Real-time evaluation of swallowing in patients with oral cancers by using cine-magnetic resonance imaging based on T2-weighted sequences

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Objective. The aim of this study was to evaluate whether a new cine-magnetic resonance imaging (CMRI) technique might be useful for evaluating swallowing function in patients with different types of oral cancers by assessing 12 CMRI-related parameters.
Study Design. In total, 111 patients with oral cancers were evaluated. We examined whether visualization of fluid flow and determination of flow direction to the trachea or the esophagus were possible with CMRI. We evaluated the correlations between CMRI-related parameters and self-reported dysphagia scores as the status of dysphagia, T classification groups as tumor staging for preoperative patients, alterations in CMRI-related parameters between pre- and postoperative patients, and the degree of invasiveness of oral cancer surgery.
Results. We could judge the flow direction to the esophagus on CMRI in all 111 patients. Six CMRI-related parameters showed significant correlations with dysphagia status. Increases in CMRI-related parameters were significantly related to deterioration of swallowing status, as shown by a decrease in self-reported dysphagia scores, advances in the T classification, and degree of invasiveness of oral cancer surgery.
Conclusions. The results of the present study suggest that CMRI can be used to directly visualize swallowing dynamics and objectively evaluate the swallowing complaints of patients with oral cancer. (Oral Surg Oral Med Oral Pathol Oral Radiol 2020;130:583−592)

The oral cavity includes structures that undergo a complex series of movements during biting, swallowing, and speech. Oral cancers and their surgical treatment may result in severe functional limitations. If oral cancers and surgery for these lesions induce oral dysfunction, various swallowing-related diseases, such as aspiration pneumonia, can occur.[1-4] Development of easy, safe, noninvasive, precise, and objective imaging techniques for the evaluation of swallowing is necessary. Videofluorography (VF) was established as the gold standard imaging modality for the evaluation of swallowing, but it is relatively invasive because of such factors as x-ray exposure and side effects of the contrast medium.[3,5] Our recent study showed that swallowing dynamics can be directly visualized by a new cine-magnetic resonance imaging (CMRI) technique based on T2-weighted sequences developed by us; CMRI can facilitate the evaluation of swallowing in patients with tongue cancer both before and after surgery.[6,7] However, those previous reports involved only patients with tongue cancer and assessed small sample sizes.[6] Swallowing problems can occur in many patients with other oral cancers, such as gingival cancers.[1,2]

In the present study, CMRI was used to evaluate swallowing function in a larger sample of patients with different oral cancers to elucidate the usefulness and significance of this CMRI technique. We evaluated whether visualization of fluid flow and determination of the flow direction to the trachea or the esophagus were

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Statement of Clinical Relevance

The findings of this study suggested that cine-magnetic resonance imaging can be used to directly visualize swallowing dynamics and objectively evaluate the swallowing complaints in patients with oral cancer.

possible with CMRI. At the same time, we evaluated the correlations between self-reported dysphagia scores as the status of dysphagia and CMRI-related parameters, correlations between the T classification groups as tumor staging for preoperative patients and CMRI-related parameters, alterations in CMRI-related parameters between pre- and postoperative patients, and correlations between the degree of invasiveness of surgery for oral cancers and CMRI-related parameters.

MATERIALS AND METHODS

Patients

Between 2012 and 2018, 111 consecutive patients with oral cancers (65 males, 46 females; mean age 58.7 years; age range 34−85 years) were examined before surgery (n = 34) and after surgery (n = 77) at the Kyushu Dental University Hospital. Informed consent was obtained from all patients before magnetic resonance imaging (MRI) examination. The institutional review board of Kyushu Dental University approved the present study (No. 12-30).

The diagnosis of oral cancer was obtained on the basis of histopathologic examination results for all patients. The primary tumors involved the tongue, floor of the mouth, mandibular gingiva, and buccal mucosa.

The 34 preoperative patients were divided into 4 groups according to the T classification,[6,8,9] with 14 patients in group T1, 12 in group T2, 2 in group T3, and 6 in group T4.

The 77 postoperative patients were also classified into 4 groups based on the degree of invasiveness of surgery for their oral cancers.[6,8,9] Type I included only marginal dissection of the tongue, lips, cheeks, maxillary gingiva, and palate and marginal dissection of the mandible for the mandibular gingiva. Type II included marginal dissection, along with tissue flap reconstruction of the tongue, lips, cheeks, and maxillary gingiva, and segmental resection of the mandible for gingival cancers. Type III included hemiglossectomy or subtotal glossectomy, along with tissue flap reconstruction of the tongue, lips, cheeks, and maxillary gingiva, and transection of the mandible for gingival cancers. Type IV included cervical dissection in addition to the above-mentioned surgery.

Self-reported dysphagia scores as the status of dysphagia

All 111 patients answered a survey with self-report of their dysphagia; the survey included questions regarding patients' impressions of their swallowing function. Based on the scores, the status of dysphagia was considered normal, slightly abnormal, or abnormal, according to Nishimura et al.[6]

CMRI imaging parameters

MRI scans were acquired by using a 1.5-T full-body MR system (EXCELART Vantage Powered by Atlas; Toshiba, Tokyo, Japan). CMRI was then performed in addition to the routine MRI examinations for all patients with oral cancers, with modification of the techniques of Tanaka et al. and Nishimura et al.[6,7] In brief, patients were placed in the supine position, and the array coil was centered on the thyroid prominence on both sides of the subject's neck. Radiofrequency-spoiled, steady-state, free-precession, field-echo images with radial encoding were acquired continuously by using parameters based on T2-related sequences for visualizing normal water, which carries little risk of complications from aspiration and can visualize various types of diseases, such as malignant tumors. The parameters were repetition time (TR) = 3.2 msec; echo time (TE) = 1.6 msec; flip angle = 45 degrees; field of view (FOV) = 250 × 225 mm^2; and slice thickness = 8 mm. To sample the MRI data space, individual images were obtained from 10 equally distributed radial spokes. The true temporal resolution was 28 frames per second, with image interpolation or data sharing in a sliding-window reconstruction with an image acquisition time of 35 msec. In concrete terms, modified MRI sequences, such as those used to image cardiac movements, were applied as a new technique for observing structures and movements of the neck region in the present study.[10,11]

Sagittal scout images covered a slightly larger FOV (256 × 256 mm^2) at the same spatial image to identify the planes of interest for dynamic imaging. The radiofrequency-spoiled, steady-state, free-precession, field-echo images with a radial encoding sequence (TR = 3.2 msec; TE = 1.6 msec; flip angle = 45 degrees) with full radial sampling of the data space and reconstruction by conventional gridding were used to acquire these images. CMRI movies of various swallows were recorded in midsagittal orientation. A 5-mL bolus of saline was administered before CMRI as a T2 extension effect because of the evaluation of swallowing for about 30 seconds.

Image evaluation

Two expert radiologists (S.N. and T.T.), recognized by the Japanese Society for Oral and Maxillofacial Radiology, reviewed all images separately, with no prior knowledge of the patients' identities. Image quality was subjectively classified as good, moderate, or low. After visualization of the fluid flow direction to the trachea or the esophagus, the respective CMRI-related parameters were standardized by the 2 examiners, who used some of the CMRI cases. The MRI scans were read in a randomized, blinded manner, and CMRI was evaluated according to Zhang et al.[12] and Kreeft et al.[13] In cases of disagreement, a final assessment was reached by consensus. Intra- and interobserver agreement was calculated on the basis of repeated examination of cases and the preconsensus evaluation.

Evaluation of swallowing dynamics included assessments of the following course (oral control, velopharyngeal closure, penetration, and aspiration), timing (transport), and clearance. For precise analysis of the swallowing dynamics, quantitative timing was examined according to Zhang et al.,[12] as mentioned below. The temporal patterns of all sphincter functions, as well as the oral transit time (OTT) and pharyngeal transit time (PTT) in seconds, were evaluated using the "6-valve model" of Logemann, which includes the lips, tongue, velopharyngeal sphincter, larynx, tongue base, pharyngeal wall, and cricopharyngeal sphincter.[14-18] Valve 1 was closed during the entire swallowing process. The orovelar opening time (OOT) in seconds represented the opening and closing of valve 2, whereas valve 3 was defined as the velopharyngeal closure time in seconds, indicated by observation of the first passavant ridge (PR1) in seconds. Valve 4 was used to determine the glottal closure time (GCT) in seconds with the duration of epiglottic retroflexion. Valve 5 was defined as the second passavant ridge (PR2) in seconds, and valve 6 was defined as the esophageal opening time (EOT) in seconds. Furthermore, measurements of the laryngeal ascent time (LAT) in seconds; laryngeal descent times (LDT) in seconds; and duration of vallecular and piriform sinus filling, which indicates deglutitive clearance; and epiglottic retroflexion were also taken.

A tissue immobility score was defined for the purpose of objective evaluation of the CMRI according to Kreeft et al.[13] This score was based on mobility of the following structures: anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall. The mobility of these structures was assessed objectively and scored as follows: 1 = normal; 2 = somewhat decreased; and 3 = decreased/immobile. In addition, contacts between the anterior tongue and the palate, between the base of the tongue and the posterior pharyngeal wall, between the base of the tongue and the soft palate, and between the soft palate and the posterior pharyngeal wall were examined and scored as either 1 = visible contact/normal or 2 = no visible contact/abnormal. Then, the scores of these 9 items were summed, and this yielded the immobility score, which ranged, in theory, from 9 (normal/mobile) to 23 (completely abnormal/severely immobile). The number of items that could not be evaluated was counted (range 0–9), and items with imperfect visualization for evaluation of contact or mobility were assigned a score of 1.

Statistical analysis

All statistical analyses were carried out by using SPSS version 23 (SPSS, Chicago, IL), with analysis of variance (ANOVA), Spearman's rank correlation coefficient, and the Student *t* test, as appropriate, to analyze differences in mean values among the groups. A significant difference was defined as $P < .05$. Correlations obtained from Spearman's rank correlation coefficient were classified into 5 grades: very weak = 0.00 to ±0.19; weak = ±0.20 to ±0.39; moderate = ±0.40 to ±0.69; strong = ±0.70 to ±0.89; and very strong = ±0.90 to ±1.00. Intra- and interobserver agreements were calculated by using the intraclass correlation coefficient.

RESULTS

Patient demographic information, primary tumor sites, T classifications, pathologic diagnoses, and surgical invasiveness in patients with oral cancer

Table I shows patient demographic information, the distributions of the sites, T classifications, and pathologic diagnoses of oral cancers, and invasiveness of surgery in the 111 patients (34 preoperative patients and 77 postoperative patients). The tongue was the most common site (102 patients), followed by the floor of the mouth and the mandibular gingiva. The most common pathologic diagnosis was squamous cell carcinoma.

Image quality of swallowing on CMRI in patients with oral cancer

The quality of images of the 111 patients with oral cancer was considered good in 61 (Figure 1 and Video 1); moderate in 44, and low in 6 (Figure 2). The flow direction to the esophagus could be judged on postoperative CMRI in all patients (see Figure 1 and Video 1), but the flow direction

Table I. Patient demographic information, tumor characteristics, and invasiveness of surgery

Age, years	
Mean ± SD	58.7 ± 14.4
Range	34–85
	Number (%)
Gender	
Male	65 (58.6)
Female	46 (41.4)
Primary tumor site	
Tongue	102 (91.9)
Floor of mouth	4 (3.6)
Mandibular gingiva	4 (3.6)
Buccal mucosa	1 (0.9)
T classification	
T1	51 (45.9)
T2	36 (32.4)
T3	6 (5.4)
T4	18 (16.2)
Pathologic diagnosis	
SCC	110 (99.1)
SPC	1 (0.9)
Surgical invasiveness (after surgery)	
Type I	37 (48.1)
Type II	20 (26.0)
Type III	6 (7.8)
Type IV	14 (18.2)

SCC, squamous cell carcinoma; *SD,* standard deviation; *SPC,* solid papillary carcinoma.

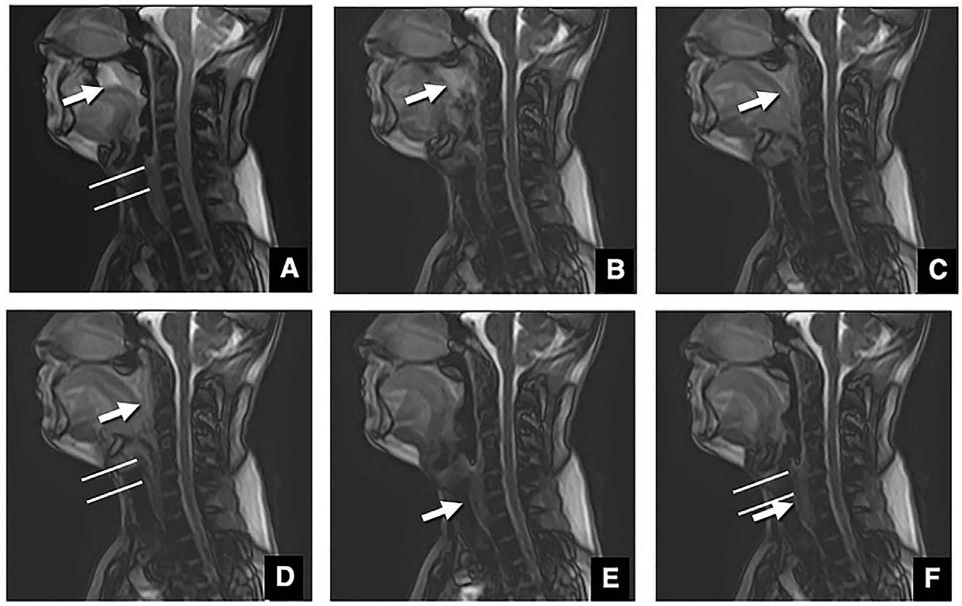

Fig. 1. A swallowing series in the mid-sagittal plane with good quality by using cine-magnetic resonance imaging (CMRI) before surgery in a 40-year-old man with right gingival cancer. The images (TR/TE = 3.2/1.6 msec; flip angle = 45 degrees; FOV = 120 × 96 mm^2) with an acquisition time of 35 msec represent distinct swallowing events. **A,** Oropharyngeal closure (0.11 seconds). **B,** Velopharyngeal closure (passavant ridge 1) (1.39 seconds). **C,** Glottal closure (1.61 seconds). **D,** Esophageal opening (passavant ridge 2) (1.68 seconds). **E,** Esophageal closure (2.39 seconds). **F,** Glottal reopening (2.61 seconds). Numbers refer to relative timings with reference to the beginning of esophageal opening (i.e., 1.68 seconds). The flow direction to the esophagus can be evaluated. The important structures for swallowing, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, posterior pharyngeal wall, and epiglottis, are all visualized on CMRI. Swallowing was successfully completed in 1 attempt. The ascent and descent of the larynx are highlighted by double lines.

to the trachea could not be judged on CMRI. In cases with good- and moderate-quality images, structures important for swallowing, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, the pharyngeal posterior wall, and epiglottis, could all be seen on the CMRI scan (see Figure 1) and on the video. The mobility of the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall could be accurately evaluated in cases with good- and moderate-quality images. However, in cases with low-quality images, the majority of structures were not clearly visible, and the images were blurry as a result of motion artifacts caused by a fast swallowing action (see Figure 2). In particular, in cases with low-quality images, the posterior pharyngeal wall and the epiglottis could not be visualized. According to the established criteria, CMRI evaluations showed intraobserver agreement of 89.3% and interobserver agreement of 85.7%.

Correlations between self-reported dysphagia scores as the status of dysphagia and CMRI-related parameters in patients with oral cancer

The self-reported dysphagia scores of the status of dysphagia were obtained for all 111 patients. Table II shows the correlations between the self-reported dysphagia scores and CMRI-related parameters (ANOVA). We found significant correlations between the self-reported dysphagia scores and OTT (r = 0.774; $P < .01$); OOT (r = 0.317; $P < .01$); PR1 (r = 0.298; $P < .01$); LAT (r = 0.328; $P < .01$); vallecular and piriform sinus filling (r = 0.244; $P < .05$); and the tissue immobility score (r = 0.506; $P < .01$) (Spearman's rank correlation coefficient).

Correlations between the T classification and CMRI-related parameters in preoperative patients with oral cancer

Table III shows the relationships between the T classification and the CMRI-related parameters of the 34 preoperative patients. The tissue immobility score was significantly different among the T classifications, with an increase in the tissue immobility score showing a significant correlation with the T classification grade (Spearman's rank correlation coefficient: r = 0.413; $P < .05$). In addition, with a larger tumor size, the mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and the pharyngeal posterior wall, tended not to change smoothly, unlike in the normal condition (Figure 3 and Video 2).

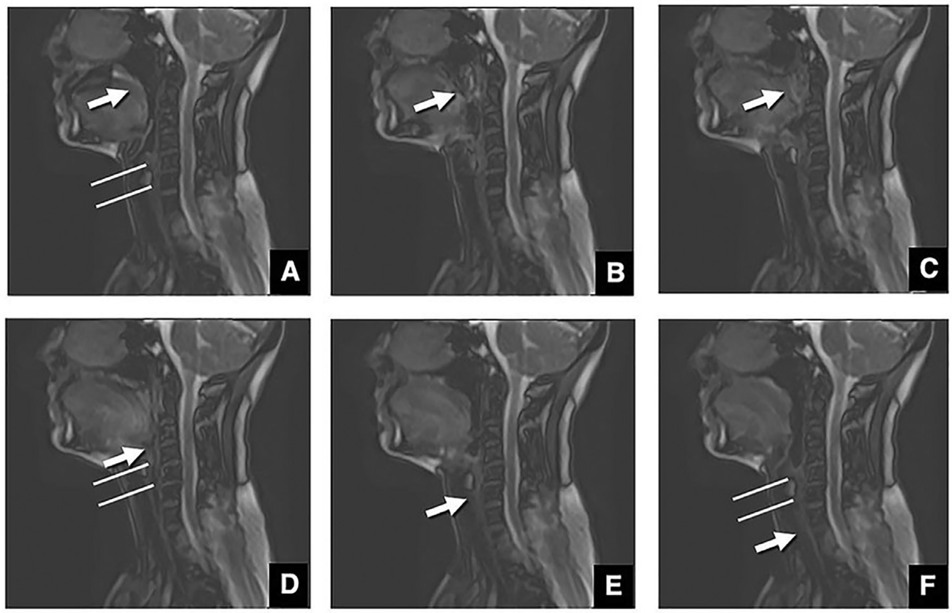

Fig. 2. A low-quality swallowing series in the midsagittal plane on cine-magnetic resonance imaging (CMRI) performed after surgery in a 51-year-old woman with right tongue cancer. **A,** Oropharyngeal closure (1.61 seconds). **B,** Velopharyngeal closure (passavant ridge 1) (2.43 seconds). **C,** Glottal closure (2.57 seconds). **D,** Esophageal opening (passavant ridge 2) (2.71 seconds). **E,** Esophageal closure (3.21 seconds). **F,** Glottal reopening (3.50 seconds). The flow direction to the esophagus can be evaluated. The majority of structures in this case with low-quality images are not clearly visible because the images are not sharp; the images are blurry because of motion artifacts caused by fast swallowing. The ascent and descent of the larynx are highlighted by double lines.

Table II. Correlations between the self-reported dysphagia scores and CMRI-related parameters Table II

CMRI-related parameters	*Self-reported dysphagia scores*		
	Normal (N = 71)	*Slightly abnormal (N = 30)*	*Abnormal (N = 10)*
OTT (sec)	1.85 ± 1.06	2.33 ± 1.77	2.64 ± 1.12
PTT (sec)	0.97 ± 0.33	1.26 ± 0.95	1.20 ± 0.65
OOT (sec)	1.07 ± 0.46	1.61 ± 1.52*	1.46 ± 0.57*
PR1 (sec)	1.16 ± 0.42	1.58 ± 1.45	1.35 ± 0.56
GCT (sec)	1.10 ± 0.52	1.48 ± 0.88*	1.33 ± 0.75
PR2 (sec)	0.90 ± 0.34	0.85 ± 0.24	0.89 ± 0.18
EOT (sec)	1.23 ± 0.49	1.16 ± 0.71	1.36 ± 0.55
LAT (sec)	0.94 ± 0.46	1.38 ± 1.21*	1.55 ± 0.98‡
LDT (sec)	1.56 ± 1.14	1.91 ± 1.64	2.65 ± 1.62
Vallecular and piriform sinus filling (sec)	0.82 ± 0.33	1.12 ± 0.50‡	0.86 ± 0.31
Epiglottic retroflexion (sec)	0.90 ± 0.40	1.52 ± 1.15‡	0.77 ± 0.26
Tissue immobility score	10.00 ± 1.43	11.53 ± 2.34‡	15.00 ± 2.54‡,§

CMRI, cine-magnetic resonance imaging; *EOT,* esophageal opening time; *GCT,* glottal closure time; *LAT,* laryngeal ascent time; *LDT,* laryngeal descent time; *OOT,* orovelar opening time; *OTT,* oral transit time; *PR1,* first passavant ridge; *PR2,* second passavant ridge; *PTT,* pharyngeal transit time; *sec,* seconds.
Among the CMRI-related time events:
*Significant difference versus normal: $P < .05$ (analysis of variance [ANOVA]).
‡Significant difference versus normal: $P < .01$.
§Significant difference versus slightly abnormal: $P < .01$.

Alterations in CMRI-related parameters between pre- and postoperative patients with oral cancer

Table IV shows the alterations in the CMRI-related parameters of the 34 preoperative and the 77 postoperative patients with oral cancer. There were significant differences in LAT and the tissue immobility score between pre- and postoperative patients (Student t test). After surgery, there was a tendency for the mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and

Table III. Correlation between T classification and CMRI-related parameters in preoperative patients

CMRI-related parameters	*T classification*			
	T1 (N = 14)	*T2 (N = 12)*	*T3 (N = 2)*	*T4 (N = 6)*
OTT (sec)	2.00 ± 1.19	1.48 ± 0.95	1.77 ± 0.53	2.29 ± 2.21
PTT (sec)	0.96 ± 0.39	0.96 ± 0.33	1.15 ± 0.07	0.94 ± 0.22
OOT (sec)	1.14 ± 0.55	1.16 ± 0.50	1.02 ± 0.03	1.85 ± 2.25
PR1 (sec)	1.15 ± 0.47	1.06 ± 0.65	1.22 ± 0.26	2.06 ± 2.23
GCT (sec)	1.39 ± 1.02	1.32 ± 1.33	1.42 ± 0.54	1.66 ± 1.06
PR2 (sec)	0.88 ± 0.39	0.84 ± 0.40	0.86 ± 0.09	0.95 ± 0.29
EOT (sec)	1.05 ± 0.47	1.70 ± 0.82	2.55 ± 0.49	1.20 ± 0.61
LAT (sec)	0.84 ± 0.48	1.24 ± 0.62	1.11 ± 0.41	0.79 ± 0.27
LDT (sec)	2.15 ± 2.22	1.48 ± 0.95	1.66 ± 0.08	2.73 ± 3.42
Vallecular and piriform sinus filling (sec)	0.83 ± 0.42	0.73 ± 0.21	1.11 ± 0.41	1.06 ± 0.26
Epiglottic retroflexion (sec)	1.03 ± 0.79	0.89 ± 0.45	1.63 ± 1.09	1.33 ± 0.79
Tissue immobility score	9.21 ± 0.43	9.25 ± 0.62	9.50 ± 0.71	10.83 ± 2.14*,†

CMRI, cine-magnetic resonance imaging; *EOT,* esophageal opening time; *GCT,* glottal closure time; *LAT,* laryngeal ascent time; *LDT,* laryngeal descent time; *OOT,* orovelar opening time; *OTT,* oral transit time; *PR1,* first passavant ridge; *PR2,* second passavant ridge; *PTT,* pharyngeal transit time; *sec,* seconds.
Among the CMRI-related time events:
*Significant difference versus T1: $P < .05$ (analysis of variance [ANOVA]).
†Significant difference versus T2: $P < .05$ (ANOVA).

pharyngeal posterior wall, not to change smoothly, unlike in the normal condition.

Of the 34 preoperative patients, 23 (67.6%) completed swallowing in 1 attempt (see Figure 1 and Video 1); 10 patients (29.4%) required 2 attempts (see Figure 3 and Video 2); and 1 (2.9%) required 3 attempts to complete swallowing. Of the 77 postoperative patients, 43 (55.8%) completed swallowing in 1 attempt; 29 patients (37.7%) required 2 attempts; and 5 (6.5%) required 3 attempts to complete swallowing (see Figure 4 and Video 3). In the 5 cases requiring 3 attempts, we noted a tendency for a bright homogeneous mass in the

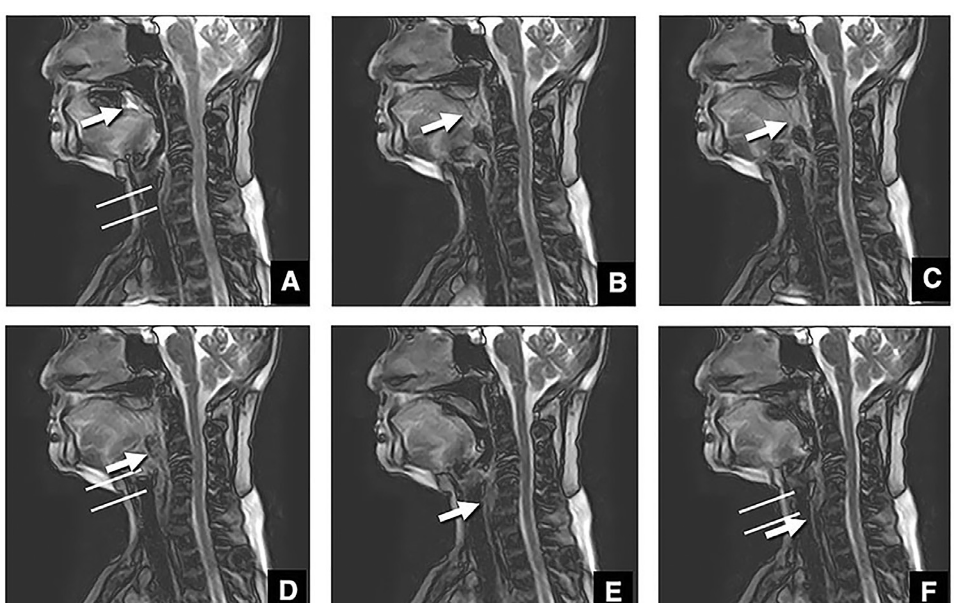

Fig. 3. A good-quality swallowing series in the midsagittal plane on cine-magnetic resonance imaging (CMRI) performed before surgery in a 58-year-old woman with right gingival cancer (T4). **A,** Oropharyngeal closure (0.25 seconds). **B,** Velopharyngeal closure (passavant ridge 1) (0.86 seconds). **C,** Glottal closure (1.21 seconds). **D,** Esophageal opening (passavant ridge 2) (1.46 seconds). **E,** Esophageal closure (2.43 seconds). **F,** Glottal reopening (3.04 seconds). The flow direction to the esophagus can be evaluated. The mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall, tended not to change smoothly, unlike in the normal condition. Swallowing was successfully completed with 2 attempts. The ascent and descent of the larynx are highlighted by double lines.

Table IV. Alteration in CMRI-related parameters between pre- and postoperative patients.

CMRI-related parameters	*Preoperative (N = 34)*	*Postoperative (N = 77)*
OTT (sec)	1.86 ± 1.30	2.14 ± 1.31
PTT (sec)	0.97 ± 0.32	1.12 ± 0.68
OOT (sec)	1.28 ± 1.05	1.24 ± 0.85
PR1 (sec)	1.32 ± 1.02	1.28 ± 0.77
GCT (sec)	1.39 ± 0.86	1.15 ± 0.56
PR2 (sec)	0.84 ± 0.31	0.91 ± 0.30
EOT (sec)	1.09 ± 0.60	1.28 ± 0.53
LAT (sec)	0.93 ± 0.51	1.20 ± 0.90*
LDT (sec)	2.07 ± 2.02	1.62 ± 0.92
Vallecular and piriform sinus filling (sec)	0.91 ± 0.40	0.90 ± 0.40
Epiglottic retroflexion (sec)	1.22 ± 1.00	0.98 ± 0.58
Tissue immobility score	9.53 ± 1.13	11.45 ± 2.48†

CMRI, cine-magnetic resonance imaging; *EOT,* esophageal opening time; *GCT,* glottal closure time; *LAT,* laryngeal ascent time; *LDT,* laryngeal descent time; *OOT,* orovelar opening time; *OTT,* oral transit time; *PR1,* first passavant ridge; *PR2,* second passavant ridge; *PTT,* pharyngeal transit time; *sec,* seconds.
Among the CMRI-related time events:
Significant difference versus before surgery:
*Statistical analysis conducted by using the Student t test $P < .05$.
†Significant difference versus preoperative $P < .01$.

oral region to become unclear, with bright homogeneous areas seen in the entire cavity (see Figures 3 and 4 and Videos 2 and 3).

Correlations between the degree of invasiveness of surgery for oral cancers and CMRI-related parameters in postoperative patients

Table V shows the relationships between the degree of invasiveness of surgery for oral cancers and the CMRI-related parameters for the 77 postoperative patients. Three parameters—OTT, LAT, and the tissue immobility score—showed significant relationships with invasiveness of surgery for oral cancers (ANOVA). Spearman's correlation coefficient was used to evaluate the correlations between the degree of invasiveness of surgery for oral cancers and the changes in the respective parameters (OTT: r = 0.239; $P < .05$; LAT: r = 0.393; $P < .01$; and the tissue immobility score: r = 0.548; $P < .01$). As the surgeries became more invasive, the parameters lengthened and worsened. Furthermore, with a more invasive surgical procedure, there was a tendency for the mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall, not to change smoothly, unlike in the normal condition (see Figure 4 and Video 3).

DISCUSSION

Our previous study showed that swallowing dynamics can be directly visualized by using a new CMRI technique, developed by us, in patients with tongue cancer before and after surgery, for an objective evaluation of patients' swallowing complaints.[6] The present study involved patients with various oral cancers, not just tongue cancer, and the sample size was increased to demonstrate that the CMRI technique can be generalized to a wide range of patients with oral cancer.

The swallowing function, including the flow direction of saline solution to the esophagus and/or the trachea, could be visualized in the present study in all 111 patients with oral cancer before and after surgery. One of the most interesting results of the present study was the tracking of flow direction. In addition, with the CMRI data, the various swallowing-related parameters were easily and precisely acquired. As was expected, we identified significant relationships between increases in the 6 parameters (OTT, OOT, PR1, LAT, vallecular and piriform sinus filling, and the tissue immobility score) and the deterioration of swallowing status, evidenced by decreases in self-reported dysphagia scores as the status of dysphagia, advances in the T classification, and the degree of surgical invasiveness for oral cancers. CMRI is a very useful tool for evaluating the swallowing function of patients with oral cancer because of its superior temporal resolution and visualization of the solution swallowed by the patient.

Moreover, unlike VF, the newly developed CMRI technique does not use ionizing radiation and a contrast medium; therefore, fewer potential side effects are expected with CMRI. Furthermore, swallowing can be examined in arbitrary image orientations without changing the patient's position during standard MRI examinations. The performance of CMRI adds only 2 minutes to scanning time.

Using CMRI data, one can easily measure the various parameters and evaluate both the precise objective parameters of the respective periods of swallowing and the changes in mobility of swallowing-related tissues.[6] In fact, unlike in VF, an MRI system was used for CMRI; therefore, the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall could be easily and precisely visualized because the high-contrast MR imaging facilitates differentiation of tissues. Furthermore, the tissue immobility scores facilitate objective evaluations of the movements of the tissues on CMRI.[11] We found significant correlations between the immobility of tissues on CMRI and the data on dysphagia deterioration based on self-reported dysphagia scores as the status of dysphagia, advances in the T classification, and the surgical invasiveness for oral cancers, as in our recent report.[6] OTT, OOT, and PR1, but not tissue immobility scores, were also significantly correlated with self-

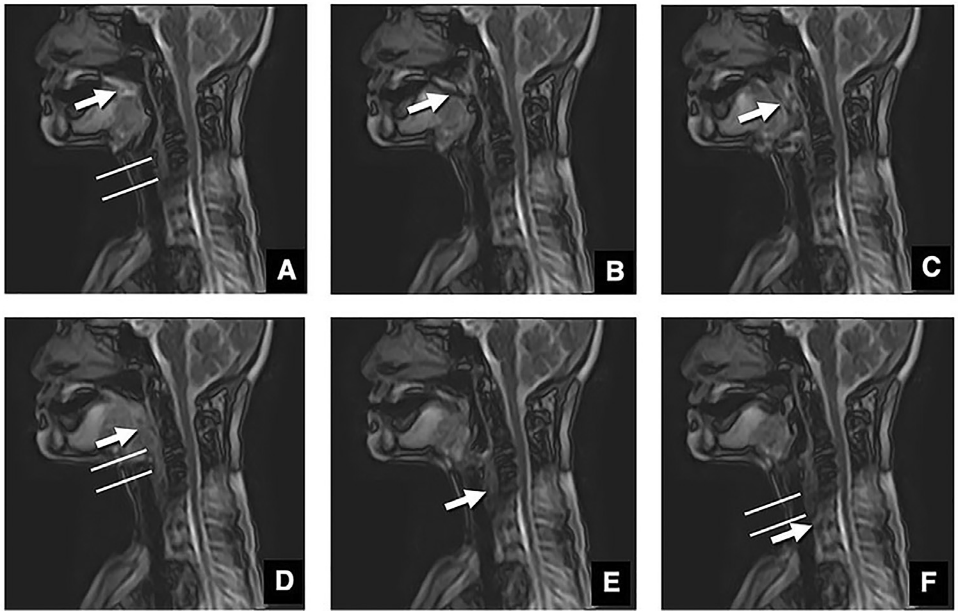

Fig. 4. A good-quality swallowing series in the midsagittal plane on cine-magnetic resonance imaging (CMRI) performed after surgery involving subtotal glossectomy, along with tissue flap reconstruction, in a 59-year-old woman with left tongue cancer. **A,** Oropharyngeal closure (0.79 seconds). **B,** Velopharyngeal closure (passavant ridge 1) (0.96 seconds). **C,** Glottal closure (1.11 seconds). **D,** Esophageal opening (passavant ridge 2) (1.43 seconds). **E,** Esophageal closure (1.71 seconds). **F,** Glottal reopening (1.89 seconds). The flow direction to the esophagus can be evaluated. Swallowing was successfully completed with 3 attempts. The mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall, tended to not change smoothly, unlike in the normal condition. The ascent and descent of the larynx are highlighted by double lines.

Table V. Correlation between the degree of invasiveness of surgery for oral cancers and CMRI-related parameters in postoperative patients

CMRI-related parameters	*Degree of surgical invasiveness*			
	Type I (N = 37)	*Type II (N = 20)*	*Type III (N = 6)*	*Type IV (N = 14)*
OTT (sec)	1.85 ± 0.89	1.80 ± 0.76	1.95 ± 1.45	3.46 ± 1.98[‡, §]
PTT (sec)	1.05 ± 0.30	1.13 ± 0.66	1.01 ± 0.43	1.34 ± 1.30
OOT (sec)	1.06 ± 0.42	1.30 ± 0.74	1.12 ± 0.49	1.66 ± 1.61
PR1 (sec)	1.14 ± 0.39	1.24 ± 0.43	1.39 ± 0.17*	1.68 ± 1.60
GCT (sec)	1.09 ± 0.29	1.35 ± 0.86	1.09 ± 0.58	1.03 ± 0.57
PR2 (sec)	0.91 ± 0.30	0.90 ± 0.39	0.86 ± 0.10	0.91 ± 0.21
EOT (sec)	1.26 ± 0.35	1.40 ± 0.77	1.34 ± 0.48	1.17 ± 0.56
LAT (sec)	0.90 ± 0.29	1.20 ± 0.71	1.13 ± 0.34	2.02 ± 1.65*
LDT (sec)	1.46 ± 0.69	1.52 ± 0.81	2.60 ± 1.87	1.74 ± 0.87
Vallecular and piriform sinus filling (sec)	0.83 ± 0.27	1.06 ± 0.65	0.87 ± 0.31	0.88 ± 0.22
Epiglottic retroflexion (sec)	0.93 ± 0.23	1.29 ± 1.02	0.75 ± 0.14 *[,†]	0.78 ± 0.24[§]
Tissue immobility score	10.16 ± 1.30*	11.45 ± 1.88 *	13.17 ± 2.40 *[,§]	14.14 ± 3.18[‡,§]

CMRI, cine-magnetic resonance imaging; *EOT,* esophageal opening time; *GCT,* glottal closure time; *LAT,* laryngeal ascent time; *LDT,* laryngeal descent time; *OOT,* orovelar opening time; *OTT,* oral transit time; *PR1,* first passavant ridge; *PR2,* second passavant ridge; *PTT,* pharyngeal transit time; *sec,* seconds.

Among the CMRI-related time events:

*Significant difference versus type I: $P < .05$ (analysis of variance [ANOVA]).

†Significant difference versus type II: $P < .05$.

‡Significant difference versus type I: $P < .01$.

§Significant difference versus type II: $P < .01$.

reported dysphagia scores on dysphagia deterioration, advances in the T classification, and the invasiveness of surgical procedures for oral cancers, as in our recent report.[6] Therefore, the increases in these 4 parameters could be used as useful landmarks for diagnosis in patients with dysphagia.[7] We are planning to produce standard criteria based on the 12 swallowing-related parameters from CMRI data as CMRI-related parameters in future studies.

In the present investigation, the 12 CMRI-related parameters were based on previous reports by Zhang et al., Kreeft et al., Nishimura et al., Tanaka et al., and Logemann's "6-valve model."[6,7,12-16] These parameters were very similar to the data from our recent report and the data from VF,[6,7,12-16] and we expected that these parameters and tissue immobility scores would provide precise evaluations of patients' swallowing functions. At the same time, evaluation of changes in the mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal posterior wall, is possible.

The results for tissue mobility were relatively similar to those of Kreeft et al., in contrast to the previous results for patients with tongue cancer.[6,12] The explanation for this may be that the sample size was relatively larger in the present study to the extent that the present data may approach actual data. On the basis of the present results, 12 CMRI-related preoperative parameters can be used to predict postoperative swallowing function in patients with many types of diseases of the oral cavity. The next stage of evaluation of CMRI will be to use it to evaluate improvement in swallowing as a result of swallowing exercises.

The present study has some limitations. First, we could not compare the newly developed CMRI with VF and videoendoscopy as the gold standard.[3,4] However, VF and videoendoscopy are relatively invasive modalities that should be avoided, if possible, for the benefit of the patient. Furthermore, we could not compare the newly developed CMRI with cine-MRI on a 3-Tesla MRI system.[12,17] At the same time, we could not compare the vertical and horizontal assessments of CMRI. The swallowing function could not be visualized by using CMRI with low field strength (about 0.2−0.5 Tesla). In addition, because of the large sample size in the present study, we could not include follow-up examinations of the same patients and, therefore, could not compare the pre- and postoperative data of the same patients. Finally, the newly developed CMRI has an acquisition time of 10 seconds, although swallowing is a very rapid process that lasts from about 1.5 to 5 seconds.[3,4,6,7,18,19] In fact, we were able to completely visualize a swallowing series in patients with oral cancers by using the present technique, but the acquisition should be appropriately performed for a swallowing series.

CONCLUSIONS

The present study suggests that CMRI can be used to directly visualize swallowing dynamics, as well as objectively evaluate the swallowing complaints of oral cancer patients.

SUPPLEMENTARY MATERIALS

Supplementary material associated with this article can be found in the online version at doi:10.1016/j.oooo.2020.05.009.

REFERENCES

1. Patterson J, Wilson JA. The clinical value of dysphagia preassessment in the management of head and neck cancer patients. *Curr Opin Otolaryngol Head Neck Surg*. 2011;19:177-181.
2. Patterson JM, McColl E, Carding PN, Kelly C, Wilson JA. Swallowing performance in patients with head and neck cancer: a simple clinical test. *Oral Oncol*. 2009;45:904-907.
3. Martin-Harris B, Jones B. The videofluorographic swallowing study. *Phys Med Rehabil Clin N Am*. 2008;19:769-785.
4. Soares TJ, Moraes DP, de Medeiros GC, Sassi FC, Zilberstein B, de Andrade CR. Oral transit time: a critical review of the literature. *Arq Bras Cir Digest*. 2015;28:144-147.
5. Kendall K, McKenzie SW, Leonard R, Goncalves M, Walker A. Timing of events in normal swallowing: a videofluoroscopic study. *Dysphagia*. 2000;15:74-83.
6. Nishimura S, Tanaka T, Oda M, et al. Functional evaluation of swallowing in patients with tongue cancers before and after surgery using high-speed continuous MR images based on T2-weighted sequences. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 2018;125:88-98.
7. Tanaka T, Oda M, Nishimura S, et al. The use of high-speed, continuous, T2-weighted magnetic resonance sequences and saline for the evaluation of swallowing. *Oral Surg Oral Med Oral Pathol Oral Radiol*. 2014;118:490-496.
8. Shah JP, Gil Z. Current concepts in management of oral cancer-surgery. *Oral Oncol*. 2009;45:394-401.
9. Shah JP, Patel SG, Singh B. *Jatin Shah's Head and Neck Surgery and Oncology*. 4th ed. Edinburgh, London, New York: Mosby; 2012.
10. Schar M, Kozerke S, Fischer SE, Boesiger P. Cardiac SSFP imaging at 3 Tesla. *Magn Reson Med*. 2004;51:799-806.
11. Li W, Li BS, Polzin JA, Mai VM, Prasad PV, Edelman RR. Myocardial delayed enhancement imaging using inversion recovery single-shot steady-state free precession: initial experience. *J Magn Reson Imaging*. 2004;20:327-330.
12. Zhang S, Olthoff A, Frahm J. Real-time magnetic resonance imaging of normal swallowing. *J Magn Reson Imaging*. 2012;35:1372-1379.
13. Kreeft AM, Rasch CR, Muller SH, Pameijer FA, Hallo E, Balm AJ. Cine MRI of swallowing in patients with advanced oral or oropharyngeal carcinoma: a feasibility study. *Eur Arch Otorhinolaryngol*. 2012;269:1703-1711.
14. Logemann JA. *Evaluation and Treatment of Swallowing Disorders*. 2nd ed. Austin, TX: PRO-ED; 1998:1-406.
15. Daniels SK, Schroeder MF, McClain M, Corey DM, Rosenbek JC, Foundas AL. Dysphagia in stroke: development of a standard method to examine swallowing recovery. *J Rehabil Res Dev*. 2006;43:347-356.
16. Logemann JA, Rademaker AW, Pauloski BR, Ohmae Y, Kahrilas PJ. Normal swallowing physiology as viewed by

videofluoroscopy and videoendoscopy. *Folia Phoniatr Logop*. 1998;50:311-319.
17. Uecker M, Zhang S, Voit D, Karaus A, Merboldt KD, Frahm J. Real-time MRI at a resolution of 20 ms. *NMR Biomed*. 2010;23:986-994.
18. Matsuo K, Palmer JB. Anatomy and physiology of feeding and swallowing: Normal and abnormal. *Phys Med Rehabil Clin N Am*. 2008;19:691-707.
19. Taniguchi H, Tsukada T, Ootaki S, Yamada Y, Inoue M. Correspondence between food consistency and suprahyoid muscle activity, tongue pressure, and bolus transit times during the oropharyngeal phase of swallowing. *J Appl Physiol*. 2008;105:791-799.

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