bolus volume, viscosity, and repeated swallows in nonstroke subjects and stroke patients. *Arch Phys Med Rehabil.* 1993; 74(10):1066–70. [PubMed: 8215858]
22. Dantas RO, Kern MK, Massey BT, Dodds WJ, Kahrilas PJ, Brasseur JG, et al. Effect of swallowed bolus variables on oral and pharyngeal phases of swallowing. *Am J Physiol.* 1990; 258(5 Pt 1):G675–81. [PubMed: 2333995]

Figure 1.

Representative images of the pharynx at rest (A) and during liquid (B) and pudding (C) swallow as well as the UES at rest (D) and during liquid (E) and puddings swallow (F). The white arrow represents the aperture of interest.

Figure 2.

Representative image showing the hand-drawn outline of the lumen at the UES level during maximal opening. A portion of the food bolus can be seen passing through this segment.

Figure 3.

Graphical representation of area measurements as a function of frame for both C2 (A) and the UES (B) for one subject across swallows for both liquid and pudding. On closer examination of these tracings, the red region illustrates the duration of closure of the pharynx (C) and opening of the UES (D).