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Review

Rheology for Safe Swallowing 3‡

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9. TRIBOLOGICAL ASPECTS

In the first stage of oral processing, the deformation and the breakdown are dominant dictated by bulk rheology, and during the transport of comminuted foods to the back area of oropharyngeal region and the subsequent swallowing, the tribological phenomenon in the narrow space between the tongue and palate is becoming more dominant[71, 248].

As has been studied in the last two decades, the tribology becomes especially more important in the later stage of oral processing particularly when the bolus is transported in the narrow gap between the tongue and the palate[71, 249]. In relation with bulk rheology, lubrication properties were shown to be opposite in starch and gums such as flax seed gum and xanthan; the increase in non-starch polysaccharides concentration increased the viscosity, viscoelastic properties and lubricating capacity. Nevertheless, when a starch-based thickening agent was used, both viscosity and viscoelastic properties displayed a minor increase, and the lubricating capacity decreased. Therefore, it was suggested that associating tribology to rheology was crucial to further define formulations with pleasant swallowing characteristics[122].

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The tribology has been studied mainly in relation with reducing the friction in mechanical engineering[250, 251]. The friction between two planes is often represented by Stribeck curve.

Instead of Hersey number $\eta\omega/p$, a film parameter Λ = the ratio of the liquid lubricant thickness to the roughness (asperity degree) is also used. Generally, the liquid thickness increases when the viscosity or the speed increases or the normal pressure decreases. Boundary regime corresponds to $\Lambda < 1$, where friction is dominated by solid/solid interactions and shearing of interfacial boundary films. The mixed lubrication or partial lubrication regime corresponds to $1 < \Lambda < 3$, where friction involves a coexistence of boundary regime and hydrodynamic regime. With a further increase in Hersey number, friction reaches a lower plateau value, corresponding to the onset of hydrodynamic lubrication. At this point, the surfaces are effectively separated by the liquid lubricant, and asperity contact has negligible effect on load support and friction. A slight increase with increasing Hersey number at the onset of hydrodynamic regime is called elastohydrodynamic lubrication regime (EHL)[251]. When the liquid film is thick, $\Lambda > 3$, the friction is dominated by lubricant rheology and hydrodynamics.

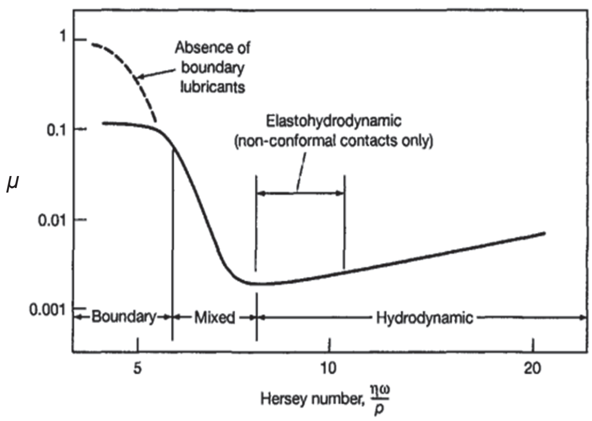


Fig. 74 Schematic representation of the friction coefficient μ as a function of Hersey number Hs = $\eta\omega/p$, where η = viscosity, ω = speed of the moving plane to the stationary plane, p = normal pressure exerting on the liquid. The friction coefficient remains a high value at boundary regime, and then decreases with increasing Hersey number in the mixed regime also referred to as "partial lubrication regime", where friction involves a combination of boundary regime and hydrodynamic regime. With further increase in Hersey number, friction is dominated by lubricant rheology and hydrodynamics[251].

In earlier tribological studies on compliant surfaces, a steel ball sliding against a silicone elastomer as model contacts, however, because of a large Young's modulus it is not a suitable model contact for the situation that both substrates are compliant. In addition, steel has a different surface chemistry than the opposing surfaces[252]. To study the tribological properties between soft compliant plates and controllable hydrophobicity, a combination of a poly(dimethylsiloxane) (PDMS) ball and a disk with controlled roughness and hydrophobicity was used as shown in Fig. 75[133].

In the MTM measuring system, the dimensionless film parameter Λ is represented by

$$\Lambda = h_{\min} / (\sigma_{\text{ball}}^2 + \sigma_{\text{disk}}^2)^{1/2}$$

where $h_{\min}$ is the minimum film thickness within the contact, and σ_{ball} and σ_{disk} are the rms (root mean square) roughness of the ball and disk, respectively.

Recently, a modified set-up of tribological measurement was used to study the Newtonian fluids (Fig. 76)[254]. Normal load as a function of entrainment speed from 0.1 to 1000 mm s^{-1} for Newtonian corn syrups (viscosity η = 0.01–3 Pas) was found constant *ca.* 3 N during the measurement, thus confirming the feasibility and attractiveness of using such set-up with a rotational rheometer to perform tribological tests.

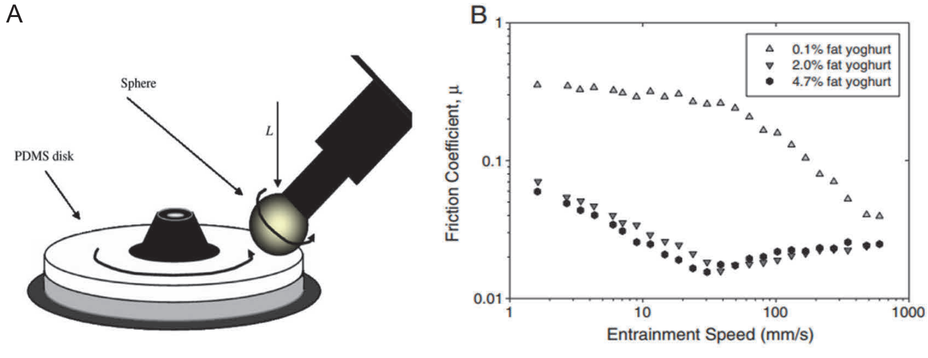


Fig. 75 A. Schematic representation of the mini traction machine (MTM), consisting of a poly(dimethylsiloxane) (PDMS) sphere and a flat PDMS disk. Both the shear and the disk are rotating in the direction shown by arrow[133]. B. Friction coefficient μ of yogurts measured by MTM, as a function of entrainment speed at 35 °C. Entrainment speed (U), defined as the average surface speed of the ball and disk, $U = (U_{\text{ball}} + U_{\text{disk}})/2$, applied normal load L = 1 N, and slide-to-roll ratio SRR = $(|U_{\text{ball}} - U_{\text{disk}}|/U)$ = 50 %[253].

Figure 77a shows the coefficient of friction μ for corn syrups of varying concentrations (η from 0.0015 to 3 Pas) as a function of entrainment speed V. The Stribeck curves were shown to be collapsed to a master curve, showing all three lubrication regimes, when μ was plotted as a function of ηV in Fig. 77b. Therefore, Gamonpilas *et al.*[254] stated that, for Newtonian liquids, the liquid viscosity is considered as a shift factor for the Stribeck curve, *i.e.*, the higher the viscosity, the shifting is more toward the hydrodynamic lubrication regime. This finding is consistent with previously published works[248, 252, 253, 255].

Another simple method to quantify the frictional resistance between the tablet or capsule and the oral cavity or gastrointestinal mucosa was proposed. An artificial skin (Sapplare®; Idemitsu Technofine Co., Ltd.), an industrial product, was used to closely mimic the skin (Fig. 78)[256].

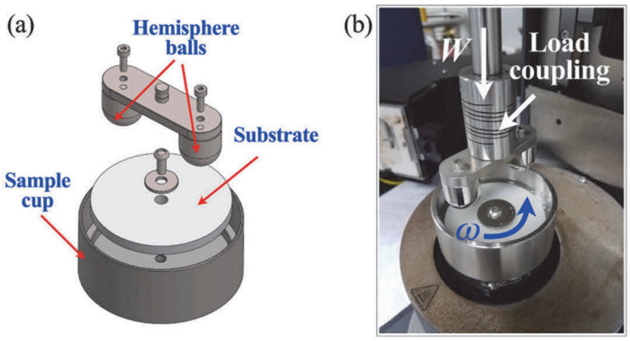


Fig. 76 (a) A schematic drawing of tribological-cell (tribo-cell) and (b) its set-up on a controlled strain rheometer ARES-G2 (TA Instruments, USA)[254].

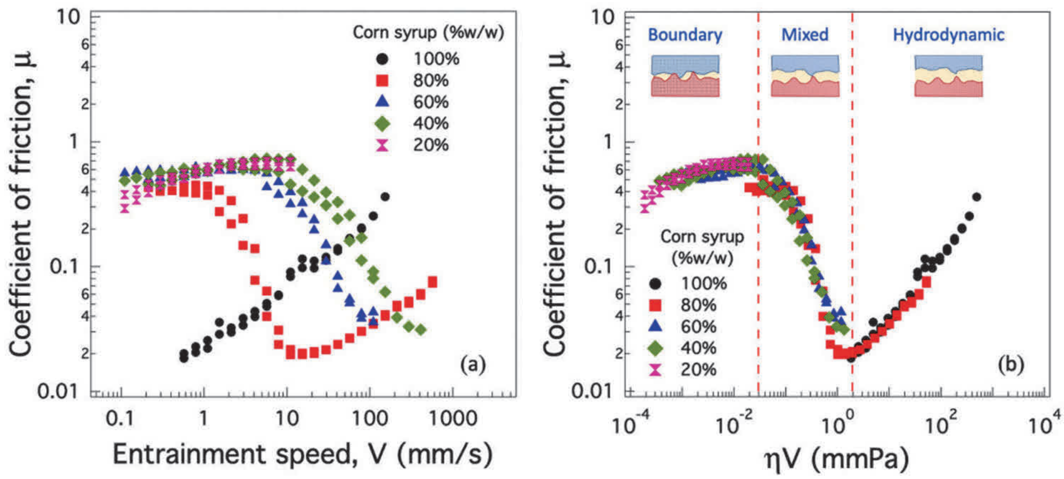


Fig. 77 Tribological properties of Newtonian liquids (20–100 % corn syrups) with varying viscosity, plotted as a function of (a) entrainment speed, V and (b) the product between viscosity and entrainment speed, ηV with the applied normal load of 3 N. Different regions of the Stribeck curve, defined as Boundary-, Mixed- and Hydrodynamic-lubrication regimes are observed and indicated by the dashed lines[254].

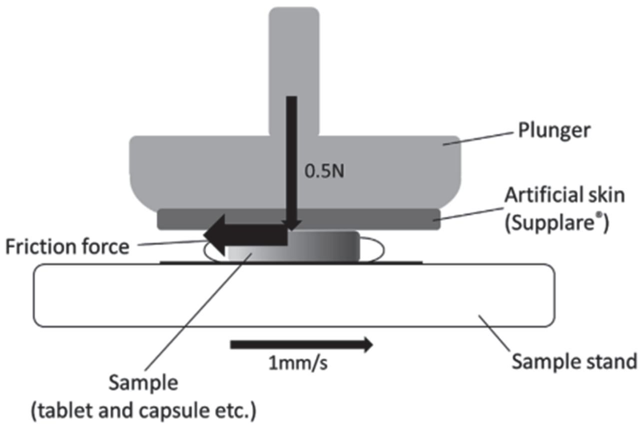


Fig. 78 A set up for friction coefficient measurements. The system can move the sample stage horizontally while applying a constant load vertically to the sample[256].

These authors fond that the surface physical properties of Sapplare® were more stable and consistent than those of collagen sheets derived from natural products. The sample was subjected to a load (0.5 N for 5 s) applied from the top corresponding to tongue press. Then, frictional force generated between the artificial skin fixed to the plunger and the sample surface was measured.

Another simple setup was proposed to measure the friction coefficient, using reciprocating movements of flat plates which can be also used at a low cost in food laboratories having a texture analyser[257] (Fig. 79).

More instruments for measuring lubrication properties in oral cavity have been recently described[249, 258]. Since the tongue movement is far more complex as mentioned in Section 5.4, friction measurements must be further developed beyond the rotational motion as MTM or the reciprocating translational motion. Further development of easy to swallow foods for disadvantaged persons need further developments of understanding and application of lubrication properties.

The lubricating mechanism was studied[259] for liquid model foods: two liquid matrices (dispersions of microparticulated whey protein (MWP) in water and MWP in o/w emulsions) and in two semi-solid gel matrices (MWP in gelatin gels and MWP in emulsion-filled gelatin gels). The lubrication ability of MWP in liquid foods was explained by the reduction of the area between the contacting surfaces and by changing the local relative motion from sliding to rolling, called a ball bearing mechanism[259-261]. This was clearly shown by the decrease in friction coefficient with increasing MWP concentration Fig. 80.

This ball-bearing mechanism was schematically shown in Fig. 81.

In semi-solid foods, addition of MWP was also found to decrease the friction, but to a smaller extent compared to liquid model foods. Since the lubrication mechanism for multi-component semi-solid foods that contain fat droplets, emulsifier, fat replacers such as MWP embedded in a gel matrix is complex, it was concluded that different components affected the lubrication properties of the composite food through different mechanisms[259]. The reduction of friction by

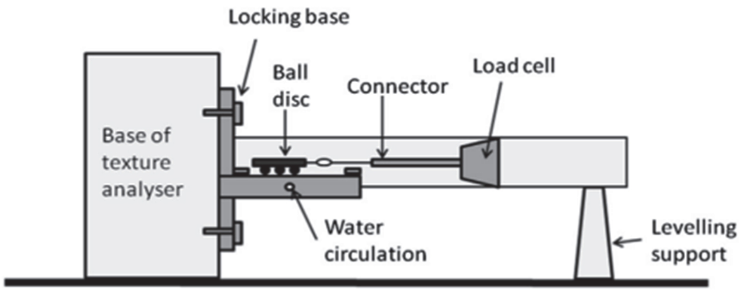


Fig. 79 A set up for friction coefficient measurements. The ball disk and the base are connected to the load cell[257].

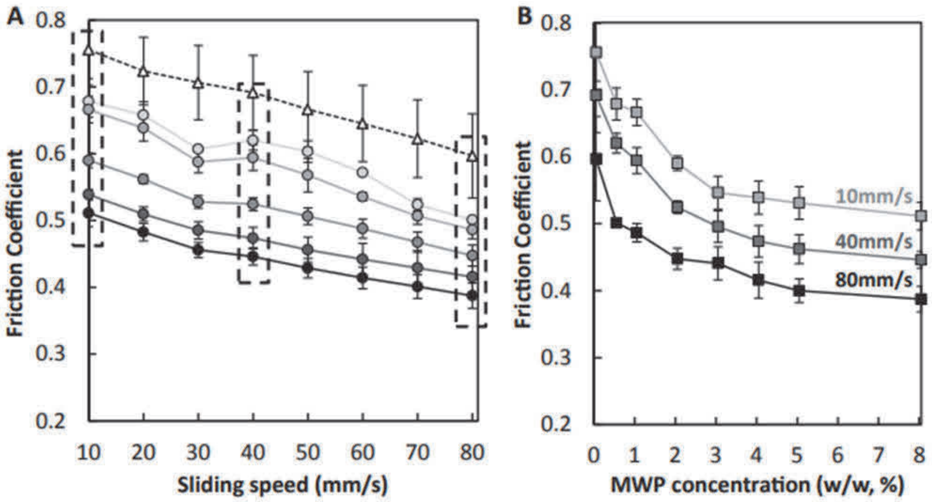


Fig. 80 A: Friction coefficient of MWP dispersions at various concentrations as a function of sliding speed. △ = 0 % MWP (= water); ● = 0.5 % MWP; ● = 1 % MWP; ● 2 % = MWP; ● = 4 % MWP; ● = 8 % MWP. B: Friction coefficient of MWP dispersions at different sliding speed as a function of MWP concentration (the same data as A, concentration at 3 % and 5 % are also shown), compared with 40 % pork fat emulsion stabilized with 1 % WPI. ■ = MWP 10 mm/s; ■ = MWP 40 mm/s; ■ MWP 80 mm/s. Error bars represent the standard deviation of the triplicates[259].

fat droplets was attributed to the formation of a fat film, called a plate-out mechanism (Fig. 82).

Oil bodies (OBs), micron- or submicron-sized natural oil droplets found in parts of plants, consisting of a core of triglycerides covered by a continuous monolayer of phospholipids embedded with OB surface proteins, oleosins (15–26 kDa), caleosins (25–35 kDa) and steroleosins (40–55 kDa), and have been studied for their emulsifying and structuring functions[262-264]. Controlling the lubrication properties is believed to be useful for designing foods for dysphagia treatment, but the mechanism of lubrication is not yet clarified. Recently, κ-carrageenan gels filled with soybean OBs bound or unbound with the gel matrix were prepared, and lubrication properties of the OB cream and OB emulsion-gels were studied[265]. Lubrication properties of the OB cream and OB emulsion-gels were found to be significantly improved in the boundary lubrication regime, compared with pure water and the kappa-carrageenan (KC) gels, and are better than the emulsion-gels with medium chain triglycerides (MCT) droplets stabilized by Tween 80 as shown in Fig. 83. A very low boundary friction coefficient (μ) of 0.038 was achieved.

The lubrication mechanism was thought to be a ball bearing effect, in which the higher the elastic modulus of the particles, the higher load they can bear, thus the better lubrication. It was corroborated by a high compression elastic modulus of OB about 6–10 MPa measured by AFM[266]. Thus, OBs act as relative stiff "bearing balls" between the contacting surfaces as schematically demonstrated in Fig. 83.

In some emulsion systems, the oil droplets deform and rupture with increasing shear, resulting in spreading of the oil and a minimum plateau of μ at the end of mixed regime, and could be explained by the plate-out mechanism. However, for the present OB cream, obvious release of oil after the tribology test was not recognized. At low sliding speed, the OB droplets in the cream could be easily entrained due to its high viscosity and fill between the two contact surfaces reducing the friction. This is because, the drag force (F_d) applied to entrain a particle in a suspension system can be estimated by the Stokes law, $F_d = 6\pi R\eta S$ where R is the radius of the droplet, η and S are the bulk viscosity of the suspension and entrainment speed at the vicinity of the contact, respectively[267]. If F_d is larger than the friction exerted on the droplet caused by the load applied on it, the droplet can be entrained into the contact surfaces. The viscosity of the soybean OB cream at shear rate of 0.01–100 s^{-1} was found much larger than that of soybean oil[266]. Therefore, OB contributed to decrease the friction by its high viscosity but not by plate-out mechanism.

In the swallowing bolus, degree of lubrication is a crucial parameter. Recent advances in tribological studies revealed the sensation of creaminess could be well explained by frictional coefficient[268]. Funami and Nakauma[269] examined the correlation coefficient between sensory characteristics, cohesiveness, spinnability, and sliminess with instrumentally observed quantities, steady shear viscosity at various shear rates, Hencky strain, data-acquisition point in the Stribeck curve (extensional speed from A to E shown in Fig. 84), breakup time and maximum viscosity in extensional viscosity measurements. As will be discussed in the following section on cohesiveness, it was indicated that perceived cohesiveness correlated the highest with the maximum extension viscosity immediately after the onset of extensional

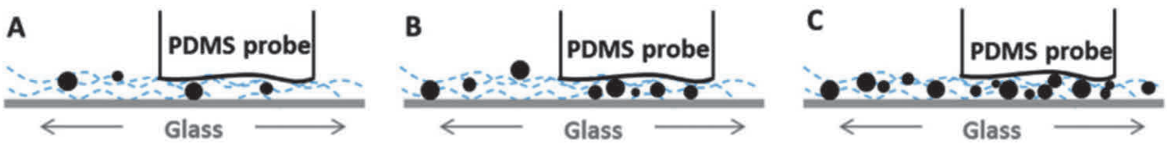


Fig. 81 Schematic representation of behavior of MWP particles (black filled circles) in liquids. A) low MWP concentration: limited number of MWP particles are in the contact zone; B) medium MWP concentration: number of MWP particles in contact zone increases forming a particle layer. C) high MWP concentration: number of MWP particles in contact zone increases further, but particle layer may become saturated[259].

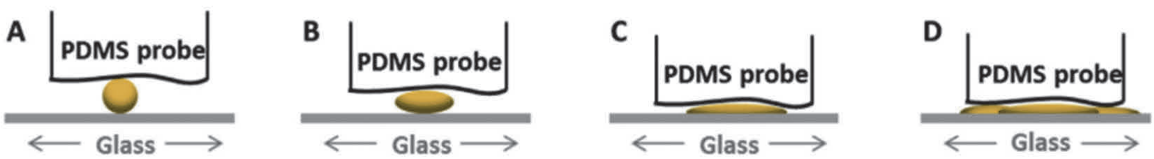


Fig. 82 Plate-out theory for the reduction of friction by fat droplet (yellow). A) Fat droplet (yellow) in between tribo-pair surfaces; B) Fat droplet deforms under shear; C) Fat droplet spreads over surface (plated out); D) Multiple plated fat droplets form fat film patches[259].

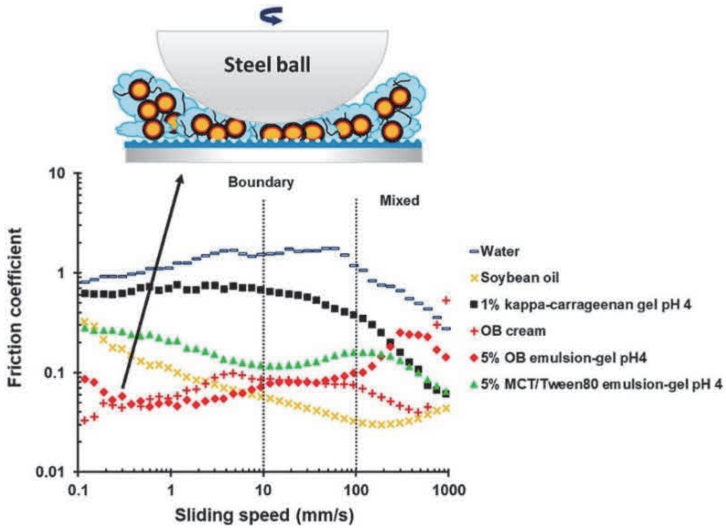


Fig. 83 Stribeck curves of water, soybean oil, soybean OB cream, 1.0 % KC gel prepared at pH 4, and 5 % OB emulsion-gel prepared at pH 4; 5 % MCT/Tween 80 emulsion-gels as a function of sliding speed. A rotating ball and a stational base disk are represented in grey, droplets are presented by orange spheres, red circles enclosing orange color represent the surface proteins, continuous phase is represented by blue color, PDMS film is represented by dark blue wave lines on disk surfaces, and KC gel network is presented by black curve lines. The vertical dashed lines at 10 mm/s and 100 mm/s are used to guide eyes. The uncertainty of the data is within 5 %[266].

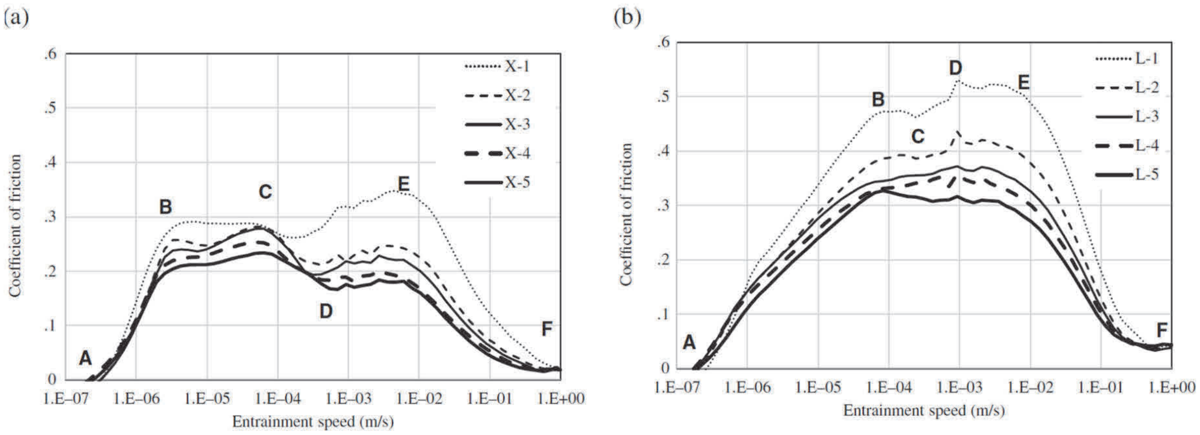


Fig. 84 Stribeck curves for solutions of (a) xanthan gum X1-X5, and (b) locust bean gum L1 L5 (b). Alphabets (A–F) indicate the points where the nature of the Stribeck curve changes, such as peaks and shoulders, in the order of occurrence with increasing entrainment speed[270].

flow, perceived spinnability correlated with extension viscosity in high Hencky strain region. Cohesiveness can be perceived through mechanically elastic response rather than mechanically viscous response, as reported earlier[67]. In relation to this, "structured fluid" having the yield stress leads to the formation of one coherent bolus that is then swallowed in one go, presenting a rheological nature for swallowing ease.

Funami and Nakauma[270] reported that perceived sliminess had the highest correlation with the friction coefficient at the point E in the Stribeck curve, which corresponds to entrainment speed of 6×10^{-3} m/s. According to a flow simulation study[271] the bolus flow for non-Newtonian fluids (xanthan gum and guar gum used in Nishinari *et al.*[199] with the viscosity more than 10 times higher than the solutions used[270] was ~ 0.3 m/s at the palate, 0.3 ~ 0.5 m/s at the pharynx, and 0.1 ~ 0.4 m/s at the larynx/esophagus, depending on feeding volume from 5 to 10 ml. Then, it was concluded that the sliminess should be perceived through relatively slow movement of bolus at the palate than bolus flow velocities at the pharynx and larynx/esophagus[270].

The materials which can mimic the tongue and palate must be further improved[272]. Carpenter *et al.*[272] using a transparent PDMS and could monitor the build-up and flow of dyed-tagged saliva proteins within the contact during sliding. It was demonstrated that using laser induced fluorescence and the resulting strong correlation (0.87) between friction and protein intensity signals, the lubricous boundary film forming ability of saliva proteins was confirmed[272]. However, the Young's modulus of PDMS is more than two orders of magnitude higher than that of the tongue. The surface of human tongue was mimicked by 3D printing. The fungiform and filiform papillae on surface of the tongue were reproduced by taking a negative impression using polyvinyl siloxane or alginate, constituents commonly used in dentistry. Then, the positive impressions obtained using polydimethylsiloxane (PDMS) and other materials were prepared. Taking into account the density of papillae on the tongue surface, the random arranged papillae was done by using Poisson distribution. The artificial tongue surface prepared in this way mimicked well the real one showing the reasonable friction coefficient and wettability[273)].

10. COHESIVENESS

Recently, it was found that the cohesiveness of fluids can be correlated with the breakup time of the fluid extension test. Fig. 85 shows the extension of 0.5 % thickened solutions of LBG, xanthan gum, guar gum and water at 25 °C. Water cannot be extended, and the xanthan solution showed the longest breakup time, indicating the highest cohesiveness.

Therefore, the previous interpretation that the probability of the aspiration is lower for the solution with a higher viscosity at lower shear rates in Fig. 47 must be complemented by another aspect of the cohesiveness, that is, xanthan gum solution is more cohesive than guar gum solutions. The cohesiveness is also a contributing factor reducing the risk of aspiration.

Filament breakup time is well correlated with the remaining liquids in a 10 mL syringe used in the IDDSI flow test as shown in Fig. 86.

Method of measurement of texture for foods prepared for individuals with difficulty in swallowing was given by the Consumer affairs agency, Japan as follows: Measurement of hardness, adhesiveness and cohesiveness. Samples should be filled in a cup of 40 mm diameter and 20 mm height (if the sample does not overflow, 15 mm height is also permissible) to a depth of 15 mm. Using an apparatus that can measure uniaxial compression stress, compression speed should be fixed at 10 mm/s and clearance should be set at 5 mm. A cylindrical plastic plunger of 20 mm diameter and 8 mm height should be lowered and raised twice. The temperature of the measurement should be set at 10 ± 2 °C for foods eaten under cold conditions or at ambient temperature, and 20 ± 2 °C and 45 ± 2 °C for foods eaten after warming (Cited in the Appendix in Nishinari *et al.*[59)]). Using this method, Kohyama measured the “cohesiveness” A_2/A_1 of water and xanthan gum

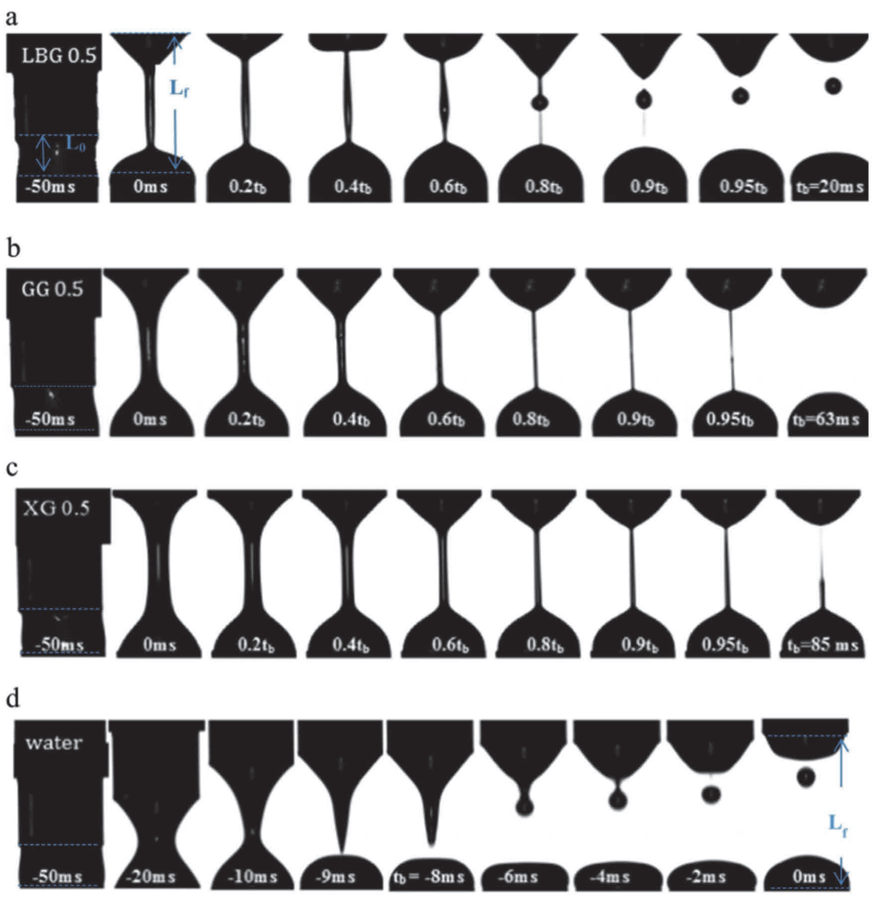


Fig. 85 Extension of 0.5 % thickened solutions 25 °C. Extension velocity 0.16 mm/ms, Initial length L_0 (= 3 mm), Initial diameter D_0 (= 6 mm), Final length L_f (= 11 mm)[200)].

solutions with different concentrations. Here, A_1 and A_2 are the area enclosed by the force curve and the baseline. In many published papers, the baseline had been taken as time, but Peleg[61] and Horiuchi *et al.*[275] took the distance because in such a framework this area A_1 and A_2 represent the work which has a clear physical meaning.

Nishinari, *et al.*[59] found that the "cohesiveness" determined by a method described by Consumer Agency decreased with increasing concentration of xanthan gum as shown below.

Therefore, to call A_2/A_1 "cohesiveness" is obviously wrong. This is because the method of measurement is wrong. The so-called "cohesiveness" obtained from the A_2/A_1 in the two bite TPA for solid should be called "recoverability" rather than cohesiveness[200]. The difference of boundary conditions in the measurement for solid and fluid samples must not be forgotten. In the estimation of A_2/A_1 or the stress ratio for the samples confined, it is obvious that a fluid recovers the initial level after removing the force, and thus the value is very close to unity. When it is possible to measure the compressive force of the semi-fluid sample without confinement, it is better to employ the terminology "flow-ability" widely used in powder flowing technology as was discussed in Section 3: How ingested foods are processed in the mouth? The condition for swallowing.

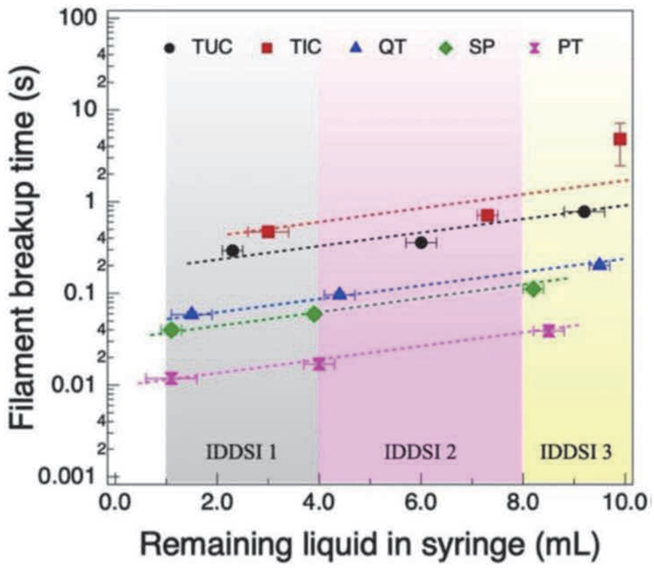


Fig. 86 The relation between the breakup time of the filament of liquids categorized by IDDSI and the remaining in the IDDSI syringe. TUC, xanthan gum (33 %), maltodextrin (66.4 %), potassium chloride (0.6 %); TIC, xanthan gum, maltodextrin, ascorbic acid; QT, xanthan gum, maltodextrin, dextrose, tricalcium phosphate (anticaking agent), SP, guar gum; PT, Tara gum, maltodextrin, calcium carbonate[274].

Table X A_2/A_1 of xanthan solutions estimated by a method by the Consumer affairs agency[59]. The A_2/A_1 value indicated in the right column for each xanthan solution must NOT be called cohesiveness[200].

xanthan %	A_2/A_1
0.0	1.00
0.5	0.908
1	0.863
2	0.831
3	0.750
4	0.736
5	0.706
6	0.693

Hadde and Chen[276] showed a good correlation with the perceived cohesiveness and the filament break-up time and the maximum extensional viscosity (Fig. 87).

Extensional viscosity η_e of solutions of xanthan gum (XG) and locust bean gum (LBG) was studied recently[270]. Extensional viscosity of XG and LBG with five different concentrations X-1–X-5 and L-1–L-5 (0.4, 0.8, 1.2, 1.6, and 2.0 g of XG or 0.6, 0.8, 0.9, 1.0, and 1.1 g (dry base each) of LBG dissolved in 200 g deionized water) were measured. For most solutions of xanthan and LBG, a positive peak of extensional viscosity was found in the Hencky strain range between 2 and 4, followed by viscosity decrease and the minimum inflection point in the Hencky strain range between 4 and 6, then increased again until the filament breakage with increasing Hencky strain beyond 6 as shown in Fig. 88. For XG, the maximum viscosity detected in the Hencky strain range 2–4 increased with polysaccharide concentration, whereas the Hencky strain at the maximum viscosity tended to decrease. For LBG, on the other hand, the peak was not detected clearly in L-1 and L-2. It was found that the extensional viscosity of LBG solutions was higher than that of xanthan solutions at higher Hencky strain range.

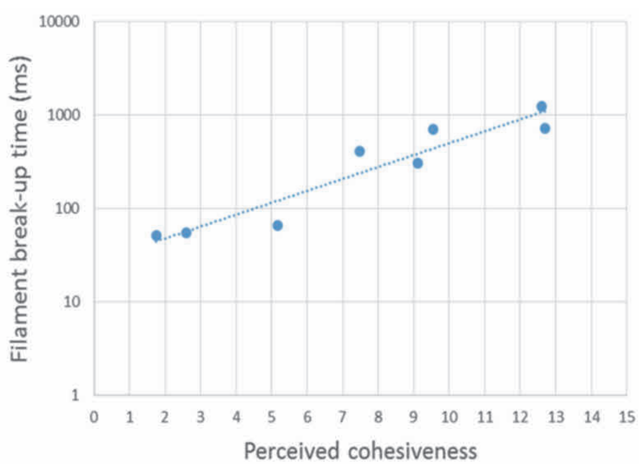


Fig. 87 The relation between the perceived cohesiveness and the filament break-up time[276].

It was found that η_e for both XG and LBG decreased and then increased with increasing Hencky strain but the increase of η_e was more noticeable for LBG, which might be explained by the difference in chain stiffness of XG and LBG[270]. Since LBG is more flexible than XG the coil-stretch transition occurs more clearly than in XG. A similar phenomenon was observed for hyaluronan (HA) solution to which NaCl was added[277]. Since sodium ions shield the electrostatic repulsion between carboxyl residues of HA molecules and constrict the coil dimensions, the extensional viscosity decreased and became strain thickening at higher extensional rates. This has been studied in more detail using a model polymer polyethylene oxide (PEO)[278]. The sensory cohesiveness evaluated on a visual analog scale of XG solution was found highly correlated with filament breakup time t_b and maximum extensional viscosity detected in the Hencky strain range from 2.5 to 4[269].

It is necessary to know the effects of dispersing media on the rheological properties of thickening agents. Figure 89a shows the filament extension of dispersion of xanthan gum with different concentrations in three different dispersing media, water, apple juice and milk. Both filament breakup time t_b and extensional viscosity were decreased at least 2-fold when dissolved in apple juice or milk, signifying

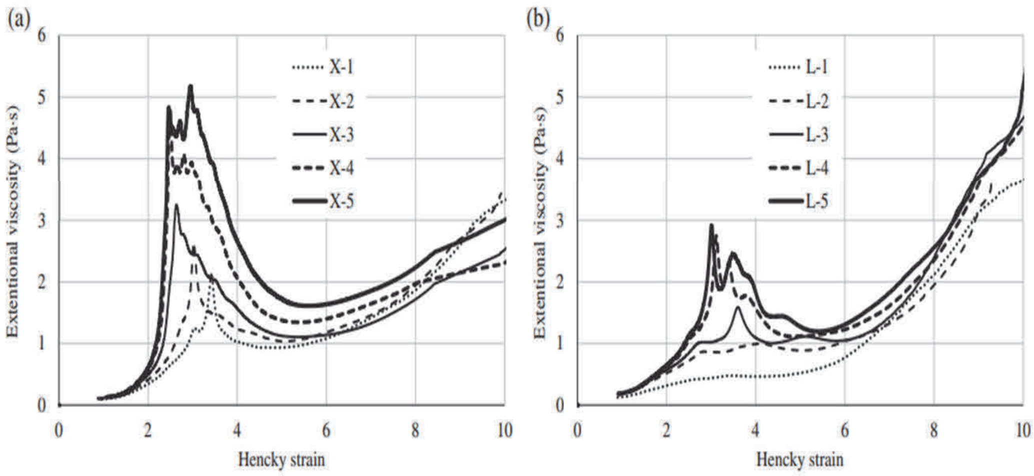
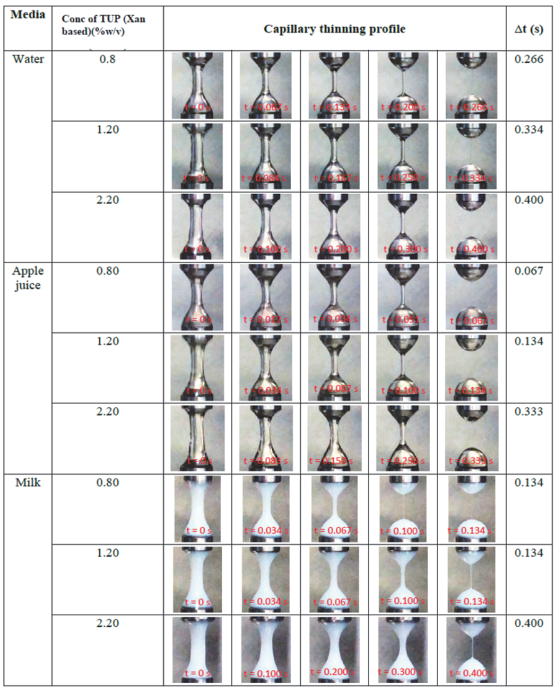
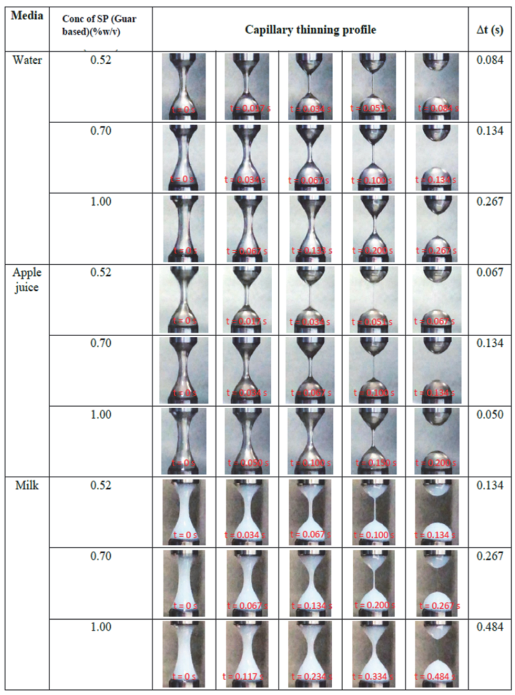


Fig. 88 Hencky strain dependence of extensional viscosity for xanthan gum (a) and locust bean gum (b) solutions[270].



(a)



(b)

Fig. 89 Filament extension of dispersion of xanthan gum (a) or guar gum (b) with different concentrations in water, apple juice and milk. Δt is the time difference after the strike to the point of filament breakup[279].

weakening extensional property.

It was found that in guar gum-based thickener, enhanced extensional properties were obtained when dissolved in milk, whereas partial hydrolysis may occur in apple juice, leading to inferior extensional property compared to that of water (Fig. 89b).

Effects of different components of plant-based particulated foods on bolus rheology are also important, and broccoli puree dispersed in xanthan solution was used to study the effects of particle size and the concentration on bolus rheology using shear and extensional measurements and compared with sensory evaluation by elderly subjects[63].

Hadde and his coworkers[280] defined the aspect ratio of the bolus at the Upper Esophageal Sphincter (UES) opening. Here, the aspect ratio was the ratio of the length to the width, which was defined in Fig. 90. The bolus aspect ratio for high extensional viscosity fluid was found lower than for low extensional viscosity fluid ($p < 0.38$). Higher maximum extensional viscosity, that is, higher IDDSI level, leads to bolus that is stronger and more resistant to elongation, i. e., the low aspect ratio, potentially reducing the risk of post-swallow residue due to bolus breakage, which is equivalent to the higher cohesiveness.

At the same time, such bolus with higher viscosity level showed the longer pharyngeal transit time, which was also

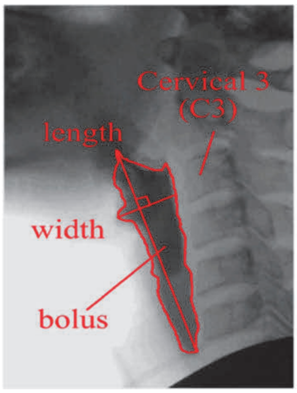


Fig. 90 Aspect ratio length/width of the extended bolus at the Upper Esophageal Sphincter (UES) opening. In this case, the aspect ratio was 4.2[280].

effective to reduce the risk of aspiration (Fig. 91). The pharyngeal transit time was defined as the time that the tail of the food bolus moves from the throat entrance (near the oral tonsils) to the end of the pharynx, which means that the entire food bolus moves slowly[280].

Figure 92 shows residual coating left in the pharyngeal area after swallowing Sample 7 (Xanthan + Maltodextrin) and Sample 8 (Modified maize starch) having equal apparent viscosity at 50 s^{-1}. While the Sample 7 showed no residue, the Sample 8 showed some residual coating left in the pharyngeal area after swallowing. While the shear viscosity was almost the same for Sample 7 and Sample 8, the maximum

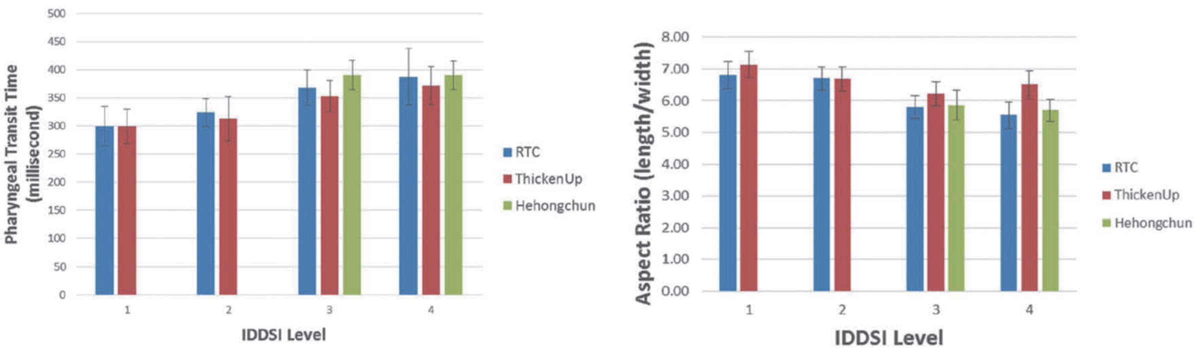


Fig. 91 Pharyngeal transit time and aspect ratio of the bolus at the Upper Esophageal Sphincter (UES) opening as a function of viscosity categorized by IDDSI. RTC ■ (xanthan + maltodextrin), ThickenUp ■ (modified maize starch), Hehongchun ■ (xanthan gum and potato starch)[280].

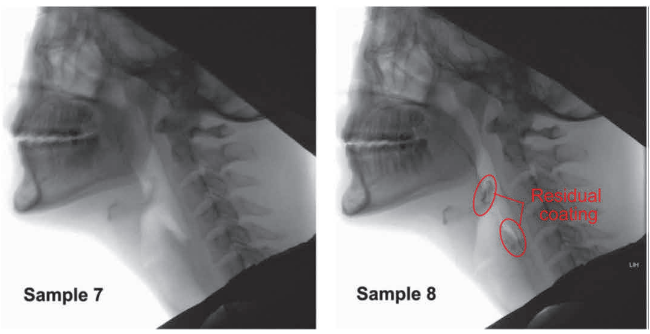


Fig. 92 Residual coating left in the pharyngeal area after swallowing sample 7 (Xanthan + Maltodextrin) & Sample 8 (Modified maize starch) having equal apparent viscosity *ca.* 725 mPas at 50 s^{-1} and at 25 °C[280].

extensional viscosity was much higher for Sample 7 than Sample 8 (35 Pas *vs* 0.4 Pas). The aspect ratio at UES was higher for Sample 8 than Sample 7, which was generally observed for all these thickeners; lower extensional viscosity samples showed higher aspect ratios. The reason why Sample 8 showed residual coating at pharyngeal area was attributed to its higher adhesiveness[280], which is consistent with previous findings that starch based thickeners are adhesive and sticky/slick than gum type thickeners that were reported to be slippery[110, 111, 281]. However, the reason why the pharyngeal transit time was found longer for Sample 7 (xanthan) than Sample 8 (starch) could not be explained if xanthan is more slippery than starch and more coherent, because xanthan could go through pharyngeal region in a shorter time than starch, as will be discussed in relation with Fig. 94.

Cohesiveness of liquid can be quantified by the strain or the time of the breakup in the extension test of liquid filament. It is related to the yield stress, but the detailed analysis has not yet been done. It is expected that the three dimensional measurement method is developed.

Figure 93 shows the effect of saliva on the extension behavior of xanthan gum based or starch-based thickeners. Effect of enzymic degradation of starch is clearly shown.

Extensional and shear viscosities of mucilaginous polysaccharides contained in okra, yam, and kelp have been studied aiming to be applied in dysphagia treatment[283]. It was found that okra and yam mucilages obeyed the Cox-Merz rule while sulfated polysaccharides extracted from kelp behaved as a structured liquid, *i.e.*, complex viscosity was higher than steady shear viscosity.

11. TRANSPORT OF BOLUS

Acoustic measurements have been done for recording the flow velocity of bolus (Fig. 94).

Figure 95 shows that as the concentration of xanthan gum increases, the viscosity of the xanthan gum solution also increases, but the time taken for transfer through the pharyngeal phase is shorter. The time t_2 refers to the period of time during which the food mass passes in the vicinity of the pharyngeal microphone installation, i. e., the time from when the head of the food mass reaches a point in the pharynx to when the tail of the food mass reaches it. This indicates how coherent the food mass is, and is different from the pharyngeal transit time used in the discussion for Fig. 87. As for the perceived swallowing ease, 0.6 % xanthan gum solution was scored the highest, while 0.75 % LBG was scored the lowest among solutions of xanthan gum (0.3–0.9 %) and LBG (0.5–0.8 %). Therefore, one coherent bolus of xanthan through the pharyngeal phase was thought to lead to perceived swallowing ease with smaller variation of flow velocity than locust bean gum solutions, leading to a greater sensation of swallowing ease. Smaller variation of flow velocity may be related with lower probability of scattering or splashing which reduced the risk of aspiration. Actually, by sensory evaluation xanthan solution was evaluation easy to be swallowed[67]. This hypothesis was corroborated recently by a rheological study on the broccoli puree in water and in xanthan designed

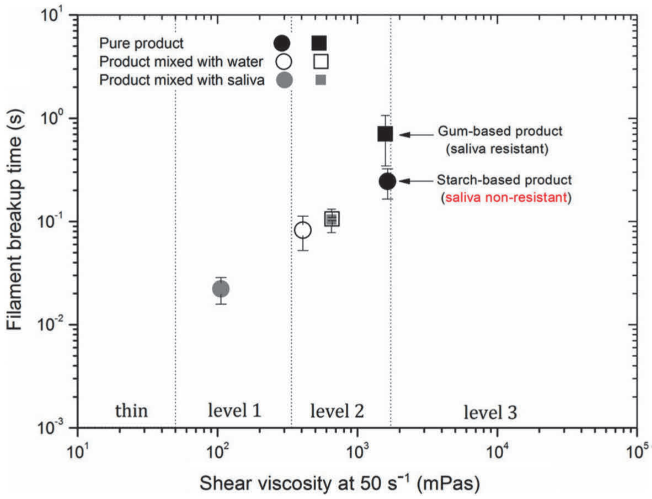


Fig. 93 Filament break-up time as a function of the viscosity categorized by NDD. Thin, Level 1, Level 2 and Level 3 according to the National Dysphagia Diet (NDD)[282].

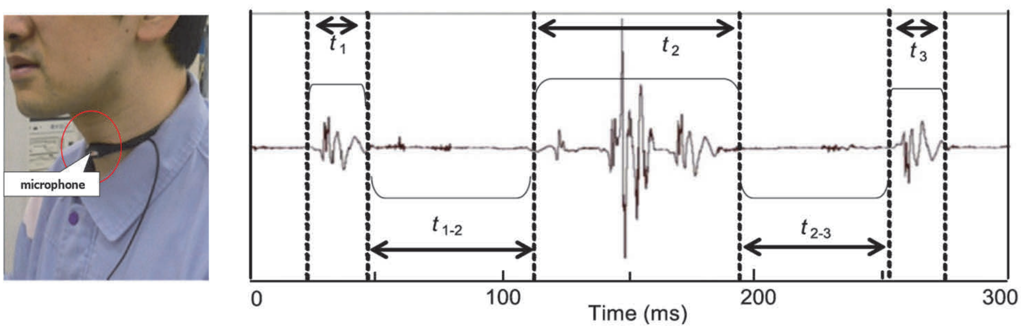


Fig. 94 Microphone set at the throat to record the sound during swallowing, and representative profile of the swallowing sound for de-ionized water[67]. Each event in the recorded swallowing sound for deionized water was ascribed to t_1, closure of the epiglottis; t_2, flow of bolus; t_3, opening of the epiglottis, respectively based on previous studies[284].

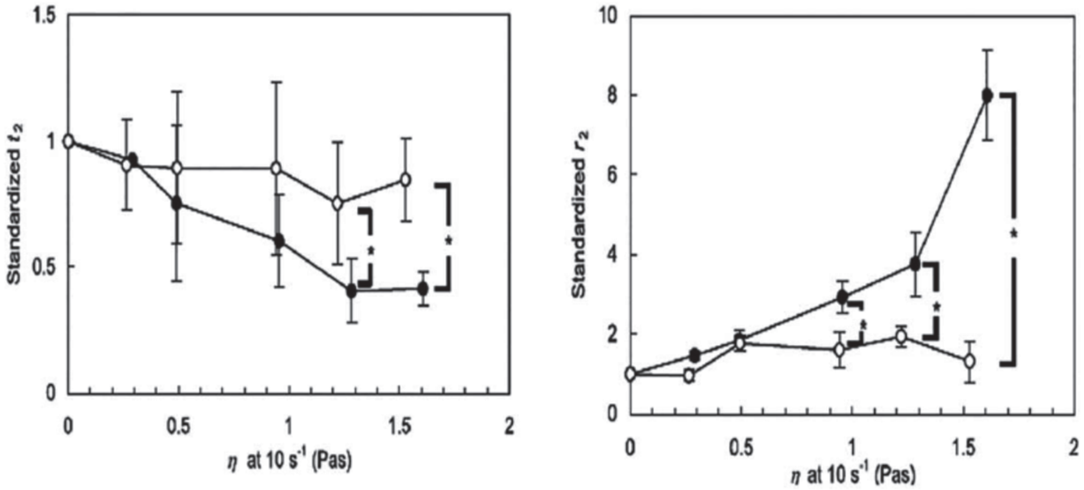


Fig. 95 Duration t_2 and acoustic balance ratio r_2 in swallowing polysaccharide solutions as a function of steady shear viscosity η at 10 s^{-1}. Open circles stand for LBG and closed circles represent xanthan[67].

for elderly persons[63], according to which the presence of yield stress and extensibility in the bolus, achieved by addition of xanthan as fluid phase, leads to particulated foods perceived as easy to swallow. This is also consistent with a recent numerical simulation of swallowing[285] which concluded that thickened solution with *Toromake* (xanthan and dextrin) flowed through the pharynx with no splashed particles and a narrower shear rate and velocity distribution while water flowed through the pharynx with small splashes of particles and wide shear rate distributions.

Flow velocity of porridge through the pharynx was measured using the ultrasonic pulse Doppler method introduced by Nakazawa in 2000s was further developed (Fig. 96)[286]. Based on this method, the velocity distribution of yogurt, and water were determined. It was found that the velocity distribution of water was wide in comparison with yogurt which was rarely aspirated. This also means that water is much less cohesive than yogurt.

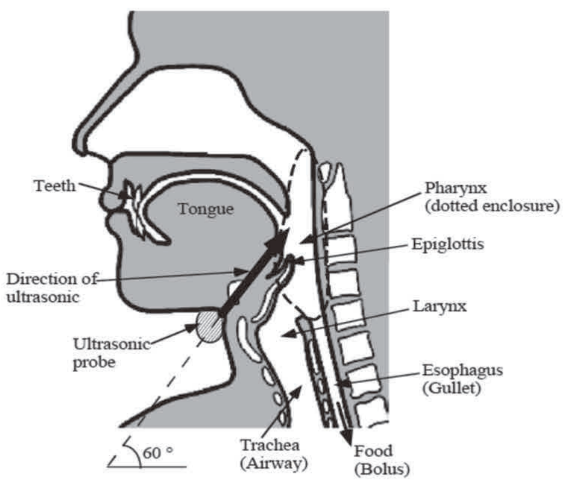


Fig. 96 Measurement of the flow velocity through the pharynx by ultrasonic pulse Doppler method[286].

Dependence of velocities of passage of thickener solutions through the pharynx on the thickener concentration is shown in Fig. 97. The velocity decreased with increasing concentration of thickeners. It was suggested that the maximum velocity of less viscous fluid was high through the pharynx and such a fluid had a risk to be aspirated.

12. HIGH-RESOLUTION MANOMETRY

High-Resolution Pharyngeal Manometry (HRPM) has been attracting much attention[288-291] because it is expected useful to understand the mechanism of bolus transport and to determine the therapeutic method. It gives pharyngeal pressure during swallowing at velopharynx, mesopharynx, and upper esophageal sphincter (UES) although videofluoroscopy (VF) and videoendoscopy (VE) are still more widely used to visualize and evaluate the swallowing dynamics in patients with dysphagia. However, both VF and VE could not quantitatively evaluate the pharyngeal pressure. The recent development of the technology could produce a high-resolution manometry catheter with 36 circumferential sensors spaced 1 cm apart (Fig. 98). After the lubrication, the catheter was inserted *ca.* 40 cm from the nostril into the esophagus allowing the pressure measurement at velopharynx, mesopharynx/tongue base, hypopharynx, upper esophageal sphincter (UES). The motion of the tongue base toward the posterior downward direction, swallowing pressure induced by pharyngeal peristaltic wave caused by pharyngeal constricting muscle, transmission of the swallowing pressure from pharynx to esophagus could be evaluated during one swallowing, thus enabling to assess the bolus driving in the pharynx. Driven out bolus is transported into esophagus via relaxation of cricopharyngeal muscle and the opening of UES caused by

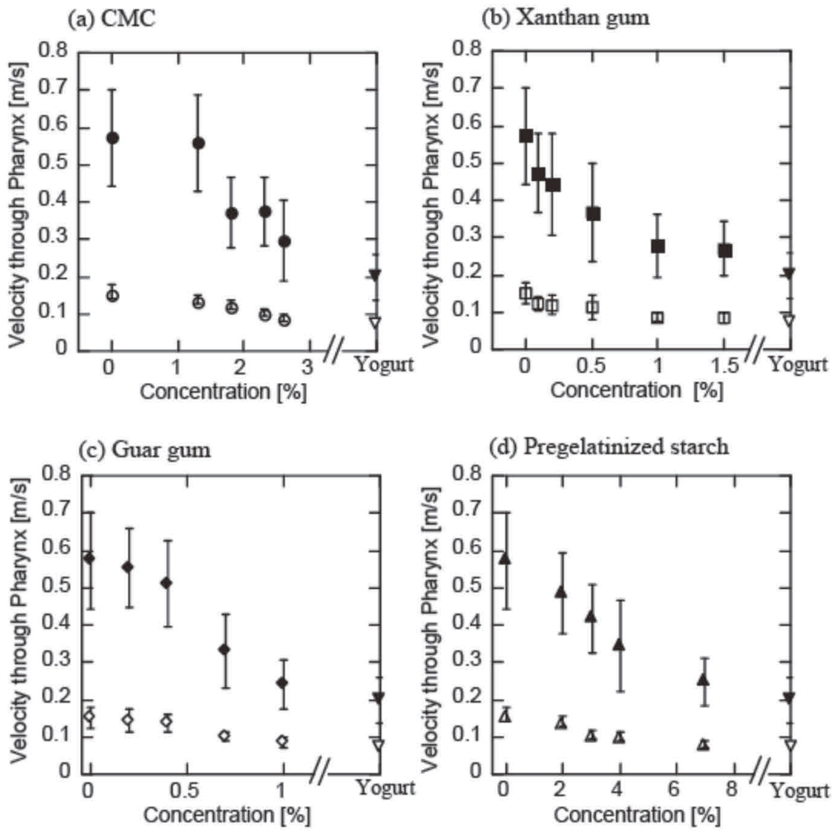


Fig. 97 Dependence of velocities of passage of thickener solutions through the pharynx on the thickener concentration. Open symbols, average; closed symbols, maximum[287].

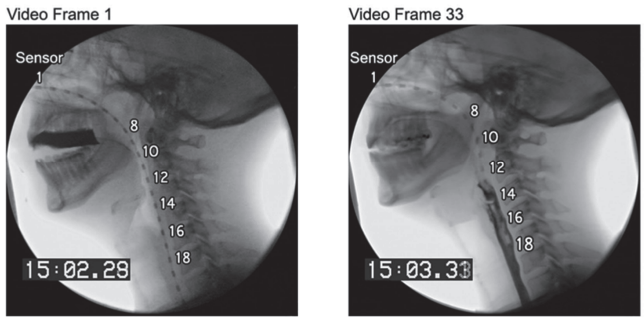


Fig. 98 Radiographic images before and during the swallow. The broken line shows a catheter (a 2.75-mm-diameter solid-state high-resolution manometry catheter incorporating 36 1-cm-spaced pressure sensors) and the number 1 and 8 ~ 18 along the catheter corresponds to sensor numbers. Bolus on the tongue in Video Frame 1was swallowed by a 42-year-old male subject, and seen in the trachea below the sensor 13 directing to the esophagus[289].

antero-upward motion of pharynx. This dynamic aspect of UES can also be analysed quantitatively (Fig. 99).

The pressure recorded during that period between the time when the bolus head arrives at the sensor and the time when the bolus tail leaves the sensor was defined as the intra-bolus pressure (IBP)[290, 292, 293]. Many efforts have been done to correlate the viscosity, volume and the IBP, but these relations have not yet been established[294, 289]. HRM combined with VFSS was shown effective to clarify the relationships between intraluminal pressures and movement of the anatomic structures while the bolus passes through the swallowing structures[295]. This enables to observe clearly the esophagogastric junction outflow obstruction and esophageal body contractility as normal or abnormal, such as achalasia, and thus effective for determining the intervention[296]. In the examination of the effects of volume and the texture, Ryu *et al.*[297] performed the HRM and VFSS. Ten healthy subjects swallowed dry, thin fluid 2 mL, thin fluid 5 mL, thin fluid 10 mL, and drinking twice to compare effects of bolus volume. To compare effect of texture, subjects swallowed thin fluid 5 mL, yogurt 5 mL, and bread twice. It was found that the bolus volume influenced significantly the pharyngeal pressure and timing, but the texture did not show any effect on pharyngeal swallowing[297].

HRM was found effective to quantify the atrophy and degeneration of pharyngeal muscles leading to dysphagia for Parkinson's disease (PD) patients[298]. It was found that the swallowing pressure at velopharynx, mesopharynx and UES regions decreased with increasing severity of PD; stage I, unilateral involvement; stage II, bilateral involvement; stage III, PD with impaired balance; stage IV, able to walk and stand unassisted but otherwise markedly incapacitated; stage V, unable to walk[298]. Velopharyngeal and oropharyngeal pressures were found to decrease, and UES opening and

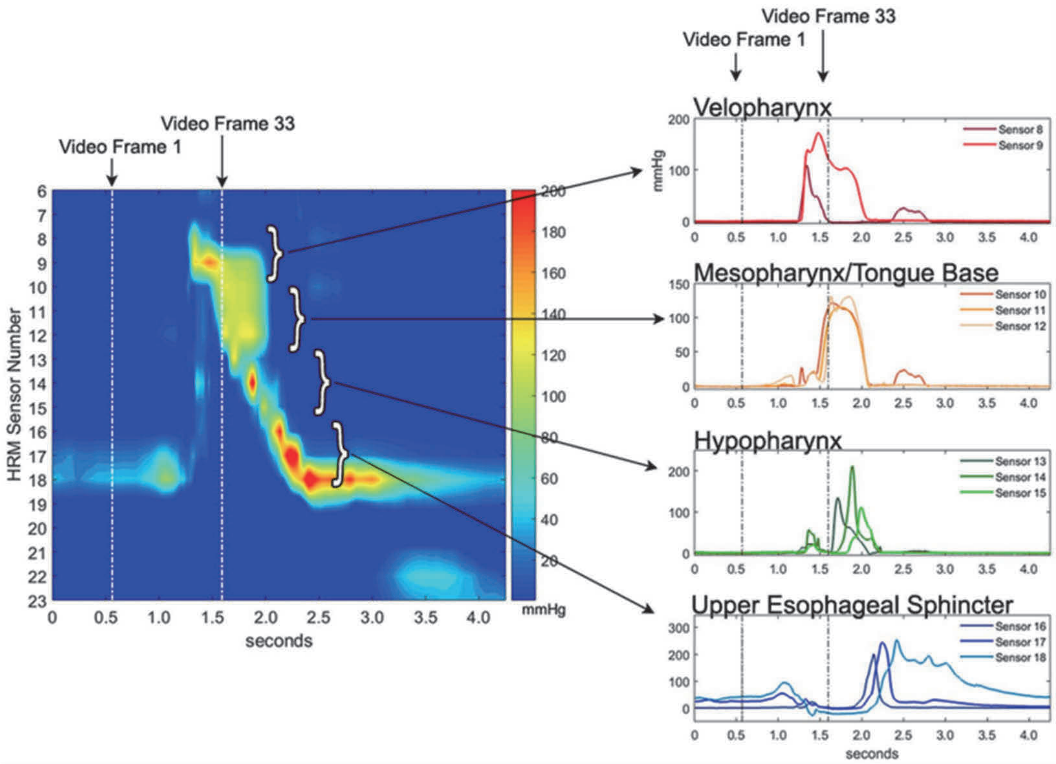


Fig. 99 (Left) Spatio-temporal record of a pharyngeal pressure during cued volitional swallowing of a 10 ml thin liquid barium bolus (IDDSI 0) by the same subject in Fig. 98. Vertical lines correspond to the time points of the two radiographic images in Fig. 98. (Right) Individual pressure signals recorded by sensors at the different axial locations along the pharynx. The four graphs show the individual pressure signals occurring within each anatomical region and illustrate the variable nature of pressures recorded throughout the pharynx[289].

contraction could not function normally in the patients with severe PD. Thus, HRPM was expected to detect subtle abnormalities by quantifying swallowing pressure in patients with PD at an early stage.

Myasthenia gravis (MG) is an autoimmune neuromuscular disease that causes weakness of skeletal muscles, usually first manifesting as droopy eyelids and double vision[299]. The incidence of dysphagia was examined in three subject groups; patients without dysphagia (group 1), patients with dysphagia (group 2), and healthy participants (group 3) based on a screening test, manometric test, electrophysiologic studies, electromyography (EMG), fiberoptic endoscopic evaluation of swallowing (FEES), and barium swallow pharyngeal esophagography (BSPE)[300]. It was found that although the number of patients with dysphagia in group 2 was significantly higher in the clinical tests ($p = 0.007$), FEES ($p = 0.001$), and EMG ($p = 0.043$) than in group 1, no difference was detected for BSPE ($p = 0.119$) and manometry ($p = 0.644$). Swallowing functions in patients with MG was thought to be affected even without symptoms.

The smooth transit of bolus complex from the pharynx to the esophagus is ensured by the complex steps of muscle contraction, and the weakness of the oropharyngeal muscle contractions was thought to induce the silent aspiration in MG patients[35]. Taking into account the earlier report of Logemann *et al.*[301] that a chin-down position is helpful for patients suffering from pharyngeal residue, reduced tongue base retraction, and insufficient airway protection, it was effective to compare oropharyngeal swallowing dysfunction in MG patients in swallowing between the neutral and chin-down positions[35]. The postural condition was initially hypothesized to widen the valleculae and place the epiglottis in a more protective position over the laryngeal inlet[301]. Although the chin-down or chin-tuck maneuver has been widely used to reduce aspiration and has been reported to be effective for various dysphagic populations, the definition of these postures has not been unified[302, 303]. Image representation of different postures as shown below (Fig. 100) was useful to remove the ambiguity and inconsistent understanding among researchers[302].

It was demonstrated that the maximum SP at the meso–hypopharynx (MHP) was significantly increased in the chin-down position ($p < 0.05$), which is effective for blowing out the pharyngeal residue (Fig. 101)[35]. Moreover, the maximum SP at the UES was significantly reduced (relaxed) ($p < 0.05$), and the duration of relaxation at the UES was significantly increased ($p < 0.05$), in the chin-down position, both of which are beneficial for bolus passage through the UES. It

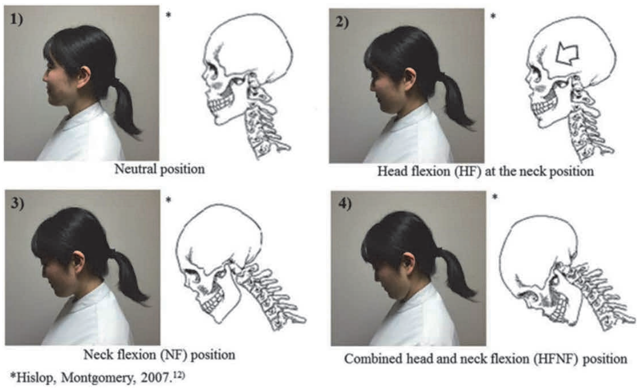


Fig. 100 Image representations for the definition of postures. 1) neutral position; 2) head flexion at the neck position; 3) neck flexion position; and 4) combined head and neck flexion position[302]. The schemas were cited from Hislop *et al.*[304].

was concluded that the chin-down position in MG patients increased the degree of UES widening with increased hypopharyngeal suction or at least the relaxed SP at UES, and thus the smooth bolus passage could be accelerated with elevation of the larynx during swallowing, which was supported with their previous perspectives that the chin-down position was assumed to improve laryngeal elevation improving simultaneously the pharyngeal clearance[35, 302, 305].

Since the examination of swallowing before and after the intravenous injection of edrophonium chloride (EC) with HRM was expected to find the weakness of the wallowing ability, HRM was performed for a 72-year-old woman diagnosed with ocular MG 8 years previously developed slight pharyngeal discomfort for 3 months, and was classified as IIb in The Myasthenia Gravis Foundation of America clinical classification[306]. These authors found that HRM could be used to evaluate weakness of the pharyngeal muscle and/or suprahyoid muscles before and after intravenous EC injection in diagnosing MG patients. They expect that the HRM assessment of slight muscle weakness in swallowing-related muscles is useful for early diagnosis or identification of recurrence, before serious complications develop.

According to a recent systematic review[291], pharyngeal HRM/HRIM in swallowing assessment remains in the developmental stage because some important experimental methods were not described or were different among research groups or even in the same research group, for example, the diameter of the catheter (mostly *ca.* 4 mm but much smaller in other papers), how/whether the topical anesthesia was done, the method of analysis was not standardized, the body position (seated or supine or not reported). In addition, the bolus consistency was not controlled or limited to simple liquids. Most papers using HRM used only liquids and very few papers reported the effects of food stimulation. Regan[307] reported that sensory stimulation, cold, sour, and carbonation increased the pharyngeal contractile integral, which was a global measure of pharyngeal contractile vigor and persistence within a space-time box I.

13. EFFECTS OF AGE ON CHEWING ABILITY

The above conclusions were based on the examination of young heathy subjects. The difference in the mastication behaviour of young and elderly subjects was reported for six different foods, apple, cheese, rice, bread, peanut, and beef[308].

Kohyama *et al.*[308] found that the number of chews and masticatory time are highly correlated. These values were greater in the elderly subjects than the young. The chewing rhythm as the ratio of the masticatory time and the number of chews was similar for both age groups. These tendencies were recognized for many foods although the EMG variables were different depending on food texture (Fig. 102). Kohyama *et al.*[309] further reported that the increase in the

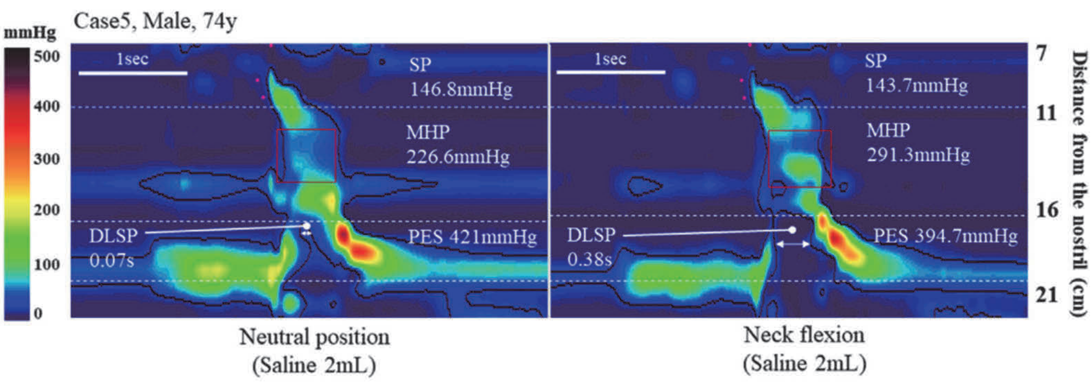


Fig. 101 Pressure topography data reflecting differences between the neutral (a. left) and chin-down positions (b. right). The patient swallowed 2 mL of physiological saline. In comparison with the neutral position, the maximum SP at the meso–hypopharynx increased from 226.6 to 291.3 mmHg, the maximum SP at the UES decreased from 421 to 394.7 mmHg, and the duration of relaxation pressure at the UES increased from 0.07 to 0.38 s in the chin-down position[35].

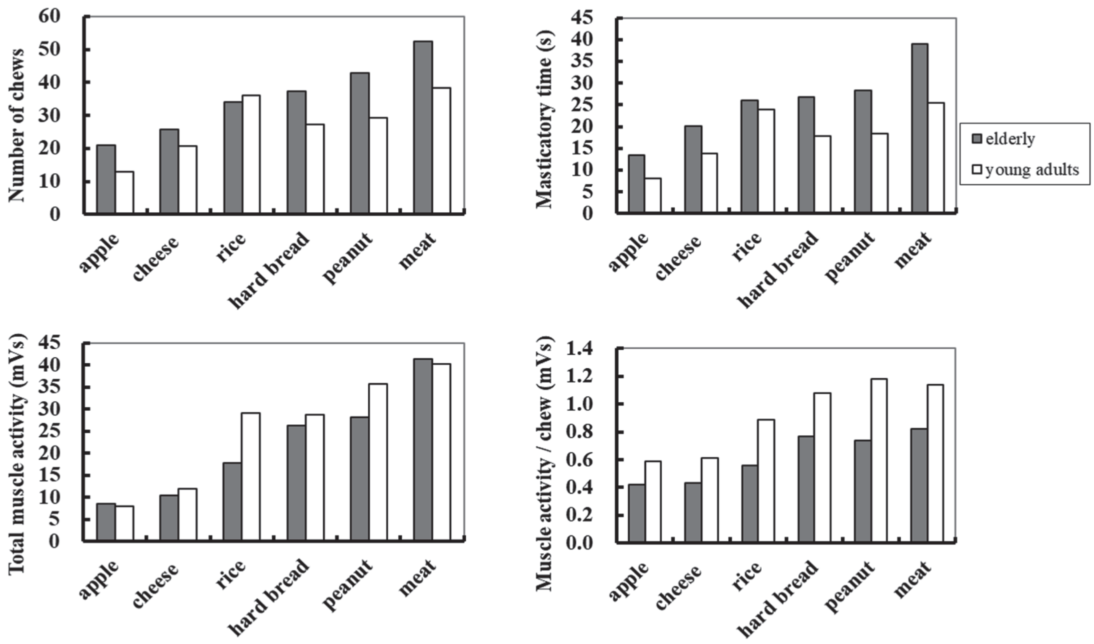


Fig. 102 The number of chews and muscle activity for six different foods, apple, cheese, rice, bread, peanut, and beef for young and elderly subjects[308].

number of chews and masticatory time for the elderly is related to decreased dental status estimated from the number of molar teeth pairs. They interpreted the increase in the number of chews and masticatory time in the elderly compensated a less effective single chewing for food breakdown in subjects with lower chewing ability.

In the examination of the difficulty/easiness of minced carrots with thickening agents, the young panel preferred the minced foods with xanthan alone, while the aged panel preferred that with the mixture of Xanthan gum and Guar gum (X : G = 0.2 : 0.4)[310]. It was found that the chewing time was shorter for the mixture of (X : G = 0.2 : 0.4) which the aged panel judged easier for oral processing. Aged persons evaluated this mixed thickening agent (X : G = 0.2 : 0.4) made bolus more coherent and thus feel comfortable, while it was not necessary to make minced carrot a more cohesive bolus for the healthy and young panel. A minced carrot mixed with thickening agent was evaluated too sticky by the young panel because their dental state and the salivation were good enough. This apparent contradiction that thickened fluids are difficult to be manipulated in the oral cavity yet were shown safer for swallowing for disadvantaged persons with reduced tongue strength and/or mobility must be further studied.

Using four types of rice products with different hardness cooked rice, soft-boiled rice, rice gruel and thin rice gruel, mastication behaviour of young and old subjects was examined[311]. The chewing number and bolus transit time parameters until the first swallow, HTT, hypopharyngeal transit time; PFAT, postfaucial aggregation time; VAT, vallecular aggregation time were observed. Chewing number and the transit time[30, 39, 311] were found to decrease with decreasing hardness for the four rice products. The chewing number was larger in elderly subjects than in young subjects for harder three products cooked rice, soft-boiled rice and rice gruel, but not different for the softest product thin rice gruel. It was difficult to count the chewing number for soft foods because chewing movement was less obvious than for harder foods. The second subsequence duration S-S2 and VAT were found significantly longer in elderly than in young subjects, and the total duration also showed the same tendency, and the authors found it consistent with a previous finding: increased oro-pharyngeal transit times and delayed initiation of the pharyngeal phase in the elderly[312]. To get clearer results, the authors stated that examinations using more subjects are required to solve the individual difference.

Five years later, the same research group[313] challenged again this problem to understand the difference mastication behaviour in young and elderly. They used soy-milk based gels with 4 different levels of hardness, 510 kPa, 50 kPa, 16 kPa and 5 kPa corresponding to Japanese Universal Design Food of 500 kPa, 50 kPa, 20 kPa, and 5 kPa, and Japanese Smile Care Food, Easy-to-chew, Can be crushed with gums, Can be crushed with tongue, and No chew, or IDDSI level, 7, 6, 5, and 4, respectively. These cubic gels (2 cm) were provided to participants in random order at ambient temperature. Twenty young adults (mean age 25) and 35 older adults (mean age 75) participated the study. It was found that the maximum peak amplitude (MPA) of the masseter muscle was significantly higher in the older adult group than in the young adult group although the MPA was not so different for the hardest model food. Both the number of chewing cycle and oral processing time were found larger irrespective hardness of ingested foods. In addition, VAT (vallecula aggregation time), FSD (first subsequence duration), S–S2 (second subsequence duration) and TD (total duration of intake) were all longer for older adults, which confirmed the previous results. These mastication parameters were related with physiological difference in two groups. The average tongue pressure measured by IOPI (Iowa Oral Performance Instrument) was 58 kPa in young adults group and 35.5 kPa in older adults group. Unstimulated salivation determined from the weight of gauze kept for 5 min in the mouth was 2.13 (g/5 min) and 1.06 (g/5 min) in young and old groups respectively. Park *et al.*[313] inferred that the sensitivity to food texture changes was lower in the older adult group than in the young adult group, which is consistent with recent finding[314]. Puleo *et al.*[314] developed a method to measure human sensitivity to graininess, using cocoa-based creams as real tested food. Since, it was successful, they applied this method to another texture attribute hardness, using 4 jellies with different hardness controlled by agar concentration. They found that young subjects were more sensitive than older, and males were more than females.

In the delivery of particulated pharmaceuticals, hydrocolloids (Xanthan and carboxymethyl cellulose (CMC)) solutions were found effective to reduce the grittiness sensation and improve the appearance, taste, mouthfeel, ease of swallowing[315]. Model microparticulated pharmaceuticals, microcrystalline cellulose pellets, namely Cellets 200 (200–355 μm) and Cellets 700 (700–1000 μm) were dispersed in 0.15–1.5 % w/v xanthan and CMC, and 5 mL dispersion was used for sensory evaluation. Among the tested samples, XG 0.5 % was found the best, requiring less concentration than CMC. The mouthfeel of CMC dispersions was felt “greasy” or “oily” in the mouth, and was rated worse than xanthan. The authors described the performance of thickening dispersion as providing ‘cushioning and lubrication’ of the particles and acting as an effective vehicle by ‘carrying the particles together’, concealing the gritty feeling of the multi-particulates and assisting swallowing. When this result is compared with previous studies of grittiness sensation[126, 127], the particulates used in the delivery of pharmaceuticals had a shape of pellet which was not soluble in water but might not be angular and in addition soft thus the grittiness might be well concealed in the hydrocolloids dispersion. It was a pity that no sugar was added to samples for sensory evaluation in addition to vanillin, which might be effective to reduce the slight odor or taste originating from hydrocolloids.

To understand better the swallowing of particles dispersed in thickener solutions, a “Cambridge throat” type setup mimicking the tongue peristalsis, introduced first by Mackley *et al.*[316] and then quantified by Hayoun *et al.*[317] was used[318]. A schematic representation is shown in Fig. 103.

Marconati *et al.*[318] used Cellets 200 and Cellets 700 as particles and solutions of xanthan (0.25, 0.5, 1 %) and CMC (0.5, 1 and 1.5 %) as thickener solutions to examine the effects of particle size and shape and the rheological properties of thickener solutions on the swallowing ease and post-swallow residues perceived in the sensory evaluation. Water is also used as a control. As reported before[315], administration of multi-particulates in water caused the gritty sensation and residues after swallowing while these were not perceived when xanthan and CMC solutions were used. The “oral” transit time was found longer in water and to increase with increasing particle size by *in vitro* experiments using a Cambridge throat. Ten among thirty subjects commented that water “does not hold the particles together in the mouth”. Smaller particles were perceived easy to be swallowed which was consistent with *in vitro* observation of shorter transit time and less “oral” residues. The *in vitro* experiment also showed the presence of the optimum consistency of the dispersing medium, not too thin and not too thick, in the range examined, 0.5 % xanthan and 1 % CMC were preferred by panelists. Since this setup is simple and thus may be used to evaluate the swallow-ease for inhomogeneous bolus such as porridge before planning the sensory evaluation.

Since the ingested food is transported from the anterior to the posterior region in the oropharynx by peristalsis, *in vitro* method of peristalsis was done by the squeezing foods

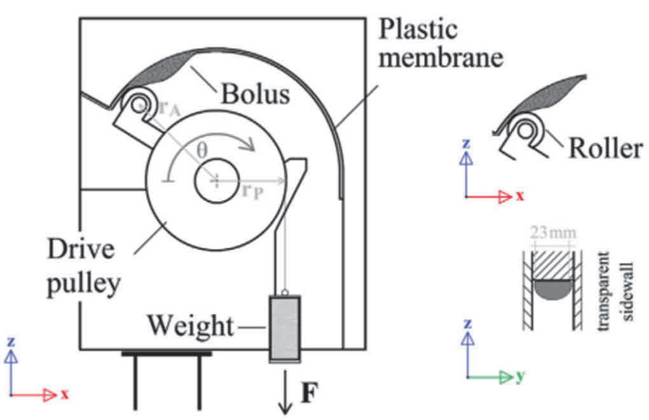


Fig. 103 A Cambridge throat. The *in vitro* experiment showing the roller at the initial position θ = π/4 and is rotating by the weight which imposes a driving force **F** represented by the downward black arrow. The bolus between the transparent walls (23 mm apart each other) is shown in the lower right[196].

contained between thin, flat and compliant membranes, upper side glued to the “hard palate” and the lower side was squeezed by a rotating roller driven by an external load in a Cambridge throat as shown in Fig. 103[317, 319]. In an *in vitro* dynamic Video Fluorographic Swallowing Study (VFSS) based on robotic technology, the motion of the mandible was controlled by the rotational and translational motion, and the position of the tongue was controlled at three points: the tongue bone (hyoid bone), the center point of the tongue, and tip of the tongue[320]. The tongue was actuated by six wires attached to the tongue bone, three to the center point of the tongue and one to the tip of the tongue. Three of those wires are common with the mandible, so the motion of the tongue is connected to that of the mandible[320].

By choosing the motional condition of the mandible and the tongue, the residue of a semisolid food at epiglottic vallecula as shown in Fig. 104a) right, and the aspiration of a thickened liquid which flowed speedily above the epiglottis as shown in Fig. 104b), were reproduced and visualized by VFSS[320]. Soft robotic simulation was further developed[321-323].

Although the thickening has been shown to reduce the risk of aspiration, there has been few studies on the effects of aspirated thickening water in the lung[324]. Nativ-Zeltzer *et al.*[324] studied this by instilling water, xanthan-gum-thickened water, and cornstarch thickened water into the lung through catheter. They found that the survival rate was decreased in starch thickened water while other two liquids did not change the survival, *i.e.*, rabbits survived until the end of the test. However, the histological examination revealed that thickened agents caused greater pulmonary inflammation, pulmonary interstitial congestion, and alveolar edema than water alone. Therefore, according to their study, thickening agents are useful to reduce the risk of aspiration, but once they were aspirated they will give more harm than water although authors mentioned the needs of more studies.

While the rheological properties of thickening colloidal solutions are useful for evaluating the safety of swallowing and the residue left after swallowing, it is also necessary to examine the rheological changes in dysphagia-oriented foods that are actually used and commercially available.

Figure 105 shows the effect of water or saliva on the steady shear viscosity of purees. While adding water slightly decreased the viscosity, more remarkable decrease was found in the boli mixed with saliva. The decrease in the viscosity was less in the bolus mixed with saliva S4 (saliva from the subject with least α-amylase activity), which is consistent with previous reports that the viscosity of starch-based thickening agent decreased by reacting with saliva[121, 325, 326].

Herranz *et al.*[327] reported also the similar tendency by measuring the storage and loss moduli for these commercial samples in the presence of saliva.

Figure 106 shows the filament extension of TUC, a commercial xanthan gum-based thickener, cereal extract and polyethylene oxide with various concentrations.

The remaining volume of liquids in the IDDSI syringe increases with increasing level of IDDSI (Table XI). However, 0.3 % w/w cereal extract belonging to Level 1 in IDDSI classification showed a longer break-up time than 1.19 % w/w TUC and 2 % w/w PEO which belong to Level 2. This suggests the inconsistency in the IDDSI classification, and must be studied further.

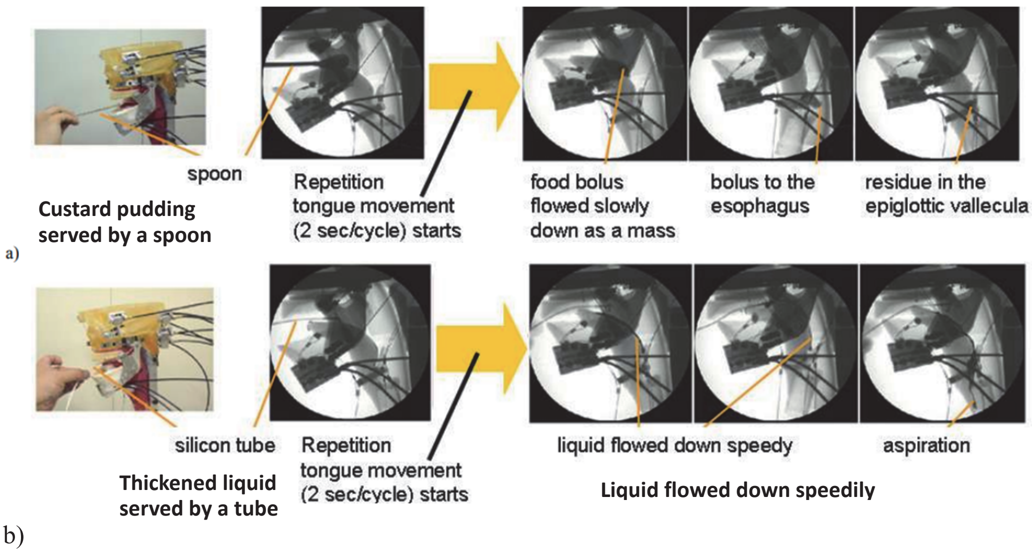


Fig. 104 Robotic dynamic Video Fluorographic Swallowing Study (VFSS) of a) semisolid model boli (custard pudding) and b) thickened liquid[320].

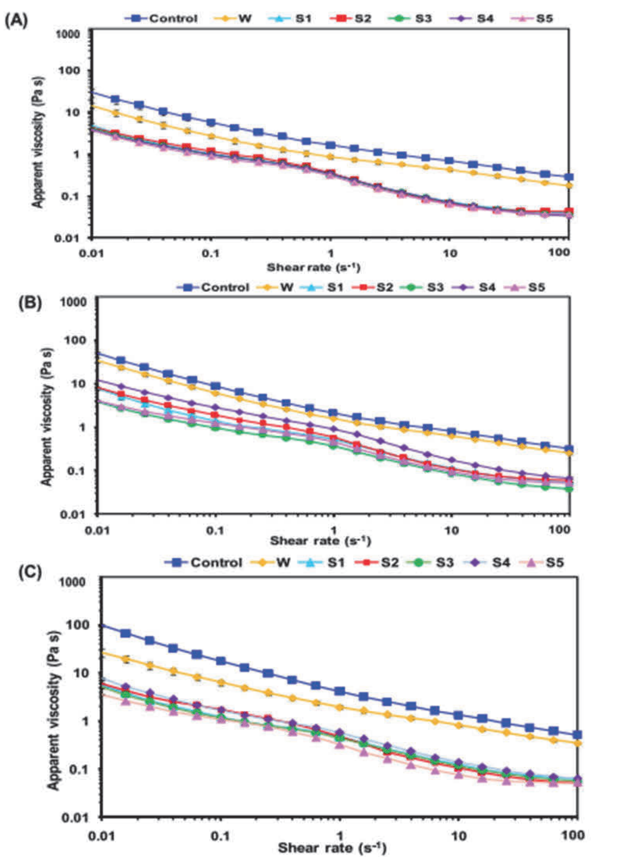


Fig. 105 Apparent viscosity as a function of shear rate for vegetables and beef purée (A), vegetables and codfish purée (B), and chicken with rice and carrots purée (C) at 37 °C[327].

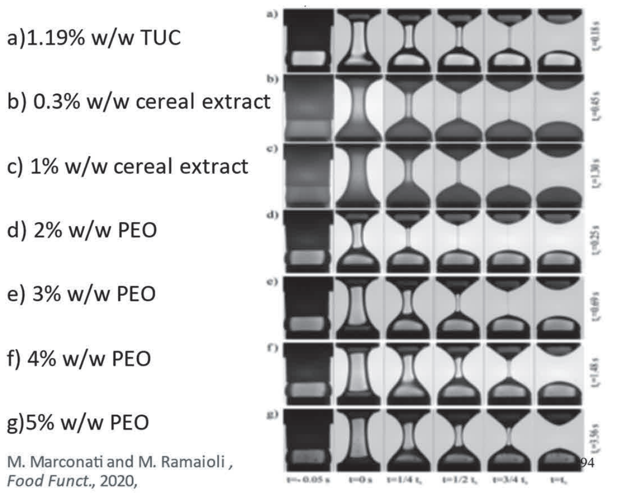


Fig. 106 Filament extension test of TUC, a commercial xanthan gum-based thickener, cereal extract and polyethylene oxide (PEO) with various concentrations[328].

Table XI Remaining volume of liquids in the IDDSI syringe and the break-up time for various liquids belonging to different IDDSI levels[328].

Liquid sample	Remaining volume (mL)	IDDSI level	Break-up time (s)
1.19 % w/w TUC	4.9 ±0.3	Level 2	0.18 ± 0.02
0.3 % w/w cereal extract	2.9 ±0.3	Level 1	0.45 ± 0.02
1 % w/w cereal extract	5.3 ±0.2	Level 2	1.30 ± 0.05
2% w/w PEO	7.0 ±0.2	Level 2	0.25 ± 0.01
3% w/w PEO	9.5 ±0.2	Level 3	0.69 ± 0.04
4% w/w PEO	9.9 ±0.1	Level 3	1.48 ± 0.03
5% w/w PEO	10.0 ±0.1	Level 4	3.56 ± 0.02

14. EFFECTS OF CHEMICAL SENSES

While effects of rheological properties on the swallowing behavior have been studied extensively, role of taste, olfaction, and trigeminal perceptions on swallowing function have been studied by fewer groups[329, 330].

Some compounds such as capsaicin and menthol have been shown to shorten the LTSR (Latent Time of Swallowing Reflex)[15, 331, 332] and have been used to improve the swallow response[332, 333]. Latency of swallowing reflex for distilled water was reported maximum at around the body temperature and was found significantly shorter at the temperature 10–20 °C and 60–70 °C and 70–80 °C[334]. Cilostazol, an anti-platelet agent has been reported to reduce the incidence of pneumonia[335], and the reduction of LTSR by the administration of cilostazol was found although its relation with substance P was not found[336].

While carbonated thin liquids (CTL) have been reported to decrease both the penetration and aspiration compared with noncarbonated thin liquids (NCTL) in the examination of oropharyngeal swallowing in 17 adults with pharyngeal delay[337], the effects of carbonation in thickened beverages of the same flavor on swallowing dynamics have not been reported. This was studied for 38 dysphagia patients[338]. The residue in vallecula and pyriform sinus were found reduced by CTL cola than by NCTL cola. The onset of the swallowing reflex was significantly earlier in the group of CTL than in the group of NTCL. Saiki *et al.*[338] concluded that CTL cola was more beneficial for dysphagia patients than NTCL. Similar conclusions were reported[339-341]. CTL was reported to reduce the risk of aspiration even for dementia patients with Lewy bodies and Parkinson's disease[342].

Transient receptor potential (TRP) channels are involved in sensory signaling for taste, thermo-sensation, mechanosensation, and nociception[343]. Among TRP channels, TRPV1 is activated by pungent compounds such as capsaicinoids (in chili pepper), piperines (in pepper), shogaols and gingerols (in ginger), and elicits a burning sensation[344, 345]. A new technique to understand the TRP is expected to shed some light to the relation between the LTSR and the pungent stimulants[343].

Since these compounds are known to be pharmacological agonists controlling TRP ion channels, Alvarez-Berdugo *et al.*[346] compared the therapeutic effects of three pharmacological agonists, capsaicinoids for TRPV1, piperine for TRPA1, and menthol for TRPM8 with those of a thickener (spoon thick modified starch according to the classification of NDD) in patients with oropharyngeal dysphagia. They observed VFS images of bolus transport and residues in pyriform sinus and vallecula, bolus penetration into the laryngeal vestibule. The three timings of the swallowing response, glossopalatal junction (GPJ) opening, laryngeal vestibule closure (LVC) and upper esophageal sphincter opening (UESO) were recorded. All the three pharmacological agonists and the modified starch thickeners reduced the laryngeal penetration, but the effect of the thickener was found greater. However, while three pharmacological agonists had no significant effect on oral residue, the spoon thick thickener significantly increased the oral residue by 173 % and pharyngeal residue by 20 %. While TRP stimulants increased bolus velocity and reduced swallow response times, thickeners reduced bolus velocity and further delay the swallow response. Among three pharmacological agonists, capsaicinoids showed the best performance. Since xanthan gum was reported to increase the residues, it is expected that the combinatorial treatment of physical and chemical intervention can improve the therapeutic effects.

15. TEXTURE DESIGN OF FOOD FOR DYSPHAGIA

Since the risk of aspiration is so serious, many papers have been published to reduce the risk using thickening agents most of which are polysaccharides[347]. On the other hand, it is important to increase the intake of protein in texture modified foods. Fish pastes have been studied for persons with lower eating ability such as babies and elderly[348-350]. Both grass carp paste[349] and salmon paste[348] which were determined suitable were found to behave as a structured liquid, *i.e.*, both G' and G'' increased only slightly with increasing frequency with $\tan\delta \sim 0.1–0.2$. This is consistent with previous findings[67, 115]. Since the suitability of texture-modified foods for a specific disadvantaged group depends on the eating ability as was categorized into 8 levels in IDDSI, the above mentioned optimum grass carp fish paste with salt, sugar, and starch was classified as level 4-pureed and extremely thick of IDDSI framework. Water addition was necessary to make a soft texture but too much addition lowered the water holding capacity (WHC). The addition of starch was effective to maintain WHC and mask the fishy odor.

Thickening agents such as xanthan and guar gum are sometimes used to help intake tablets containing magnesium oxide, but it often causes non-disintegration[351, 352]. Controlling the immersion time of tablets in thickened solution was found effective to prevent the non-disintegration[353]. Yogurt made with *L. cremoris* FC was found to be useful as a deglutition aid for tablets[354, 355].

Cooked beef pastes with xanthan gum, guar gum, k-carrageenan, and locust bean gum were chosen for dysphagia patients using 3D printing foods. These mixtures should be extruded with less energy and after extrusion they sometimes are required to maintain the shape. Much efforts have been done to satisfy these contradictory requirements. It was found that the modulus was found to increase with increasing temperature in thermal scanning rheological measurement accompanied with protein denaturation and it was found to increase during cooling[356, 357] which had been attributed to hydrogen bond formation[357-359].

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. However, the level must be controlled so that the mastication ability of the patient will not be weakened or lost via disuse atrophy. Food for such persons should be designed easy to masticate and swallow, but during oral processing, appetite, mastication, and swallowing ability must be maintained with eating pleasure. This may depend on the ability of each person, and thus such personalized food can be processed for each person. One possible approach may be the application of 3D printing, which is still in a developing stage[360-362]. This will be a challenge for the food industry, and the collaboration among different sectors, medical doctors, nurses, food scientists & engineers, speech therapists, psychologists, is necessary for dysphagia problems.

16. CONCLUSION

Although the cause of the aspiration depends on the etiology, the modification of the rheological properties of ingested food or of the bolus during and after the oral processing, will change the flow behavior and may be able to reduce the risk of aspiration. The prevention of aspiration needs a multiangle approach and thus collaboration between different disciplines is required. Exchange of knowledge accumulated in each discipline must be encouraged and barrier between different disciplines should be lowered for further collaboration. A common knowledge in one discipline is not always well known in the other discipline. We hope that the present review will be helpful to fill the gap.

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APPENDIX

Japanese societies on dysphagia and related problems:

The Japanese Society for Mastication Science and Health Promotion http://sosyaku.umin.jp/

The Japanese Society of Dysphagia Rehabilitation (JSDR) http://www.jsdr.or.jp

Japanese Society for Functional Structure of Nutrient (JSFSN) http://jsfsn.net/contact.html

Japanese Society for Clinical Nutrition and Metabolism https://www.jspen.or.jp/

The Japan Bronco-esophagological Society http://kishoku.gr.jp/public/disease01.html

Japan Care Food Conference (Universal design foods) http://www.udf.jp/

Glossary

The following abbreviations and technical terms are concisely described by Hiiemae in J. Texture Studies, 35 (2004) 171-200

Abbreviations

Central Pattern Generator (CPG), CPG for mastication, Swallowing CPG, Cinefluorography (CFG), Videofluorography (VF or VFG), Electromyography (EMG), Tooth-Food-Tooth Contact (tft contact), Intercuspal Phase (IP), OroPharyngeal Aggregation Time (OPAT)

Technical terms

Bite, Bolus, Active side, Balancing side, Centric occlusion, Upper and Lower Occlusal Planes, Complete Feeding Sequence/Process, Sub-Sequences, Ingestion, Stage I transport, Processing (or Chewing), Stage II Transport, Clearance, Posterior Oral Seal, Oropharynx, Hypopharynx

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