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Review

Rheology for Safe Swallowing 1‡

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In aged society, the number of persons with difficulty in mastication and swallowing is increasing, and the aspiration-induced pneumonia is one of the top causes of death in the elderly. Although the detailed mechanism of aspiration is still not well understood, great efforts have been done to prevent the aspiration, and thickening of bolus has been found effective to reduce the risk of aspiration. It was pointed out earlier that excessive thickening reduces the palatability and the intake of fluids leading to dehydration and malnutrition and to formation of the residue as a risk of aspiration. In the present review, the physiological aspects of food oral processing conducted in the mouth by teeth, tongue, saliva have been introduced, and practical evaluation methods of rheological properties used in hospitals and nursing care facilities are described. Viscosity of commonly used polysaccharide-based thickening agents is described in relation with yield stress, thixotropy together with tribological aspects which play important roles in swallowing. To improve the control of texture, new thickening agents and modifying methods of rheological properties are described. Emerging methods to study the swallowing process have been also discussed. Finally, the importance of integration and collaboration of different disciplines is emphasized.
Key Words: Bolus / Mastication / Yield stress / Aspiration / Cohesive

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1. INTRODUCTION

Important cause of death is reported as malignant neoplasm, tumor, heart disease, cerebrovascular disease, aging, pneumonia, and aspiration-induced pneumonia in 2020 in Japan. Among these, the aspiration-induced pneumonia is more important in elderly[1].

While the average life expectancy in Japan is the longest in the world, the gap between the average life expectancy and the healthy life expectancy *ca.* 8-12 years is thought to cause the decreased quality of life (QOL) as well as the burden on the national finance. https://www.mhlw.go.jp/stf/wp/hakusyo/kousei/19/backdata/01-01-02-06.html

MHLW advises people to review their lifestyle and optimize nutrition, physical activity and social participation to prevent the frailty. Frailty is a distinctive health state related to the aging process in which multiple body systems, mind, body and social connections gradually lose their in-built reserves. The cascade of functional decline in older adults from independence (no frailty), through to frailty and disability in the absence of intervention is shown in Fig. 1[2]. To ensure the nutrition, eating safely is a prerequisite, but as mentioned above the aspiration induced pneumonia is becoming the important problem in relation with dysphagia. The term “dysphagia” originates from the Greek *dys*- meaning bad or disordered, and the *phag*- meaning “eat”.

Japanese Society of Gerodontology analyzed the problem and published a position paper to solve this problem[3]. According to this analysis, before the stage of oral dysfunction, the oral hypofunction or even before that the problem begins from oral frailty, which is characterized by decreased articulation, slight choking/spillage while eating, increased number of unchewable foods. This is not disease and is a condition. These authors selected 7 conditions (poor oral hygiene, oral dryness, reduced occlusal force, decreased tongue-lip motor function, decreased tongue pressure (contact pressure of the tongue on the hard palate during oral processing), decreased masticatory function, and deterioration of swallowing function) for making a diagnosis of oral hypofunction and thereby making intervention and training to restore the state of oral hypofunction back to the state of oral frailty.

Another position paper was written by the Japanese Society of Dysphagia Rehabilitation, the Japanese Association of Rehabilitation Nutrition, the Japanese Association on Sarcopenia and Frailty, and the Society of Swallowing and Dysphagia of Japan to consolidate the currently available evidence on the topics of sarcopenia and dysphagia[4]. These authors defined sarcopenic dysphagia as dysphagia caused by sarcopenia of the whole body and swallowing-related muscles, and included aging and secondary sarcopenia after inactivity, malnutrition and disease (wasting disorder and cachexia). They emphasize the importance of the study the fundamental issue of how dysphagia caused by sarcopenia of the swallowing muscles, and the dysphagia rehabilitation, such as resistance training of the swallowing muscles and nutritional intervention. Etymologically, sarcopenia, is a combination of the Greek *sarx*, meaning “muscle”, and *penia*, meaning “to lose”[4, 5].

To examine how the aging and sarcopenia reduce the mastication ability, tongue pressure and jaw-opening force were observed for 197 older adults (97 men, mean age 78.5 ± 6.6 years; 100 women, mean age 77.8 ± 6.2 years)[6]. Mean tongue pressure was found to be 26.3 ± 7.8 kPa in men and 24.6 ± 7.2 kPa in women. The mean jaw-opening force was 6.3 ± 1.6 kg in men and 5.2 ± 1.3 kg in women. Machida *et al.*[6] found that fatty infiltration and amyloid deposits increase with aging, and muscle fibers decreased in tongue muscle, leading to decreased tongue pressure. They suggested that aging decreased tongue pressure more than jaw-opening force, and affected men more than women. Sarcopenia affected tongue pressure and jaw-opening force, with the exception of jaw-opening force in women. They concluded that taking into account the reduction of the tongue pressure and the jaw opening force, it is necessary to provide appropriate interventions preventing dysphagia.

Since a microaspiration, a small amount of saliva during sleep can occur in healthy persons, it is a large-volume aspiration that causes the aspiration pneumonia, and thus it is an

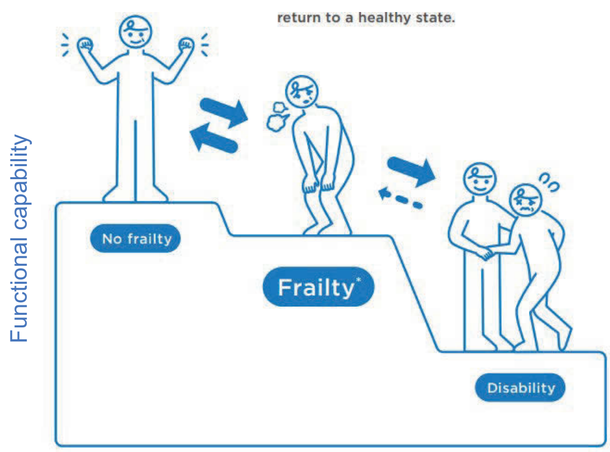

Fig. 1 Frailty is positioned as a pre-disability (pre-care dependency) stage of a condition that requires nursing care, but refers to patients in a high-risk situation that can lead to various health disorders, including disability and mortality[2]. Such patients are not only physically vulnerable, they also tend to suffer from a multitude of problems, such as mental, psychological, and social vulnerabilities. Clinical Guide for Frailty 2018[7] 200327_frailty_pamphlet_en[nouhin] (mhlw.go.jp).

infection caused by specific microorganisms[8]. Ups and downs of lung microbiota have been overviewed and the effectiveness of different antibiotics has been compared based on information accumulated in many hospitals[8]. In addition to the poor oral health and oropharyngeal colonization by respiratory pathogens, oropharyngeal dysphagia with impaired safety of swallow, aspirations, and frequently, impaired cough reflex, and frailty with malnutrition and poor immunity were pointed out as key elements in the pathophysiology of aspiration pneumonia[9]. Fernandez *et al.*[9] thus emphasized the importance of therapeutic strategies rather than pathophysiology. Ebihara, Sekiya, Miyagi, Ebihara, and Okazaki[10] who have shown that chronic repeated microaspiration of sterile material caused the aspiration pneumonia in mouse lung. They also showed that chronic repeated microaspiration induced chronic inflammation in both frail elderly people and mouse lung. Since the aspiration is caused by dysphagia[11], Ebihara *et al.*[10, 12] emphasized the importance of function-oriented therapy rather than pathogen-oriented therapy.

Although the relation between the dysphagia and aspiration pneumonia was not clearly understood, multi-angle approach will be useful to improve the understanding and therapy.

Since dysphagia needs to be understood by multidisciplinary approach, and several review papers have been already published[10-16], the present review aims to focus on the rheological and colloidal aspects[17, 18] to provide more comprehensive understanding of these aspects for dysphagia problem.

Since the pureed or paste like foods are not liked not only from their appearance but also from their monotonous sensory texture, food industries produced many more palatable foods using different techniques such as enzymatic softening, although the three-dimensional printing is still not yet developed[19]. Professional caregivers, dentists and nurses are offering exercises to improve the QOL of persons with difficulty in mastication and swallowing to prevent recurrence of aspiration pneumonia[20].

If the normal eating is dangerous for persons with difficulty in mastication and deglutition, it seems better to nourish them with parenteral nutrition through veins and actually it is effective in certain cases. Humans do not live to eat, but eating palatable foods is good and important for all especially for sick people because parenteral alimentation is possible to cause abiotrophy and may lead to disuse atrophy of gastrointestinal tract including oral organs if it is used over an extended time period. Bourne raised an example of the large number of dentists in developed country in spite of the possibility to nourish through tubing, which demonstrates that people wish to eat from the mouth, and that the enjoyment of meals is a key element of the quality of life[21]. Therefore, in addition to the safe transport of ingested food to the digestive organs through the esophagus to the stomach, food quality satisfying both nutrition and palatability must be ensured, and all these interrelated problems must be taken into account.

In the present paper, rheological basis of safe swallowing is described. Since rheology plays an important role in mastication and swallowing, many papers have been published, and further collaboration between different disciplines is urgently required[22-24]. When swallowed foods go not into the esophagus but into the trachea (windpipe) or when swallowed material has entered the trachea below the level of the true vocal folds, it is called **aspiration**[25]. When swallowed food entered into the laryngeal vestibule, this is called **penetration**[26]. Silent aspiration is defined as aspiration occurring without elicitation of a cough reflex[27].

In addition to aspiration-induced pneumonia, choking caused by konjac-based jellies has attracted much attention since last decades. These sweet jellies were favorite foods for some people, and unfortunate accidents were reported. Choking accidents caused by sticky rice (glutinous rice) cake (*mochi*), cooked rice, apples, grapes, and candies have been reported, and the Japanese Consumer Affairs Agency tries to bring attention to such accidents:

https://www.caa.go.jp/policies/policy/consumer_safety/release/pdf/consumer_safety_cms204_20201223_01.pdf

Foods shown in Table I are thought to be avoided for persons with difficulty in mastication and swallowing (Table I).

Table I Three categories of foods that are not well tolerated by individuals with swallowing problems[27].

Crumbly and Noncohesive Foods	
Plain ground meat, chicken, or fish	Cornbread
Scrambled eggs	Cottage cheese
Jello	Coconut
Crackers	Nuts and seeds
Peas, corn, or legumes	
Mixed Consistency Foods	
Vegetable soup	Salad with dressing
Soup with large pieces or chunks of food	Canned fruit
Cold cereal with milk	Gelatin with fruit
Citrus fruit	Yogurt with fruit
Sticky Foods	
Dry mashed potatoes	
Peanut butter	
Fresh white or refined wheat bread	
Fudge or butterscotch sauce/caramel	
Bagels or soft rolls	

In the dysphagia management in hospitals, the Food Intake LEVEL Scale (FILS) has been proposed and widely used (Table II).

2. PHYSIOLOGICAL BASIS OF SWALLOWING

It is necessary to know the structure of oropharyngeal organs. Figure 2a and 2b are taken from the open access textbook of anatomy and physiology, and Hiiemae and Palmer[29], respectively.

To define the aspiration more quantitatively, Penetration-Aspiration Scale (PAS) was proposed[31] based on videofluoroscopic swallowing (VFSS) examinations of dysphagic subjects (Table III).

The effect of viscosity on the PAS and the aspiration was examined by using barium sulfate thickened with starch or gum for 100 patients, and both PAS and the number of aspiration were found to decrease with increasing viscosity[32].

A fiberoptic endoscopic evaluation of swallowing (FEES) test has been widely used because of its cost- and time-effectiveness over VFSS without large-scale X-ray

Table II Food Intake LEVEL Scale categorizing the severity of dysphagia into 10 levels[28].

Food Intake LEVEL Scale

No oral intake
- Level 1: No swallowing training is performed except for oral care.
- Level 2: Swallowing training not using food is performed.
- Level 3: Swallowing training using a small quantity of food is performed.

Oral intake and alternative nutrition
- Level 4: Easy-to-swallow food less than the quantity of a meal (enjoyment level) is ingested orally.
- Level 5: Easy-to-swallow food is orally ingested in one to two meals, but alternative nutrition is also given.
- Level 6: The patient is supported primarily by ingestion of easy-to-swallow food in three meals, but alternative nutrition is used as a complement.

Oral intake alone
- Level 7: Easy-to-swallow food is orally ingested in three meals. No alternative nutrition is given.
- Level 8: The patient eats three meals by excluding food that is particularly difficult to swallow.
- Level 9: There is no dietary restriction, and the patient ingests three meals orally, but medical considerations are given.
- Level 10: There is no dietary restriction, and the patient ingests three meals orally (normal).

Swallowing training: Training conducted by an expert, well-instructed caregiver, or the patient himself/herself to improve the swallowing function.
Easy-to-swallow food: Food that is prepared so that it is easy to swallow even without mastication, for example, meat and vegetables are gelatinized or homogenized in a mixer.
Alternative nutrition: Non-oral nutrition such as tube feeding and drip infusion.
Food that is particularly difficult to eat: dry and brittle food, hard food, water, and so on.
Medical considerations: guidance, tests, examinations, and so on, for symptoms suggestive of swallowing disorders such as choking and the feeling of food remaining in the pharynx.

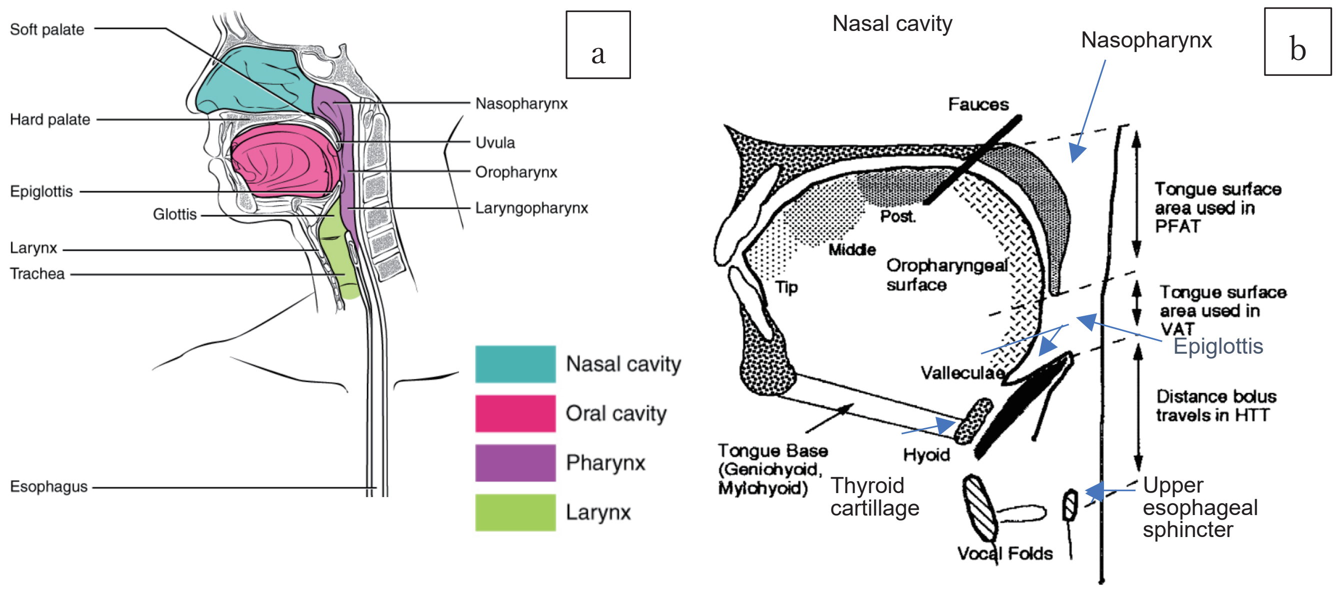

Fig. 2a Sagittal section of nasal, oral pharynx and larynx. (From Anatomy and Physiology - OpenStax, Rice University). 2b The pharyngeal surface of the tongue is facing the soft palate at the upper part, and the oropharynx below the uvula. The sequential events after bolus formation, bolus accumulation and deglutition are shown at right. PFAT, postfaucial aggregation time; VAT, vallecular aggregation time. HTT, hypopharyngeal transit time[29, 30]. This 4 stage model is discussed later.

Table III Final version of the 8-Point Penetration-Aspiration Scale[31).]

1. Material does not enter the airway
2. Material enters the airway, remains above the vocal folds, and is ejected from the airway
3. Material enters the airway, remains above the vocal folds, and is not ejected from the airway
4. Material enters the airway, contacts the vocal folds, and is ejected from the airway
5. Material enters the airway, contacts the vocal folds, and is not ejected from the airway
6. Material enters the airway, passes below the vocal folds and is ejected into the larynx or out of the airway
7. Material enters the airway, passes below the vocal folds, and is not ejected from the trachea despite effort
8. Material enters the airway, passes below the vocal folds, and no effort is made to eject

equipment and in addition immobile patients can undergo FEES at their bedside[33)]. Hyodo, Nishikubo, & Hirose[34)] proposed a scoring quantitatively the swallowing difficulty from FESS measurement. This method (Hyodo score) consists of the summation of 4 VFSS parameters each having 4-point (0, normal; 1, mildly impaired; 2 moderately impaired; and 3, severely impaired), and thus the sum ranges from 0 to 12. Four VFSS parameters are (1) the degree of salivary pooling at the vallecula and pharyngeal clearance in the pyriform sinuses; (2) the glottal closure reflex induced by touching the epiglottis or arytenoid with the endoscope; (3) swallowing reflex initiation assessed by white-out timing; and (4) pharyngeal clearance after swallowing blue-dyed water[33-35)]. The ratio of aspiration was found to increase with increasing the Hyodo scores (Fig. 3).

3. HOW INGESTED FOODS ARE PROCESSED IN THE MOUTH? THE CONDITION FOR SWALLOWING

Since the texture is a total sensation of physical properties perceived in the mouth, Szczesniak[36)] called it a sensory property. However, it is well known that the sensory evaluation of hardness, stickiness, adhesiveness and other parameters shows the individual difference and the reproducibility is not always good even for one panelist because of the fatigue and adaptation. In addition, it is time consuming and expensive to train the panelists. Thus, the instrumental measurement has been done typically by two cycles of compression and decompression of solid foods, called TPA (texture profile analysis)[36)]. Some caution is necessary to perform the TPA. Since most foods are not a pure elastic material, mechanical parameters obtained by such TPA method depends on the compression speed, and unfortunately this was neglected by many previous reports[37)].

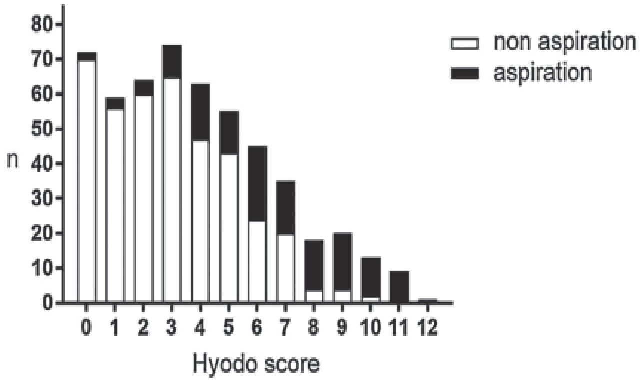

Fig. 3 The number of patients according to the Hyodo scores obtained from 528 patients. Black and white boxes represent patients with and without aspiration, respectively[33)].

Lets' discuss first the hardness which is the peak force in the first compression. If the solid foods are observed to break at the peak force, then the hardness can be converted to a stress (Pa) at fracture for the foods. This is assuming that the shape and size of the samples can be determined. However, if the shapes of the samples are irregular, and/or that the force continues to rise even though the samples have been observed to have fractured, then the determination of the stress at fracture is difficult. Hence, many papers report the hardness in terms of the peak force (N) and it should be noted that the hardness value will change if a different shape and/or size is used. Furthermore, since most solid or semi-solid foods are not purely elastic but often viscoelastic, the observed force at fracture depends on the compression speed[37-39)]. Bourne[37)] pointed out that a good correlation was found for two cheese samples, Gouda cheese and White Stilton cheese, between the instrumental measurement and the sensory evaluation only when the compression velocity was selected appropriately. A sensory panel always rated Gouda cheese as being harder than White Stilton cheese. The compression force was found greater for Gouda than White Stilton only when the compression velocity was 20, 50 and 100 cm/min. The rheological test was found to correlate well with the sensory test only when the compression velocity was 20, 50 and 100 cm/min (100 cm/min was found the best).

It should be noted that a clear peak force is not found in the compression for plastic materials such as butter and margarine, and the maximum force in the compression test is often used for representing the hardness. Not only the compression velocity as discussed above and elsewhere[39)], the friction between the sample surface and the platen (plunger) plays an important role affecting the peak force in the uniaxial compression.

Figure 4 shows the stress-strain curves for cylindrical Mozzarella cheese specimens with different heights. While the stress-strain curves in uniaxial compression in the presence of a lubricant coincided, those without lubricant differed in samples with different heights because of the different degrees of barreling[40)]. Therefore, it is important to take this into account when talking about the hardness.

Indentation method has been used for foods which cannot be made into a well-defined shape with irregular curvature. Goh & Scanlon[40)] worked out the indentation for fat particle gels, shortening, butter and margarine based on indentation tests and the numerical calculations, which is expected to give clear physical basis for the empirically determined TPA hardness.

Adhesiveness in food science is usually determined from the negative area in TPA force–time curve, during the upstroke of the plunger, which corresponds to the resistance of the material to the plunger being lifted, thus reflecting the sample adhesion to the plunger or the difficulty of pulling away the plunger (or teeth) from the food[41)]. Since TPA is generally used to mimic the human mastication, the adhesiveness determination by TPA test for a dried food such as biscuit or potato chips without adding saliva or water could not be recommended. Other possible pitfalls have been pointed out in Brenner & Nishinari.

Healthy persons usually do not care the oral processing and enjoy foods without being conscious. The mouth process model was proposed in 1988 by Hutchings and Lillford[42)]. In this mouth process model, some typical food trajectories are represented in three dimensional space, structure (z-axis), time (x-axis), and lubrication (y-axis) as shown in Fig. 5.

According to this model, solid food should be comminuted into smaller fragments and mixed with saliva to be lubricated and forms a bolus before swallowing. A raw oyster is very slippery with low adhesion or friction, and very difficult to control in the mouth as commented by Wu, Guneratne, Collado, Corke & Lucas[43)]. Thus, a slippery food such as a raw oyster and beverages/drinks are usually swallowed immediately except in the wine tasting or in a similar situation/condition. The structure of a dry sponge cake is weak, but it needs to be masticated and mixed with saliva to increase the lubricity. This essential point has been discussed more actively by many workers[39, 44-47)] after the 1st Food Summit on "Texture-perception and measurement" in Wageningen[48)]. Not all the foods follow the trajectory depicted in Fig. 5. Rosenthal[49)] found that the structure of paste of oil seed was strengthened in the initial phase of the mouth process, which he called "hard-to-swallow" sensation. Rosenthal and Yilmaz[49)] reported that both the compressive force and the tack, closely correlated with the adhesiveness, increased with increasing the amount of the added water up to ca 25 % before decreasing with the further addition. Because of the

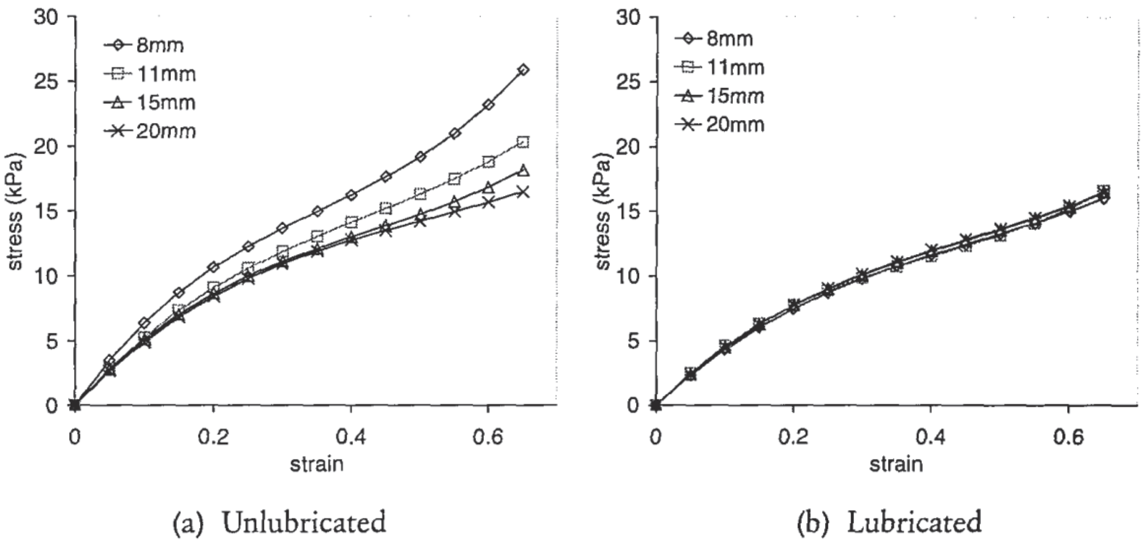

Fig. 4 Stress-strain curves for Mozzarella specimens with different initial heights H = 8, 11, 15, and 20 mm[40)] at 21 °C. Stress is given by $Ph/(\pi R^2 H)$, and strain is $\ln(H/h)$, where P is the instantaneous force, R (= 10mm) is the initial radius of the specimen, H and h are the initial and instantaneous specimen heights respectively. A synthetic grease which contains Teflon was used as lubricant.

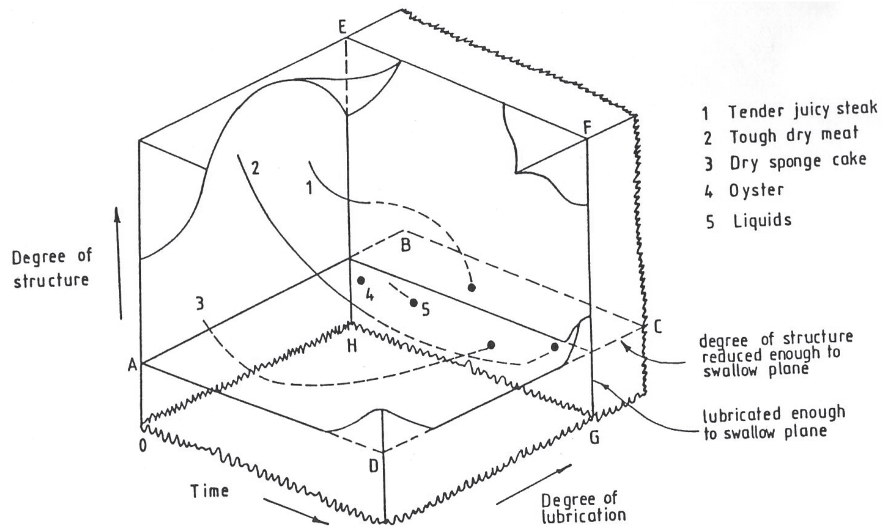

Fig. 5 The mouth process model[42].

arrow of the time, we cannot go back to the future, the original schematic representation in Rosenthal and Yilmaz[49] was corrected to that shown in Fig. 6. As shown in this example, the trajectory of ingested food depends strongly on the food properties.

Shiozawa, Kohyama & Yanagisawa[50] reported the three TPA parameters, hardness, adhesiveness and cohesiveness for boli, formed by 11 healthy adults, of peanuts, sticky rice cake (*mochi*), and biscuit at three stages, M stage, the half-way stage of mastication, L stage, immediately prior to swallowing, +20 % stage, where the number of chewing strokes 20 % beyond a point at which swallowing would usually occur. While the hardness decreased with increasing number of chewing through three stages for all three food types, the adhesiveness showed a maximum at L stage for peanuts and biscuit. It was thought that at least the adhesiveness ~ 1 kJ/m^3 was required to form a bolus at L stage for most foods. While the adhesiveness of rice cake bolus decreased, it should be reminded that the adhesiveness of rice cake (*mochi*) ~ 2 kJ/m^3 even at +20 % stage is much higher than that of other foods.

The cohesiveness for rice cake bolus did not change throughout the stages while this parameter increased and showed a maximum at L stage for peanuts, which coincided with a previous report by Prinz and Lucas[51]. The cohesiveness for biscuit bolus first increased from M to L stage, and remained unchanged thereafter.

Stickiness of cooked rice was reported as the most important attribute determining the liking in Japan[52]. The sensory stickiness was found closely correlated with the negative force peak and the area (energy) in the TPA in addition to the stickiness/hardness balance for the determinant factor of the liking. Recently, this was further corroborated[53, 54]. Liking

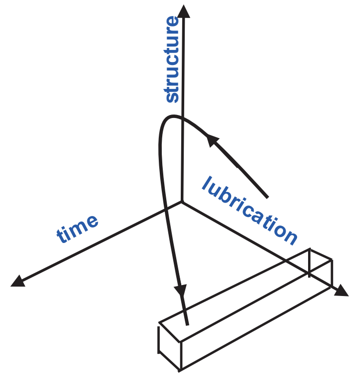

Fig. 6 A typical trajectory of a hard-to-swallow type food such as oil seed pastes. This exemplary trajectory is not included in the original Hutchings-Lillford mouth process model shown in Fig. 5. In the initial stage, the "structure" is increased by absorbing water or saliva[38].

for stickiness is known to differ among different food culture. Broadly speaking, stickiness in cooked rice is disfavored in India, Bangladesh, Nepal, Sri Lanka, Malaysia, Thailand, Burma and the West in general, while it is preferred in Japan and Korea; intermediate characteristics seem to be preferred in Indonesia, the Philippines and Vietnam[55]. On the other hand, the stickiness is not liked for noodles in Japan, and the incorporation of alginate or pectin was found useful to reduce the stickiness of rice noodles[56]. It may be worthwhile to remind the definition of cohesion and adhesion to avoid the confusion[54, 57, 58]. The cohesion refers to the product-product bonding or particle-particle bonding while the adhesion means the bonding between the product and the teeth or tongue or palate in FOP and the surface of the equipment such as pipe or metal surface in food production where, it is typically considered a negative characteristic as it leads to problems such as clogging, scaling and fouling of equipment[58].

The cohesiveness widely used in TPA was unfortunately sometimes misleading[59]. The term "cohesiveness" was first defined in food science as the strength of the internal bonds making up the body of the product and it was determined experimentally as the ratio of the area under the curve of the second bite to that of the first bite in texture profile analysis (TPA)[60]. However, the physical meaning of this concept was not clear, because the x-axis in TPA was the time, and Peleg changed it to the deformation, so that the area under the curve would represent the work or energy[61, 62]. This is in line with the flow-ability index used widely in powder technology[63]. Flow-ability of solid particles is characterized quantitatively by the flow index, the ratio ffc of unconfined yield strength to the consolidation stress. The larger value of ffc indicates the higher flow-ability, where the consolidation stress and the unconfined yield strength are determined in the uniaxial compression test of solid particles filled in a hollow cylinder and those without a hollow cylinder. The flow behaviour of solid particles is classified by the value of the flow index ffc, as: $ffc < 1$ not flowing, $1 < ffc < 2$ very cohesive, $2 < ffc < 4$ cohesive, $4 < ffc < 10$ easy-flowing, $10 < ffc$ free-flowing[63]. As for the cohesiveness for fluids, the extensional viscosity and breakup in the extension of fluid filament was found to give a good measure[38, 64, 65].

It was thought that cohesiveness is important for ease in swallowing where the scattering into smaller pieces will lead to the aspiration[66, 67]. On the other hand, adhesive bolus will stick to the oral surfaces and will remain as the residue after swallowing, which in the worst case will cause the aspiration.

For five different types of foods, Melba toast, Gouda cheese, raw carrot, breakfast cake, peanuts, van der Bilt & Abbink[68] found that the muscular work W_m per chewing cycle decreased monotonically with increasing number of chewing for Gouda cheese, raw carrot, breakfast cake, while the W_m increased first and then decreased for melba toast and peanuts. The muscular work (W_m) was estimated as the muscle activities of electromyography (EMG). These authors found that chewing cycle duration decreased first and showed a minimum and then increased until swallowing for all five foods.

In short, foods are crushed and mixed with saliva thus lubricated and are formed into a bolus, transported to the posterior part of the mouth and then swallowed. In the initial phase of food oral processing, bulk rheology plays a dominant role, while in the later phase, especially in the bolus transport by the tongue, the tribological aspect becomes more important[43, 69-71].

To understand and prevent the aspiration, it is necessary to study how the ingested foods are processed by oral organs in more detail. The swallowing phenomenon had been studied by videofluorography (VF) using command swallow; subjects or patients swallowed liquids with a signal given by the instructor. The swallow was divided into four sequential stages: oral preparatory, oral propulsive, pharyngeal, and esophageal stages. This four stage model was adequate for analysis of the swallow of liquid without chewing, but could not explain the swallow accompanying the chewing of solid foods. Palmer and Hiiemae[29, 30, 72] proposed a process model to analyze the oral processing of wide range of foods including solid foods. For solid foods, food processing is divided into four stages: the Stage I, Stage II (food processing in the oral cavity can overlap temporally with the aggregation in the oropharynx), pharyngeal stage and esophageal stage[73, 74]. How the ingested foods are processed in the mouth differs for liquids and solids. Even for a liquid bolus, four stages must be studied: Oralpreparatory stage, oral propulsive stage, pharyngeal stage and esophageal stage (Fig. 7).

Although the detailed mechanism governed by oral mechanoreceptors is still unknown, in the archetypical

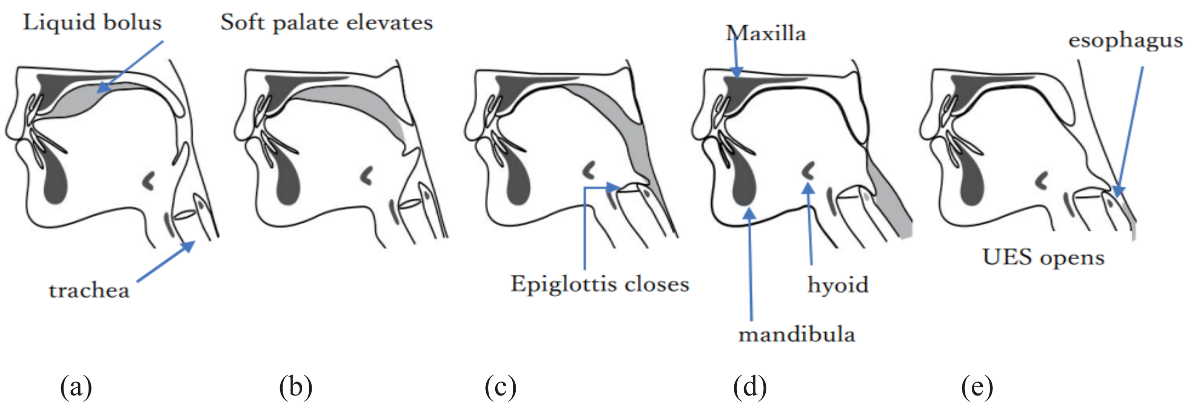

Fig. 7 Schematic images of a liquid swallow in lateral projection of VF. (a) The liquid bolus is first held between the hard palate and the tongue dorsal. (b) The liquid bolus is propelled and the soft palate is elevated to seal off the nasopharynx, preventing postnasal bolus leaking. The area of tongue–palate contact gradually expands from front to back, squeezing the bolus backward. (c) The liquid bolus is squeezed to the back and the epiglottis closes to prevent the liquid bolus leaking into the trachea. (d) Pharyngeal swallow immediately follows oral propulsion. (e) The upper esophageal sphincter (UES) opens[75].

'liquid swallow', the aliquot of liquid is organized in the oral cavity, the tongue rises toward the hard palate anteriorly and begins to push the liquid posteriorly toward the fauces; the posterior oral seal between the soft palate and tongue abruptly opens, the bolus is passed rapidly through the open fauces and into the pharynx. It is then propelled into the esophagus by a combination of tongue and pharyngeal movements[30].

Lucas & Luke[76] described the mastication by two functions: a selection function which determines the probability of particle fracture and a breakage function which is the size distribution of fragmented food particles produced by a bite. The size distribution of crushed particles has been studied extensively. However, the first few chew and the produced particle size have not been so well understood. Prinz and Lucas[77] examined this problem using 1-mm thick pink dental wax wafers with different shapes (rectangles, squares, circular disc). They found that the tongue appears to preferentially orientate particles so that their longest axis is parallel to the mesio-distal axis of the post-canine dentition. By this positioning the selective function might be maximized, thus would yield the highest new food surface area per bite. The Stage I transport is the mechanism by which the bite (the volume of the solid food placed on the tongue) is moved from the anterior oral cavity to the occlusal surfaces of the post-canine teeth (premolars and molars)[29, 30, 78], and this movement of food bolus monitored by a Sirognathograph (Fig. 8) and EMG was consistent with the above-mentioned description by Prinz & Lucas[77].

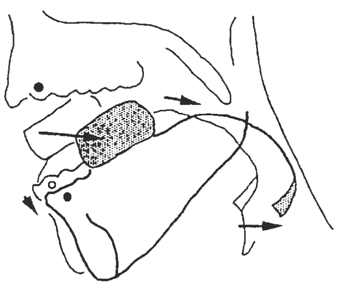

Fig. 8 Stage I transport. A 6 g piece of shortbread cookie was deposited on a slightly elevated tongue surface. As the jaw opens a little more (arrowhead), the tongue surface drops below the occlusal plane of the lower postcanine teeth and is pulled sharply backwards with the hyoid (longer arrows) The lumen of the pharynx is almost obliterated (bottom right arrow). This 'pull-back' lasted about 280 ms and was followed by elevation and rotation of the tongue surface bringing the cookie into position on the molars ready for tooth-food-tooth contact and the first power stroke[30]. Jaw movements were recorded using a Sirognathograph, which registers the deviation of a small magnet (10 × 5 mm, 10 Gauss) glued to the lower central incisors with cyanoacrylic adhesive from a baseline position established with the individual's teeth in centric occlusion[78].

Matsuo &Palmer[79] examined the linkage of soft palate and jaw movement (Figs. 7 & 8).

In the study of the temporo-spatial linkage of soft palate and jaw movements during eating three solid foods with different hardness, banana, chicken spread and cookie (each 6 g), the movement of the soft palate (SP) is monitored by a marker at the edge of the tube located on the soft palate, and that of the jaw was monitored by a marker glued to the lower canine as shown in Fig. 9[80]. The position and the amplitude of the cyclic motion of the SP gradually increased as the sequence progressed from mastication, oropharyngeal bolus aggregation and swallowing. In the oropharyngeal bolus aggregation period, SP rose at higher position than at the mastication period, which was interpreted as the free space increase to help the transport of the bolus to the posterior region. The position of SP was found higher with increasing hardness of food. The increase in SP displacement in later cycles was thought to facilitate bolus transport by opening the fauces, and additionally provide a route for odors to reach the nasopharynx. The pharynx is closed at the moment of swallowing to prevent the reflux of the bolus from the pharynx to nasal cavity.

In the subsequent study of the movement of the tongue, jaw, hyoid during eating and speech, Matsuo & Palmer[79],

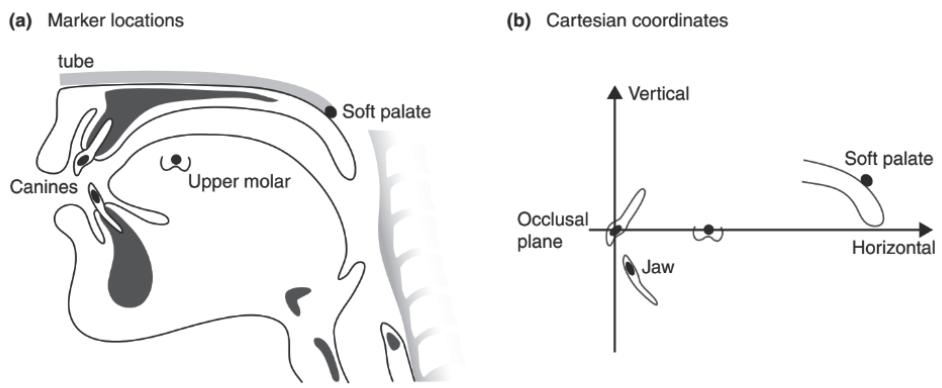

Fig. 9 In the study of the movement of soft palate and the jaw, the markers (5 mm diameter lead discs) were glued at upper first molar, at upper and lower canines, and at the edge of the tube inserted from the nose and located on the soft palate[79, 80].

based on the analysis of the vertical movement, thought that the physical connection of two muscles, the genioglossus running from the mental spine of the mandible into the midline of the tongue body and the hyoglossus running from the superior border of the greater horn of the hyoid bone to the lateral side of the tongue, was thought to make strong kinematic linkage from the jaw or hyoid to the different parts of the tongue during eating. They concluded that vertical movement of the anterior part of the tongue was determined by vertical jaw movement during eating of food, while the posterior part of the tongue was more affected by vertical hyoid movement (Fig. 10). From the analysis of the horizontal movement, the coordinated contractions of the muscles of the tongue and hyoid, attached to the mandible and to the cranial bones, was thought to lead to synchronous antero-posterior movements of the tongue and hyoid during eating[79].

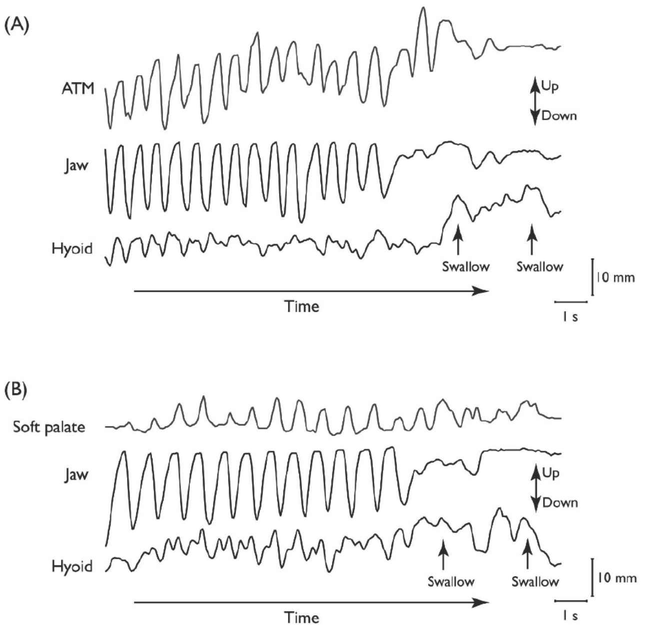

Fig. 10 Movements of the jaw, hyoid, and (A) tongue or (B) soft palate over time. Vertical positions of (A) the anterior tongue marker (ATM), lower jaw, and hyoid bone, and (B) the soft palate, lower jaw, and hyoid bone during eating. Movement towards the top of the figure is upwards. The markers were glued at anterior and posterior part of the dried dorsal tongue (ATM & PTM) in addition to the markers at lower and upper canines and at hyoid. No tube was inserted transnasally. The positions of the structures are plotted relative to the upper jaw over time. Rhythmic movement of the tongue and soft palate is temporally linked to cyclic jaw movement[73].

It is important to know the difference between stage II transport and the oral propulsive phase for liquid drinking. While the stage II transport occurs intermittently during chewing and the bolus is accumulated in the oropharynx or vallecula (Fig. 11), the pharyngeal swallowing follows immediately after the propulsion of liquid food.

Palmer clarified that the transport of the food bolus from the oral cavity to the pharynx is driven by the tongue and did not depend on the gravity by quantifying the time interval of three subsequences: 1) Oral processing time (OP) defined as the interval from the start of that subsequence until the leading edge of the contrast material reached the inferior border of the mandible, 2) Vallecular aggregation time (VAT) -The onset of VAT was operationally defined as the time at which the leading edge of the contrast material reached the inferior border of the mandible, 3) Pharyngeal swallow duration (PS) -PS was the duration of the pharyngeal phase of the swallow. Pharyngeal phase onset was operationally defined as the start of sudden, rapid superior and anterior motion of the hyoid bone. Pharyngeal phase ending was defined as the moment the hyoid completed its return phase, having moved anteriorly and superiorly and reversed direction. These measurements were done by VF recording of 5 healthy subjects during eating hard (cookie and peanuts) and soft (banana and chicken spread) foods containing barium, first seated upright and then kneeling face down (quadruped position). OP was found longer for hard foods than for soft foods. The measured intervals (OP, VAT, and PS) did not vary significantly between the two soft foods (chicken spread and banana) ($p > 0.99$), so data for these two foods were combined, as were the data for the two hard foods (peanuts and cookie) ($p > 0.99$).

OP mostly consisted of chewing cycles (reducing particle size, softening food and mixing with saliva) and was longer for hard than for soft foods, as expected. As shown clearly in Fig. 12, OP was longer in upright than face-down position, which suggested that gravity was not required to move food into the vallecula.

Saitoh[81] showed a patient who aspirated water can swallow a paste with higher viscosity or even water when the trunk was reclined (Fig. 13). This information is directly

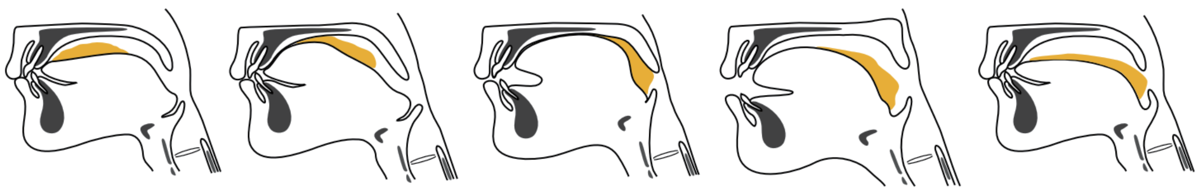

Fig. 11 Schematic images of stage II transport. The tongue transports the bolus by squeezing, from the palate through the fauces, and into the pharynx. The bolus head reaches the vallecula while food processing still continues[73].

related to how to take care of patients. By reclining the body position, the location of the larynx should be relatively above the entrance of esophagus, decreasing the chance of aspiration (Fig. 14). Although the epiglottis does not close the entrance to the trachea in a person with dysphagia in Fig. 14, it is not always the case. It is generally observed that the epiglottis is not sufficiently closed or it does not close at all in persons with difficulty in mastication and swallowing.

Effects of the viscosity of liquid component in two phase foods consisting of solid and liquid such as 5 g of steamed rice +3 mL of water[83] or 4 g of corned beef hash +5 mL of liquid barium[74] have been studied. These studies showed that the swallow initiation was delayed and the bolus location was located at higher position in the pharynx with increasing viscosity of the liquid. Thus, these authors concluded that adding thickening agents to otherwise thin dysphagic two phase food might be beneficial to reduce the risk of aspiration. Subjects were 18 healthy adults with mean age 26.7 ± 3.7 years, and jaw motion was measured by a 3D motion-tracking system, and the food transport in the pharynx was observed with a fibroscopic endoscope in the study by Matsuo *et al.*[83].

Printz and Lucas[72] proposed the hypothesis that the swallowing occurred at the moment when the cohesive force becomes maximum. In their analysis, the viscous force F_V required to separate the agglomerated particles was evaluated by the separation force of two parallel discs $F_V = \frac{3\pi\eta R^4}{4td^2}$ [84], where η is the viscosity of the oral fluid filling spaces between two discs, R is the diameter of the disc, t is the time span over which the separation takes place and d is the average distance between two discs (Fig. 15). Adhesive force exerting between the agglomerated particles and the oral surface (palate and the tongue) F_A is given by $F_A = 4\pi r\lambda$ where r is the radius of the spherical particle and λ is the surface tension of the oral fluid. Cohesive force F_C is given by $F_C = F_V - F_A$[85].

In the oral processing of both Brazil nuts and raw carrot with two different textures, Printz and Lucas[86] found that the swallowing occurred at the moment when the cohesive force became maximum after about 25 chews (Fig. 15b). Crushed particles were made into a bolus and the cohesiveness increased in the initial phase, but a delayed swallowing and a further chewing led to the separation of fragmented particles

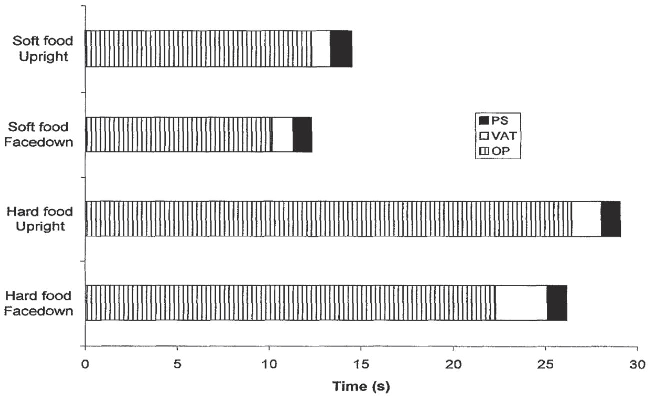

Fig. 12 Timelines for soft and hard foods in upright and facedown positions. First OP (oral processing time) then VAT (vallecular aggregation time) and PS (pharyngeal swallowing duration) followed sequentially. The total length of each horizontal bar represents the mean subsequence duration[72].

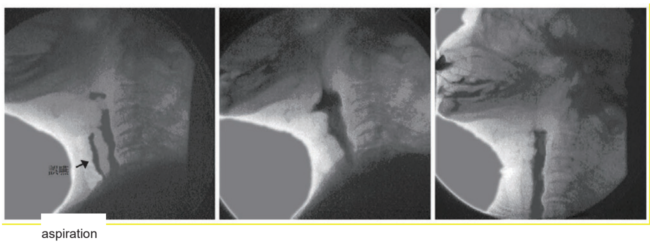

Fig. 13 Effects of texture of foods and posture of a patient on the swallowing monitored by VF. Water was aspirated (left), but a paste was not aspirated (middle). Water was not aspirated when the trunk was reclined (right)[81].

Fig. 14 Schematic representation of effects of posture on the swallowing. Left, Upright posture; Right, 30° reclining posture. Although the epiglottis does not close to prevent the penetration of the bolus into the trachea in this figure, the probability of the bolus entering to the trachea is much lower than that being transferred to the esophagus because of the change in the vertical position of larynx relative to the entrance of the esophagus[82].

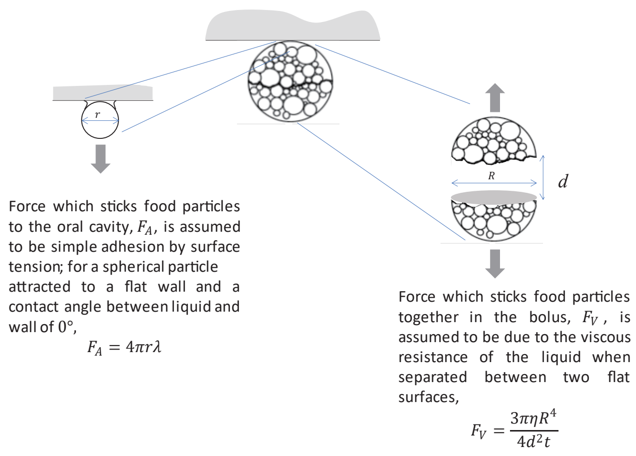

Fig. 15a In the derivation of viscous force, the force to separate the agglomerated crushed food particles was assumed to be represented by the force to pull apart two parallel discs with a Newtonian fluid filling the gap between the discs[84, 85].

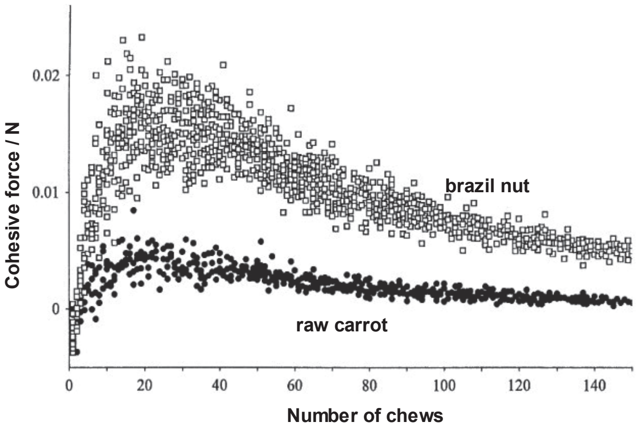

Fig. 15b The cohesive force plotted against the number of chews taken in the masticatory sequence for raw carrot (closed circles) and Brazil nut (open squares) obtained by computer simulation. In spite of the difference in the texture of these two foods, the peak of the cohesive force is seen at about 20 ~ 25 chews[86].

by excessive saliva leading to the lower value of cohesiveness. This led to the loss of the integrity of bolus and increased the risk of aspiration. Matsuo & Fujishima[73] pointed out the similarity to the situation that arises when eating a biphasic food that includes both soft solid and thin liquid components, such as miso soup with tofu in Japan. As predicted by Prinz and Lucas, the low viscosity liquid component can flow rapidly down to the hypopharynx a few seconds before swallowing under the influence of gravity, while the solid component remains in the oral cavity for food processing. When liquid enters the hypopharynx during chewing, it approaches the laryngeal vestibule at a time when the larynx remains open. This may cause aspiration, especially in patients with dysphagia and impaired swallow initiation.

The concept of cohesiveness was not understood clearly, and it became a matter of debate, which will be discussed later.

4. THICKENING CAN PREVENT THE ASPIRATION?

Is viscosity important? It should be noted that the term “thick” is usually used in sensorial evaluation mainly induced by the attribute of the fluid viscosity, while the “viscosity” is rigorously defined in fluid mechanics both for Newtonian and non-Newtonian fluids[57]. The term thickening in food science and technology has been used to mean the increase in viscosity, usually shear viscosity. Recently, the cohesiveness was recognized important as well in the swallowing[86] and in this context the extensional viscosity has been attracting much attention in relation with dysphagia[57]. This will be discussed later. It has been known empirically that high viscous liquid is safer than thin liquid such as water, tea, juice, consommé soup (thin and clear soup), and so some thickening agent is believed to be effective to prevent the aspiration (Fig. 16).

Since the aspiration occurs frequently in the neurogenic patients, it is meaningful to examine the prevalence among such patients. Clavé, de Kraa, Arreola, Girvent, Faree, Palomera *et al.*[26] studied 46 patients with brain damage, 46 with neurodegenerative diseases and eight healthy volunteers by VF during the swallowing 3-20 mL barium liquid (20.4 mPas), nectar (274.4 mPas) and pudding (3931.2 mPas) boluses with the viscosity at room temperature. A similar tendency that the prevalence of aspiration as well as Penetration Aspiration Scale decreased with increasing viscosity was reported for 100 dysphagic patients using thin liquid barium,

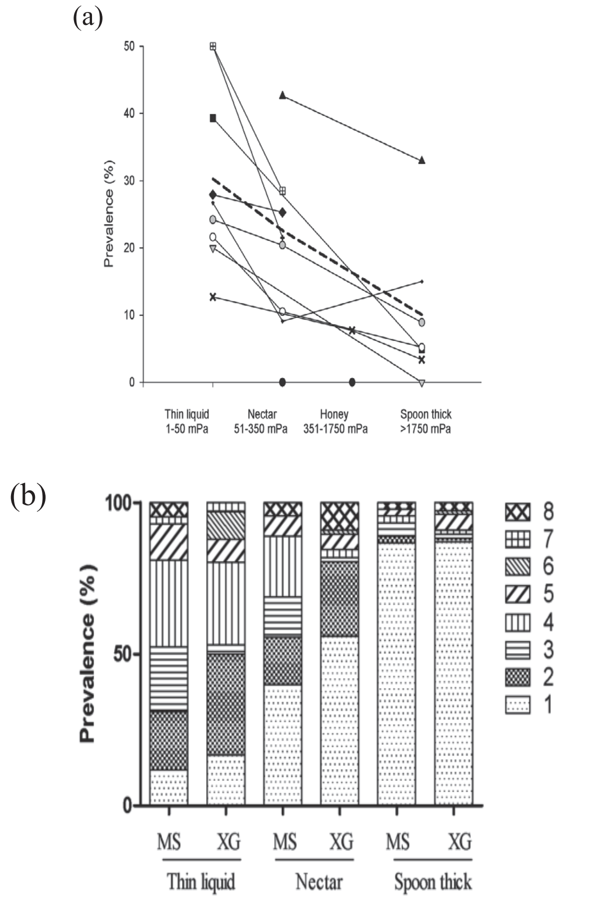

Fig. 16 (a) Prevalence of patients with aspiration according to the level of viscosity gathered from the literature. The aspiration was measured by videofluoroscopy (VFS) or fiberoptic endoscopic evaluation of swallowing (FEES). Note the overall viscosity-dependent reduction on the prevalence of aspiration with maximal therapeutic effect at spoon-thick viscosity. Different symbols are from different research groups. Broken line shows the average of the data from different laboratories[87]. Four viscosity levels, Thin liquid, honey, nectar and spoon thick were defined by National Dysphagia Diet (NDD) Task Force in 2002, and later it was replaced by The International Dysphagia Diet Standardisation Initiative (IDDSI)[88, 89]. (b) Prevalence of penetration–aspiration scale scores (shown in Table II) for each thickener and viscosity. MS, modified starch; XG, xanthan gum[90].

liquid barium thickened with a starch-based agent, and liquid barium thickened with a xanthan gum-based agent[32].

The oral transit time became longer with increasing bolus viscosity delaying the pharyngeal swallow, and a bolus position at swallow initiation is raised in the pharynx[26, 75, 91, 92].

However, some contradictory papers have also been published. Kaneoka, Pisegna, Saito, *et al.*[93] pointed out the lack of evidence of the efficacy for the prevention of aspiration by using thickened fluids.

The International Dysphagia Diet Standardisation Initiative (IDDSI) was founded in 2013 with the goal of developing new international standardized terminology and definitions to describe texture modified foods and thickened liquids used for individuals with dysphagia of all ages, in all care settings, and all cultures.

IDDSI framework testing method consisting of a continuum of 8 levels (0-7) Levels was released in 2017 and updated in 2019 (Fig. 17). The evaluation and classification method proposed in IDDSI aim to be used by people with dysphagia or by caregivers, clinicians, food service professionals, or industry without using sophisticated machines or tools to confirm the level a food or drink fits into Cichero *et al.*[89]. IDDSI committee members wish that this document is to be read in conjunction with the IDDSI documents which can all be found on the IDDSI website (https://iddsi.org/).

Since the barium suspension is widely used to diagnose the severity of the aspiration, it is important to know the validity of the classification of IDDSI level for liquids with and without barium. Barbon and Steele[95] examined this for starch-based and xanthan-based thickeners with and without barium (20 %w/v) at slightly, mildly and moderately thick liquids (IDDSI level 1, 2 and 3). The quantity of xanthan added to get the same level of thickness represented by the remained liquid volume in the IDDSI syringe was found much lower than that of starch. The addition of 20 %w/v barium to the thickening agent was found to increase further the thickness particularly for starch-based thickening agents. All the liquids were found stable 3 h after mixing except the one containing starch stored in the refrigerator. However, a small amount of thickening agents might change the level category so that the authors called attention to clinicians to use the thickening agent to ensure that the liquid is in the middle range thickness of each level. Since both barium and iodine are used as contrast medium in Japan, the effect of these contrast media on IDDSI syringe test was examined recently[96]. They pointed out that the viscosity of xanthan gum-based solution increased while the density also increased by adding these contrast media, and that it is necessary to examine the opposite effect of the viscosity increase increasing the remained volume in the syringe after 10 s, and the density increase decreasing the volume remained. They examined the flow behavior of six commercially available xanthan gum-based thickened solution with and without contrast media, and all the solutions showed similar curves when the concentration of thickeners are plotted as a function of viscosity at 50 s^{-1}.

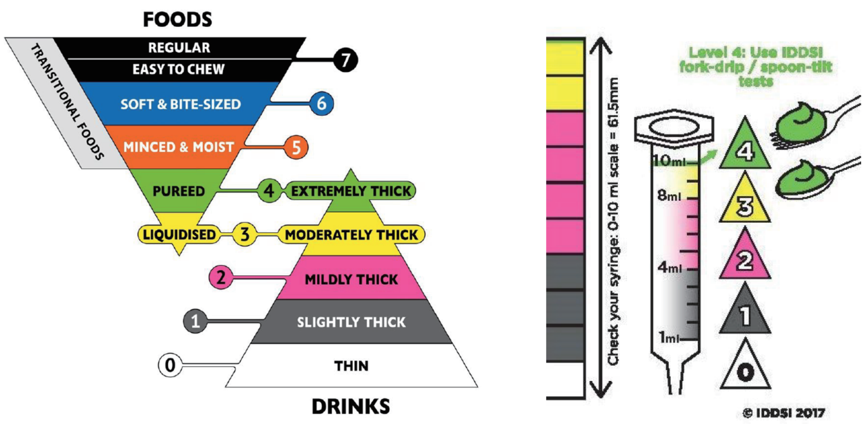

Fig. 17 IDDSI categories of different consistencies. IDDSI flow test is recommended for drinks and liquids of Level 0 to Level 3 such as gravy, sauces and nutritional supplements. It is necessary to ensure that all products should be thoroughly stirred as non-homogenous liquids may give inconsistent results. Foams found in carbonated drinks may appear thick on the flow test as they are less liable to flow under their own weight, as their density is lower. Foams may also be unstable over time and release thinner liquids as the carbonated bubbles burst. For extremely thick drinks (Level 4), that do not flow through a 10 mL syringe in 10 seconds and are best consumed with a spoon, the IDDSI Fork Drip Test and/or Spoon Tilt Test are recommended as methods for determining consistency[94].

Since the flow test proposed by IDDSI specifies the use of a particular syringe type, which is unfortunately not easily available in Japan, several commonly used syringe in Japan was examined to compare the effect of internal syringe shape on the flow test[97]. These authors found a TERUMO syringe was very close to the IDDSI specified syringe.

The international standardization of food texture and liquid consistency is, of course, important and quite useful. On the other hand, unique food cultures and eating behaviors are rooted in each country throughout the world as well[73]. In the development of suitable foods for elderly with dysphagia, a traditional dish *rendang* has been selected in Malaysia. *Rendang* paste composed of ginger, turmeric, lemongrass, garlic, shallot etc. is mixed with finely crushed chicken and heated to make chicken *rendang*. Chicken *rendang* was selected for dysphagia treatment in Malaysia to avoid the rejection caused by food neophobia. Thickeners, modified corn starch, sago starch and tapioca starch, or xanthan gum or carboxymethyl cellulose gum (CMC) was mixed with chicken *rendang* puree to modify the texture. It was found that incorporation of 30 % CMC was found best because this mixture exhibited the highest value of viscosity and yield stress and a highly shear thinning behaviour upon mechanical shearing. This mixture was thought to form a cohesive bolus to minimize disintegration of food matrices, hence minimizing the risk of aspiration[98].

Recently textural characteristics of different foods in more than 20 countries have been published[99]. As Matsuo and Fujishima say, the food texture of dysphagia diets also differs among countries because of food culture and history. In Japan, the 5-stage Seirei Dysphagia Diets, or the so-called Dysphagia Diet Pyramid, were developed in 1993 as the first standardized dysphagia diet categorization system in Japan, and then, the Japanese Dysphagia Diet 2013 (JDD2013) was developed by the Japanese Society of Dysphagia Rehabilitation (JSDR) based on the 5 category levels of the Dysphagia Diet Pyramid. The JDD2013 is now commonly used as the standardized index for dysphagic diets in Japa[73].

The JDD2013 consists of five categories (Fig. 18 and Table IV). Code 0j is swallow-training jelly, which can be placed directly in the mouth and swallowed without chewing (*i.e.*, can be swallowed whole). Code 0t is thickened liquid, which applies to tea or fruit juice thickened with a thickening-adjustment food. The food containing protein is classified as Code 1j. Code 1j is a jelly/pudding/mousse-like food product that does not require chewing. It is homogeneous and soft, with little syneresis.

Code 2 is food in the form of a paste that is sub-classified into 2-1 or 2-2 based on heterogeneity. Code 2-1 is homogeneous food with particles smaller than 850 μm, while Code 2-2 is for inhomogeneous materials containing soft grains (*i.e.*, a blender diet). Typically, Code 2 foods are considered blender, mixer, puréed, or paste foods. Code 3 food contains solid forms, which can be crushed even without teeth into a bolus. Code 4 food can be handled with teeth and is difficult to crush between the tongue and palate. Some general foods of not too hard, not too sticky, and not too crumbly are classified into this category. JDD2013 did not determine the physical property evaluation so that it can be used by general clinicians[73].

Code 0j defined in JDD2013 is swallow-training jelly, which can be swallowed without chewing (*i.e.*, can be swallowed whole). It must be equivalent to the bolus formed after mastication in the mouth. Chen and Lolivret[100] adopted the residence time in the oral cavity when determining the ease

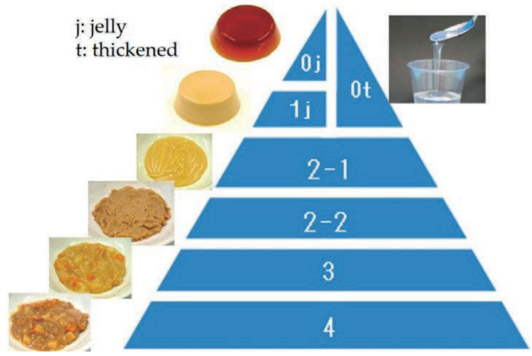

Fig. 18 Schema of diet pyramid by JDD2013[73].

Table IV The TPA parameters, adhesiveness, cohesiveness and hardness of the Dysphagia Diet Pyramid and the JDD2013[73].

Dysphagia Pyramid: Level **JDD2013: Code**	**0** **0j**	**1,2** **1j**	**3** **2-1, 2-2**	**4** **3, 4**
Hardness (N/m^2)	2000-7000	0-12,000	≤ 15,000	≤ 40,000
Cohesiveness	0.2-0.5	0.2-0.7	0.2-0.9	0-1.0
Adhesiveness (J/m^3)	≤ 200	≤ 300	≤ 1,000	≤ 1,000

of eating. If this time is zero, it must be the easiest food to be eaten. From the viewpoint of the problem that eating food is a very important action contributing the QOL, the food which can be swallowed without chewing cannot be the ideal, most suitable food because the pleasure/enjoyment is felt during mastication. This argument was used as mentioned above by Bourne[37)] who pointed out the big number of dentists in the developed countries where the liquid intake or injection will suffice to supply the necessary nutrition.

Liquids thickened by xanthan gum-based thickeners are divided into three categories, mildly thick (50-150 mPas), moderately thick (150-300 mPas), and extremely thick (300-500 mPas) with the viscosity range measured at 50 s^{-1} [101)].

While JDD2013 shows the classification of foods for dysphagia based on simple and widely used TPA parameters and viscosity measured at 50 s^{-1} [73)], IDDSI intend to show the classification of the consistency without using a machine or tool so that people with dysphagia or by caregivers, clinicians, food service professionals can determine the consistency level by using a syringe, fork or spoon. Recently, a new version of JDD2013 was published[102)].

Since the syringes produced by different makers have different shapes and sizes, IDDSI committee is trying to make a standardized syringe. For the moment, it was recommended to use a syringe and to follow the procedure shown in the home page of IDDSI[103)].

For a simple screening the oropharyngeal dysphagia, the volume-viscosity swallow test (V-VST) has been widely used[104)]. Lin *et al.*[104)] modified V-VST adding a volume of 3 ml instead of 20 ml and replacing starch by xanthan gum as a thickening agent in the conventional V-VST. They performed a VF swallowing study (VFSS) using 3 volumes (*i.e.*, 3, 5, and 10 ml) and 4 viscosities (*i.e.*, water, mildly thick, moderately thick, and extremely thick). They found the better discriminating ability based on the assessment of the sensitivity and specificity values of clinical signs of impaired efficiency (labial seal, residue) and impaired safety of swallowing (cough, voice changes, and oxygen desaturation ≥ 3 %) in comparison to the results of VFSS. They pointed out that cough, voice change and oxygen desaturation are common clinical signs for impaired swallowing, but the isolated usage of only one of these measures was insufficient.

Su, Zheng, Chen, Xie, Han, Yang, …Chen[105)] reported swallowing time (the time when the participant is ready to swallow to the completion of swallow), number of swallows and coughs during the test for 5 subject groups with different swallowing abilities from Grade 1 to Grade 5, where Grade 1 to 5 was assigned based on Water Drinking Test. The level number of Grade increased with increasing the swallowing difficulty; Grade 1: capable of drinking (swallow) all water in one go with no side effect; Grade 2: capable of drinking all water by two swallows without causing coughing; Grade 3: capable of swallowing in one go, but accompanied by coughing; Grade 4: need multiple swallows, and also have coughing; Grade 5: need multiple swallows accompanied with frequent coughing. No subject was identified as Grade 5 dysphagia among the 26 participants.

Su *et al.*[105)] found that subjects of Grade 4 require significantly longer time and an increased number of swallows. However, it seems that increased sample consistency is particularly beneficial to this group of subjects, where a higher consistency leads to a reduced swallowing time and a lower number of swallow, while no obvious difference was observed for subjects in the other three group (closer to normal healthier group). For severe dysphagia patients (*e.g.*, Grade 4), the average swallowing time increased with reduced viscosity and increased volume. Su *et al.*[105)] recognized the advantage for IDDSI than NDD, which was shown by the difference between samples of 1.16 and 2.36 % which were categorized at different IDDSI levels in spite of on the same NDD category. Further, they found a strong correlation between the dysphagia grades obtained from the Water Drinking Test and the IDDSI thickness levels, which implied correlation between the capability of swallowing and the thickness level of liquids.

5. BOLUS RHEOLOGY

5.1 Instrumental evaluation of mechanical properties of foods

As for a simple method to estimate the viscosity without using an expensive viscometer, many methods have been proposed. The Bostwick Consistometer: (a) sample is in first compartment with gate closed; (b) gate is open and sample has flowed along the second compartment (Fig. 19).

The viscosity estimated by Bostwick method was compared with that evaluated by the IDDSI method (Fig. 20). Since both methods are based on the volume which flowed during a fixed time, 30 s in Bostwick method and 10 s in IDDSI method, it is possible to compare directly.

Actually, the correlation between Bostwick method and the IDDSI method turned out very good.

Line Spread Test (LST) is another simple method to estimate the viscosity. The liquid sample contained in a cylinder was allowed to spread along the circles by removing the cylinder. After 30 s or one minute, the amount of spread was

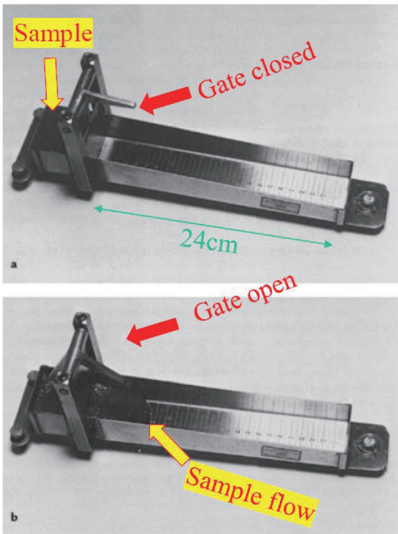

Fig. 19 The Bostwick Consistometer: (a) sample is in first compartment with gate closed; (b) gate is open and sample has flowed along the second compartment[37].

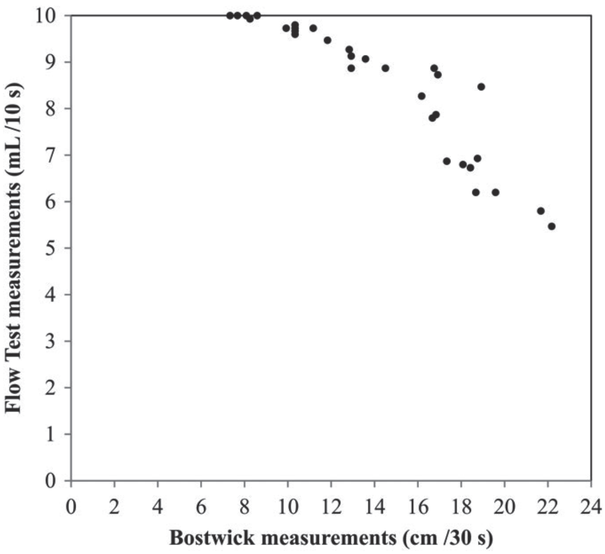

Fig. 20 Relationship between Bostwick measurements and IDDSI. Flow Test measurements for each tested thickened liquid (n = 32). The scale in the graphic has been set in accordance with the real scale of each instrument to show their coverage[106].

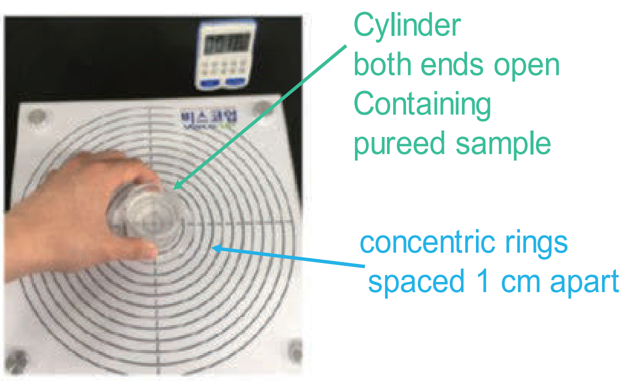

Fig. 21 In Line Spread Test, the sample confined in the cylinder was allowed to spread along the circles. After one minute, the amount of spread was measured at four points on the circles and averaged[107].

measured at four or six points on the concentric circles and averaged (Fig. 21).

The LST was recently used to evaluate the textural properties of thickeners because it is simple and accessible[108]. LST and IDDSI were found to be consistent (Fig. 22). The liquid with low viscosity showed a large distance in LST and a small quantity was left in the IDDSI syringe.

The consistency of liquids was quantified by two distance measurement methods, Bostwick method and LST, and the time measurement using a Zahn viscosity cup (measuring the flow time of liquid through an orifice at the bottom of a bullet-shaped stainless steel cup (44-ml capacity))[109]. Garcia *et al.*[109] found a high correlation between Bostwick method and LST, while a Zahn viscosity measurement did not provide objective information about liquid consistency, the reason of which was attributed that a Zahn viscosity method was only successful for Newtonian fluids. Since a Zahn method was similar to the IDDSI syringe method, this type of measurement should be further refined.

Based on computational fluid dynamics (CFD) simulation, Hanson, Jamshidi, Redfearn, Begley, & Steele[110] examined the validity of IDDSI using three different liquids with different shear thinning behaviors, glycerol as a Newtonian fluid, Starch-based Resource ThickenUpTM and xanthan gum-based Resource ThickenUpTM Clear (both products of Nestlé Health Science) (Fig. 23).

Gum-based liquids were perceived as "slippery" in comparison to other types of thick liquid because the velocity at the edges was high (Fig. 24), which was consistent with a previous report[111].

The consistency of extremely thick purée can be evaluated with spoon tilt method.

After blender treatment, food inks of Bok Choi, carrot, pea were sieved, and added xanthan, κ-carrageenan, and/or locust bean gum (LBG) (Fig. 25).

The consistency of soft solid foods can be evaluated by pressing with fork or spoon (IDDSI, 2019).

The degree of thickness (*toromi* in Japanese) evaluated by tilting spoon is categorized into four groups, French dressing-like, pork-cutlet sauce-like, ketchup-like, mayonnaise-like by Japan Care Food Conference which proposes Universal Design Foods[113].

As is well known, soft foods can be crushed between the tongue and the hard palate[114]. Japan Care food conference showed the degree of hardness for cooked rice which is staple food in Japan. The hardness of cooked rice can be controlled by the amount of water and the cooking time[113].

There are many softened foods by partial enzymatic

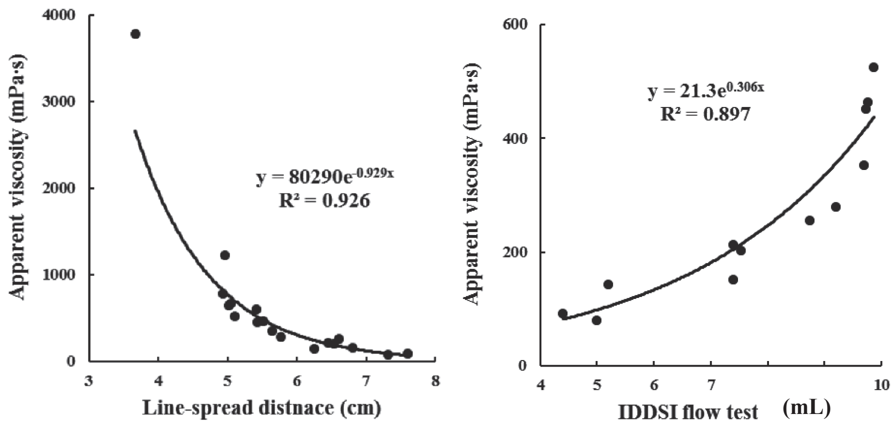

Fig. 22 Relationships of apparent viscosity (η_a at 50 s^{-1}) and flow distance (LST) or flow volume (IDDSI flow test) values of thickened water samples prepared with six food thickeners at different thickness levels[107].

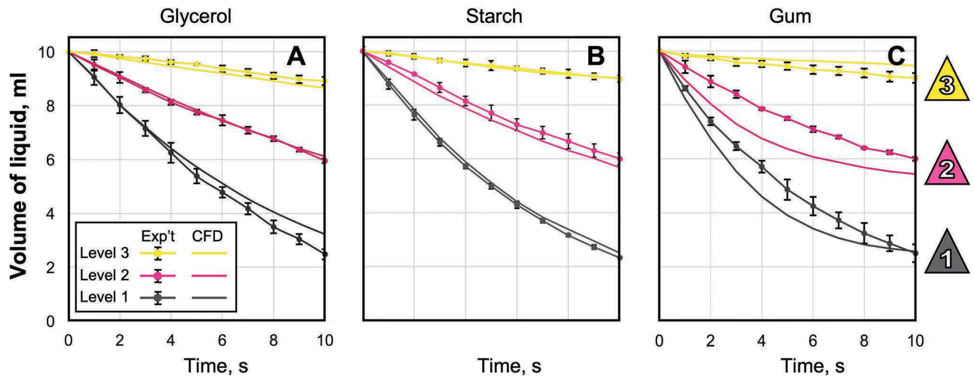

Fig. 23 (A-C) CFD simulation of the volume of liquid remaining in the syringe barrel during the 10 s IDDSI flow test duration, in comparison with experimental data. Mean ± SD of the three repeated runs indicated by error bars. (A) Glycerol/water; (B) Starch thickened water; (C) Gum-thickened water. Panels share a common y axis. IDDSI level labels (1-3) are indicated on the right-hand side[110].

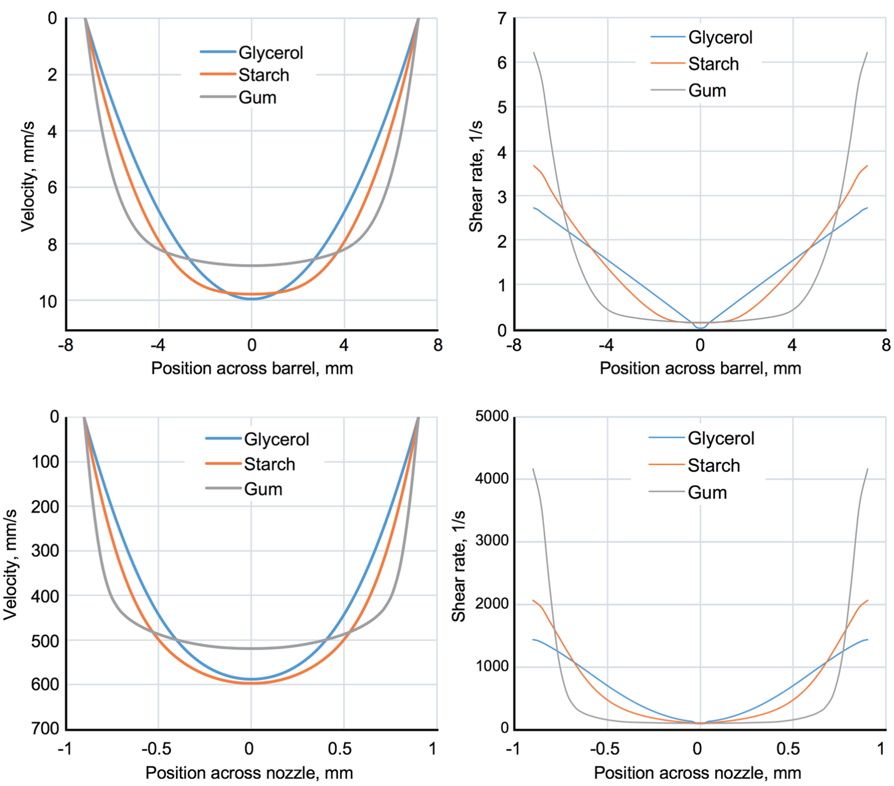

Fig. 24 Computed flow velocity (Left) and shear rate (Right) in the syringe barrel (Top) and at the nozzle-end orifice (Bottom). IDDSI Level 1 liquids shown, at t = 3 s from start of test. Non-Newtonian (Gum and Starch) liquids show disproportionately higher shear rates at the edges, with higher maximum values than Newtonian (Glycerol)[110].

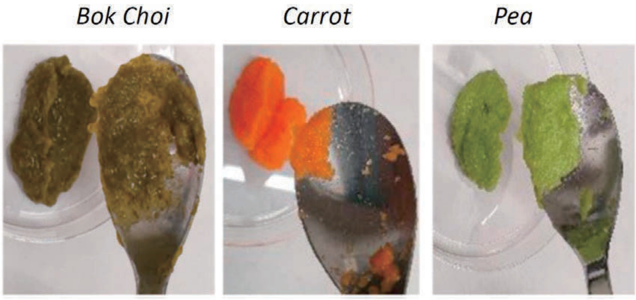

Fig. 25 Examples of foods belonging IDDSI Level 4 texture of which is estimated by spoon tilting[112].

hydrolysis. Pureed foods have the same nutritional value but the appearance is not liked by consumers. Many commercially available foods soft enough to be crushed between the tongue and the palate can be seen at the home page of Japan Care Food Conference: https://www.udf.jp/products/detail.php?product_id=1354.

5.2 Effect of size reduction and saliva

It is useful to study rheological properties of bolus to understand the mastication process as a function of the degree of mastication. A simple combination of compression and rotation of a plunger mimics well the bolus formation as shown in Fig. 26[66, 115].

Four model boli composed of deacylated gellan gum and psyllium seed gum were prepared. Concentrations of single component gels of gellan alone were 0.075 % and 0.15 %, and those of composite gels (mixed gels of deacylated gellan gum and psyllium seed gum) were 1.0 % and 1.5 %. These concentrations were determined to make yield gel strength of ca 1000 Pa (for 1.0 % composite gel and 0.075 % gellan gel) and ca 4000 Pa (for 1.5 % composite gel and 0.15 % gellan gel) at 20 °C. As a reference, 1.0 % and 1.5 % solutions of psyllium seed gum were used.

Figure 27 shows the frequency dependence of storage modulus G' for four model boli with psyllium seed gum solutions. While G' for boli prepared from composite gels decreased only slightly by adding saliva, the value for boli prepared from single component gels of gellan alone decreased remarkably by adding saliva.

In addition, the sensory evaluation showed that cohesiveness was found much higher for composite gels than for single component gels, and thus the composite gels were found much easier to be swallowed than single component gels in spite of higher adhesiveness (Fig. 28). This originates from the insensitivity of rheological properties for composite gels by the addition of saliva. It has been reported that higher adhesiveness decreased the swallowing ease for semi-solid foods, requiring most efforts in pharyngeal swallow in the elderly[116].

If rheological properties of foods prior to oral processing are close to those of bolus, the mastication effort could be lower indicating the swallowing ease. The weak frequency dependence of G' for model boli shown in Fig. 27 together with low tan δ is the signature for structured fluids (previously called weak gels) and was found a cohesive behaviour in swallowing without being scattered into separated fragments[66, 67] as will be discussed later again. This criterion for

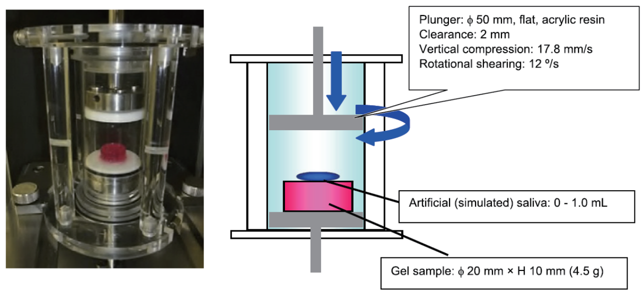

Fig. 26 Instrumental mastication simulator to prepare model bolus[66, 115].

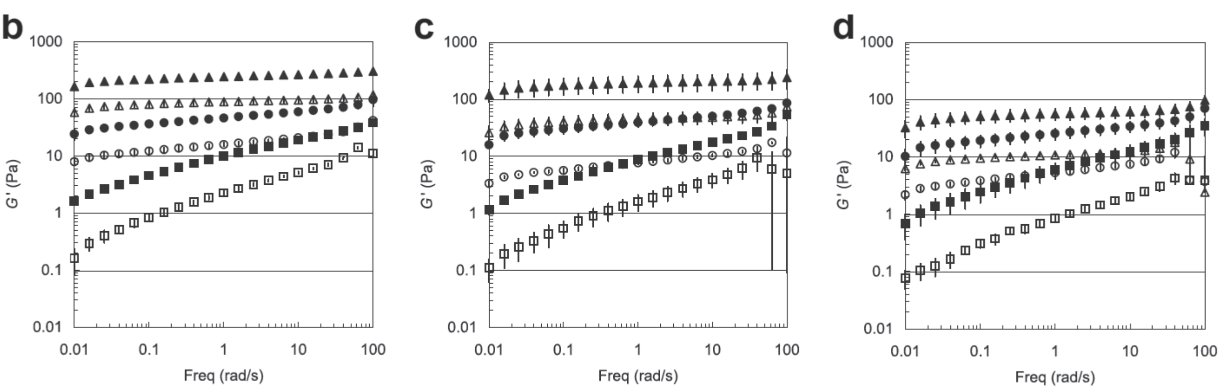

Fig. 27 Frequency dependence of G' for model boli prepared instrumentally with and without artificial saliva. A model bolus was prepared from a 4.5 g cylindrical gel (20 mm diameter and 10 mm height) using a simulator shown in Fig. 22. (b) model bolus in the absence of artificial saliva; (c) model bolus in the presence of 0.5 ml artificial saliva; (d) model bolus in the presence of 1.0 ml artificial saliva. Measurements were carried out at 20 °C at a fixed strain of 1 % in the frequency range from 0.01 to 100 rad/s. ○: 1.0 % composite gel (a mixture of deacylated gellan gum and psyllium seed gum); ●: 1.5 % composite gel; △: 0.075 % deacylated gellan gum gel; ▲: 0.15 % deacylated gellan gum gel; □: 1.0 % psyllium seed gum; ■: 1.5 psyllium seed gum. Data are presented as means ± SD of triplicate[66].

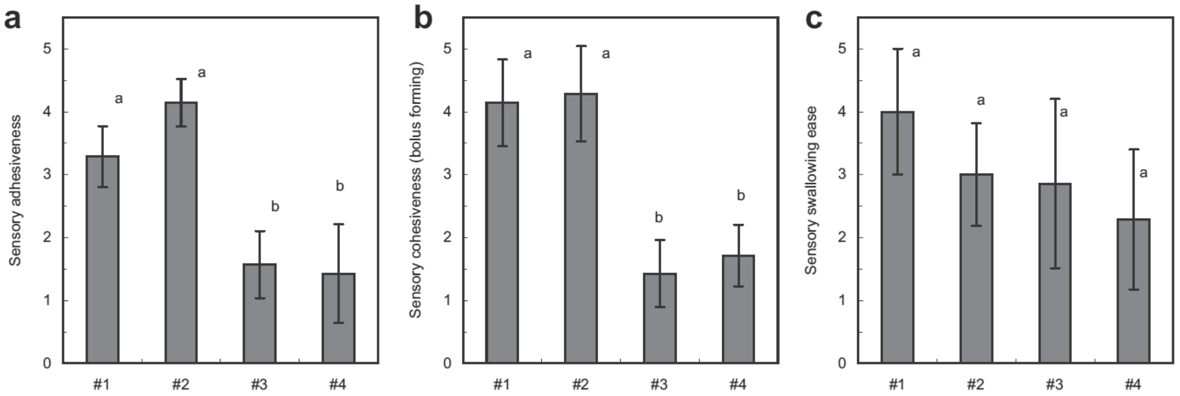

Fig. 28 Sensory scores during swallowing. (a) adhesiveness; (b) cohesiveness (bolus forming); (c) swallowing ease. #1: 1.0 % mixture of deacylated gellan gum and psyllium seed gum; #2: 1.5 % mixture; #3: 0.075 % deacylated gellan gum; #4: 0.15 % deacylated gellan gum. Each sensory attribute was evaluated on a 5-degree scale; the larger the values, the greater the each attribute is. Data are means ± SD of seven subjects. Values with different superscripts are significantly different ($p < 0.05$)[66].

safely swallowable bolus was adopted by Suebsaen, Suksatit, Kanha, Laokuldilok[117] who proposed banana soft dessert gels containing agar, carrageenan, and gelatin for the elderly with dysphagia.

A similar instrumental mastication consisting of compression and decompression with and without rotational shearing was used to evaluate the rheological change for semi-solid foods[118] and for model food sauces[119]. More recently, rheological change by a similar instrumental mastication was examined for tailor made pea cream thickened with various polysaccharides, carrageenan, gellan, xanthan, CMC, guar gum, tara gum, konjac glucomannan (KGM), high methoxyl pectin, and Nutilis® (NI) (ingredients: modified waxy maize starch, guar gum, xanthan gum, tara gum, maltodextrin and E1442: hydroxypropyl distarch phosphate) and Nutavant® (NA) (ingredients: modified maize starch)[120]. Talens *et al.*[120] found that the addition of saliva decreased the maximum positive normal force corresponding to "consistency" and the maximum negative normal force corresponding to "adhesiveness" in the repeated compression and decompression as well as the apparent shear viscosity, which was ascribed to the dilution although the saliva was reported to function as a binder to form the bolus and as a lubricant for fragmented particles to make the bolus structurally homogeneous and cohesive[66]. The decrease was found most conspicuous in the sample thickened by NA and NI, which was attributed to α-amylase degradation of starch granules in both NA and NI.

The starch base thickening agents previously used in dysphagia treatment were reported to be degraded during oral processing by amylase in saliva, and were thought to be not convenient in designing thickening agents[121-123].

Ishihara *et al.*[115] further studied the stress relaxation of the above-mentioned boli prepared from 0.075 % and 0.15 % gels of gellan alone, and 1.0 % and 1.5 % mixed gels of deacylated gellan gum and psyllium seed. The stress relaxation curves were analyzed by five element model consisting of two Maxwell elements and one spring connected in parallel:

$G(t) = G_\infty + G_1 \exp(-t/\tau_1) + G_2 \exp(-t/\tau_2)$, $(\tau_1 < \tau_2)$, where $G(t)$ represents the relaxation modulus, defined as the ratio of the shear stress to the constant strain given at $t = 0$, G_∞, the equilibrium modulus, G_1 and G_2, the faster and the slower reaction component, τ_1 and τ_2 are relaxation times, respectively. It was found that both G_1 and G_2 decreased with increasing addition of saliva, and this decrease was more conspicuous in boli prepared from gels of gellan alone than those from composite gels. Both τ_1 and τ_2 for boli prepared from composite gels were found smaller than for gels of gellan alone, and were less affected by the addition of saliva. All these findings are consistent with the results obtained from dynamic viscoelastic measurements as mentioned. The size distribution of instrumentally prepared boli is different from that of human mastication and expectoration because smaller fragments are lost in the intermediate swallowing during human oral processing. This was not a disadvantage of instrumental mastication because human subjects in insufficient oral health cannot modulate physiologic parameters of mastication (*e.g.*, the number of mastication cycles in the sequence) due to the lack of mastication strategy to make the granularity of bolus in predetermined state[124]. This ensured the validity of the study by Ishihara *et al.*[115] . Fragmented particles of these boli adhere easily one another and do not separate to one independent particulate, making it difficult to characterize particulate bolus by sieving, and the optical scanning method was used for analyzing size distribution of four model boli from 0.075 % and 0.15 % gels of gellan alone, and 1.0 % and 1.5 % mixed gels of deacylated gellan gum and psyllium seed. The fragmentation pattern was represented by the logarithmically normal curve. For bolus prepared from 1.5 % mixed gels of deacylated gellan gum and psyllium seed with the higher gel-strength forming large size beyond 100 mm^2, the distribution deviated from the log normal fitting curve, presumably due to adhesion of fragmented gel particulates. As was reported previously[66], in spite of the larger particulate size, the bolus from gellan/psyllium composite gels was not evaluated difficult to be swallowed. This might be related with the grittiness sensation which was enhanced by the angularity in addition to the size of particles[125-127]. Chen *et al.*[125] showed that the mean particle size in the boli decreased with increasing hardness of the foods (weak jelly, peach, strong jelly, cottage cheese, carrot, cashew nut, peanut, etc.) before mastication[128, 129]. This grittiness sensation caused by the angularity of particles and the hardness of particles could be analyzed more quantitatively by tribological measurements, and should be analyzed. Although particulate size is important for swallowing ease, the miscibility with saliva was thought to be more important for the composite gels. Saliva provides viscosity and lubricity, leading to the increase in cohesiveness of bolus by binding food particulates each other. Thus, the bolus from the composite gels flows as one coherent bolus in swallowing with small variation of the flow speed and without scattering into smaller fractions, therefore easier to swallow than the bolus from gellan single gels[66].

Bolus can be modelled by granular agglomerate[130]. The decrease in the storage modulus of artificially prepared bolus from deacylated gellan and its mixture with psyllium seed gum with increasing saliva content shown in Fig. 27 could be understood from the behavior of granular matters. The storage modulus G' of wet granular matters increased first to a certain liquid content with increasing liquid content and a further addition of the liquid decreases G' as is widely observed for wet granular matters[131]. Møller, & Bonn[132] found that rescaled storage moduli $G' \rightarrow G'/0.054\, R^{-1/3} \mathrm{E}^{2/3} \gamma^{1/3}$, where E stands for Young's modulus of the beads, γ the surface tension of the liquid, R the radius of the beads, collapsed into one master curve for seven beads - liquid pairs. Their seven pairs were as follows: 1:100 μm polystyrene beads and silicone oil, 2:100 μm glass beads and water, 3:100 μm glass beads and silicone oil, 4:100 μm sand and water, 5:25 μm glass beads and silicone oil, 6:3 μm PMMA beads and silicone oil, 7:100 μm polystyrene beads and silicone oil. Although Young's modulus of glass bead is one order magnitude higher than that of polystyrene bead, this collapse was found for all these beads-liquid pairs. This typical granular matter behavior was consistent with behavior in wet granular matters widely observed[131].

5.3 Tongue squeezing and the tongue pressure

Human saliva is two orders of magnitude lower than that of water in the boundary friction coefficient[133], and the lubrication of food bolus is determined by the miscibility with saliva. This is why the saliva incorporation in bolus rheology and tribology is important[134].

The selection of strategy of humans for the ingested foods with different hardness has been examined by mimicking the squeezing of gels between the tongue and the hard palate. Since the tongue is tightened or tensioned when the food is hard, it is necessary to know the hardness of the tongue. The thickness and the Young's modulus of the tongue were measured using the digimatic micrometer and the strain sensor.

Thickness of the human tongue 7.53 ± 0.99 mm (relaxed) and 11.09 ± 2.18 mm (tension), respectively. Apparent Young's modulus was 12.2 ± 4.2 kPa (relaxed) and 122.5 ± 58.5 kPa (tension), respectively (Fig. 29). Artificial tongues of various strengths were prepared from silicone rubber. These values are larger than 2.67 ± 0.29 kPa obtained by magnetic resonance elastography[135] and 5.52 ± 1.19 kPa[136]. Napadow, Kamm & Gilbert[137] used the Young's Modulus of the tongue at contracted (E = 10 kPa) and relaxed state (E = 6 kPa) in their study on the bending of the tongue. Zhou *et al.*[138] reported the Young's modulus of the tongue based on the study of diagnosis of tongue squamous cell carcinoma since it was known that the modulus decreases with worsening of the symptom. The Young's modulus was measured by AFM nanoindentation via the rate-jump method, and the Young's modulus was found ranging from 3.7 to 6.6 kPa. The apparent Young's modulus of the human tongue determined by Ishihara *et al.*[139] was at 20 % strain because as is well

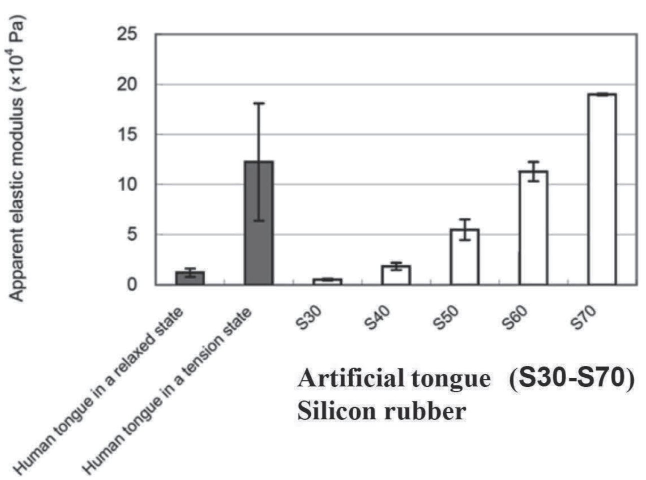

Fig. 29 Apparent elastic modulus of human and artificial tongues from silicone rubber. Apparent elastic modulus was determined by the stress/strain ratio at 20 % strain. Data were presented as means ± SD in triplicate using eight subjects[139].

known it is difficult to draw a tangent at a limiting small strain. Haddad *et al.*[136] also used the force-deformation curve at a smaller deformation range than 25 %. Since the tongue is not a purely elastic material, and the stress-strain curve is downward convex, the slope of the tangent increases with increasing strain.

Mechanical properties of agar gels as model food substances are shown in Table V.

Figure 30 shows a schematic representation of the compression of a food gel between the artificial tongue and the hard palate. A food gel is put on the artificial tongue and was compressed by the metal probe which plays a role of the hard palate.

Photos taken at every 0.2 s just after the contact of the metal probe and the agar gel are shown in Fig. 31. For the artificial tongue S40 (shown in Fig. 29, the strength between the relaxed state and the tension state of the human tongue), a soft gel A3 is more deformed than the artificial tongue and broken after 0.8 s, while for a firmer agar gel A6 the artificial tongue also deformed. When the artificial tongue S60 (shown in Fig. 29, the strength between the relaxed state and the tension state, but closer to the tension state), a soft agar gel A3 was broken at an earlier stage 0.6 s.

The black bar (Fig. 32) using the strategy to fracture the food between the tongue and the palate decreased with increasing the hardness of agar gels from A1 to A7 indicating

Table V Mechanical properties of agar gels as model food substances Data represent mean ± SD of triplicate. Crosshead speed for compression was 10 mm/s. Agar gels were molded into cylindrical shape of 20 mm in diameter and 10 mm in height. Apparent elastic modulus was determined by the stress/strain ratio at 20 % strain through compression[139].

	Mechanical properties		at 20% strain
Agar gel	Fracture strain (%)	Fracture force (N)	Apparent elastic modulus (× 10^4 Pa)
A1	62.16 ± 1.74	4.25 ± 0.16	0.54 ± 0.03
A2	57.20 ± 0.94	5.41 ± 0.28	1.25 ± 0.21
A3	57.30 ± 0.41	6.92 ± 0.46	1.47 ± 0.23
A4	58.92 ± 0.93	8.03 ± 0.84	1.75 ± 0.04
A5	59.35 ± 0.68	22.54 ± 0.33	5.35 ± 0.30
A6	59.32 ± 1.02	36.21 ± 2.21	9.79 ± 0.17
A7	60.76 ± 0.79	50.99 ± 2.42	14.46 ± 0.71

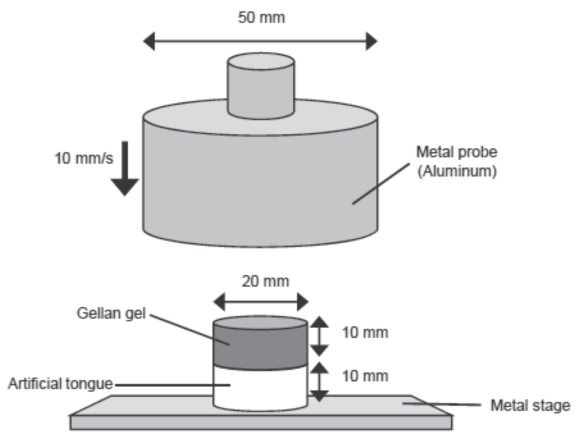

Fig. 30 Schematic representation of the compression of a food gel between the artificial tongue and the hard palate[140].

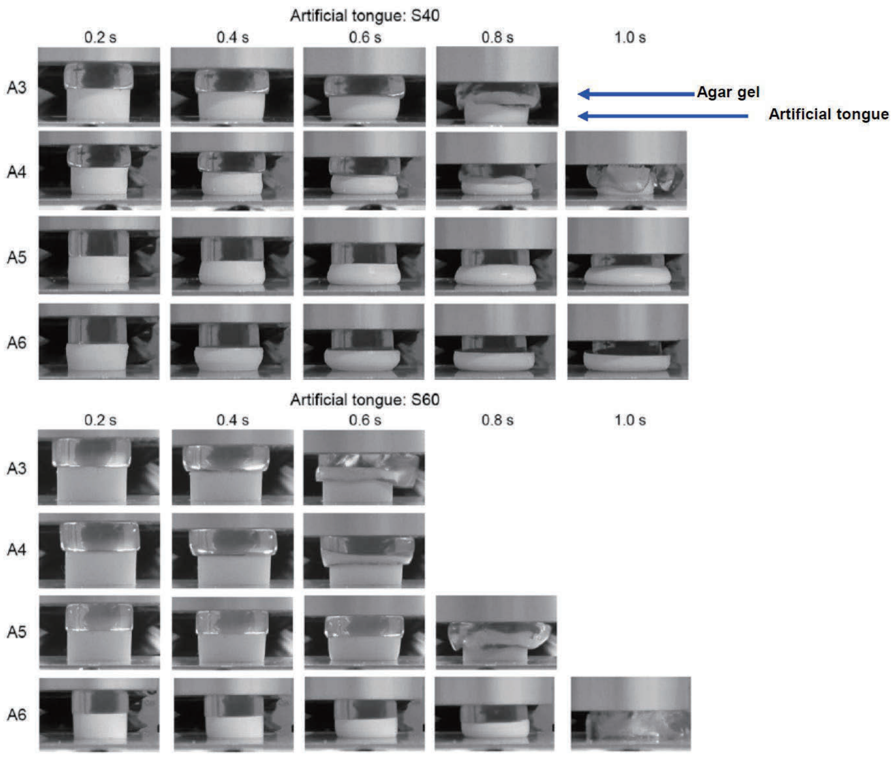

Fig. 31 Photos taken at every 0.2 s just after the contact of the metal probe and the agar gel[139].

that humans begin to use teeth beyond a certain gel hardness.

Fig. 33 shows the tongue-palate squeezing simulation of an agar gel A5 or A6 compressed between an artificial tongue S50 or S60 at 10 mm/s, 20 °C. At this intermediate situation, the strain of both the tongue and the food are comparable.

To investigate the oral processing of agar and gelatin gels, Takahashi and Nakazawa[141] observed the palatal pressure through pressure transducers installed at three locations on the palate. For bite-size gels, the palatal pressure and the work were found to increase up to an instrumentally observed rupture strength of 7-10 × 10^4 Pa, and it then decreased or remained constant. Therefore, these authors interpreted these results as follows: the oral action changed from crushing by the tongue against the palate to biting by the teeth as the rupture strength of these gels exceeded beyond the value mentioned above. The order of magnitude for the critical rupture strength above which the biting of the teeth was selected as a strategy of crushing corroborated the later study by Ishihara *et al.*[139].

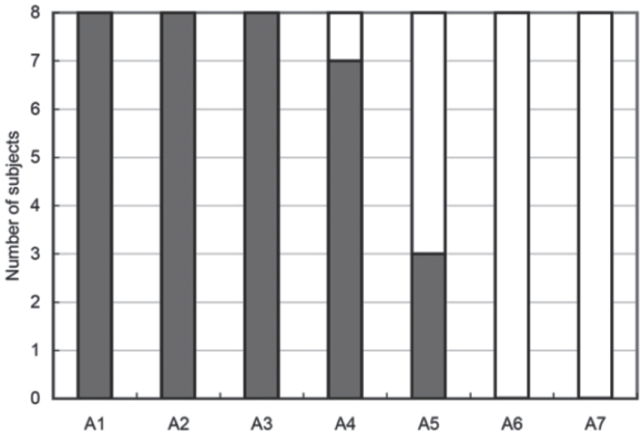

Fig. 32 The number of subjects who use the strategy to fracture the food between the tongue and the palate (black bar) and the strategy to fracture the food with teeth (white bar) for different agar gels from A1 to A7 as shown in Table V[139].

Figure 34 shows the muscle activity during the processing of a food gel monitored by electromyogram. During the tongue-palate compression, both the right and left masseter muscle did not show any activity, and only the suprahyoid showed an activity. For the teeth mastication, both the right and left masseter muscle as well as the suprahyoid showed activities.

During the uniaxial compression at a much faster velocity 0.1 mm/min, it was observed that water expelled out from the side surface of the cylinder[142]. Does exuded liquid make a subject continue the squeezing a gel between the tongue and the palate? This liquid makes the surface of the gel more slippery and lubricated and thus the subject tends to stop the squeezing? This effect of exuded water on the squeezing behavior must be studied in the future.

The tongue pressure is measured by various methods[19]. An inexpensive, safe, sterilizable/disposable probe assembled from a balloon and a tuberculin test syringe cylinder (Fig. 35a) was designed and this JMS method has been widely used in Japan[143]. However, this method cannot be used to

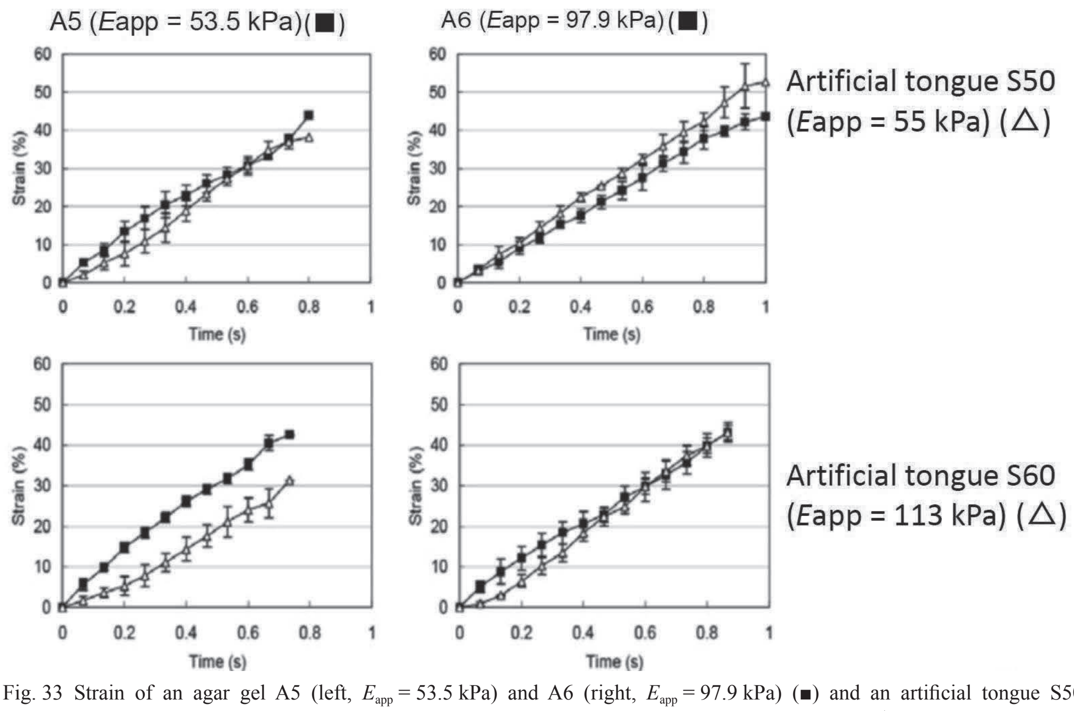

Fig. 33 Strain of an agar gel A5 (left, E_{app} = 53.5 kPa) and A6 (right, E_{app} = 97.9 kPa) (■) and an artificial tongue S50 (E_{app} = 55 kPa) (upper figures) and an artificial tongue S60 (E_{app} = 113 kPa) (lower figures) (△) during compression. Both agar gels and artificial tongues are of a cylinder with 20 mm diameter and 10 mm height and compressed at 10 mm/s, 20 °C[139].

measure the tongue pressure during mastication of foods. Hori and Ono proposed a method of tongue pressure measurement using a thin sheet sensor installed in the oral cavity. The sensor has five channels in the anterior, central, and posterior parts in the middle, and the right and left channels in the exterior part (Fig. 35b).

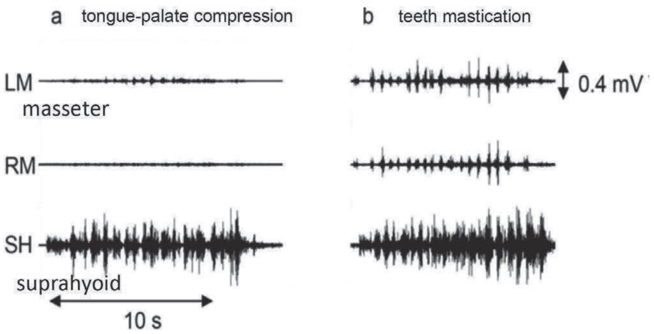

Fig. 34 The EMG signals from the left (LM) and right (RM) masseter muscles and the suprahyoid musculature (SH) were presented for the same subject when the subject used the tongue-palate compression (a) and the teeth mastication (b) as an oral strategy for size reduction. Results from the subject during oral processing of different gels are shown[139].

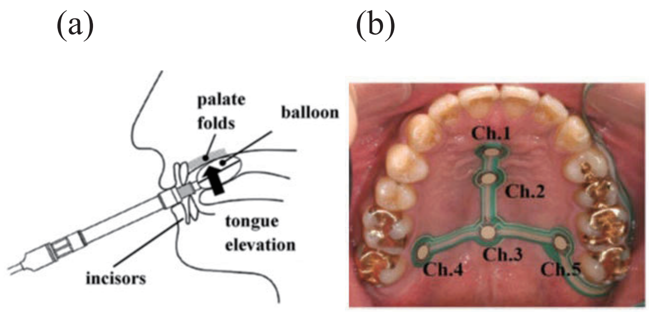

Fig. 35 (a) Tongue pressure measurement by a balloon method. (b) A 0.1 mm thick sensor sheet fitting to the curvature of the hard palate. Ch. 1, the anterior-midline of the hard palate; Ch. 2, the center midline of the hard palate; Ch. 3, the posterior midline of the hard palate; Ch. 4 (Ch. R), the right posterior of the hard palate; Ch. 5 (Ch. L), the left posterior of the hard palate[144, 145].

Figure 36 shows the instrumental uniaxial compression of deformable gels S1-S3 made from the mixture of 90 % psyllium seed gum, 3.3 % deacylated gellan gum, and brittle gels G1-G3 made from deacylated gellan gum alone. While the compression stress for deformable gels as a function of time showed monotonical increase and reached the peak before yielding (Fig. 36A), brittle gels showed multiple peaks accompanying the fracture (Fig. 36B).

Figure 37 shows the typical waveforms detected at five different positions Ch. 1 to Ch. 5 on the hard palate by the ultrathin sensor system shown in the right figure of Fig. 35b. In this study, the subjects were instructed not to chew by teeth. Both waveforms are similar to those observed by instrumental compression; the tongue pressure increased showing one peak value for a deformable gel S3 (Fig. 37A) while it showed multiple peaks for a brittle gel G3 (Fig. 37B).

It was believed that the mechanical properties of the bolus just before swallowing are the same for all the foods indicating that the mechanical properties of the bolus are independent of the initial texture of ingested foods. However, this hypothesis was questioned by these studies. It was clarified that the work of the tongue just before swallowing depends not only on the initial mechanical properties of foods but also on the oral processing before the swallowing[68, 144].

As shown in Fig. 37, the tongue pressure is produced from the midline of the palate at Ch. 1, Ch. 2 and Ch. 3 and then to the circumferential region of the palate Ch. 4 and Ch. 5[144]. This temporal change in tongue pressure development was different from that during swallowing, in which a food bolus was transported from the anterior to the posterior region of the palate[144, 146]. To understand the effect of the mechanical properties of bolus on the swallowing behavior, the maximal voluntary tongue pressure (MVTP; the pressure of the tongue to press the palate with the utmost effort when the

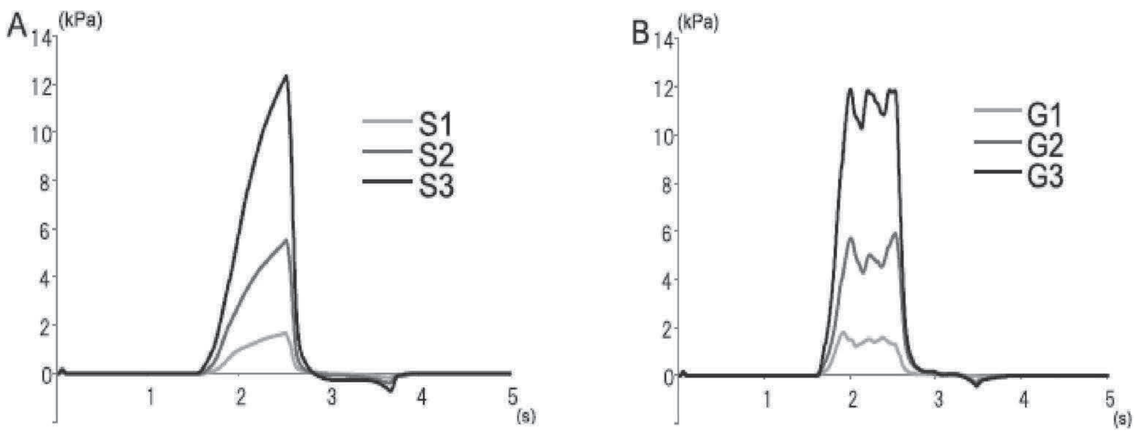

Fig. 36 Typical sample waveforms of stress-time curves by instrumental test of three consistencies of deformable gels S1-S3 (A) and brittle gels G1-G3 (B). Compression speed, 10 mm/s; temperature, 20 °C[145].

subject was instructed to press the tongue to the entire palate for 5 s with the utmost effort to record MVTP) was examined because it was reported to decrease with age[146)]. Four model gels, with fracture force 10N (A10 and C10) and 30N (A30, and C30) (determined for 20 mm diameter and 10 mm height cylindrical gel) were prepared by mixing deacylated and high-acyl gellan. Both A10 and A30 were prepared by deacylated gellan alone and thus were brittle with lower fracture strain ~ 45 %, while C10 and C30 containing acylated gellan gum and were deformable with fracture strain ~ 75 %. Using these model gels, Murakami *et al.*[146)] found that the MVTP of midline of the palate and the mechanical properties of gels are associated with the maximal amplitude of tongue pressure during squeezing and that the number of squeezing was higher for gels with higher fracture force, but it was not affected by the fracture strain as had been found previously[144, 147, 148)]. Since the maximal amplitude in each squeezing cycle was found positively correlated with the individual maximal voluntary tongue pressure, and the number of squeezes until swallowing was found negatively correlated with maximal voluntary tongue pressure, Murakami *et al.*[146)] expected that MVTP could be a good index to select safe food for persons with dysphagia. However, since this was conducted for healthy young persons, they wish to extend the study to include elderly and patients with difficulty in mastication and swallowing.

The tongue pressure measurements were shown useful also for the early and quantitative detection of tongue motor disability during swallowing in patients with Parkinson disease (PD)[149)]. PD is a progressive, neurodegenerative disease originating from the degeneration of substantia nigra dopaminergic neurons and is characterized by symptoms such as tremor/shaking, rigidity and/or muscle stiffness, bradykinesia/slowing down of motion, postural instability and difficulty in swallowing, chewing and speaking[150, 151)]. It is necessary to establish a treatment method for PD patients which requires big-data analyses of VFSS or FEES images collected from a homogeneous PD patient group, but this has not been done at all[152)]. Prevalence of silent aspiration was reported higher in patients with PD[43, 153-155)]. The maximal tongue pressure at Ch. 1 - Ch. 5 (Fig. 34b) was significantly lower in patients with PD than in healthy controls (8 men and 12 women; mean age, 71.6 years). Furthermore, the maximal tongue pressure was significantly lower in dysphagic PD patients than non-dysphagic PD patients. Further study using tongue pressure for PD patients in combination with VFSS during 5 ml barium liquid swallowing (12 men, 12 women; mean age, 70.4 years) showed that the dysphagic PD group had prolonged duration of tongue pressure and time to peak pressure and a reduced pressure gradient compared with the non-dysphagic PD group although maximum tongue pressure was not different between two groups[149)]. Another study on the relation between the tongue pressure and the dysphagia in PD patients showed the significant difference in the tongue pressure duration, time to peak pressure, and pressure gradient for 24 PD patients (12 men, 12 women; mean age ± SD: 70.4 ± 7.9 years; age range 54-89 years) as shown in the following figures[156)] (Fig. 38).

Simultaneous recording of suprahyoid EMG activity, three pressure sensors installed at the thyroid cartilage and swallowing sound was found useful to understand the swallowing mechanism[157)] (Fig. 40).

Nakagawa ad Matsuo[158)] recently examined the relation between the tongue pressure and frailty for 100 elderly persons using a balloon method. They used Process Lead Food Model developed at Fujita Health University (Aichi, Japan) to estimate the weakening of eating ability of subjects. They found a good correlation between the eating ability and the tongue pressure, and proposed a training to prevent elderly persons from falling into frailty state.

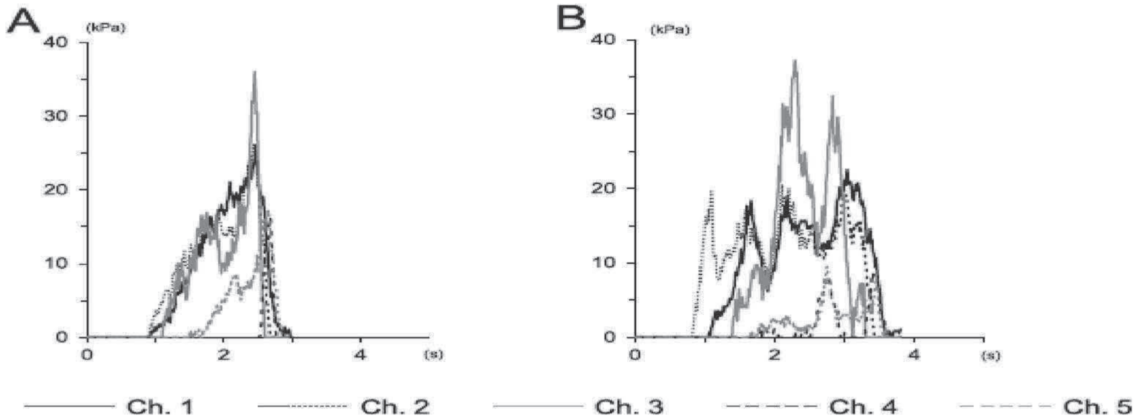

Fig. 37 Typical sample waveforms of tongue pressure during the initial squeezing of a deformable S3 gel (A) and a brittle gel G3 (B) detected at different positions of the hard palate[144)].

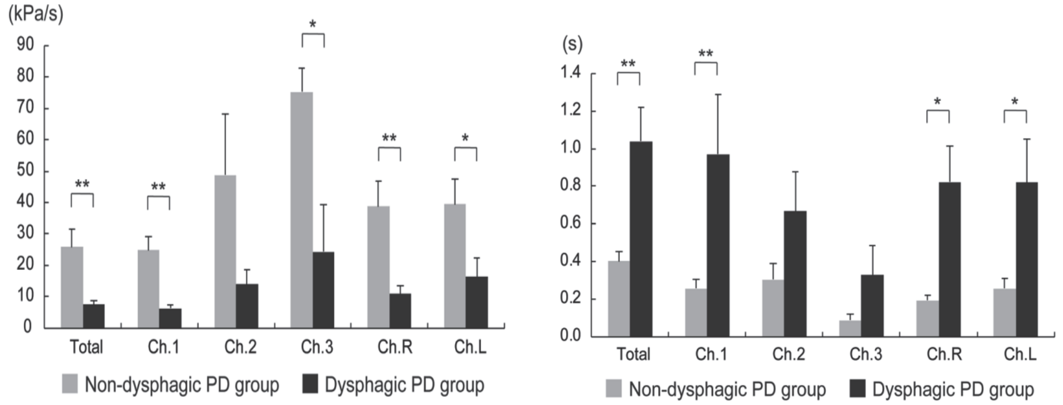

Fig. 38 Comparison of the pressure gradient (left) and the time to peak pressure at total waveform and five measurement points for the non-dysphagic PD group and the dysphagic PD group. Ch. channel. *$p < 0.05$; **$p < 0.01$. Error bars represent ± 1 standard error of the mean (SEM)[156].

5.4 Tongue movement

The tongue movement during oral processing was studied during Stage II Transport by monitoring the small horizontal tongue marker[159]. It was found that the monitored movement was consistent with "squeeze-back" mechanism of bolus propulsion proposed by Hiiemae and Palmer[29], and that the tongue movements were strongly influenced by food texture. The vertical dimension was found large in chewing and Stage II Transport which was attributed to food particle reduction and transport.

It was reported that the tongue can move at speeds of up to 200 mm/s[160]. To understand the formation and transportation of bolus in the oral cavity, the tongue movement and pressure must be observed simultaneously. Electromagnetic articulography (EMA) has been applied to monitor the tongue motion during swallowing[161, 162].

In the swallowing, tipper type and the dipper type were distinguished: in a tipper type the swallowing is initiated with the tip of the tongue against the incisors and the bolus is on the dorsum of the tongue, while in a dipper type the swallow of the bolus is initially positioned beneath the anterior part of the tongue[163]. Dipper types were found in all ages, but found more prevalent in aged group[163]. Steele *et al.*[164] demonstrated that the duration of tongue motion during swallowing is prolonged with ageing, and this was confirmed recently[165]. Bourdiol *et al.*[162] classified the movement of pattern into 3 types: Type I, tipper pattern; Type II, dipper pattern; and Type III, in which the three portions of the tongue descend, the saliva is confined between the back of the tongue and the palate. Recently, the synchronous measurements of the tongue pressure and the tongue movement were performed by installing the sheet sensor as shown in Fig. 35 (b) and two EMA markers on the anterior and posterior part on the tongue[166].

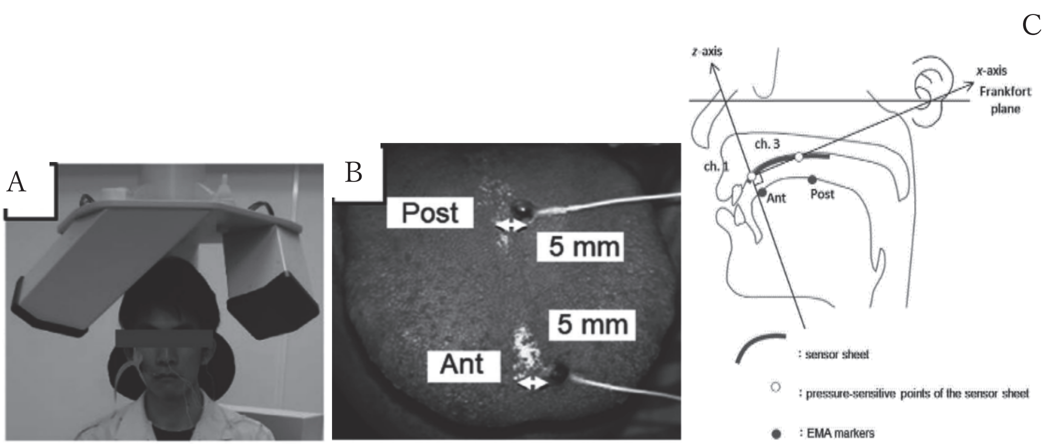

Fig. 39 Simultaneous recording of tongue motion and tongue pressure. (A) Electromagnetic articulography (EMA) measurement setting. (B) Placement of the EMA marker on the tongue. (C) Position of the tongue pressure sensor and EMA markers in the sagittal plane. A magnetic field is formed by the transmitter (A) at the top, and when the marker shown (B) moves in the magnetic field, a current is generated. A denture compatibility test material (Dent spot, Showa Pharmaceutical Co., Ltd.) was applied to Chs. 1 and 3 of the sensor sheet attached to the palate. To prevent the marker from touching the pressure-sensitive points, the positions of the markers were set 5 mm to the left of the marked area (B). Abbreviations: Ant, anterior; Ch., channel; Post, posterior (Kodama et al, 2021). As for the definition of Frankfort plane see Cheng, Leow, & Lim[167].

The EMA monitoring of the tongue motion is recorded only during intervals for which the tongue is not contact with the hard plate because the tongue stops moving during this period of contact[168]. The setup shown in Fig. 39 enabled the analysis of the temporal correlation between the tongue motion and the tongue pressure during swallowing. Kodama *et al.*[166] examined the effect of bolus volume (using water) on the tongue pressure and motion but did not examine the effect of the viscosity. It seems that there has been no work on the effects of rheological properties on the swallow type dipper or tipper, which must influence the tongue pressure and tongue movement. Since the simultaneous monitoring of the tongue pressure and the tongue motion is expected to give us deeper insight of the swallowing dynamics, the further study is urgently required especially including the effects of varying textures of boluses with a constant volume.

A bionic swallowing device (BSD) mimicking human-tongue motion during swallowing which used the cam-link and push-rod mechanisms was designed[169]. In this device, the tongue root point (TRP) was the origin of the relative coordinate system, and the zygapophyseal point on the cervical vertebra was the origin of the absolute coordinate system. The TRP and 20 equidistant points along the tongue surface were extracted based on the origin of the absolute coordinate system to obtain the absolute curve motion. The simulated trajectory obtained from BSD was found close to the real tongue trajectory observed by video fluorography images. In this bionic swallowing device (BSD), the swallowing time was defined as the time taken for food transportation from the tongue tip to the cervical esophagus. In BSD study, the swallowing time decreased with the increased swallowing grade (SG) for swallowing barium meal solutions of the same viscosity. SG from 1, 2, 3, 4, and 5 in Qian *et al.*[169] corresponded to Kunieda's Food Intake LEVEL Scale (FILS) shown in Table II (which was called Swallow score in a BSD study) from 10 (normal health) to 6 (less swallowing ability). In other words, the increasing SG corresponds to the decrease in FILS. Therefore, thus defined swallowing time decreased with decreasing FILS, and therefore the swallowing time was the shortest in the normal healthy person, which is consistent

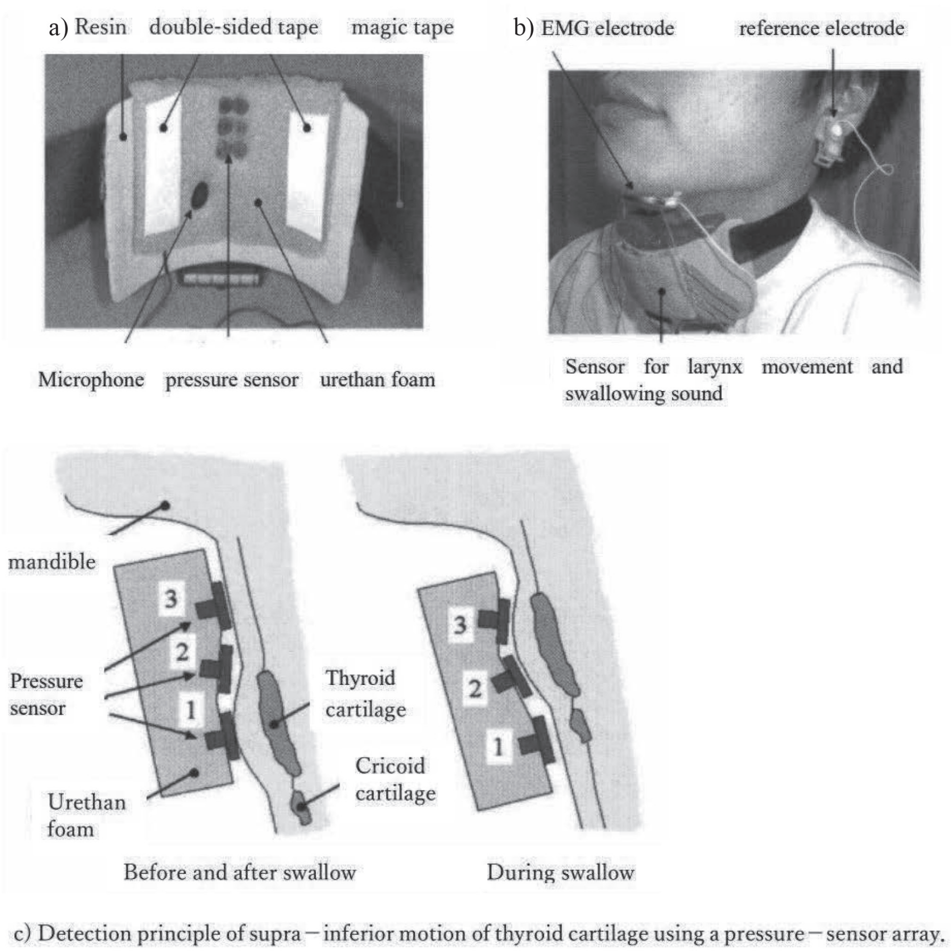

Fig. 40 Method of simultaneous measurement of suprahyoid EMG, larynx movement, and swallowing sound; a) An interior view of the sensing device equipped with detectors for larynx movement and swallowing sound, b) Mounting of EMG electrodes and the sensing device for larynx movement and swallowing sound, c) Larynx elevation can be detected as an upwards movement of thyroid cartilage[157].

with Su *et al.*[105]. Recently, devices mimicking the human swallowing have been reviewed[170-172]. Since the in vitro or in silico studies can study the situation in which patients may face to the danger if the different test foods of varying textures with different taste and aroma might lead to the aspiration during diagnosis, the alternative study is expected to predict the safe choice.

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