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NUMERICAL ANALYSES OF FOOD BOLUS VELOCITY AND FORCE ON EPIGLOTTIS DURING SWALLOWING USING 3D SWALLOWING SIMULATOR “SWALLOW VISION®”

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Abstract. To determine the relationship among the food bolus velocity, force on epiglottis and swallowing easiness, we carried out swallowing simulation by MPS(Moving Particle Simulation)-method using a three-dimensional swallowing simulator “Swallow Vision®”. The configuration and velocity distribution of food bolus (water and thickener), the force on epiglottis by food bolus were visualized by Swallow Vision®. From simulation results indicated that the average velocity of water was faster than that of the thickener. The velocity distribution of the thickener was narrower than that of water. The force applied by the thickener was greater than that applied by water. It was inffered that there was a relationship between the velocity of a food bolus and swallowing easiness by the difference in velocity distribution of water and the thickener. On the other hand, the force on the epiglottis exhibited a relationship with the swallowing easiness by comparison of water thickener. We believe that Swallow Vision® could possibly be applied to evaluations such as evaluations of swallowing easiness and feeling.

1 INTRODUCTION

Recently, the mortality rate because of pneumonia has been increasing as the number of aged in society increases. The main cause of pneumonia in the elderly is mis-swallowing. To prevent mis-swallowing, it is important to adjust the properties of food served at nursing or public welfare facilities.

Several biometric measurement-based researches have been conducted to study the appropriate food properties for persons who having swallowing difficulties. Kumagai et al. [1] used an ultrasonography-based noninvasive measurement method to study the velocity around the pharynx was. This measurement method could obtain the velocity distribution of food boluses. However, it could not obtain information about the configuration and location of food boluses. Osato et al. [2] developed a measurement method for the contact pressure at the pharynx. The method had a poor reproducibility because subjects suffered from exhaustion due to invasive devices. Video fluorography (VF) has been popular as a visualization method for food boluses during swallowing [3]. In this method, examinees are exposed to X-ray radiation. However, VF could not obtain quantitative information on food boluses. Some researchers have conducted numerical simulations for obtaining physical values and visual information on the organs and food boluses simultaneously. Numerical simulation of human swallowing was conducted using the finite element method [4]. Ishida et al. reported a two-dimensional swallowing simulation using particle method [5]. However, this simulation could not simulate the three-dimensional behavior of swallowing. Therefore, we conducted numerical analyses for the movement and configuration of food boluses and organs, and considered the swallowing easiness with three-dimensional swallowing action simulator "Swallow Vision®".

2 THEORY

2.1 Governing equations

The MPS (moving particle simulation) method developed by Koshizuka et al. [6] is a well-known method for studying a free surface or large transformations of a fluid. The governing equations are expressed using the laws of conservation of mass and momentum:

$$\frac{\partial \rho}{\partial t} = 0 \tag{1}$$

$$\frac{D\mathrm{u}}{Dt} = -\frac{1}{\rho}\nabla P + \mathrm{f} \tag{2}$$

where ρ denotes the density [kg/m^3], P is the pressure [Pa], u is the velocity [m/s], and f is the external force . The governing equations are discretized as particle interaction models [6].

2.2 Particle interaction models

A particle interacts with a neighboring particle via a weight function w (r), which is defined as

$$w(r) = \begin{cases} \dfrac{r_e}{r} - 1 & 0 \le r \le r_e \\ 0 & r_e \le r \end{cases} \tag{3}$$

where r is the distance between two particles and r_e is a finite distance. The interactions are restricted to r_e [6].

2.3 Potential coefficient for calculating surface tension

The surface tension is an important factor for calculating the free surface of a liquid bolus. In the MPS method, the surface tension isconsidered to be the potential coefficient, which is defined as follows:

$$C_f = 138\sigma \Big/ \rho \ell_0^{\,2} \left(r_e \big/ \ell_0 \right)^5 \tag{4}$$

$$C_{fs} = \frac{1}{2}(1+\cos\theta)C_f \tag{5}$$

where C_f and C_{fs} are the potential coefficients for the fluid, and the fluid and solid, respectively; σ is the surface tension [N/m]; ρ is the density [kg/m^3]; r_e is the influence radius; l_0 is the initial distance of the particle; and θ is the contact angle [7].

2.4 Non-Newtonian fluid model

In Swallow Vision®, viscosity, which depends on the sheer rate of a food bolus as a non-Newtonian fluid, is described using the power-law model as follows [7]:

$$\mu = C_1 \cdot \dot{\gamma}^{C2} \cdot \exp(C_3 \cdot T) \tag{6}$$

where μ is the viscosity [mPa·s], $\dot{\gamma}$ is the sheer rate [1/s], and C_1 ,$C_2$and C_3 are constants [-].

2.5 Force interaction between particle and organ models

The load caused by particles is treated as the product of the acceleration and mass of particles which contact to wall, as shown below [8]:

$$F = -\sum_{i \in wall\,interaction} m_i \left(-\frac{1}{\rho} \nabla P + \mathrm{f} \right) \tag{7}$$

where ρ denotes the density [kg/m^3], P is the pressure [Pa], **f** is the external acceleration [m/s^2], and m is the mass of a particle [kg].

3 EXPERIMENTAL

3.1 Method to create accurate human swallowing model and definitions of moving parts

Swallow Vision® was developed on the basis of the three-dimensional MPS method. The organ models created using Swallow Vision® (Fig. 1) were reconstructed from CT, VF and MRI images [9]. The accuracy of configuration and movement (organs and food boluses) of Swallow Vision® has been validated in the past by researchers [9], [10]. The accurate human swallowing model used in Swallow Vision® was manufactured based on the CT and MRI images. The jawbone, vertebrae, hyoid bone, tongue, soft palate, and pharynx were depicted semi-automatically by changing the brightness. These parts were used to guide the modeling of other organs, which were traced manually based on anatomical knowledge and the structural relationships among the organs. The detailed modeling processes have been reported previously [9]. The moving parts of the three-dimensional swallowing model were defined by four objects (tongue, soft palate, epiglottis, and pharynx) as shown in Fig. 1 (a).

A regions of interes was set up to extract the velocity of food bolus around the pharynx (Fig. 1 (b)), and another region of interest was set up to count the particle number around epiglottis (Fig. 1 (c)).

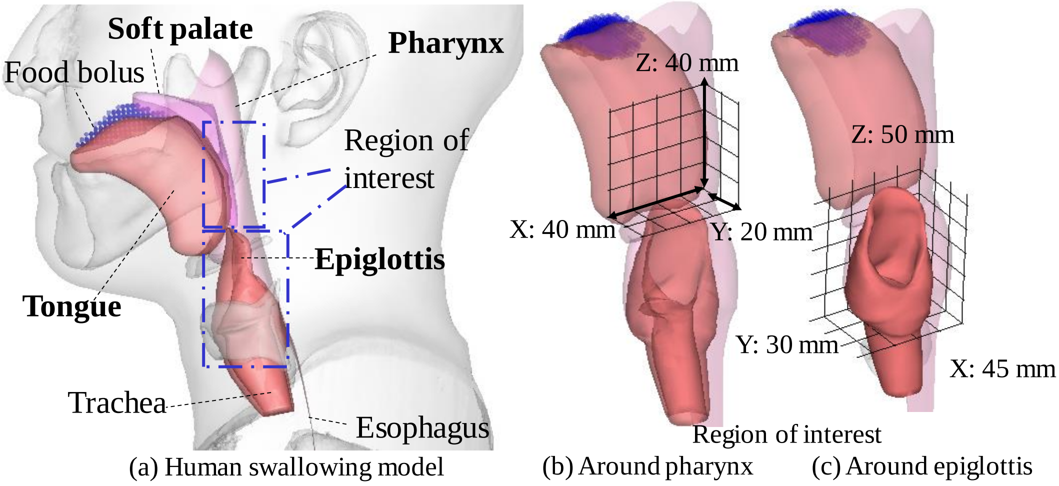

Figure 1 Human swallowing model and region of interest

3.5 Solver and simulation procedure

Swallow Vision® was developed using customized commercial software (Particleworks ver. 4.0, Prometech Software Inc.). Software preprocessing produced a df file containing distance functions, and a customized solver was used to perform the analysis. To depict the action of human swallowing accurately, a time resolution of the simulation was 1/300 s was used for the simulation. We produced 700 df files for each part to cover the entire period during one swallow. Thus, the total number of df files was 2,800. These time dependent objects depicted the forced transformation of the organs.

3.2 Measurement of physical properties of samples

The contact angle and surface tension on organs must be measured to calculate the food bolus behavior by the MPS-method. To avoid ethical issues that might have resulted from the use of human organs, we used the pig' organs. The measurement apparatus was "Drop Master 500" (Kyowa Interface Science Co., Ltd.) [10]. The rheogram of the thickener was measured by the "Physica MCR301" (Anton Paar Inc.). The measured rheogram was described using in power-law model.

3.3 Materials and properties

The simulated food samples were water and a thickener (Toromake SP, Meiji Co., Ltd.); both water and the thickner contained a contrast medium (OYPALOMIN 370, Fuji Pharma Co., Ltd.). The properties of the food samples, input parameter, and the solver settings are listed in Table 1. The potential coefficient was calculated using Eqs. (4) and (5).

Table 1 Physical properties of simulated food models

				Water (with contrast medium)	Thickener Meiji Toromake SP 2% (with contrast medium)
Viscosity		ν	[mPa·s]	Newtonian fluid Liquid - Liquid 2.5 Liquid - Solid** 5.0	Non-Newtonian fluid Power law $\mu = C_1 \cdot \dot{\gamma}^{c2} \cdot \exp(C_3 \cdot T)$ C_1 = 5.636, C_2 = -0.724, C_3 = 0
Surface tension		σ	[N/m]	0.072	0.024
Contact angle	Tongue***	θ_{fs_T}	[°]	43.0	71.6
	Soft palate**	θ_{fs_S}	[°]	60.0	76.1
	Larynx**	θ_{fs_L}	[°]	85.0	85.0
	Pharynx***	θ_{fs_P}	[°]	36.0	76.1
Potential coefficient	Liquid	C_f	[-]	2.160	0.715
	Tongue	C_{fs_T}	[-]	1.870	0.470
	Soft palate	C_{fs_S}	[-]	1.620	0.443
	Larynx	C_{fs_L}	[-]	1.174	0.388
	Pharynx	C_{fs_P}	[-]	1.954	0.443

Density 1000 [kg/m^3], Particle diameter 2 [mm], effective radius 4.1 [-]

* Contrast medium: Fuji Pharma Co. Ltd OYPALOMIN 370 (mixing ratio 1:1)

** Fitting parameter

*** Measurement using pig's organs

4 RESULTS AND DISCUSSION

4.1 Comparison of food bolus velocities using velocity profiles

The velocity and the configuration of food boluses and organs were simulated using the water and the thickener in an enclosed area inside of the region of interest in Fig. 1 (b).

The contours of the frequency distribution of the velocity (velocity distribution) of water and the thikener are shown in Figs. 2 and 3, respectively. The time axis of graphs began on the time when food boluses enter the region of interest (b). The velocity range of the thickener was narrower than that of water. Moreover, the thickener flowed in the form of a mass and water flowed with splashing in the time range 0.08 - 0.12 s, as shown in the velocity profiles in Figs. 2 and 3. The fluctuation of the velocity range of the thickener was smaller than that of water. This difference in the velocity distributions and visualization results indicated that the thickener flows uniformly and splashes to a lesser extent than water. It was inferred that the thickener is easier to swallow than water.

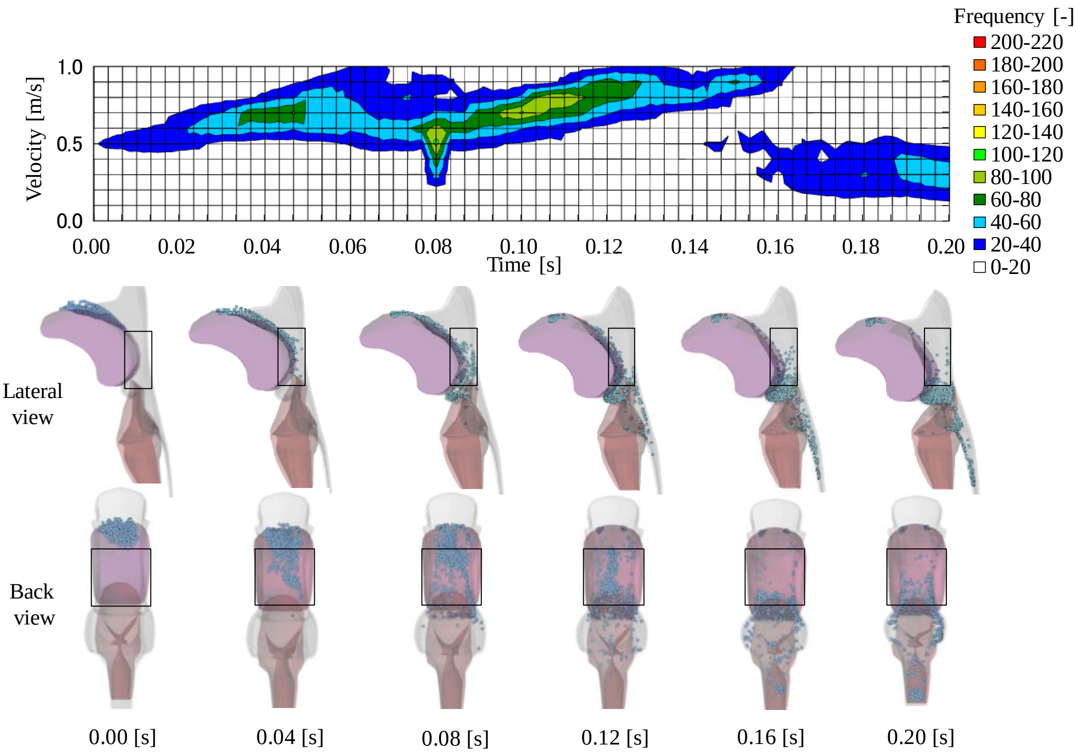

Figure 2 Velocity profiles and configuration of water

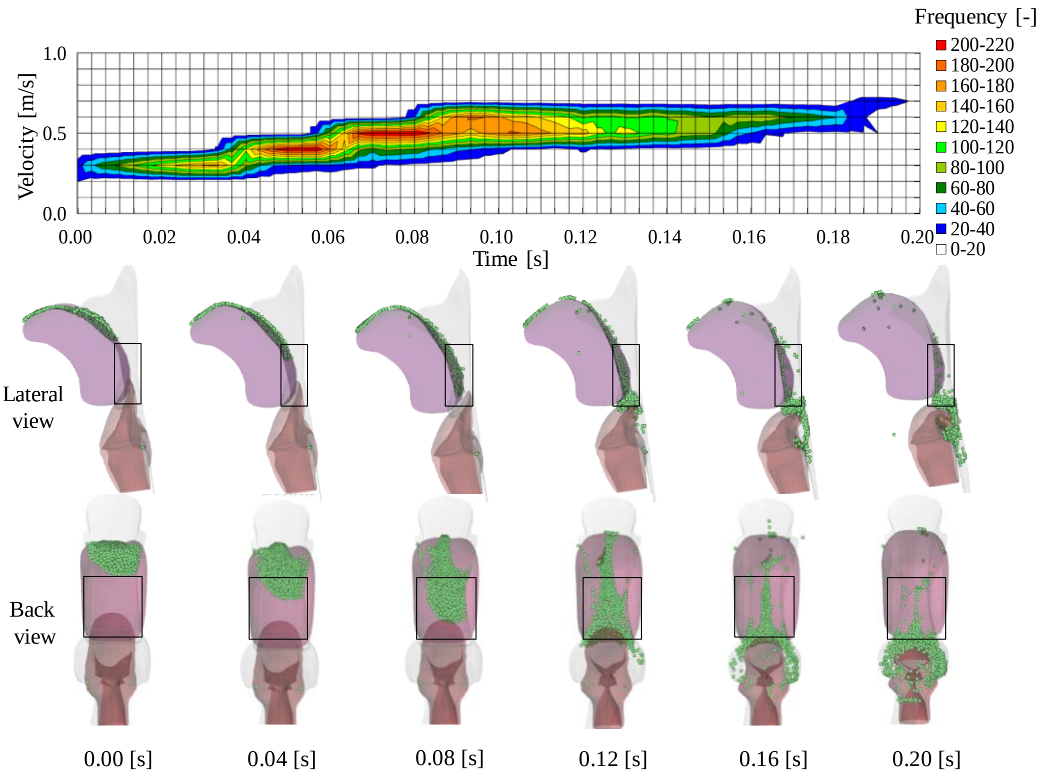

Figure 3 Velocity profiles and configuration of thickesaner

4.2 Changes of force on epiglottis related to food bolus configuration

The time-dependent change in the force on the epiglottis by the food bolus is shown in Fig. 4. The force on the epiglottis was calculated by Eq. 7. The force applied by the thickener was greater than that applied by water. This result indicated that the number of thickener particles in contact with the epiglottis was much higher than the number of water particles per unit of time as shown in Fig. 5. In the visualization result shown in the graph of the time-dependent change in the force, the thickener flowed uniformly throughout the epiglottis. It was assumed that the difference in the force on the epiglottis was influenced by the flow configuration of the food bolus. Therefore, it was assumed that the force on the epiglottis applied by food bolus was impotrtant factor to consider the swallowing easiness.

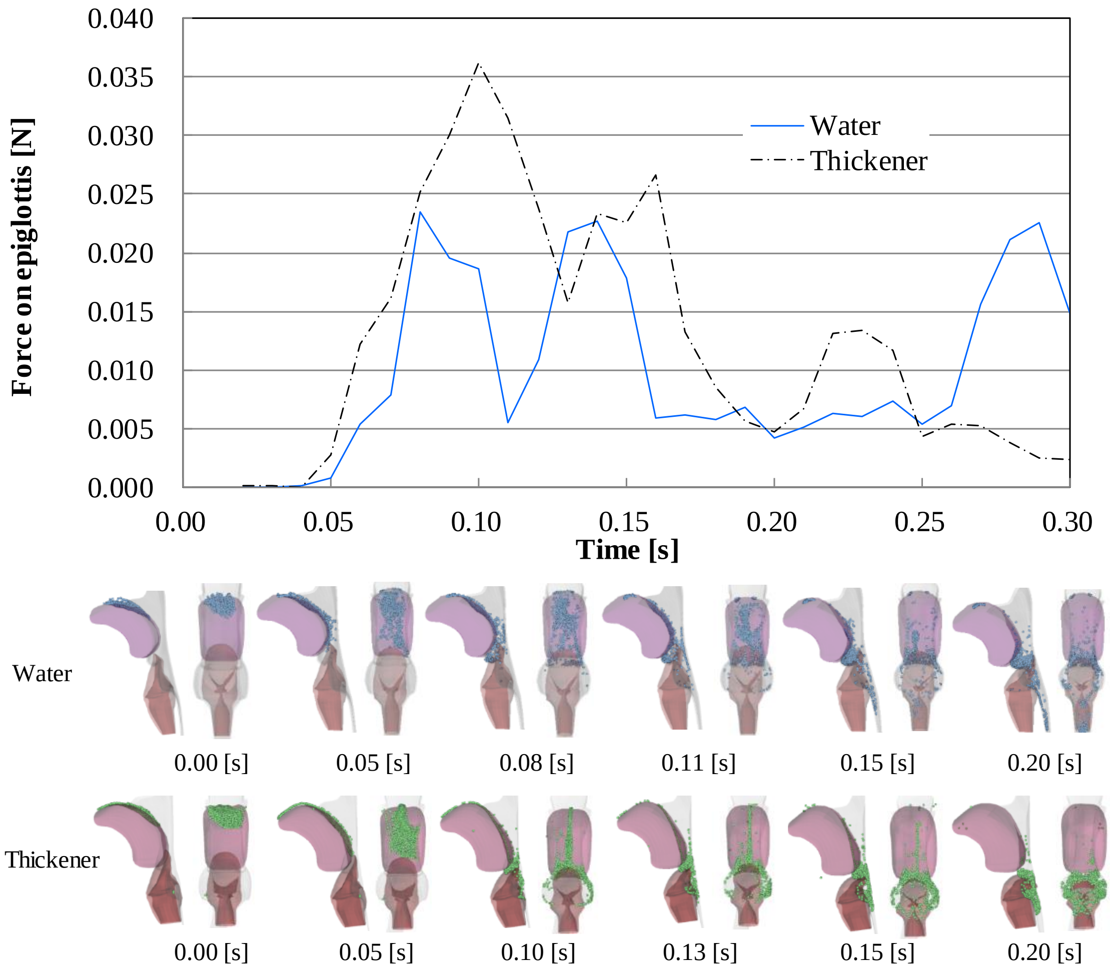

Figure 4 Time-dependent change in force on epiglottis and food bolus behavior around epiglottis

4.3 Comparison of time-dependent change in number of particles around epiglottis

The time-dependent change in the number of particles around the epiglottis is shown in Fig. 5. The particles were counted in the region of interest shown in Fig. 1(c). Both of food bolus were reached in the region of interest (c) at the nealy same time 0.05 s. As shown in Fig. 2, 3 due to the velocity of water bolus was faster than that of thickener. The early dischage of water from region of interest could be observed in the food bolus configuration between 0.10 – 0.20 s. Thus, water bolus resident time at region of interest (c) was shorter than thickener. For this reason, the increase slope of water was smaller than that of thickener. From this result, it was inferred that the thickener flowed uniformly out of the region of interest (c), and there was a difference in the force on the epiglottis applied water and thickener as shown in Fig. 4.

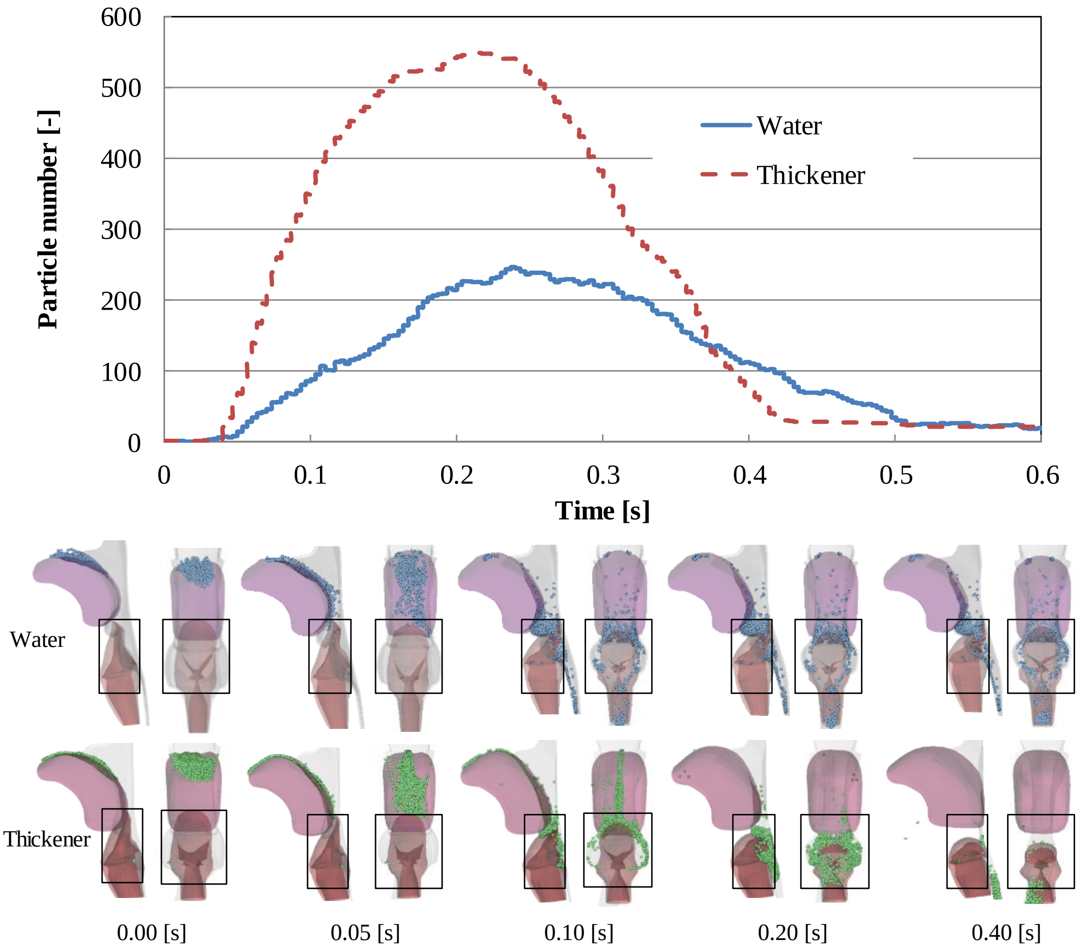

Figure 5 Time-dependent change in number of particles in region of interest (b)

5 CONCLUSION

The three-dimensional swallowing simulator Swallow Vision® was able to simulate the human swallowing action. The food bolus velocity, force on the epiglottis, and configuration of the food bolus were obtained simultaneously by Swallow Vision®.

It was confirmed that the distribution range of the water velocity was wider and the fluctuation of the velocity distribution was larger than those of the thickener. From the distribution of the food bolus velocity, it was inferred that in the pharynx, water flows diffusively with splashes and the thickener flows uniformly with less splashes than water. This result indicated that the velocity of the food bolus was related to swallowing easiness. In addition, there was a difference in the force on the epiglottis between water and the thickener. Thus, the force on the epiglottis might be related to the swallowing easiness. It was assumed that Swallow Vision® has a possibility to evaluate the swallowing easiness associated with each physical property of the food bolus.

In the current version, Swallow Vision® did not consider the negative pressure in the lower zone of the pharynx, which is caused by the rapid opening of the esophagus. This effect of the negative pressure should be considered in the next study.

Swallow Vision® might be useful to analyze the swallowing easiness search the appropriate food properties for people having difficulty in swallowing.

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