**Original Research**

# Real-Time Magnetic Resonance Imaging of Normal Swallowing

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**Purpose:** To evaluate the use of a novel real-time magnetic resonance imaging (MRI) technique for the assessment of normal swallowing dynamics.

**Materials and Methods:** In a cohort of 10 healthy subjects, real-time MRI movies at 24.3 frames per second were obtained in sagittal, coronal, and axial orientation during self-controlled swallows of 5 mL pineapple juice as oral contrast bolus. All studies were performed with the use of a commercial MRI system at 3 T combining two sets of radiofrequency receiver coils. Real-time movies relied on a fast low-angle shot (FLASH) MRI sequence with radial undersampling and image reconstruction by nonlinear inversion yielding 41.23 msec acquisition time for an in-plane resolution of 1.5 mm. Evaluations focused on clinical image quality as well as visualization and temporal quantification of distinct swallowing functions.

**Results:** Throughout the entire process, the swallowing dynamics were well depicted and characterized with almost no visible image artifacts in all subjects. The midsagittal plane turned out to be most valuable. The movies allowed for a quantitative determination of the temporal pattern of all swallowing events.

**Conclusion:** The proposed real-time MRI technique yields noninvasive, robust, and quantitative access to the physiology of normal swallowing in healthy subjects at high temporal resolution and image quality.

**Key Words:** real-time MRI; dynamic imaging; swallowing; deglutition; dysphagia
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DYSPHAGIA IS A SERIOUS SEQUELAE in different neurological diseases as well as in functional disorders due to posttreatment deficits after surgery, radiotherapy, or chemotherapy. The problem is twofold: while the clinical evaluation seeks detailed access to the timing, direction, and efficiency (clearance) of swallowing, the technical approach should be safe and quick as well as robust and reliable (1,2).

The gold standard for swallowing diagnostics is videofluoroscopy, with a typical temporal resolution of at least 25 frames per second (fps). The whole process of deglutition can be visualized in a coronal or sagittal plane. Its disadvantage is the x-ray exposition of the patient and the missing axial plane. Accordingly, flexible endoscopic evaluations of swallowing (FEES) have gained diagnostic importance due to their reduced invasiveness, simplicity, and low cost. On the other hand, FEES suffers from the well-known "white out" during the pharyngeal phase, which is of greatest interest (3).

The aim of this study was to evaluate the performance of a recently introduced real-time magnetic resonance imaging (MRI) technique with high temporal resolution (4) to study deglutition in normal subjects.

## MATERIALS AND METHODS

### Subjects

Ten normal volunteers (four men, six women; age 28 ± 3 years [mean ± standard deviation]; range 26–35 years), with no history or presence of dyspnea, dysphonia, and dysphagia were recruited from the local university. The whole study was approved by the Institutional Review Board and all participants gave written informed consent before each examination. Absence of any swallowing or oro-mandibular dysfunction was ensured by the personal medical history of all subjects as well as by FEES performed by an experienced otorhinolaryngologist (Rater 1) prior to real-time MRI.

### Real-Time MRI

Dynamic imaging of swallowing was conducted at 3 T with the use of a commercial MRI system (Tim Trio, Siemens Healthcare, Erlangen, Germany) and the previously described acquisition and reconstruction technique for real-time MRI (4,5). As shown in Fig. 1a, subjects were examined in a supine position by combining a small flexible radiofrequency (RF) receiver coil covering the lower face (Siemens Healthcare) with a bilateral 2 × 4 array coil centered to the thyroid

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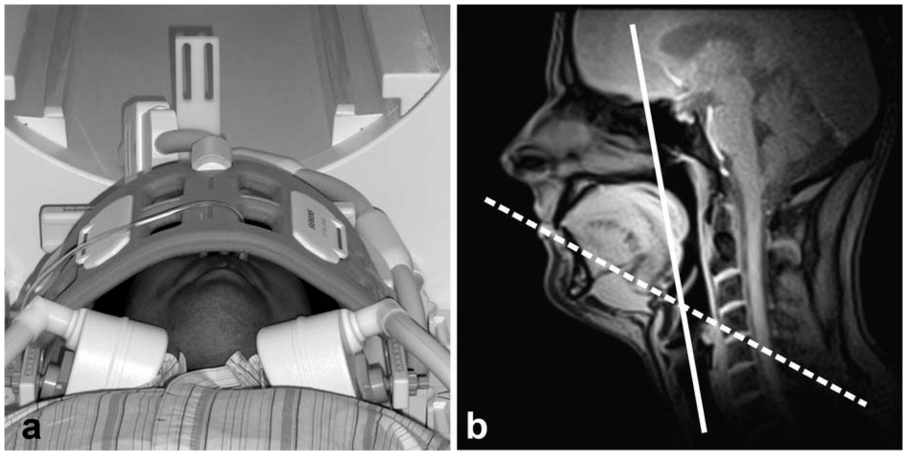


**Figure 1. a:** Coil setup combining a small flexible receiver coil covering the lower face and a bilateral 2 × 4 array coil centered to the thyroid prominence. **b:** T1-weighted scout image (mid-sagittal plane, TR/TE = 2.20/1.46 msec, flip angle 5°, field of view 256 × 256 $mm^2$, 1.5 × 1.5 × 10 $mm^3$) used for defining the planes for real-time MRI: mid-sagittal plane as shown here, coronal plane (straight line), and axial plane (broken line).

prominence on both sides of the neck (NORAS MRI products, Hoechberg, Germany). T1-weighted RF-spoiled fast low-angle shot (FLASH) gradient-echo images with radial encoding were continuously acquired with the following parameters: repetition time TR = 2.17 msec, echo time TE = 1.44 msec, flip angle 5°, field of view 192 × 192 $mm^2$, in-plane resolution 1.5 × 1.5 $mm^2$, and slice thickness 10 mm. Individual images were obtained from 19 radial spokes equally distributed to sample the MRI data space (6). The corresponding image acquisition time of 41.23 msec resulted in a true temporal resolution of 24.3 fps, ie, without image interpolation or data sharing in a sliding-window reconstruction.

In order to locate the planes of interest for dynamic imaging, sagittal scout images covered a slightly larger 256 × 256 $mm^2$ field of view at the same spatial resolution (Fig. 1b). These images were also acquired with the RF-spoiled radial FLASH sequence (TR = 2.20 msec, TE = 1.46 msec, flip angle 5°), but with full radial sampling of the data space and reconstruction by conventional gridding (6).

Multiple real-time MRI movies of different swallows were recorded in mid-sagittal, coronal, and axial orientation. As shown in Fig. 1, the mid-sagittal plane covered the upper aerodigestive tract including the mouth, nasopharynx, pharynx, larynx, and the uppermost gastrointestinal tract represented by the upper part of the esophagus. The coronal plane was located parallel to the posterior pharyngeal wall at the level of the respiratory tract (straight line in Fig. 1b), while the axial plane was set perpendicular to the epiglottis (broken line in Fig. 1b).

Pineapple juice served as an oral contrast agent because of its T1 shortening effect due to an inherently high concentration of paramagnetic manganese (7). It therefore results in a high signal in T1-weighted images. The pineapple juice was thickened with yeast (Quick & Dick, Pfrimmer Nutrica, Erlangen, Germany) to improve the visibility of actions and movements during swallowing.

Swallows were instructed by one otorhinolaryngologist (Rater 1) standing by the subject throughout the MRI examination. After the onset of each real-time measurement a bolus of 5 mL thickened pineapple juice was manually injected with the use of a 50-mL syringe connected to a conventional flexible infusion tube with a diameter of 3 mm. The end of the tube was fixed to the subject's mouth in order to secure oral bolus formation as the juice slowly filled the mouth (Fig. 1a). The end of the bolus administration was cued by the otorhinolaryngologist, after which the volunteer performed a swallow in a natural manner at a comfortable rate. The bolus was given once for each real-time measurement, which lasted for about 18 sec.

Because all relevant anatomical structures are in movement during swallowing, movies of individual swallows were sequentially recorded in five parallel axial and coronal sections (10-mm thickness, 5-mm shifts). The section in which the deglutition was best illustrated was chosen for image evaluation.

### *Image Evaluation*

The image quality of real-time MRI movies was evaluated by one otorhinolaryngo-logist (Rater 1) and one radiologist (Rater 2) blinded to the subject data. The subject order was randomized, but images from the same subject were reviewed at the same time according to diagnostic practice.

Swallowing dynamics were assessed for direction (oral control, velo-pharyngeal closure, penetration, and aspiration), timing (transport), and clearance. Accordingly, subjects were classified as normal (no distortion), mild distortion, moderate distortion, and severe distortion, respectively. The ability to detect and characterize distinct swallowing events was rated on a 5-point scale for each subject, with a score of 1 indicating no detectability; a score of 2, poor detectability; a score of 3, detectable; a score of 4, good detectability; and a score of 5, excellent detectability. The group-averaged scores are given as mean ± standard deviation.

In addition, the best orientation for detection and characterization was selected among sagittal, coronal, and axial planes for all swallowing measurements and subjects. No choice or multiple choices were also allowed, in case that none of the orientations or more than one orientation were optimal.

### *Quantitative Timings*

The temporal pattern of all sphincter functions as well as the oral and pharyngeal transit times (OTT

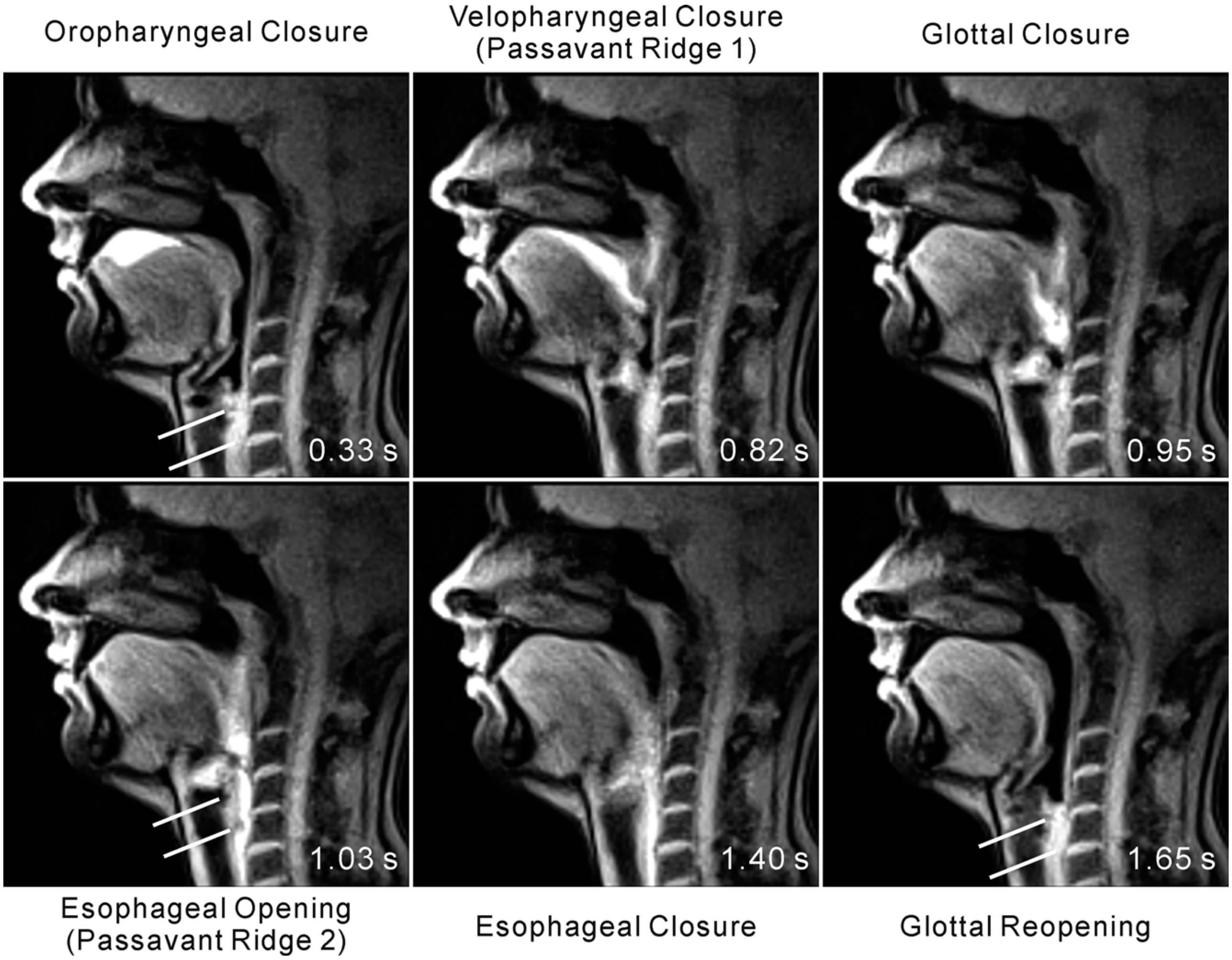


**Figure 2.** Real-time MRI of normal swallowing in the mid-sagittal plane (26-year-old healthy female subject). The images (TR/TE = 2.17/1.44 msec, flip angle 5°, field of view 192 × 192 $mm^2$, 1.5 × 1.5 × 10 $mm^3$) with an acquisition time of 41.23 msec represent distinct swallowing events from a corresponding movie of a single swallow at 24.3 fps (see Supporting Movie 1). Numbers refer to relative timings with reference to the beginning of the esophageal opening (ie, 1.03 sec). The ascent and descent of the larynx is highlighted by double lines.

and PTT) were measured according to Logemann's "six-valve model" (2), namely, lips (1), oral tongue (2), velopharyngeal sphincter (3), larynx (4), tongue base and pharyngeal wall (5), and cricopharyngeal sphincter (6). Valve 1 was closed during the entire swallowing process. The opening and closure of valve 2 was represented by the orovelar opening time (OOT). Valve 3 was defined as velo-pharyngeal closure time (VCT) and was indicated by the observation of the first passavant ridge (PR1). The glottal closure time (GCT) together with the duration of the epiglottic retroflexion determined valve 4. Valve 5 and valve 6 were defined as the second passavant ridge (PR2) and the esophageal opening time (EOT), respectively. In addition, the time periods of the laryngeal ascent and descent times (LAT and LDT) as well as the duration of vallecular and piriform sinus filling, which indicates the deglutitive clearance, were also measured.

For each swallowing measurement, the beginning of the esophageal opening was taken as a reference. This definition accounted for intermeasurement differences in overall swallow length, which were mainly caused by the oral bolus preparation before the onset of the swallow, and allowed for easy access to intra- and intersubject variability in the physiology of the swallowing process. The reference was arbitrarily defined as image number 25, which yielded a time stamp of 1.03 s (ie, 25 image acquisition times). Noteworthy, the accuracy of the individual timings relative to the reference, and therefore also their corresponding differences (ie, durations of swallowing events), was limited by the acquisition time for one image (ie, 41 msec in the current study).

## RESULTS

Real-time MRI of swallowing was not only feasible in all subjects, but also robust in terms of practical performance. No volunteer noticed or exhibited any problems with swallowing in a supine position and for the current coil setup. For each subject the total MRI examination time was about 6 minutes, comprising 8 to 10 swallows (ie, real-time movies) in different

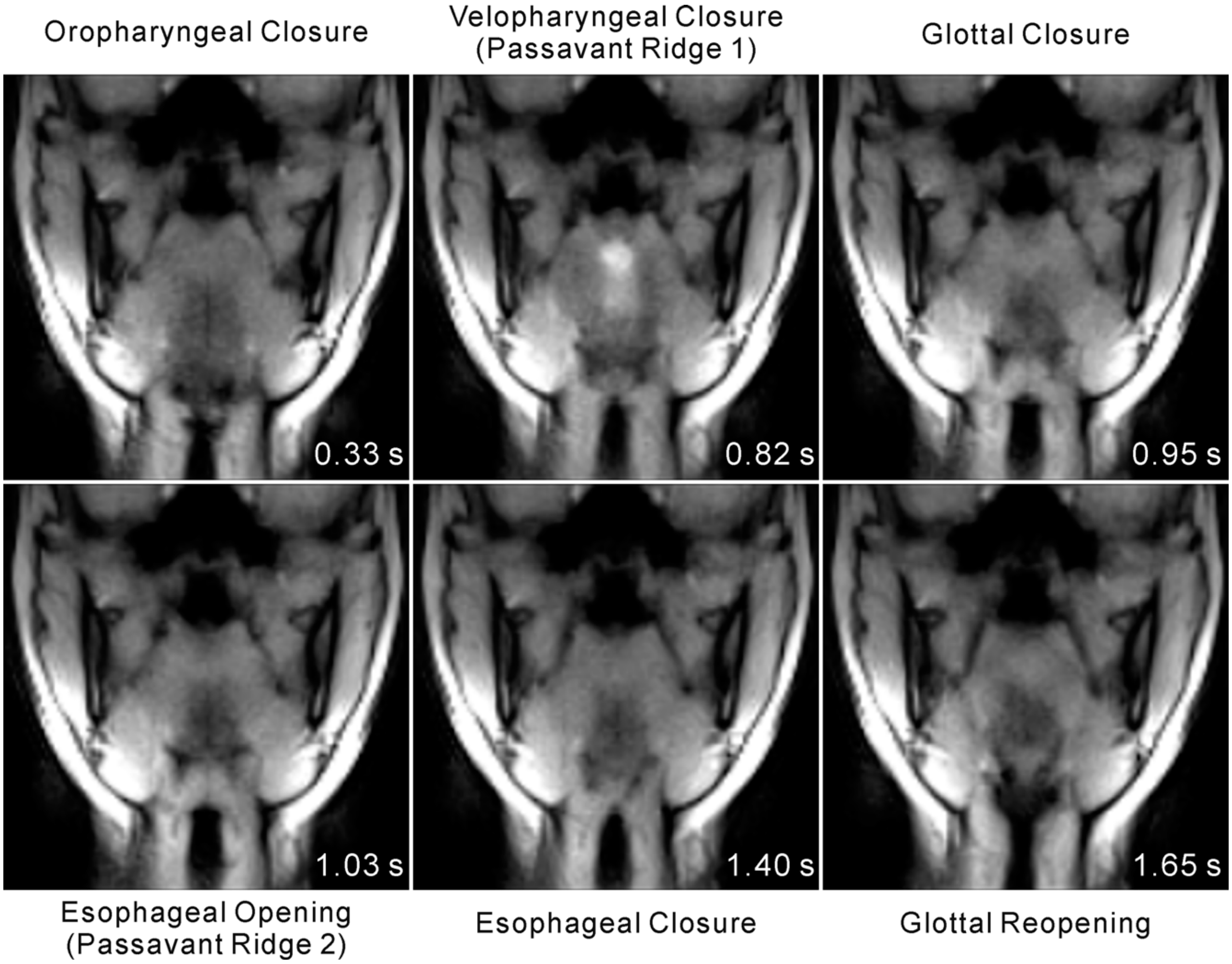


**Figure 3.** Real-time MRI of normal swallowing in a coronal plane (same subject and parameters as in Fig. 2). The images represent distinct swallowing events (relative timings as in Fig. 2) from a corresponding movie of a single swallow at 24.3 fps (see Supporting Movie 2).

imaging planes. The standardized procedure for coil setup and individual adjustment led to a total in-room time of less than 15 minutes.

Because only healthy volunteers were recruited, both real-time MRI and FEES revealed normal swallowing dynamics for all subjects with no distortion in oral control, velopharyngeal closure, penetration, aspiration, and clearance. It should be noted, however, that the main purpose of this pilot study was to evaluate the performance of the new real-time MRI technique rather than to achieve a comprehensive correlation of MRI findings with other methods in a specific patient population.

Figure 2 shows selected images from a movie (Supporting Movie 1) of a female subject during a single swallow. The different relative timepoints refer to the beginning of velopharyngeal closure, glottal closure, esophageal opening (ie, 1.03 sec) and closure, and glottal reopening. The images further demonstrate the ascent and descent of the larynx (double lines). Corresponding images of the same swallowing events in a coronal and axial plane are depicted in Figs. 3 and 4, respectively. They were selected from separate movies of the same subject (Supporting Movies 2 and 3).

The mean score for detectability of all swallowing dynamics from both raters was $4.6 \pm 0.6$ (5 = excellent detectability). With regard to individual functions, the mean scores from both raters were: $4.7 \pm 0.6$ for oral control, $4.6 \pm 0.7$ for velopharyngeal closure, $4.5 \pm 0.6$ for penetration, $4.7 \pm 0.5$ for aspiration, $4.7 \pm 0.5$ for transport, and $4.5 \pm 0.5$ for clearance, respectively. While one rater (Rater 1) gave a maximum score for all functions ($5.0 \pm 0.0$), the mean scores from the other rater (Rater 2) for the aforementioned individual functions were $4.4 \pm 0.7$, $4.1 \pm 0.7$, $3.9 \pm 0.3$, $4.3 \pm 0.5$, $4.4 \pm 0.5$, and $4.0 \pm 0.0$, respectively.

In general, the sagittal plane was found to be the best orientation for detection and characterization of swallowing dynamics from both raters: 67% of the total 90 choices from Rater 1 and 100% of the total 55 choices from Rater 2. The coronal plane was considered the optimal orientation for detection of penetration and aspiration from one rater (Rater 1): 22% of the total 90 choices. The axial plane was chosen as the optimal orientation for detection of bolus clearance from the same rater (Rater 1): 11% of the total 90 choices.

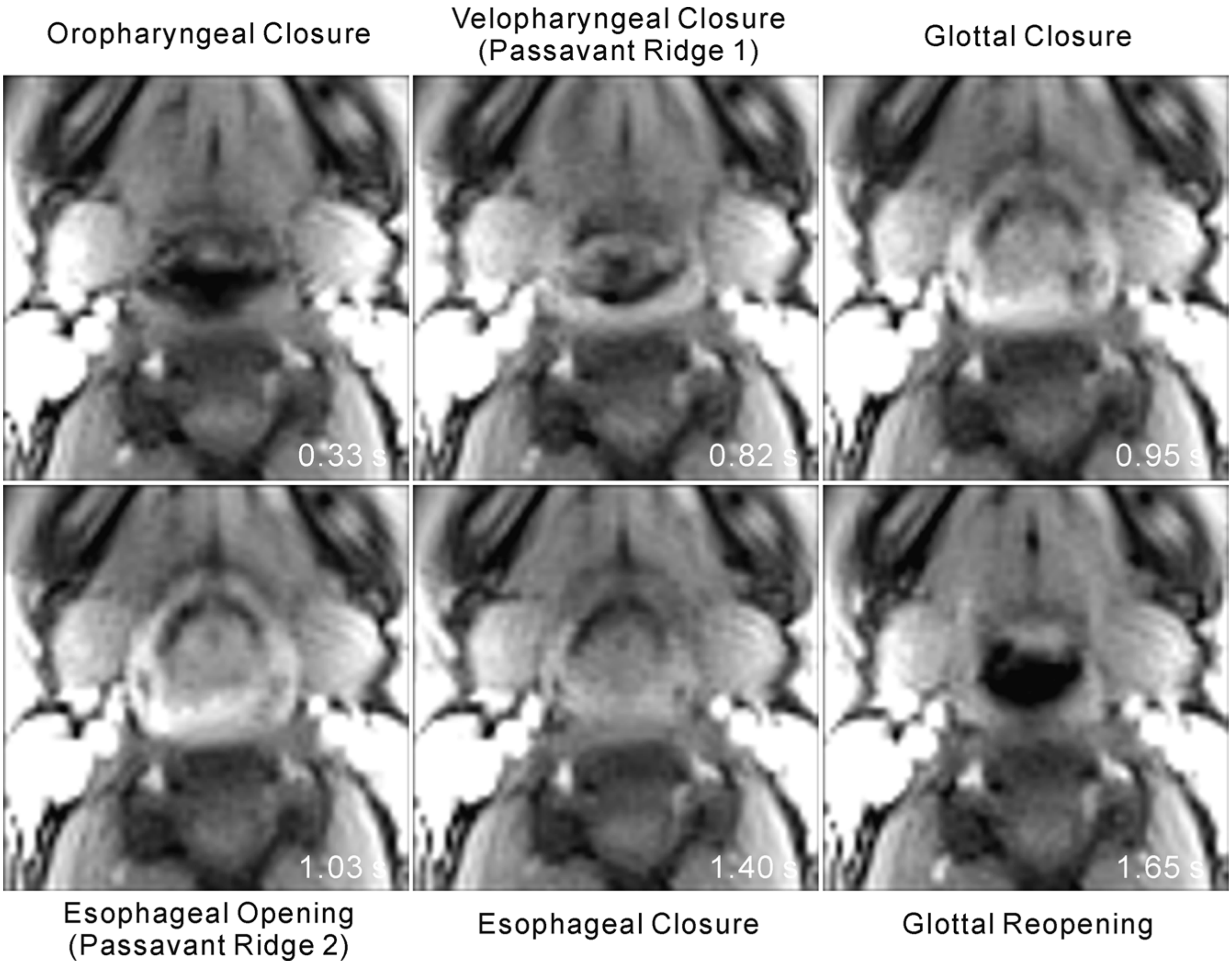


**Figure 4.** Real-time MRI of normal swallowing in an axial plane (same subject and parameters as in Fig. 2). The images represent distinct swallowing events (relative timings as in Fig. 2) from a corresponding movie of a single swallow at 24.3 fps (see Supporting Movie 3).

The overall swallow length varied from 1 to 2 sec between subjects with a mean duration of 1.55 ± 0.29 sec. Figure 5 presents a comprehensive temporal pattern of 11 distinct events (ie, onset and duration) that could be determined for a single swallow in a female subject. The mean durations averaged across subjects are summarized in Table 1 together with literature values where available.

## DISCUSSION

Swallowing is a very fast process which involves several involuntary and closely coordinated actions. In our cohort of healthy young subjects these actions occur within about 1.5 sec starting from the oral phase to laryngeal descent. Thus, high temporal resolution is mandatory to delineate the different physiological functions involved. With the advent of fast imaging techniques, the use of MRI has gained considerable interest for studying the dynamics of a swallow. However, previous studies either relied on a cine mode with pseudodynamic recordings of limited physiological relevance (8–10), or used "near-real-time" acquisitions with low and partially inadequate frame rates of 2 to 16 fps (11–18).

The real-time MRI method proposed here for the first time reaches a true temporal resolution of 24.3 fps comparable to that of standard videofluoroscopy as the established clinical method of choice. This speed is demonstrated to allow for a detailed MRI visualization of all movements during swallowing. Moreover, in comparison to previous studies the present results are superior in terms of image quality. This is largely due to the use of an advanced acquisition and reconstruction technique in combination with optimized RF receiver coils. The former avoids any signal loss or geometric distortion because of the insensitivity of short-TE gradient-echo images to susceptibility differences or off-resonance effects (19). These problems usually occur at tissue interfaces or between tissues and air and are known to affect image acquisitions in the oral and pharyngo-laryngeal area for MRI sequences with long echo times such as echo planar imaging (12,13) and spiral imaging (20). On the other hand, our very short acquisition time of

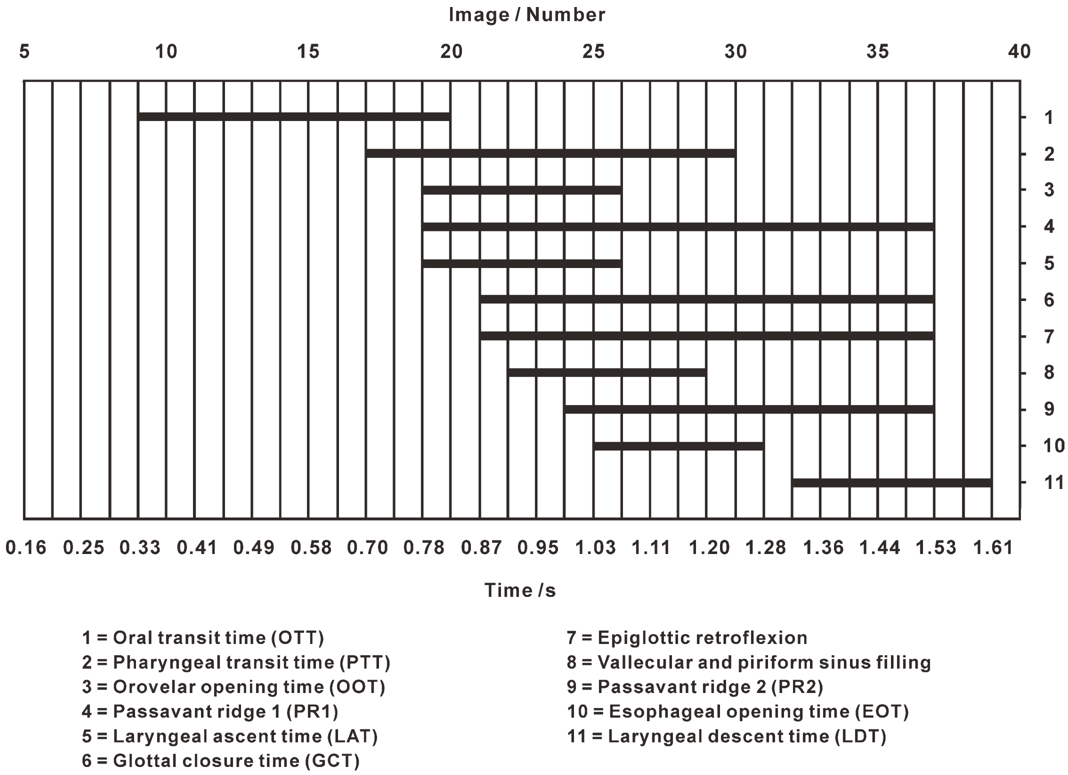


**Figure 5.** Quantitative durations of the functions of a single swallow as obtained by real-time MRI at 41.23 msec resolution (same subject as in Fig. 2). Relative timings refer to the beginning of the esophageal opening, which was arbitrarily chosen as image number 25 corresponding to a time stamp of 1.03 sec (ie, 25 acquisition times). The physiologic events are sorted according to their start times from 1 to 11.

41 msec almost completely avoids visible motion artifacts or blurring of anatomical structures due to rapid movements. Such effects are typically seen when the imaging process involves data sharing in a sliding-window reconstruction (15,21).

The present frame rate also allows for accurate temporal determinations of individual swallowing events. In fact, Table 1 demonstrates general agreement of pertinent durations with data from videofluoroscopy, which were obtained from healthy subjects in a sitting position (1,3,22). For example, the mean PTT of 0.67 found here was previously reported to be 0.84 sec (1), 0.70 sec (22), and 0.72 sec (23), respectively. Moreover, the present durations of the laryngeal vertical movement and the glottal closure were 0.98 sec and 0.63 sec, while previous studies reported 1.0 sec (3) for the former and 0.5 sec (3) and 0.68 sec (22) for the latter. The largest variation in the present study was found for OTT, which is in line with a correspondingly large range of literature values (1,22,23).

Deviations from previous studies were observed for some relative timings to esophageal opening. Most important, and despite a large variation, the glottal closure consistently occurred ahead of the esophageal opening in all 10 volunteers with a mean time difference of 0.19 ± 0.14 sec. This is in contrast to Logemann et al's (3) observation where these two motions were described as "simultaneous." It agrees with Dodds et al's finding (22), although their value of 0.05 sec is much smaller. Moreover, Dodds et al reported the palatal closure at about 0.35 sec before the esophageal opening (22), while we found the velopharyngeal closure (PR1) at about 0.23 ± 0.07 sec prior to the esophageal opening. While the significance of these differences and the related intra- and interindividual variability is still an open question,

Table 1
Mean Durations of Swallowing Events

| Function | Present study* duration/sec | Previous work duration/sec |
|---|---|---|
| OTT: oral transit time | 0.44 ± 0.23 | 0.46 ± 0.32 (1), 0.5 (22), 0.19 ± 0.13 (23) |
| PTT: pharyngeal transit time | 0.67 ± 0.10 | 0.84 (1), 0.70 (22), 0.72 (23) |
| OOT: orovelar opening time | 0.28 ± 0.09 | — |
| PR1: passavant ridge 1 | 0.66 ± 0.14 | — |
| LAT: laryngeal ascent time | 0.41 ± 0.11 | — |
| GCT: glottal closure time | 0.63 ± 0.16 | 0.5 (3), 0.68 (22) |
| Epiglottic retroflexion | 0.67 ± 0.08 | — |
| Vallecular & piriform sinus filling | 0.49 ± 0.15 | — |
| PR2: passavant ridge 2 | 0.50 ± 0.06 | 0.45 (22) |
| EOT: esophageal opening time | 0.26 ± 0.04 | 0.4 (3), 0.5 (22) |
| LDT: laryngeal descent time | 0.57 ± 0.15 | — |

*$n$ = 10, values given as mean ± standard deviation.

Table 2
Preferred Orientations for Real-Time MRI Evaluations of Swallowing

| | Sagittal | Coronal | Axial |
|---|---|---|---|
| Oral control | √ | | |
| Velopharyngeal closure | √ | | |
| Penetration | √ | √* | |
| Aspiration | √ | √* | |
| Transport | √ | | |
| Clearance (retention) | √ | | |
| OTT: oral transit time | √ | | |
| PTT: pharyngeal transit time | √ | | |
| OOT: orovelar opening time | √ | | |
| VCT/PR1: passavant ridge 1 | √ | | |
| LAT: laryngeal ascent time | √ | (√) | |
| GCT: glottal closure time | | √ | (√) |
| Epiglottic retroflexion | √ | | |
| Vallecular & piriform sinus filling | | | √ |
| PR2: passavant ridge 2 | √ | (√) | |
| EOT: esophageal opening time | √ | | (√) |
| LDT: laryngeal descent time | √ | (√) | |

Top: clinical parameters; bottom: timing parameters.
√ Preferred as first choice; (√) secondary choice; *chosen by only one rater.

they might have been influenced by the lying position in the MRI magnet, as gravity can alter the behavior of muscles during swallowing (10). In any case, the present data may serve as reference values for swallowing in the supine position and provide a basis for further investigations in patients with dysphagia.

Logemann (2) stated that the pharyngeal wall is not observed as a "peristaltic wave," but that instead the movement of the tongue pushes the bolus forward. In contrast, we found two confluent peristaltic waves in all 10 subjects. While the passavant ridges involved the lateral pharyngeal wall as the first wave, the second one occurred concurrently with the opening of the cricopharyngeal sphincter and was followed by the esophageal peristaltic wave. This can be observed in both sagittal and coronal planes (Figs. 2, 3), but is even better demonstrated in the Supporting Movies 1 and 2. Such a concurrent movement, together with a normal timing and coordinated function of individual valves, enables a full clearance of the bolus in the aerodigestive tract and thus a solid protection of the airway.

An inherent advantage of MRI is the ability to examine swallowing in arbitrary image orientations without changing the position of the patient. The present study for the first time evaluated the potential clinical significance of different orientations as summarized in Table 2. Despite a limited number of subjects, our results clearly demonstrate that a sagittal plane is the most valuable orientation, for example, for an optimal assessment of OTT, PTT, OOT, VCT, PR, epiglottic retroflexion, EOT, LAT, and LDT. However, the glottal closure (GCT) can be best visualized in the coronal plane and secondarily in the axial plane. In addition, for quantification of relevant durations and evaluation of valve functions, all imaging planes are essential. In particular, coronal and axial planes may provide supportive information for the evaluation of penetration, aspiration, and clearance, although such evaluations need to be proven in clinical studies of patients with dysphagia.

In this study no volunteer experienced any problems with regard to swallowing in a supine position. During pilot examinations the volume of the bolus was adjusted to 5 mL, so that most subjects swallowed only once. In addition, a standardized examination protocol and a total in-room time of only 15 minutes considerably reduced subject discomfort and facilitated the whole procedure. Patient studies of swallowing in the supine position have been reported (13–17), but special care should be taken for patients with neurological disorders to avoid possible complications from aspiration. Finally, the proposed technique is independent from either the field strength or the type of the MRI magnet including systems for upright studies.

Despite pronounced advances in temporal resolution and image quality, the main limitation of the present study is the restriction to a single-slice acquisition. While a simultaneous multislice acquisition of parallel and/or orthogonal sections would be more efficient (5), it is also desirable for synchronizing motions in different planes or to observe through-plane motion during swallows. It is our expectation that a further improvement of the reconstruction algorithm for real-time MRI may solve this problem in the foreseeable future.

In conclusion, this work evaluated the performance of a new real-time MRI technique for studying the dynamics of normal swallowing in healthy subjects—a physiological movement for which a robust, efficient, and safe approach is required. The proposed noninvasive MRI method provides comprehensive functional information about all relevant anatomical movements during swallows and allows for a quantification of its dynamics. Further thorough studies of swallowing physiology and pathology with comparison to established techniques are now warranted.

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