Functional evaluation of swallowing in patients with tongue cancer before and after surgery using high-speed continuous magnetic resonance imaging based on T2-weighted sequences

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Objectives. The aim of this study was to determine the usefulness of evaluating the function of swallowing before and after surgery in patients with tongue cancer by using T2-weighted sequences of high-speed continuous magnetic resonance imaging (HSCMRI).
Study Design. The imaging findings and related parameters on HSCMRI along with those on routine MRI examinations before and after surgery were examined in 19 patients with tongue cancer. In addition, changes in various parameters during 1 year after surgery were evaluated in 10 patients.
Results. In most patients examined, the direction of flow to the esophagus could be seen on HSCMRI before and after surgery. Significant correlations were observed among 4 parameters and in the responses to a dysphagia questionnaire.
Conclusions. The results of the present study suggest that the dynamics of swallowing can be directly visualized on HSCMRI by using 4 parameters that permit the evaluation of changes before and after surgery, and this enables objective evaluation of patients' swallowing complaints. (Oral Surg Oral Med Oral Pathol Oral Radiol 2018;125:88–98)

The oral, pharyngeal, laryngeal, and esophageal regions are mobile structures that move in a complex series of movements during biting, swallowing, and speech. Cancers in these regions may cause severe functional limitations. Furthermore, dysphagia can result in various complications, such as aspiration pneumonia or stridor.[1,2] Each patient requires easy, safe, noninvasive, and precise evaluations of swallowing on routine examinations. Therefore, in a previous study, we developed and showed the usefulness of a technique using T2-weighted sequences of high-speed continuous magnetic resonance imaging (HSCMRI) using a 1.5-T MR system to visualize solutions flowing through the pharyngeal and laryngeal regions after administration of a 5-mL saline solution.[3] However, in the previous study, all participants were healthy volunteers. The clinical applicability of this technique in patients with impairment of swallowing remained unknown.

In the present study, the function of swallowing before and after surgery was compared in patients with oral cancer by using HSCMRI, and this technique's usefulness and importance were evaluated.

PATIENTS AND METHODS

Patients

A total of 19 consecutive patients (11 males, 8 females; mean age 54.1 years; range 34-82 years) with tongue cancer were evaluated before and after surgery at the Kyushu Dental University Hospital between 2012 and 2016. Of the 19 patients, 10 were evaluated at follow-up examinations 1 month, 3 months, 6 months, and 1 year later. The institutional review board of Kyushu Dental University approved the present study (No. 12-30). All patients provided their informed consent before MRI examination.

The 19 patients, all with squamous cell carcinomas, as confirmed by pathology, were divided into 3 groups

Statement of Clinical Relevance

The function of swallowing in patients with tongue cancer can be evaluated accurately by using high-speed continuous magnetic resonance imaging based on T2-weighted sequences.

The Human Investigations Committee of Kyushu Dental University protected individuals' rights. The present study was approved by the institutional review board of Kyushu Dental University (No. 12-30). This study was supported, in part, by grants-in-aid for scientific research from the Ministry of Education, Science, Sports and Culture of Japan, No. 24592838.
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Table I. Distribution of cases by tumor (T) classification and tumor site

	Number of cases		
Tumor site	*T1*	*T2*	*T3/T4*
Lateral edge of tongue	8	3	—
Lateral edge of tongue to sublingual side of tongue	1	1	2
Sublingual side of tongue	—	1	1
Dorsum of tongue	—	1	—
Lateral edge of tongue to center of mouth	—	—	1
Total	9	6	4

Table II. Distribution of cases by surgical procedure and tumor site

	Number of cases			
Tumor site	*MD*	*MDF*	*HMGS*	*STGS*
Lateral edge of tongue	8	3	—	—
Lateral edge of tongue to sublingual side of tongue	—	1	1	2
Sublingual side of tongue	—	—	2	—
Dorsum of tongue	—	1	—	—
Lateral edge of tongue to center of mouth	—	—	1	—
Total	8	5	4	2

MD, marginal dissection; *MDF*, MD with tissue flap reconstruction; *HMGS*, hemiglossectomy; *STGS*, subtotal glossectomy.

according to the tumor (T) classification: group T1, 9 patients; group T2, 6 patients; and groups T3 and T4, 4 patients each (Table I).

After surgery, the 19 patients were divided into 4 groups according to the surgical procedure: only marginal dissection (MD, 8 patients); MD with tissue flap reconstruction (MDF, 5 patients); hemiglossectomy (HMGS, 4 patients) with tissue flap reconstruction; and subtotal glossectomy (STGS; 2 patients) with tissue flap reconstruction (Table II).

Imaging parameters of HSCMRI

A 1.5-T full-body MRI system (EXCELART Vantage Powered by Atlas; Toshiba, Tokyo, Japan) was used to acquire the MRI scans. Routine MRI included the following 3 sequences: (1) short T1 inversion recovery (STIR); (2) fast spin echo T1-weighted images; and (3) fast spin echo T1-weighted images with contrast-medium enhancement. Table III shows the details of the parameters. All patients then underwent HSCMRI, using a modification of the technique of Tanaka et al.[3] (Table III). In brief, a bilateral array coil that was centered on the thyroid prominence on both sides of the neck was used, and all patients were examined while in the supine position. No other coils could be used. Radiofrequency-spoiled steady-state free precession field-echo images with radial encoding were acquired continuously with the following parameters: repetition time (TR) = 3.2 ms; echo time (TE) = 1.6 ms; flip angle (FA) = 45°; field of view (FOV) = 250 × 225 mm^2; and slice thickness 8 mm. Individual images were obtained from 10 radial spokes that were distributed equally to sample the MRI data space. With an image acquisition time of 35.71 ms, the true temporal resolution was 28 fps, with image interpolation or data sharing in a sliding-window reconstruction.

To locate the planes of interest for dynamic imaging, sagittal scout images cover a slightly larger FOV (256 × 256 mm^2) at the same spatial resolution. Radiofrequency-spoiled steady-state free precession field-echo images with radial encoding sequence (TR = 3.2 ms; TE = 1.6 ms; FA = 45°) with full radial sampling of the data space and reconstruction by conventional gridding were used to acquire these images.

HSCMRI videos of different swallows were recorded in midsagittal orientation. A 5-mL saline solution was administered as a bolus before HSCMRI as a T2 extension effect because of the evaluation of patients' swallowing for about 30 seconds.

Image evaluation

Two expert radiologists (S.N. and T.T.), affiliated to the Japanese Society for Oral and Maxillofacial Radiology, independently reviewed all images, with no prior knowledge of the patients' identities. The MRI scans were read in a randomized, blinded manner, with evaluation of HSCMRI, according to Zhang et al.[4] and Kreeft et al.[5]

Evaluations of the dynamics of swallowing included assessments of direction (oral control, velopharyngeal closure, penetration, and aspiration), timing (transport), and clearance. Patients were then classified as normal (no distortion) or showing mild, moderate, or severe distortion. For a more precise analysis of the dynamics of swallowing, quantitative timing was evaluated, according to Zhang et al., as mentioned below. The temporal patterns of all sphincter functions, as well as the oral and pharyngeal transit times (OTT and PTT, respectively), were evaluated by using Logemass's "six-valve model,"[6] namely, lips,[7] tongue,[6] velopharyngeal sphincter,[8] larynx,[9] tongue base and pharyngeal wall,[10] and cricopharyngeal sphincter.[11] Valve 1 was closed during the entire swallowing process. The orovelar opening time (OOT) was represented by the opening and closure of valve 2, and the velopharyngeal closure time (VCT), which was indicated by observation of the first passavant ridge (PR1), was represented by the opening and closure of valve 3. The glottal closure time (GCT) was represented by the opening and closure of valve 4, with the duration of epiglottic retroflexion. The second passavant ridge (PR2) was represented by the opening and closure of valve 5, and the esophageal opening time (EOT) was represented by the opening and closure of valve 6. In ad-

Table III. Imaging parameters of each sequence

	Sequences			
	STIR	*T1 WI*	*T1 WI with contrast medium*	*HSCMRI*
TR (ms)	4700	820	840	3.2
TE (ms)	75	15	20	1.6
Flip angle (°)	90	90	90	45
FOV (mm)	250 × 225	250 × 225	250 × 225	250 × 225
Section thickness (mm)	6	6	6	8
intersection gap (mm)	1.2	1.2	1.2	—
Matrix (pixels)	272 × 272	224 × 320	224 × 320	120 × 96

STIR, short T1 inversion recovery; *T1 WI*, T1-weighted image; *HSCMRI*, high-speed continuous magnetic resonance imaging; *TR*, repetition time; *TE*, echo time; *FOV*, field of view.

dition, the laryngeal ascent and descent times (LAT and LDT, respectively), along with the duration of vallecular and piriform sinus filling, which indicates deglutitive clearance, were also measured.

A tissue immobility score was defined to enable objective evaluations of the HSCMRI scans, according to Kreeft et al., based on mobility of specific structures (the anterior tongue, the tongue base, the posterior pharyngeal wall, the palate, and the floor of the mouth). The mobility of these structures was objectively assessed and scored as follows: 1 (normal); 2 (somewhat decreased); and 3 (decreased/immobile). Contacts between the anterior tongue and the palate, the base of the tongue and the posterior pharyngeal wall, the base of the tongue and the soft palate, and the soft palate and the posterior pharyngeal wall were evaluated and scored as either 1 (visible contact/normal) or 2 (no visible contact/abnormal). The scores of these 9 items were added up, with the immobility score varying, in theory, from 9 (normal/mobile) to 23 (completely abnormal/severely immobile). A normal score (1) was assigned to items whose visualization was insufficient to evaluate contact or mobility, and the items that could not be evaluated were counted (ranging from 0 to 9).

Dysphagia questionnaire and statistical analysis

The study patients were asked to describe their swallowing as "normal," "slightly wrong," and "wrong" based on subjective impressions. SPSS software version 11 (SPSS Inc., Chicago, IL) was used for all statistical analyses. Analysis of variance (ANOVA) and Student t test were used, as appropriate, to analyze differences in mean values among groups, with $P < .05$ taken as indicating a significant difference. Correlations on Spearman analysis were classified into 5 grades: very weak, 0.00 to ±0.20; weak, ±0.20 to ±0.40; moderate, ±0.40 to ±0.70; strong, ±0.70 to ±0.90; and very strong, ±0.90 to ±1.00.

RESULTS

Image quality of continuous swallowing on hscmri in patients with tongue cancer before and after surgery

The quality of images taken before and after surgery was considered high in 17 patients (Figure 1), moderate in 1, and low in 1 (Figure 2). The mean score for the detectability of all swallowing dynamics of both raters was 4.6 ± 0.6. In high- and moderate-quality cases, all important structures, such as the anterior tongue, base of the tongue, soft palate, posterior pharyngeal wall, floor of the mouth, and epiglottis, or swallowing were seen on HSCMRI (see Figure 1). They were also visualized as movie files. Mobility of the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal back wall could be accurately evaluated in high- and moderate-quality cases.

However, in the 1 case with low-quality images, the major structures were not clearly visible, and the images were blurred because of motion artifacts caused by fast swallowing (see Figure 2). In particular, visualization of the epiglottis and the posterior pharyngeal wall was not possible in the low-quality case. Using the criteria, HSCMRI evaluations showed intraobserver agreement of 89.1% and interobserver agreement of 81.8%. There were no significant differences in intra- or interobserver agreement between the images before and after surgery.

Relationships between questionnaire responses and HSCMRI parameters

The results of the dysphagia questionnaires administered before and after surgery were available for all 19 patients. The correlations between the dysphagia scores and the HSCMRI parameters are shown in Table IV. Significant differences in the values of 4 parameters (OTT, OOT, PR1, and tissue immobility score) were seen among the 3 grades. The values of all parameters were significantly greater with worse dysphagia. A significant correlation was found between the questionnaire responses and the 4 parameters, OTT ($r = 0.349$; $P < .05$), OOT ($r = 0.329$; $P < .05$), PR1 ($r = 0.329$; $P < .05$), and tissue immobility score ($r = 0.687$; $P < .01$).

Relationships between T classifications and HSCMRI parameters of continuous swallowing in patients with tongue cancer before surgery

In all 19 patients, the direction of flow to the esophagus could be determined on HSCMRI (see Figure 1;

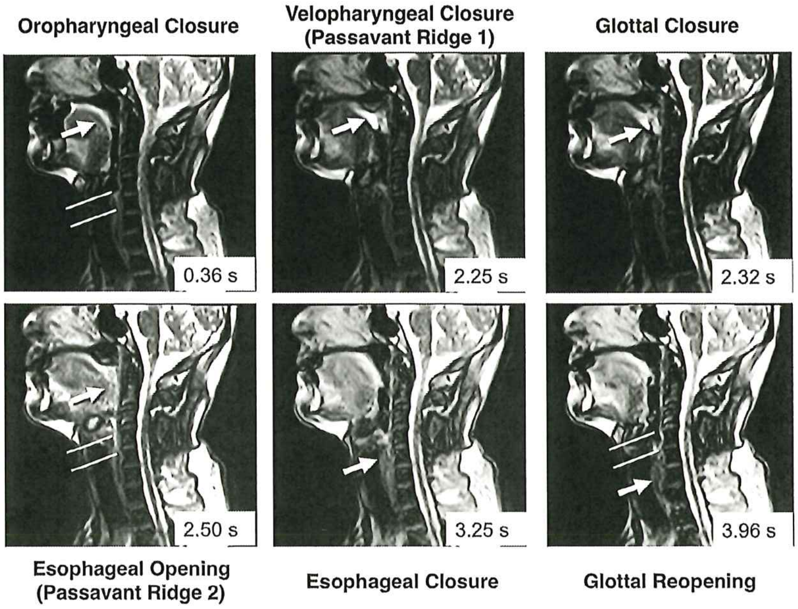

Fig. 1. A good-quality swallowing series in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) before surgery in a 56-year-old man with cancer of the left tongue. The images (repetition time/echo time [TR/TE] = 3.2/1.6 ms; flip angle = 45°; field of view [FOV] = 120 × 96 mm^2) with acquisition time of 35.71 ms represent distinct swallowing events. The numbers refer to relative timings with reference to the beginning of esophageal opening (i.e., 2.54 seconds). The ascent and descent of the larynx are highlighted by double lines.

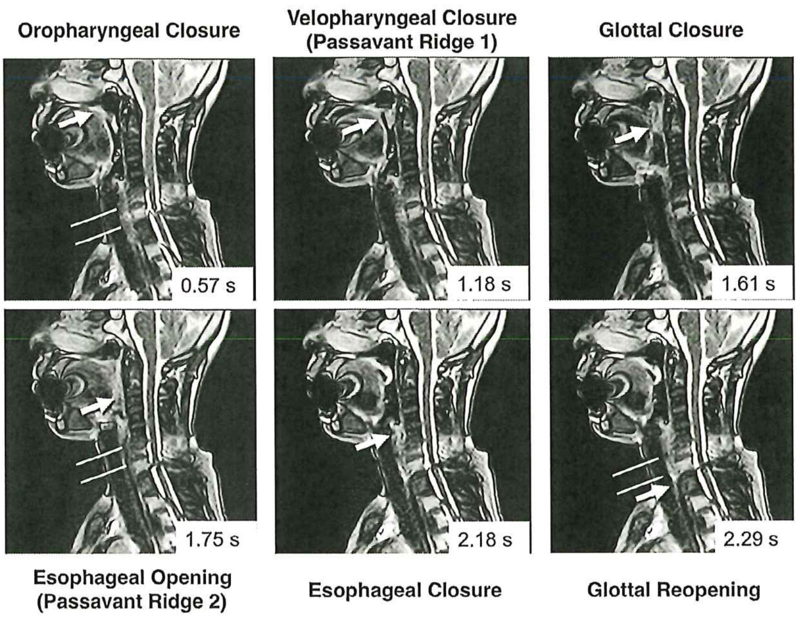

Fig. 2. A low-quality swallowing series in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) after surgery in an 82-year-old man with cancer of the left tongue. A bright homogeneous clump in the oral regions is very unclear, and bright homogeneous areas in the whole cavity are not visualized.

Movie 1). Representative high-quality images (see Figure 1) first show the solution flowing after administration of 5 mL of saline solution into the subject's mouth; the solution could be seen as a bright homogeneous clump in the oral regions, with optimal visualization of different anatomic structures. The solution could be visualized in the pharynx as a bright homogeneous line (see Figure 1). Finally, the solution could be seen entering

Table IV. Correlations between the dysphagia scores by grade and parameter

	Questionnaires		
	"Normal" (N = 23)	*"Little wrong" (N = 11)*	*"Wrong" (N = 4)*
Parameters, seconds			
OTT	1.22 ± 0.41	1.52 ± 0.27	2.19 ± 0.78*
PTT	1.03 ± 0.32	1.05 ± 0.27	1.05 ± 0.22
OOT	1.17 ± 0.43	1.21 ± 0.45	2.41 ± 0.41‖,¶
PR1	1.41 ± 0.51	1.48 ± 0.49	2.97 ± 1.61†,‖
LAT	0.89 ± 0.36	0.96 ± 0.41	1.16 ± 0.54
GCT	1.00 ± 0.29	1.19 ± 0.79	0.73 ± 0.10†
Epiglottic retroflexion	0.84 ± 0.27	1.01 ± 0.66	0.61 ± 0.18
Vallecular and piriform sinus filling	0.87 ± 0.41	0.91 ± 0.25	1.03 ± 0.22
PR2	0.99 ± 0.33	1.02 ± 0.27	1.19 ± 0.39
EOT	1.24 ± 0.63	1.08 ± 0.35	1.08 ± 0.30
LDT	1.28 ± 0.40	1.12 ± 0.41	1.22 ± 0.42
Tissue immobility score	9.61 ± 1.27	12.55 ± 2.77‖	15.75 ± 1.26‖,†

Among the time events: Significant difference of $P < .05$ versus *"Normal," †"Little Wrong,"; $P < .01$ versus ‖"Normal," ¶"Little Wrong."
OTT, oral transit times; *PTT*, pharyngeal transit times; *OOT*, orovelar opening time; *PR1*, first passavant ridge; *LAT*, laryngeal ascent time; *GCT*, glottal closure time; *PR2*, second passavant ridge; *EOT*, esophageal opening time; *LDT*, laryngeal descent time.

Table V. Changes in the number of patients with multiple swallows between before and after surgery

	Number of cases		
	Once	*Twice*	*Three times*
Before surgery	15	3	1
After surgery	11	6	2

the gate of the esophagus, but not the larynx and the entrance of the trachea (see Figure 1). All 19 patients swallowed the liquid completely (see Figure 1; Movie 1). Fifteen patients successfully completed the ingestion and swallowing of liquid before surgery at 1 attempt (Table V), whereas 3 patients required 2 attempts (Figure 3; Movie 2), and one required 3 attempts (see Table V). In these last 4 cases, the bright homogeneous clump tended to become unclear in the oral regions, and bright homogeneous areas were seen in the whole cavity (see Figure 3).

The 12 parameters of the 3 groups (T1, T2, or T3/T4) of the 19 patients before surgery are shown in Table VI. The data from T1 and T2 groups were basically similar to the data from the volunteers in our previous study. A significant difference in the tissue immobility score was observed among the T1, T2, and T3/T4 groups (see Table VI). The tissue immobility scores were significantly greater with worse T classifications, with a significant correlation between the T classification and the tissue immobility score (r = 0.768; $P < .01$). With 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 pharyngeal back wall, tended not to be smooth, unlike normal tissues, on HSCMRI (Figure 4).

Changes in visualization and parameters of continuous swallowing on HSCMRI in patients with tongue cancer from before to after surgery

The direction of flow to the esophagus could also be evaluated on HSCMRI after surgery in all 19 patients, but the direction of flow to the trachea could not be evaluated on HSCMRI. Ingestion and swallowing after surgery in 11 patients were also successfully completed in 1 attempt. However, 6 patients required 2 attempts, and 2 patients required 3 attempts (Figure 5; Movie 3) (see Table V). The number of patients requiring multiple swallows increased significantly from before to after surgery. The 12 parameters of swallowing after surgery for the 19 patients are shown in Table VII. There were significant differences in 9 parameters (OTT, PTT, OOT, PR1, LAT, vallecular and piriform sinus, PR2, EOT, and tissue immobility score) between before and after surgery for tongue cancer (see Table VII). The postoperative values of the 9 parameters were significantly larger and had deteriorated more compared with the values before surgery.

Relationships among the parameters of continuous swallowing and among the surgical procedures

The relationships between the 12 parameters after surgery and among the surgical procedures in the 19 patients are shown in Table VIII. Significant differences among the surgical procedures were seen in 4 parameters (OTT, OOT, PR1, and tissue immobility score) (see Table VIII). The values of the 4 parameters were significantly greater in relation to the degree of invasiveness of the surgical procedures. The correlations between the degree of invasiveness of the surgical procedures for tongue cancer and the changes in the respective parameters were evaluated using Spearman's correlation coefficient (OTT: r = 0.509, $P < .05$; OOT: r = 0.492, $P < .05$; PR1: r = 0.508, $P < .05$; and tissue immobility score: r = 0.641,

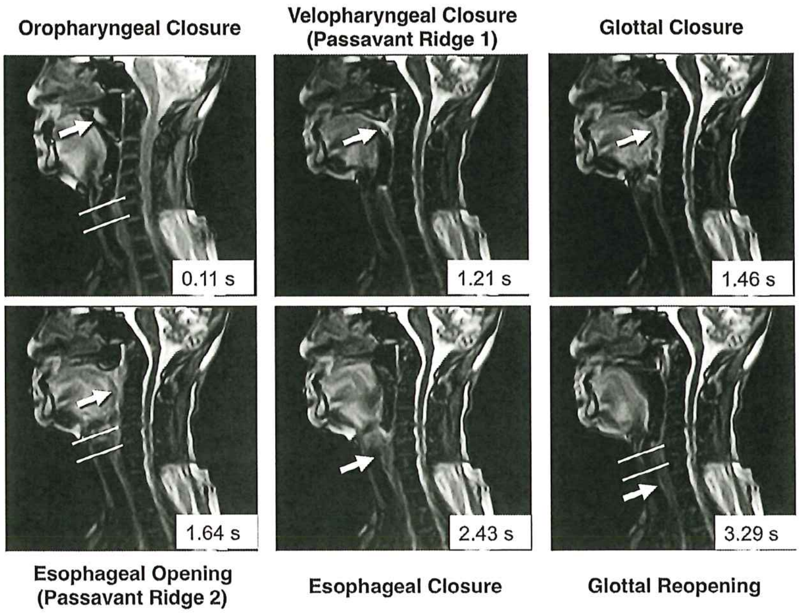

Fig. 3. A good-quality swallowing series in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) before subtotal glossectomy (STGS) with tissue flap reconstruction in a 70-year-old man with cancer of the left tongue. The swallowing is successful after 2 attempts.

Table VI. Parameters and tissue immobility scores of swallowing before surgery

	Groups		
	T1 (N = 9)	*T2 (N = 6)*	*T3/T4 (N = 4)*
Parameters, seconds			
OTT	1.17 ± 0.44	1.02 ± 0.19	1.12 ± 0.11
PTT	0.94 ± 0.12	0.88 ± 0.14	0.79 ± 0.88
OOT	1.12 ± 0.44	1.09 ± 0.25	1.27 ± 0.12
PR1	1.35 ± 0.55	1.20 ± 0.33	1.39 ± 0.42
LAT	0.81 ± 0.33	0.70 ± 0.24	0.73 ± 0.18
GCT	0.91 ± 0.26	0.90 ± 0.22	0.73 ± 0.18
Epiglottic retroflexion	0.73 ± 0.17	0.83 ± 0.19	1.21 ± 1.07*
Vallecular and piriform sinus filling	0.72 ± 0.22	0.74 ± 0.14	0.78 ± 0.17
PR2	0.93 ± 0.25	0.78 ± 0.10	0.99 ± 0.42
EOT	0.93 ± 0.25	1.20 ± 0.84	0.81 ± 0.18
LDT	1.29 ± 0.50	1.51 ± 0.20	1.09 ± 0.23
Tissue immobility score	9	9.50 ± 0.84	10.50 ± 0.58‡,§

Among the time events: Significant difference of $P < .05$ versus *T1; $P < .01$ versus ‡T1, §T2.
OTT, oral transit times; *PTT*, pharyngeal transit times; *OOT*, orovelar opening time; *PR1*, first passavant ridge; *LAT*, laryngeal ascent time; *GCT*, glottal closure time; *PR2*, second passavant ridge; *EOT*, esophageal opening time; *LDT*, laryngeal descent time.

$P < .01$). The more invasive and the longer the surgeries were, the worse were the 4 parameters mentioned above. In fact, when the surgical procedure was more invasive, the mobility of the swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal back wall, tended to not be smooth, unlike normal tissues (see Figure 5).

Improvements in parameters, including tissue immobility scores on continuous swallowing according to time after surgery

The changes in the 12 parameters in 10 patients according to the time after surgery are shown in Table IX. Significant differences were seen in 4 parameters (OTT, OOT, PR1, and tissue immobility score) according to the time after surgery (Figure 6; see Table IX). The values of 4 parameters were significantly shorter with time after surgery. The correlations between the time after tongue cancer surgery and improvements of the respective parameters were evaluated by using Spearman's correlation coefficient (OTT: $r = -0.374$, $P < .05$; OOT: $r = -0.396$; $P < .05$; and PR1: $r = -0.467$, $P < .01$; tissue immobility score: $r = -0.312$, $P < .05$). The longer the time after surgery, the shorter and better were the 4 parameters mentioned above.

DISCUSSION

Oropharyngeal dysphagia is one of the dysfunctions that occur in patients with tongue cancer. Furthermore, even after appropriate surgery for tongue cancer, the dysphagia persists. This is particularly true in the advanced stages of cancer. Easy and precise evaluation of dysphagia is therefore very important and significant for patients. Therefore, our previously developed HSCMRI technique was used to evaluate the swallowing function in patients with tongue cancer.

The present study demonstrated that HSCMRI, which could visualize swallowing, was very useful for evaluating the swallowing function in patients with tongue

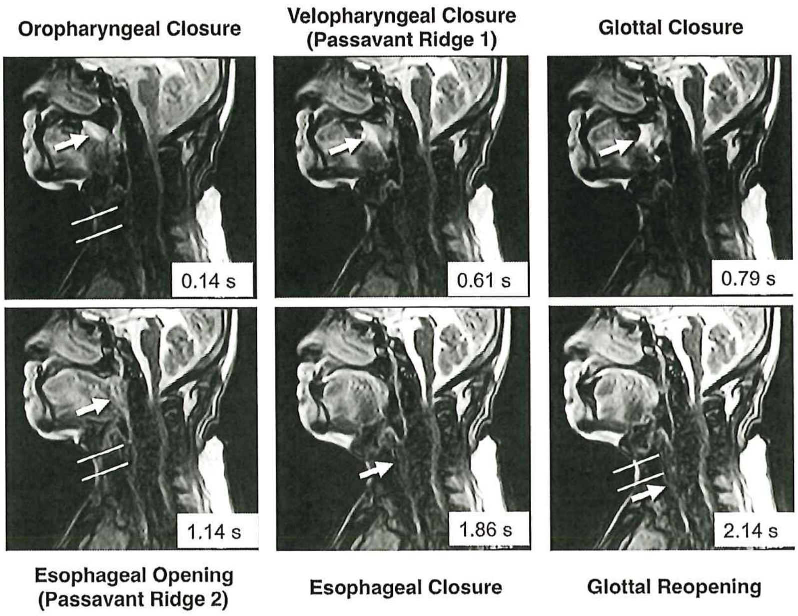

Fig. 4. A good-quality swallowing series in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) before surgery in a 70-year-old man with cancer of the left tongue (T4). The mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal back wall, is not smooth, unlike normal tissues.

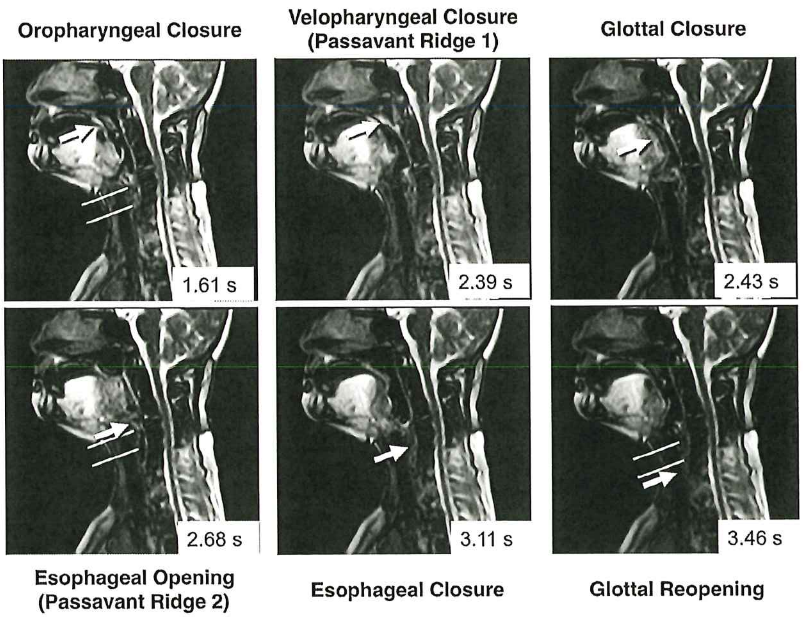

Fig. 5. A good-quality swallowing series in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) after subtotal glossectomy (STGS) with tissue flap reconstruction in a 78-year-old man with cancer of the left tongue. The swallowing was successfully completed after 3 attempts.

cancer because of its better temporal resolution and better visualization of the solution. In fact, with HSCMRI, swallowing function could be successfully visualized, whether the direction of flow of saline solution was to the esophagus, to the trachea, or to both in all patients before and after surgery. That is why the evaluation focused only on the direction of swallowing, and thus the determination of whether swallowing is normal or abnormal may be made on the basis of whether the material swallowed flowed directly to the esophagus or to the trachea.

Table VII. Changes in various parameters and tissue immobility scores of swallowing of 19 patients before and after surgery

	Before surgery	*After surgery*
Parameters, seconds		
OTT	1.08 ± 0.33	1.74 ± 0.77*
PTT	0.89 ± 0.13	1.18 ± 0.33*
OOT	1.05 ± 0.36	1.57 ± 0.63*
PR1	1.30 ± 0.45	1.88 ± 0.99†
LAT	0.76 ± 0.27	1.12 ± 0.41*
GCT	1.02 ± 0.62	1.04 ± 0.33
Epiglottic retroflexion	0.86 ± 0.50	0.87 ± 0.34
Vallecular and piriform sinus filling	0.74 ± 0.18	1.07 ± 0.41†
PR2	0.90 ± 0.23	1.15 ± 0.34*
EOT	0.99 ± 0.50	1.37 ± 0.51†
LDT	1.32 ± 0.39	1.41 ± 0.82
Tissue immobility score	9.26 ± 0.55	11.05 ± 2.70†

Among the time events: Significant differences versus before surgery: *$P < .05$; †$P < .01$.
OTT, oral transit times; *PTT*, pharyngeal transit times; *OOT*, orovelar opening time; *PR1*, first passavant ridge; *LAT*, laryngeal ascent time; *GCT*, glottal closure time; *PR2*, second passavant ridge; *EOT*, esophageal opening time; *LDT*, laryngeal descent time.

The other significant point about the usefulness of HSCMRI is that this technique can be used to evaluate both the objective parameters of each phase of swallowing and the changes in the mobility of the swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal back wall. This is because HSCMRI can visualize tissues and tumors by using T2-weighted imaging-related sequences. The alterations of certain parameters by HSCMRI should be related to alterations of numbers on videofluorography (VF) associated with deterioration of swallowing with physical changes.[6,12-18] Specifically, the proposed 4 parameters are OTT, OOT, PR1, and the tissue immobility score on HSCMR. Certainly, these 4 parameters were significantly correlated with the 3 grades—normal, slightly worse, and worse—on the present study's questionnaire, as in earlier reports.[3-6] In fact, with worse grades, these parameters (OTT, OOT, PR1, and tissue immobility score) on HSCMRI were also worse as swallowing deteriorated. In addition, these 4 parameters were significantly correlated with the extent of the surgical procedures for tongue cancer. In particular, a significant correlation was seen between the tissue immobility score on HSCMRI and the T classification of the tongue cancer. With a worse T classification or a more invasive surgical procedure, the parameters were longer and showed more deterioration. Because the evaluation of swallowing was performed by using MRI, soft tissue visualization was more precise than with VF. Thus, the tissue immobility scores on HSCMRI may be very useful and appropriate, and they could be used to accurately evaluate changes in swallowing status. Of interest, the values of the 4 parameters, including the tissue immobility score, were significantly related to the time after surgery. It seems that HSCMRI could appropriately and easily evaluate the swallowing function noninvasively in patients with tongue cancer before and after surgery. In other words, the results of the present study demonstrate that HSCMRI can be used to objectively evaluate not only the involuntary movements of swallowing to determine whether the flow is to the esophagus and/or to the trachea but also the spontaneous movements of swallowing based on the mobility of swallowing-related tissues.

Currently, precise assessment of the swallowing function is performed on VF, which is the gold standard for the evaluation of swallowing. However, with the VF technique, both the operators and the patients are exposed

Table VIII. Relationships among the 12 parameters after surgery in 19 patients and among the surgical procedures

	Groups			
	MD (N = 8)	*MDF (N = 5)*	*HMGS (N = 4)*	*STGS (N = 2)*
Parameters, seconds				
OTT	1.43 ± 0.36	1.35 ± 0.43	2.35 ± 1.17	2.70 ± 0.23*†
PTT	1.29 ± 0.43	1.15 ± 0.30	1.09 ± 0.05	1.02 ± 0.38
OOT	1.38 ± 0.49	1.16 ± 0.48	2.13 ± 0.60	2.23 ± 0.48*,†
PR1	1.67 ± 0.40	1.34 ± 0.53	2.35 ± 1.55	3.16 ± 1.44*,†
LAT	1.14 ± 0.34	0.86 ± 0.37	1.16 ± 0.53	1.59 ± 0.33
GCT	1.17 ± 0.35	1.09 ± 0.36	0.86 ± 0.18	0.73 ± 0.13
Epiglottic retroflexion	1.01 ± 0.37	0.92 ± 0.34	0.71 ± 0.19	0.52 ± 0.13
Vallecular and piriform sinus filling	1.23 ± 0.55	0.86 ± 0.20	1.09 ± 0.22	0.86 ± 0.00
PR2	1.32 ± 0.34	0.82 ± 0.10*	1.31 ± 0.26	0.98 ± 0.33
EOT	1.53 ± 0.58	1.27 ± 0.53	1.14 ± 0.33	0.86 ± 0.25
LDT	1.13 ± 0.42	1.17 ± 0.52	1.12 ± 0.46	1.20 ± 0.18
Tissue immobility score	10.13 ± 1.36	10.40 ± 1.34	14.00 ± 3.56	15.50 ± 0.71§,‖

Among the time events: Significant difference of $P < .05$ versus *MD, †MDF; $P < .01$ versus §MD, ‖MDF.
MD, marginal dissection; MDF, marginal dissection with tissue flap reconstruction; HMGS, hemiglossectomy; *STGS*, subtotal glossectomy; *OTT*, oral transit times; *PTT*, pharyngeal transit times; *OOT*, orovelar opening time; *PR1*, first passavant ridge; *LAT*, laryngeal ascent time; *GCT*, glottal closure time; *PR2*, second passavant ridge; *EOT*, esophageal opening time; *LDT*, laryngeal descent time.

Table IX. Changes in 12 parameters in 10 patients by time after surgery

		After surgery			
	Before surgery	*After 1 month*	*After 3 months*	*After 6 months*	*After 1 year*
Parameters, seconds					
OTT	$1.14 \pm 0.42^{*}$	$2.09 \pm 0.99^{\S}$	1.36 ± 0.61	1.16 ± 0.35	1.39 ± 0.81
PTT	0.91 ± 0.13	1.15 ± 0.16	1.14 ± 0.30	1.08 ± 0.11	1.16 ± 0.18
OOT	$1.11 \pm 0.41^{*}$	$1.75 \pm 0.87^{\S}$	1.24 ± 0.71	0.96 ± 0.32	1.08 ± 0.71
PR1	$1.25 \pm 0.44^{*}$	$2.39 \pm 1.20^{\dagger\dagger}$	1.63 ± 0.89	1.16 ± 0.32	1.36 ± 0.69
LAT	$0.82 \pm 0.30^{*}$	$1.16 \pm 0.40^{\dagger}$	0.81 ± 0.19	1.01 ± 0.33	1.12 ± 0.62
GCT	$0.76 \pm 0.18^{\dagger\dagger}$	0.97 ± 0.31	1.27 ± 1.35	0.89 ± 0.29	0.99 ± 0.12
Epiglottic retroflexion	$0.67 \pm 0.13^{\S}$	0.81 ± 0.33	1.10 ± 1.22	0.76 ± 0.16	0.87 ± 0.20
Vallecular and piriform sinus filling	$0.71 \pm 0.19^{*}$	1.00 ± 0.35	0.93 ± 0.41	0.78 ± 0.20	0.80 ± 0.23
PR2	$0.80 \pm 0.19^{\|}$	1.21 ± 0.30	0.98 ± 0.24	0.88 ± 0.12	0.93 ± 0.14
EOT	$0.96 \pm 0.23^{*,**}$	$1.20 \pm 0.41^{**}$	1.10 ± 0.27	1.14 ± 0.21	1.09 ± 0.15
LDT	1.33 ± 0.32	1.20 ± 0.39	1.19 ± 0.53	1.08 ± 0.37	1.33 ± 0.32
Tissue immobility score	$9.50 \pm 0.85^{*,\dagger,\ddagger,\S}$	12.60 ± 2.27	11.80 ± 1.55	11.10 ± 2.18	10.90 ± 1.97

Among the time events: Significant difference of $P < .05$ versus *1 month, †3 month, ‡6 month, §1 year; $P < .01$ versus $\|$1 month, **6 month, ††1 year.

OTT, oral transit times; *PTT*, pharyngeal transit times; *OOT*, orovelar opening time; *PR1*, first passavant ridge; *LAT*, laryngeal ascent time; *GCT*, glottal closure time; *PR2*, second passavant ridge; *EOT*, esophageal opening time; *LDT*, laryngeal descent time.

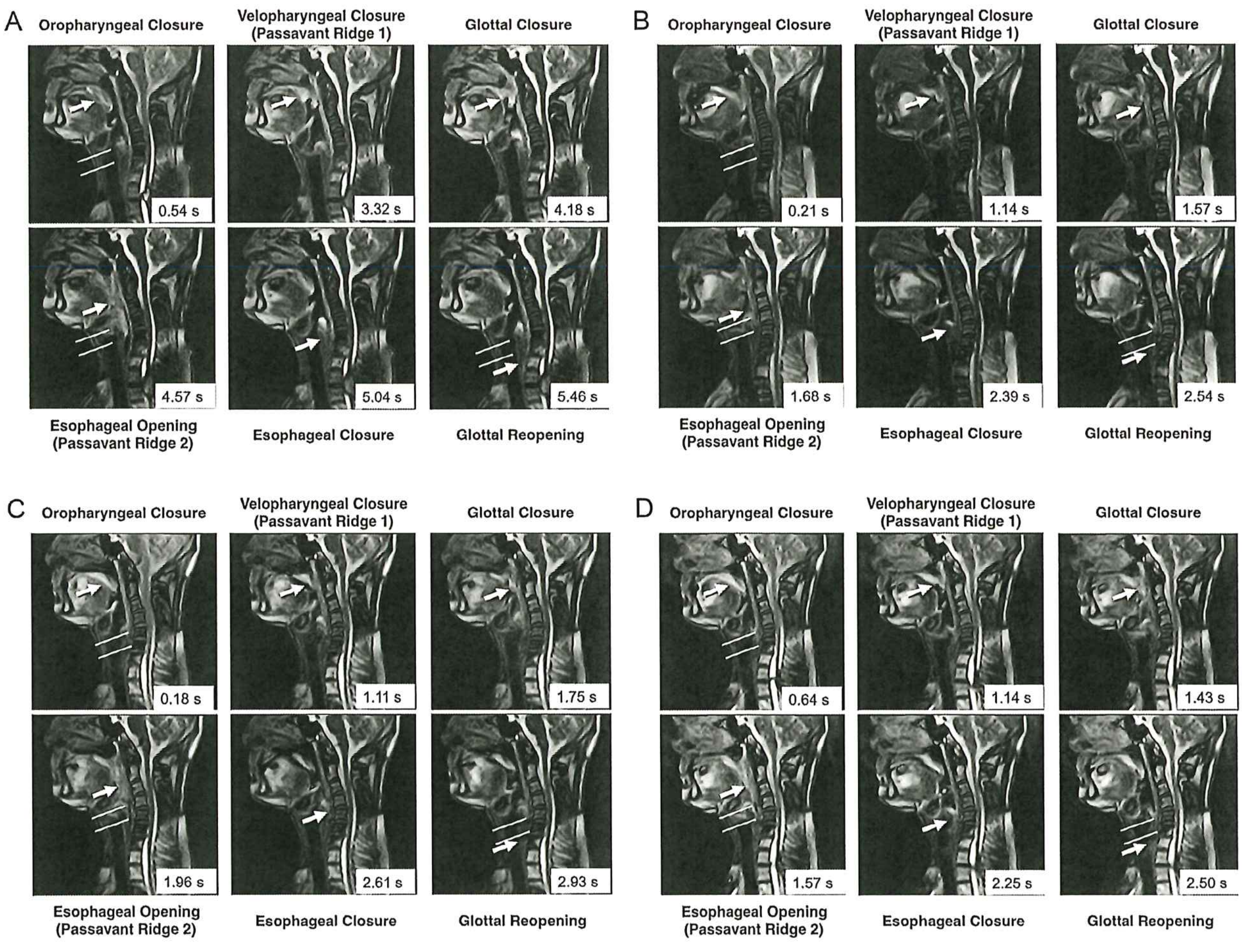

Fig. 6. Good-quality images of improvement in swallowing in the midsagittal plane obtained by using high-speed continuous magnetic resonance imaging (HSCMRI) according to the time after subtotal glossectomy (STGS) with tissue flap reconstruction in a 78-year-old man with cancer of the left tongue. At 1 month after surgery (**A**), the mobility of swallowing-related tissues, such as the anterior tongue, base of the tongue, soft palate, floor of the mouth, and pharyngeal back wall, tends to show smooth motion that continues at 3 months (**B**), at 6 months (**C**), and 1 year (**D**).

to ionizing radiation. Furthermore, the VF examination is performed in addition to routine imaging examinations. A contrast medium is also necessary, and side effects, such as aspiration pneumonitis, could result from mis-swallowing. HSCMRI avoids these risks, and swallowing can be examined in arbitrary image orientations without changing the patient's position, in addition to standard MRI examinations. The additional time required for HSCMRI is only 2 minutes.

In the present study, 12 parameters, including the tissue immobility score, were used to perform exact evaluations of the swallowing function in patients before and after surgery based on previous reports by Zhang et al.,[4] Kreeft et al.,[5] Tanaka et al.,[3] and Logemass's "six-valve model"[6] as objective parameters. The objective parameters, according to the "six-valve model," in the present study were similar to those in previous reports involving volunteers.[19,20] The results obtained were expected, and it is useful and significant that swallowing could be evaluated by using objective data based on diagnostic imaging. In addition, these parameters, including the tissue immobility score, appear to provide accurate evaluations of the swallowing function in patients. However, the values for tissue mobility were higher than those reported by Kreeft et al.[5] This may be explained by the fact the extent and status of the tongue in of the patients in the present study were relatively less than those of the patients in the study by Kreeft et al. based on the TNM (tumor–node–metastasis) classifications in the respective studies.[5]

Given the present results, it may be possible to predict the swallowing function after surgery for patients with various diseases involving the oral cavity on the basis of preoperative HSCMRI examination. We plan to use HSCMRI to evaluate improvement of swallowing following exercises for swallowing.

The sequences of the present technique were used as in modified real-time cardiac imaging and helped visualize the swallowing function with high-speed (28 fps), continuous, T2-weighted MRI. The temporal resolution of the previous technique was 10 images per second,[3] and the present technique could be modified. A cine-MRI using T2-weighted imaging has been reported,[5] but temporal resolution was 1.3 images per second, with the resulting need to analyze repeated swallows.[5] Although cine-MRI using T1-weighted imaging appears to offer better temporal resolution compared with that using T2-weighted imaging,[4] the higher temporal resolution of 28 images per second with the present technique resembled that of cine-MRI using T1-weighted imaging (24.7 fps) with a 3-T MRI system.[5] Temporal resolution of real time-MRI using T1-weighted imaging for other purposes has improved to 30 fps.[21] However, the temporal resolution of the present technique was higher than that of VF, and we suggest that the present level is sufficient.

For the present technique, the patient should be placed in the supine position. In the MRI literature, the swallowing movements examined would thus naturally differ from those made by an individual in the normal upright position.[11,13,22] However, it has been reported that transsphincteric flow increases in the horizontal and inverted positions but that total swallowing duration, such as OTT and PTT, were unaffected by body position in normal volunteers.[23] In addition, our previous data (0.67-0.84 s for PTT and 0.5-1.0 s for OTT) for swallowing events in volunteers were found to be almost identical to those of normal events, as demonstrated by VF.[3,21] In other words, functional evaluations of swallowing by using the present new technique with MRI were consistent with those by VF despite differences in subject position. As expected, OTT and PTT before surgery in patients with tongue cancers were 1.08 ± 0.33 seconds and 0.89 ± 0.13 seconds, and they were relatively high, compared with the values of VF and those in previous reports, including ours.[3,4,7,8,24] A possible explanation is that the swallowing function in the patients in the present study were different from that of volunteers because all of the patients in the present study had tongue cancer. In addition, there might be differences in the data between the 2 groups because the average age of our study patients was greater than that of subjects in previous studies.[3,4,7,8] Moreover, there were significant difference between parameters before and after surgery for tongue cancer, and some parameters, including OTT and PTT, after surgery were longer than those before surgeries. This seems quite reasonable. No patient experienced pulmonary aspiration before and after surgery in the present study. In addition, no patient was dissatisfied with oral administration of saline solution in the supine position. Therefore, we speculated that there would be few disadvantages with use of the supine position and that the advantages of MRI would outweigh them. Future studies should include more controls and patients. The criteria for some parameters of the swallowing function could be determined by using cine-MRI.

There were several limitations of the present study. First, a gold standard was not included. VF and videoendoscopy are relatively invasive techniques, and they could not be performed because of ethical constraints. The second limitation was the acquisition time of 10 seconds. Swallowing occurs quickly, in as little as 1.5 seconds and as much as 5 seconds.[12] It was possible to visualize a series of swallowing in patients with tongue cancer by using our technique, but the acquisition needs to be appropriately applied. The third limitation of the study was that our hospital did not have a 3-T MRI system, and some techniques of cine-MRI, including our technique, cannot be done with a 3-T MRI system. Although the discrimination and mobility of the genioglossus, the geniohyoid, and the intrinsic tongue muscles were also evaluated, they were not included in the immobility score. There was only 1 low-quality image in the 19 cases, and the blurriness of images was caused by motion artifacts as a result of fast swallowing. Therefore, there was no case in which the images were blurred as a result of neck motion in the present study. In future studies, the scores of the movements of the respective soft tissues on HSCMRI should be included for the purpose of more objective evaluation. The effects of chemotherapy and radiotherapy on the swallowing function could not be evaluated in the present study because the sample size was small. However, as indicated by our findings in the present study, chemotherapy and radiotherapy may have relatively little effect on the swallowing function, and we are planning to evaluate the effects of these therapies on swallowing in our next study.

CONCLUSIONS

The present technique could be used to noninvasively evaluate the swallowing function, in addition to examining tongue cancer, without changing the coil for acquisition of MRI signals. Therefore, we are convinced that the present technique should be added to the MRI evaluations of tongue cancer.

SUPPLEMENTARY DATA

Supplementary data related to this article can be found at https://doi.org/10.1016/j.oooo.2017.09.012.

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