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REVIEW ARTICLE

Evaluation of tongue motor biomechanics during swallowing—From oral feeding models to quantitative sensing methods

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Summary In today's aging society, dentists are more likely to treat patients with dysphagia and are required to select an optimal treatment option based on a complete understanding of the swallowing function. Although the tongue plays an important role in mastication and swallowing as described in human oral feeding models developed in 1990s, physiological significances of tongue function has been poorly understood due to the difficulty in monitoring and analyzing it. This review summarizes recent approaches used to evaluate tongue function during swallowing quantitatively mainly focusing on modern sensing methods such as manofluorography, sensing probes, pressure sensors installed in the palatal plates and ultrasound imaging of tongue movement. Basic understanding on the kinematics and biomechanics of tongue movement during swallowing in normal subjects was provided by the series of studies. There have been few studies, however, on the pathological change of tongue function in dysphagic patients. Therefore further improvement in measurement devices and technologies and additional multidisciplinary studies are needed to establish therapeutic evidence regarding tongue movement, as well as the best prosthodontic approach for dysphagia rehabilitation.

Contents

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1. Introduction

With the growth of the elderly population in the late 20th century, an increasing number of people are experiencing eating difficulties due to the effects of aging and age-related diseases such as cerebrovascular accidents and sensory-motor disorders associated with neurologic diseases. A loss of feeding ability also occurs as a consequence of head and neck cancer, despite improvements in treatment outcomes, and is partly responsible for deterioration in quality of life (QOL). Videofluorography (VF), the gold standard for the evaluation of dysphagia, has contributed to the development of human oral feeding models [1—5] and also helped clarify the pathological state in dysphagic patients in the 1980s. Dentists, who are responsible for oral function, should understand these oral feeding models, especially tongue movement during mastication and swallowing, because they will likely treat more patients with dysphagia as the elderly population increases.

Since a focus on the prepharyngeal swallow was suggested by Leopold and Kagel [1] in 1983, a basic framework for the oral feeding model has been acquired and reinforced. During this time, a process was sought to clarify tongue movement from mastication to swallowing and define the implications of these movements. A basic understanding was reached concerning how the tongue collaborated with other organs in mastication and swallowing in both healthy and dysphagic individuals. Meanwhile, our increased understanding identified limitations of observational studies using VF and other imaging techniques [6], including the fact that was impossible to kinematically demonstrate tongue biomechanics by image analysis alone, and that an application of VF to healthy subjects was considered unethical because it involved radiation exposure. To overcome these challenges, novel means of tongue evaluation were developed that combined VF and other means or used different methods altogether.

The difficulty in evaluating tongue function arises not only from measurement techniques but also from the specificity of the masticating and swallowing movements themselves. Many organs work together to produce these complicated and skillful movements. Several studies have been conducted with a wide range of techniques to confirm the functional significance of tongue movement described using oral feeding models. By analyzing the direct and indirect measurement results of tongue movement, pressure within the oral cavity and pharynx, and bolus motion, these studies have elucidated the biomechanics of tongue movement during swallowing. The various techniques used by these studies are useful in gaining insight into the significance of tongue movement and are now applied as quantitative measurement methods used to collect clinically relevant information. The present review first summarizes basic understanding of tongue function described in human feeding models developed by the VF studies, and then the recent approaches used to investigate tongue function during swallowing by using various sensing methods developed for clarifying the kinematic and biological significance of tongue function, and the use of ultrasound (US) imaging of tongue movement as the most accepted substitute for VF.

2. Tongue function described in human oral feeding models

2.1. Five stages of ingestion

In 1983, the "five stages of ingestion," intending to accurately diagnose problems in human oral ingestion, was proposed by Leopold and Kagel [1]. In their model, process of human eating was explained as anticipatory stage, preparatory stage, lingual stage, pharyngeal stage and esophageal stage in sequential order. Dysphagia was generally regarded as an abnormality in the final motor sequence of ingestion, that is, a simple problem that occurs in the pharynx during swallowing. Leopold and Kagel [1] advocated the importance of examining the voluntary movement process before the swallowing reflex using a comprehensive view. This model became the cornerstone for the subsequent development of dysphagia rehabilitation. They summarized the substances for evaluating VF images during swallowing using this model where much importance was attached to the tongue movement in preparatory and lingual stages, namely initiation, maintenance, termination and efficiency of mastication and lingual searching and transfer activity in the preparatory stage and lingual seal between oral cavity and pharynx should be evaluated carefully. Although tongue function was merely observed qualitatively and coordination with other swallow related organs was yet to be known in this model, the significance of tongue function was described clearly in the sequence of human feeding.

2.2. Five phase of oral stage

In the 1990s, the oral feeding process between food intake and swallowing reflex was divided into five phases by Feinberg [2]. In his model, the process of oral stage was explained by five phases such as ingestion, processing or preparation, transfer represent preswallow activity, lingual activity and transitional phase in the sequential order. As a result, it became easier to understand the biomechanical significance of tongue movement in the processing, transfer and propulsion of a bolus, and analyze the specific problems in each phase. In this model, tongue function was described in two biomechanical conceptions, such as a lingual delivery pump where the anterior part of the tongue was "the piston" and the glossopalatal seal was "the exit valve", and a grossopharyngeal propulsion pump where the base of the tongue acted as "the driving piston". The pressure generated by the tongue during former activity was relatively lower than that during later activity. It is noteworthy that Feinberg referred to two specific steps of the swallow reflex, namely the one and two step types, respectively; the former being a swallow reflex that comes immediately after the tongue transfers a bolus into the pharynx, and the latter is coming with an obvious interval after a virtually whole bolus enters the pharynx.

2.3. Process model

Palmer et al. [3], also interested in the mechanism of the oral stage, engaged in the simultaneous monitoring of VF and electromyography (EMG) to investigate the coordination between mastication and swallowing. They showed some important findings, such as the correlation of the mandibular and lingual movement cycles, transfer of a food bolus prior to the swallowing reflex, and the cooperation of the swallow reflex and jaw movement. Together with the study results of Hiiemae et al. [4], who closely examined the mastication-to-swallowing process in animals, these findings were presented as the "Process Model" in 1997, the same year as the establishment of the Japanese Society of Dysphagia Rehabilitation [5]. The model showed diversified tongue movements from oral intake to the swallowing of solids over five phases (Table 1), where breakdown of solid food portions (food processing) and bolus formation in the oral cavity and oropharynx (stage II transport) progress simultaneously.

3. Biomechanical analysis of tongue movement during swallowing

3.1. Manometry in the oral cavity and pharynx

3.1.1. Pressure-flow dynamics in the oropharyngeal swallow

The pressure-flow dynamics over the oral and pharyngeal stages were described clearly via simultaneous monitoring of VF, strain gauge probes distributed inside the oral cavity, and pharyngeal manometry (pressure measurement) [7]. Intraoral pressure generated at the contact surface of the tongue and palate, which develops from the anterior side toward the posterior side and peaks over time, was greater than that of the mouth floor or vestibulum oris, and the pressure primarily drove a food bolus from the oral cavity into the pharynx. The physiological mechanism involved in swallowing a liquid barium meal was revealed using a simultaneous recording of VF and intrabolus pressure (manofluorography) [8]. Findings told that when a food bolus was pushed from the oral cavity into the pharynx by the driving force of the tongue, prebolus negative suction pressure arose with laryngeal elevation and the opening of the UES, whereupon the pharyngeal wall contracted to clear the bolus tail from the pharyngeal cavity [8].

Table 1 Outline of tongue movement described in the process model [5].

Ingestion
The mouth opens widely as the *tongue* drops down to make the room in the mouth for entering bite.
Stage I transport
The *tongue* shifts bodily backward in the oral cavity to carry the bite of food on its surface and rotates to deliver the food to the chewing surface of molar teeth.
Food processing
Once food reaches the molar region, it is softened and reduced in size as it is chewed, manipulated and mixed with saliva. During chewing, jaw movement is linked to cyclic motions of the *tongue* and hyoid bone. The *tongue* moves upward and downward in association with jaw closing and opening, and also forward and backward. These horizontal motions of the *tongue* are out of phase with its vertical motions.
Stage II transport
Portion of food bolus is propelled through the faucial pillars into oropharynx where it is stored in anticipation of swallowing. Some food remains in the oral cavity where Processing continues. During Stage II transport cyclic motions of the jaw and *tongue* continue in a linked pattern. In some cycles food is pulled backward on the surface of the *tongue*, and in other cycles *tongue* pushes it against the palate and squeezes it back along the palate and into oropharynx.
Hypopharyngeal transit
As the pharyngeal swallow begins, the food bolus in the oropharynx is propelled through the hypopharynx into esophagus. Bolus propulsion is produced primarily by backward thrust of *tongue* onto oropharynx.

Figure 1 Iowa oral performance instrument (IOPI, left), and its usage in the measurement of maximum tongue pressure (right). (Through the courtesy of Prof. Isami Kumakura, Kawasaki University of Medicine and Welfare.)

3.1.2. Modification according to bolus volume and viscosity

During rehabilitation for patients with dysphagia, the patient's condition determines the bolus size, food consistency, and use of a compensatory swallowing technique [9]. Among these items, bolus size and viscosity were investigated using manofluorography to determine the influence of these factors on tongue activity during swallowing [10—12]. The role of the tongue during swallowing included bolus containment, volume accommodation, and a major contributor to bolus propulsion [10]. Intrabolus pressure in the early phase developed in sync with the posterior transfer of the tongue base and varied with the volume of the bolus, but late intrabolus pressure was unaffected by volume, even synchronizing with the posterior pharyngeal wall [11]. An increase in bolus volume accelerated the onset of pharyngeal contraction and the movements of the tongue base, soft palate and UES, whereas an increase in viscosity prolonged the oral and pharyngeal transit of the bolus and extended the duration of the pharyngeal peristaltic waves and that of the UES opening [12]. These results suggest that the swallowing function might be modified according to the volume and viscosity of food, with essentially different adjustment modes. A series of findings obtained by manometry and/or manofluorography [7—12] not only marked the first milestone in understanding the oral cavity and pharynx as a single functional unit, but also gave us a clue for planning a rehabilitation strategy by elucidating the pathologic condition of dysphagia. The functions of the tongue were also characterized as voluntary, and the tongue base as a reflex within the course of the studies.

3.2. Measurement of the tongue pressure via the sensing probe

3.2.1. Iowa oral performance instrument

As the overall biomechanics of the oropharyngeal swallow were clarified by VF and manometry, the lingual function, the key contributor to food transportation, attracted the attention of investigators. In the mid-1990s, this resulted in the consecutive development of new methods to measure the pressure generated by the contact between the tongue and palate. The Iowa oral performance instrument (IOPI, Blaise Medical, Hendersonville, TN, USA; Fig. 1) was constructed of an amplifier with a digital display of pressures in kilopascals (kPa) and bulb shaped pressure sensor. This instrument has been used to measure the tongue's pulsive and clearing forces, and revealed that these forces were modulated with the viscosity of the bolus but not with the volume [13]. It was also shown that tongue pressure could change fourfold when volitional modulation was applied, and that the anterior two-thirds of the tongue had a high modulation capacity that exceeded that of the tongue base [13]. Measurement of the maximum lingual isometric pressure (tongue strength) and maximum lingual swallowing pressure (swallowing pressure) in young and older adults by IOPI demonstrated that the maximum lingual swallowing pressure between both groups was equivalent, but that the tongue strength was significantly lower in the older group [14]. Tongue strength and endurance were quantified in subjects of all ages to analyze the relationship with gender and age; tongue strength was superior in men compared with women and decreased with age, but no gender or age differences were noted for tongue endurance [15]. Although gender and age effects on tongue strength were also assessed in another investigation, mean pressure during swallowing and percentage of tongue strength used during swallowing were not correlated to gender and age but were correlated to food consistencies [16]. Comparisons of tongue strength and endurance between patients with oral phase dysphagia and age-matched normal subjects revealed a significant reduction only in the tongue strength of dysphagic patients [17]. IOPI is commercially available and generally used as an evaluation tool in rehabilitation for tongue muscle strengthening.

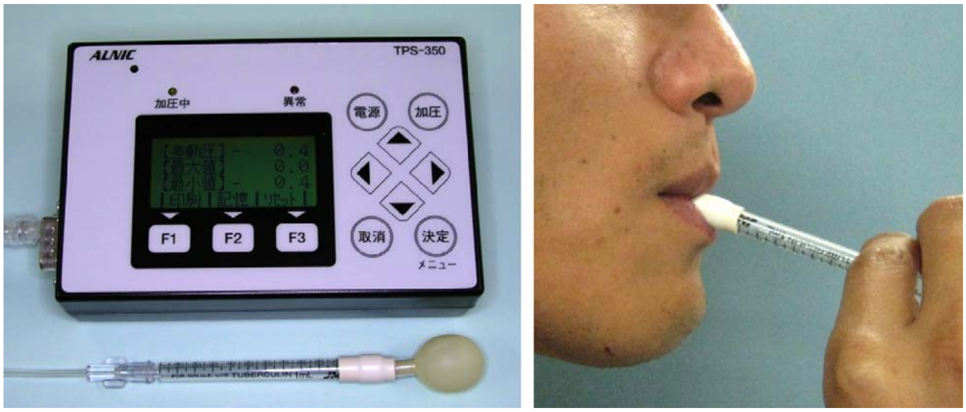

Figure 2 A disposable balloon probe system (left), and its usage in the measurement of maximum tongue pressure (right). (Through the courtesy of Dr. Kazuhiro Tsuga and Prof. Yasumasa Akagawa, Hiroshima University Graduate School of Biomechanical Sciences.)

3.2.2. Handy probe

A disposable handy probe system (TPS-350, Alnic, Higashi-hiroshima, Japan; Fig. 2) to monitor maximum voluntary tongue pressure and swallowing pressure was developed in Japan (Prototype; not yet being commercially available). Reports showed that both tongue strength and swallowing pressures were negatively correlated with age, but neither was correlated with sex or the state of dentition [18]. However, it is important to recognize that measurement of tongue pressure using IOPI or the handy probe may influence the swallowing movement because these devices require the insertion of a balloon-equipped probe into the oral cavity. Additionally, the hand-held probe design renders the standardization of measurement points insufficient. These factors are likely to be the cause of controversy regarding the association between age and swallowing pressure. Most recently, a mouthguard type device for measuring tongue pressure (Madison oral strengthening therapeutic device), which could be fitted to personal dentition and hard palate, was introduced [19]. Replicable mouth placement will be useful for standardized evaluation of tongue exercises to improve lingual strength as well as for the quantitative diagnosis of oral problems in dysphagic patients.

Devices such as IOPI and the handy probe, however, are easy to use and adequate for mass measurement. The tongue strength of each age group [20] and its decline in the elderly as a clinical sign of dysphagia [21] were determined via the use of handy probes. Handy probes are now used in a wide range of oral studies in the elderly, as shown in a study of elderly patients that examined the effect of the tongue strength on oral and pharyngeal residue after mastication and swallowing [22]. Tongue strength was found to be the predictive factor which decreased oral residue and increased pharyngeal residue in the case of swallow once after 30 chewing actions of bread, which suggested the importance of multiple swallow in the elderly with poor masticatory ability. Another study used the handy probe to test the effect of the palatal plate on swallowing pressure [23]. Although perceived difficulty in swallowing increased by wearing palatal plate, tongue strength and swallowing pressure were not influenced in healthy dentate subjects.

3.2.3. Sensing probe with multiple measuring points

Tongue pressure measurement by intraoral probes with multiple sensing points enabled the detailed evaluation of tongue function during the oral stage of ingestion. Tongue motion and coordination with laryngeal elevation were analyzed using probes with two front and back transducers and laryngeal movement sensors [24]. The device, however, must still be held by the subject's hands. In contrast, air filled bulbs (Fig. 3) can measure tongue pressure at three points on the anterior, middle, and posterior parts of the palate; these bulbs are fixed

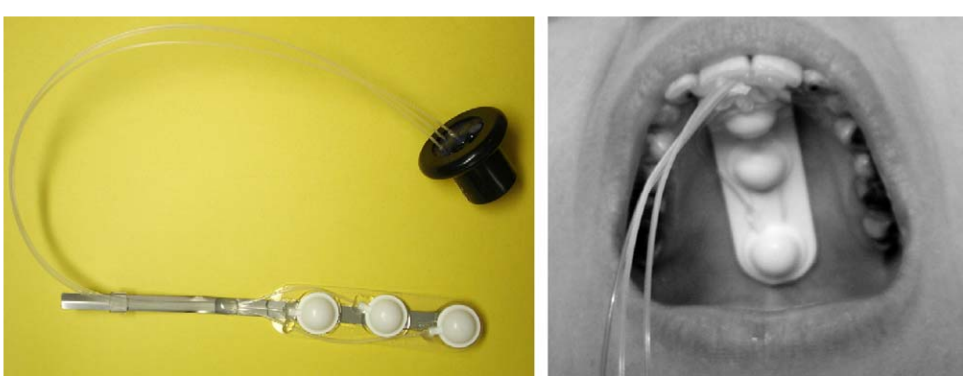

Figure 3 An air filled bulbs placed on the palate for measuring tongue pressure during swallowing. (Through the courtesy of Dr. Mitsuyoshi Yoshida, Dr. Kazuhiro Tsuga and Prof. Yasumasa Akagawa, Hiroshima University Graduate School of Biomechanical Sciences.)

to the median palate with an adhesive. A study comparing swallowing motion using VF with or without the bulbs showed that the bulbs had no influence on normal swallowing patterns [25]. The tongue strength and swallowing pressure were compared between elderly subjects (mean age, 81 years) and young subjects (mean age, 51 years) using this system [26]. Age-related reductions in tongue strength and no significant differences in swallowing pressure were noted between the two groups. It is noteworthy, however, that age-related prolongation of the time to reach the peak of both pressures was found, which suggests the advantage of this system for identifying changes in swallowing behavior. The effect of training to improve the pharyngeal swallow was evaluated via the use of air-filled bulbs, and it was suggested that the tongue-pressing exercise was as effective as lifting the head into a dorsal position (head-lift exercise, Shaker method) [27].

3.3. Measurement of tongue pressure by the experimental palatal plate with sensors

3.3.1. Background of procedure

Through their experience, dentists know that changes in the palatal shape of a maxillary denture can impact the patient's articulation, mastication, and swallowing. Given the efficacy of palatal augmentation prostheses in the rehabilitation of patients having undergone a glossectomy [28], the importance of the compatibility of the tongue and palate for normal tongue function is also well understood. In terms of orthodontic treatment, tongue pressure added onto the loop of the transitional arch during swallowing has attracted attention as the source of an orthotic force [29]. In the late-1990s in Japan, concurrently with the growing clinical interest in such findings, sensors built in a palatal plate or the palatal surface of a maxillary denture came into use for studies of tongue pressure measurement. Although most of these studies used one to 10 strain-gauge type pressure sensors, a unique rubber sensor sheet with 80 sensing points for evaluating tongue pressure distribution on the hard palate was reported [30]. The authors, reviewing previous study results, investigated tongue pressure patterns using an experimental palatal plate in which seven pressure sensors were embedded, and demonstrated the basic patterns during water swallowing [31] and when gummy jelly was masticated and swallowed [32].

3.3.2. Tongue pressure during swallowing

Characteristics of the tongue pressure pattern against the palate are determined by the onset order at each point, as well as the duration, and maximum value of the pressure generated during the swallow (Fig. 4) [31]. When 15 ml of water was ingested, tongue pressure occurred initially at the anterio-median part of the palate (Ch. 1), followed by the anterio-circumferential part (Chs. 4 and 6). In the midline, tongue pressure arose forward to backward, namely Ch. 1 → Ch. 2 → Ch. 3, in which Ch. 3 was the final part perceiving tongue pressure among the seven sensors. The tongue pressure at each point reached a peak immediately, then slowly diminished and disappeared. The tongue pressure at Ch. 1 lasted longer and the maximum pressure value was greater than that at all other points. The observed patterns were consistent with the lingual mechanical role reported to date and suggest the necessity of further analysis on the kinematic role of each part of the tongue. Trials to describe the detail of tongue movement during swallowing have been continued by VF [33] and electromagnetic articulography [34], where the trajectories of many points on the tongue and jaw have been recorded and analyzed quantitatively. It was reported that the tongue blade showed higher variability corresponding to the different swallowing tasks than the tongue body and dorsum [34]. Tongue pressure production measured by this type of experimental palatal plate had the temporal coordination patterns with the activity of jaw and oropharyngeal muscles during voluntarily triggered swallow [35]. It can suggest the possibility of comprehensive evaluation of swallowing by the simultaneous recording of tongue pressure, swallowing sound and laryngeal movement.

3.3.3. Tongue pressure during mastication

An experimental palatal plate and mandibular kinesiography were used to record tongue pressure and mandibular movements during the mastication and swallowing of gummy jelly; this simultaneous recording suggested two interesting findings [32]. One finding is the tongue pressure pattern, coordinated with mandibular movement in each masticatory cycle, in which tongue pressure develops in the occlusal phase and disappears in the opening phase. This pattern, consistent with the EMG coordination pattern during masticatory movement previously reported [36], is reasonable

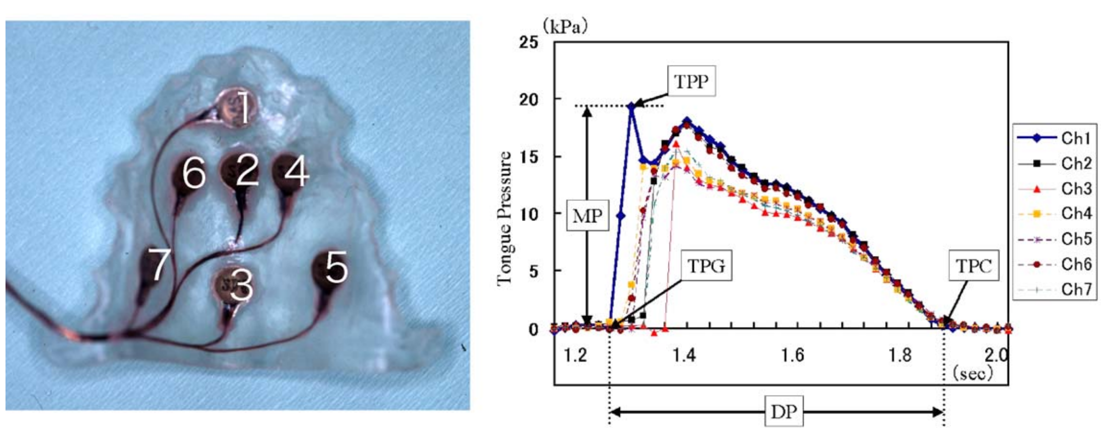

Figure 4 An experimental palatal plate with seven pressure sensors (left), and the representative wave of tongue pressure during swallowing (right): MP: maximum magnitude of tongue pressure; TPP: time of the peak of tongue pressure; TPG: time of tongue pressure generation (onset); TPC: time of tongue pressure ceasing (offset); DP: duration of tongue pressure.

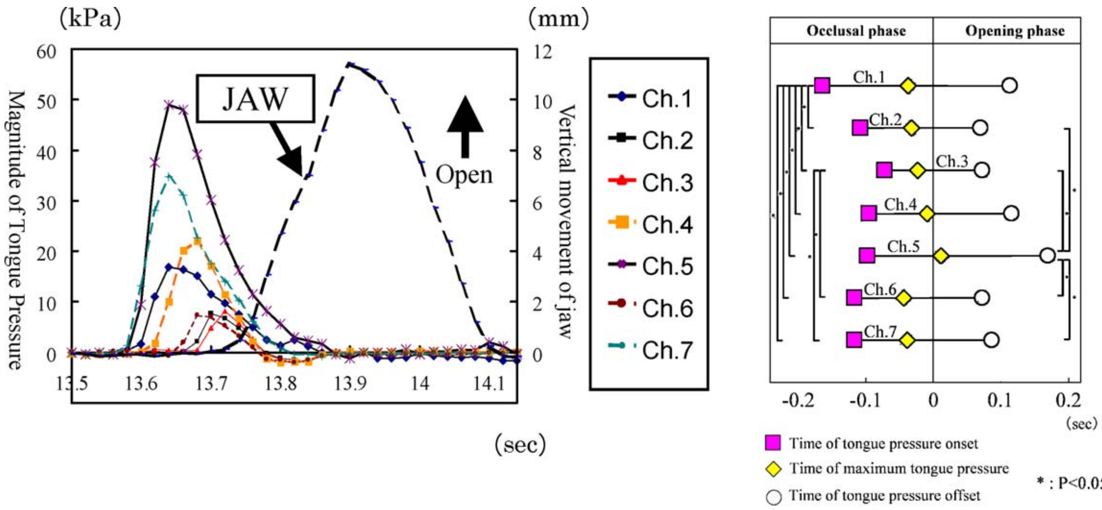

Figure 5 A representative recording of tongue pressure against hard palate and vertical trajectory of the jaw movement in the masticatory cycle (left), and the coordination between tongue pressure and jaw movement (right). Significant difference of sequential order in the onset and offset of tongue pressure is shown.

enough to bite and crush solid food to form a bolus. The second finding is the prolongation of the pressure duration of each mastication cycle, accompanied by an elevation of the maximum value, before swallowing a bolus of gummy jelly (Fig. 5). This finding supports our previous results of the VF study, whereby a temporal change of the tongue-palate compatibility was evaluated during the mastication of gummy jelly [37]. We presume that these changes indicate an activation of tongue movement associated with the initiation of the "stage II transport" [5] (Table 1) of the jelly bolus observed by VF. To sum up, these findings suggest not only the coordinated movement pattern of the tongue and mandible during the mastication process, but the presence of a tongue control system that interacts with sensory inputs from variable bolus consistencies. This process, which takes place between mastication and the pharyngeal swallow, has been studied from the point of preventing aspiration. Recently, a VF study evaluating the chewing and swallowing process for the mixture of a liquid and solid food showed that chewing with active tongue-palate contact appeared to reduce the effectiveness of the tongue-palate seal and might increase the risk of aspiration [38].

3.3.4. Maxillary denture with pressure sensors

Change in the swallowing behavior of edentulous patients wearing complete dentures was investigated using pressure sensors installed in the maxillary denture [39]. Simultaneously, monitoring of tongue pressure with pressure sensors and an EMG of the submental muscle and laryngeal movement in 16 edentulous patients, who wore both maxillary and mandibular dentures or a mandibular denture alone, and those without any dentures, revealed that the duration of the preparatory stage was longer in patients with a mandibular denture and without dentures but that the duration of the pharyngeal stage remained unchanged [39]. Results of a study on the relationship between the occlusal vertical dimension and tongue pressure during swallowing showed that an increase in occlusal vertical dimension could reduce tongue pressure during swallowing in four young dentulous and eight older edentulous adults [40]. The effects of the height of vertical occlusal support on the tongue pressure pattern in eight edentulous patients who wore their original experimental biteplate loaded with two tongue pressure sensors was examined in the same study. In patients without any support, or in those with a lower vertical dimension, the duration of tongue pressure in the anterior palate was shortened. Moreover, in patients without occlusal support, there was a tendency for the integrated tongue pressure to increase in the lateral areas, suggesting a compensatory effect of the tongue function for changes in oral dimensions or the loss of mandibular support [41]. These reports suggest that the edentulous condition is likely to impair the efficiency of swallowing not only in the preparatory and lingual stages, but also the pharyngeal stage, and that wearing complete dentures has an important effect on swallowing safety in the elderly.

3.4. Measurement of tongue pressure by the sensor sheet system

Experimental palatal plates with pressure sensors are the most useful tool to quantify the basic pattern of tongue movement during spontaneous mastication and swallowing, as they are stringently standardized for measurement points and allow complete biting. However, clinical application is difficult because such prostheses require advanced techniques and are expensive to manufacture. Subjects may also require an acclimatization period to get used to the uncomfortable feeling produced by the thickness of the plate [42]. Keiser et al. [43] created a cobalt chrome palatal plate and performed a simultaneous recording of the pressure at the lips and cheeks during swallowing, but discovered only inconstant patterns with wide intra- and inter-individual variability, which may be ascribed to the absence of an acclimation period. As a breakthrough for these problems, a tongue pressure sensor sheet (Nitta, Osaka, Japan, Prototype; not yet being commercially available) capable of being used without acclimation periods was developed (Fig. 6) [44—46]. This tongue pressure measurement system is supplied as a ready-to-use product, which easily adheres to the palate

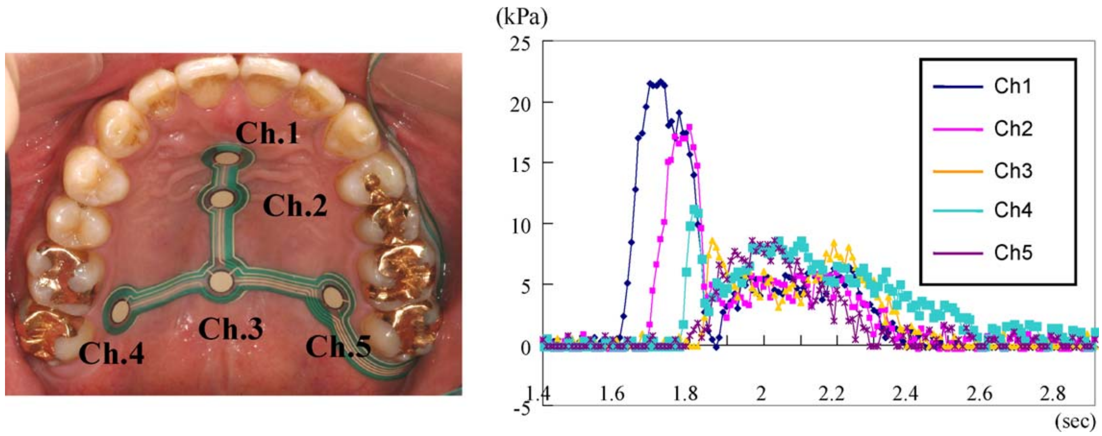

Figure 6 A sensor sheet for measuring tongue pressure attached on the palate with denture adhesive (left), and a representative recording of tongue pressure during swallowing (right).

during use. The T-shaped sensor sheet has five sensing points and is available in three sizes, allowing the choice of a proper size according to the subject's palate. As well as the aforementioned experimental palatal plate, the sensor sheet can also assess the tongue pressure pattern at each part of the palate [44]. The usefulness of this device has already been demonstrated by the evaluation of swallowing function in patients with a stroke [45] or in the preparation of palatal augmentation prostheses (PAP) for patients with head and neck cancer [46]. Magnitude of tongue pressure during swallowing in post-stroke patients was smaller than that in healthy subjects at the measuring points along the median line (Chs. 1—3, Fig. 6), larger in the non-paralyzed side than in the paralyzed side, and was influenced by the result of water swallowing test and state of occlusal support [45]. Increase in the magnitude of tongue pressure and the normalization in the pressure distribution by the PAP improved the bolus transit in the oral phase of swallowing [46].

4. Ultrasound imaging of tongue movement

Tongue movement during swallowing and articulating was evaluated in a series of studies using ultrasonography (US), which is capable of showing the outline of soft tissues. One of the great advantages of US over VF is that it involves no radiation exposure. If reproducibility and a quantitative analysis method can be developed, US will be a more beneficial testing procedure.

Coordination between swallowing movement of the tongue and hyoid bone motion was assessed in healthy volunteers in a sagittal section by placing a pellet on two spots of the tongue as a marker [47]. Analysis of US images in a coronal section [48] showed that the grooving depth was maximized to 300 ms before the swallowing reflex to enclose the food bolus. Frame by frame analysis of US images revealed that elongation of swallowing duration and multiple lingual gestures during swallowing were signs of subclinical changes associated with normal aging [49]. Temporal reconstruction of the swallowing movement of the tongue in healthy subjects and patients with dysphagia based on US images demonstrated the highly informative nature of these images [50]. Coordinated mastication of the tongue and cheeks was analyzed via the simultaneous monitoring of US images in a coronal section, with pressure transducers attached to the molars, and masseter EMG [51]. Recent studies sought to use tongue movement wave patterns to develop techniques to assess the swallowing function [52,53]. Analysis of sequential coordination between inflection point found in the waveform of tongue movement in the M-mode and swallowing sound could provide objective parameter for evaluating swallowing function [52]. Measurement of the duration of grooving and tongue contact in the M-mode wave form PAP was useful for confirming the improvement of swallowing function by a PAP [53].

The association between elaborate tongue movement and masticatory performance was investigated using US [54,55]. Comparison of lingual up and down movement with a metronome between young and older subjects revealed that tongue movements of older subjects were less rhythmical than those of younger subjects [54]. Tongue movements in young dentates, elderly dentates and elderly complete denture wearers during the mastication of peanuts were recorded to analyze the correlation between age and masticatory performance with the standard deviations of cycle time as a parameter of tongue motor skill (Fig. 7) [55]. A significant

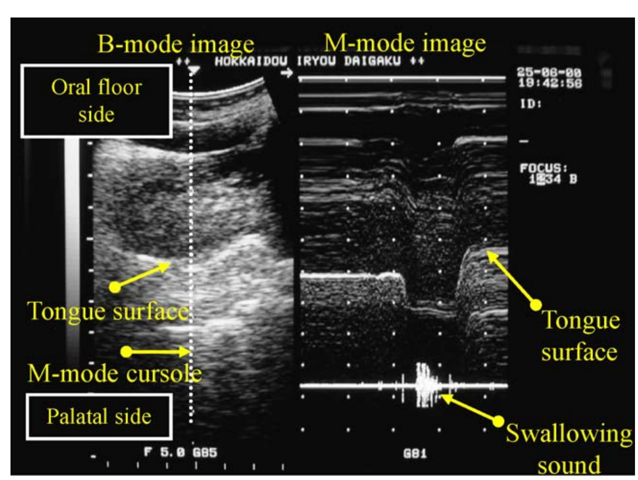

Figure 7 Ultrasound sonographic image of the tongue movement during swallowing in B-mode and M-mode. (Through the courtesy of Dr. Hisashi Koshino and Prof. Toshihiro Hirai, School of Dentistry, Health Science University of Hokkaido.)

decline was observed in tongue motor skill among elderly dentates and complete denture wearers compared with younger subjects. Also, among complete denture wearers, there was a significant correlation between masticatory performance and tongue motor skill.

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