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Development of a numerical simulator of human swallowing using a particle method

(Part 2. Evaluation of the accuracy of a swallowing simulation using the 3D MPS method)

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Abstract—**The aim of this study was to develop and evaluate the accuracy of a three-dimensional (3D) numerical simulator of the swallowing action using the 3D moving particle simulation (MPS) method, which can simulate splashes and rapid changes in the free surfaces of food materials. The 3D numerical simulator of the swallowing action using the MPS method was developed based on accurate organ models, which contains forced transformation by elapsed time. The validity of the simulation results were evaluated qualitatively based on comparisons with videofluorography (VF) images. To evaluate the validity of the simulation results quantitatively, the normalized brightness around the vallecula was used as the evaluation parameter. The positions and configurations of the food bolus during each time step were compared in the simulated and VF images. The simulation results corresponded to the VF images during each time step in the visual evaluations, which suggested that the simulation was qualitatively correct. The normalized brightness of the simulated and VF images corresponded exactly at all time steps. This showed that the simulation results, which contained information on changes in the organs and the food bolus, were numerically correct. Based on these results, the accuracy of this simulator was high and it could be used to study the mechanism of disorders that cause dysphasia. This simulator also calculated the shear rate at a specific point and the timing with Newtonian and non-Newtonian fluids. We think that the information provided by this simulator could be useful for development of food products, medicines, and in rehabilitation facilities.**

I. Introduction

In many developed countries today, aging society advances year after year. The cause of unexpected death of elderly people is mainly aspiration-related pneumonia [1]. Thus, the emergence of swallowing difficulties is part of the aging process. To improve the quality of life for elderly people, there is a need for research and development into the safety of food and the mechanisms of swallowing disorders. Previously, the determination of the safety food for people with swallowing disorders or patients with swallowing difficulty involved the testing of food considered to be appropriate by trial and error. This method risked choking on food bolus or aspiration pneumonia in elderly people and patients.

In this study, we aimed to understand the action of the food bolus and the organs during the swallowing process by developing a numerical simulator using the three-dimensional (3D) moving particle simulation (MPS) method, which treated the food bolus as particles. We evaluated the simulation accuracy qualitatively and quantitatively.

Several studies on the swallowing action have been carried out. In the numerical simulation, the transformation of a jelly configuration and organs were studies using the 3D finite element method (FEM) [2]. This study did not consider the time-dependent forced transformation of the structures of organs when the organs were transformed by the force of the falling food bolus. In a medical-image-based simulation, researchers estimated the forces from the organs and the movement of the food bolus using VF images [3]. A coupled simulation was carried out using FEM with accurate 3D organs and a food bolus with jelly properties [4]. The accurate 3D FEM models have considered the forced transformations in a coupled simulation of the organs, the liquid bolus, and splashes of the liquid during calculations [5]. The mainstream numerical simulations of the swallowing action are FEM. The MPS method which can calculate the fluid splashes and large transformations have been used recently. The MPS method was proposed to simulate the swallowing action [6], but the validity of the simulation was not evaluated.

There have been no studies on the flow configuration with changes in 3D effects, viscosity, and shear rate during the swallowing process, especially around the epiglottis. Evaluations of the accuracy of the simulation results have not been carried out.

In this study, we confirmed that a 3D swallowing simulator developed using the 3D MPS method was qualitatively and quantitatively accurate based on comparisons with VF images of a normal subject. This simulator could calculate the shear rate during the swallowing process. This allowed us to estimate the viscosity changes of a food product with non-Newtonian properties and it could be used to develop safe and comfortable foods for people with swallowing difficulties and patients with dysphasia.

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II. THEORY

A. Governing equations

The MPS method developed by Koshizuka *et al*. [7] is a well-known method for studying a free surface or large transformations of a fluid. The governing equations are expressed using the conservation laws 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 [7].

B. Particle interaction models

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

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

where r is the distance between two particles and r_e is the finite distance. The interactions are restricted to r_e [7].

C. Potential coefficient for calculating the 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 is handled as 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 [N/m] is the surface tension, ρ [kg/m^3] is the density, r_e is the influence radius, and l_0 is the initial distance of the particle, θ is contact angle [8].

III. EXPERIMENTAL

A. Videofluorography of swallowing

VF images were used to evaluate the validity of the 3D human swallowing simulator using the 3D MPS method. The subject of the VF was a normal volunteer (25-year old male) who provided an informed consent for this study. A VF image was taken every 1/30 s from the front and side in the usual manner.

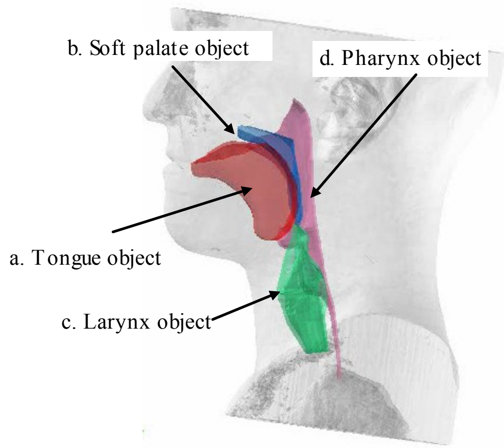

Figure 1. Moving parts of simulation model

B. Measurements of the contact angle and surface tension

The contact angle and the surface tension were required for the numerical simulation. It was difficult to obtain human organs, so organs of a pig were used instead to measure the contact angle between the organs and the liquid. The surface tension and contact angle were measured by a visualization method using a surface tension meter (Kyowa Interface Science Co., Ltd, Drop Master 500; needle diameter = 0.4 mm).

C. Execution of the accurate human swallowing model and the definition of the moving parts

The accurate human swallowing model used in the simulation was manufactured based on the CT image. The jaw bone, vertebrae, hyoid bone, tongue, soft palate, and the space of the 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 between the organs. The detailed modeling processes have been reported previously [9].

The moving parts of the 3D swallowing model were defined by four objects (a, tongue object; b, soft palate object; c, larynx object; d, pharynx object), as shown in Fig. 1.

D. Solver and simulation procedure

The 3D numerical simulator was developed using customized commercial software (Particleworks2.5 Prometech Software Inc.). The software preprocessing produced a df file containing distance functions, and the customized solver performed the analysis. To accurately depict the action of human swallowing, the simulation required a precise time interval of 1/300 s. 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 transformations of the organs.

Table 1. Properties of sample
(water with contrast medium [iopamidol])

Volume of sample		V	[mL]	6
Density		ρ	[kg/m^3]	1000
Kinematic viscosity		ν	[m^2/s]	2.5×10^{-6}
Surface tension		σ	[N/m]	0.072
Contact angle	Tongue	θ_{fs_T}	[°]	43
	Soft palate	θ_{fs_S}	[°]	60
	Larynx object	θ_{fs_L}	[°]	85
	Pharynx	θ_{fs_P}	[°]	36
Potential coefficient	Liquid	C_f	[-]	2.16
	Tongue	C_{fs_T}	[-]	1.87
	Soft palate	C_{fs_S}	[-]	1.62
	Larynx	C_{fs_L}	[-]	1.174
	Pharynx	C_{fs_P}	[-]	1.954

Table 2. Input data for simulation
Software: Particleworks 2.5
(customized with time dependent object forced transformation)

Initial distance of particle	d_{in}	[m]	0.002
Number of particles	N_p	[-]	1432
Radius of interaction	r_e	[-]	4.1
Kinetic viscosity between fluid and wall	ν_{fs}	[m^2/s]	2.5×10^{-6}

E. Materials and properties

The simulated food sample was water and contrast medium (iopamidol). The properties of the food sample, the input data, and the solver settings are shown in Table 1 and Table 2. The potential coefficient was calculated using Eqs. (4) and (5).

F. Evaluation method

In the qualitative evaluation, the simulation results were compared with the VF images of each time step. The simulated and VF images were synchronized based on the arrival time of the food bolus at the epiglottis vallecula.

To evaluate the validity of the simulation results quantitatively, the normalized brightness B_n [-] around the epiglottis was used as the evaluation parameter. The normalized brightness was defined as

$$B_n = \frac{B_t - B_{min}}{B_{max} - B_{min}} \quad (6)$$

where B_t [-] was the brightness calculated using image processing software (Image J, National Institutes of Health, USA), B_{max} [-] was the maximum brightness of all measurements, and B_{min} [-] was the minimum brightness value.

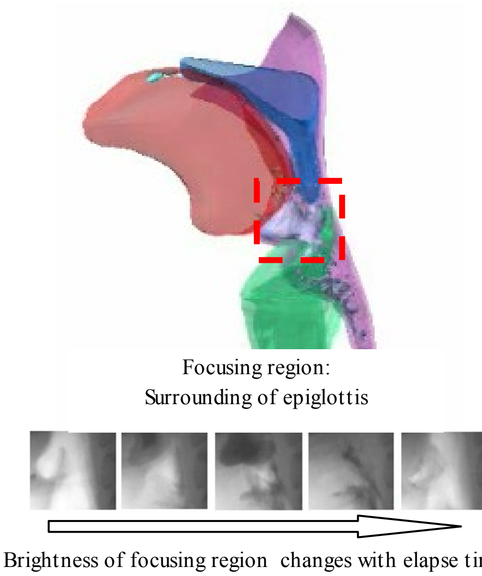

Figure 2. Region for the calculation of normalized brightness

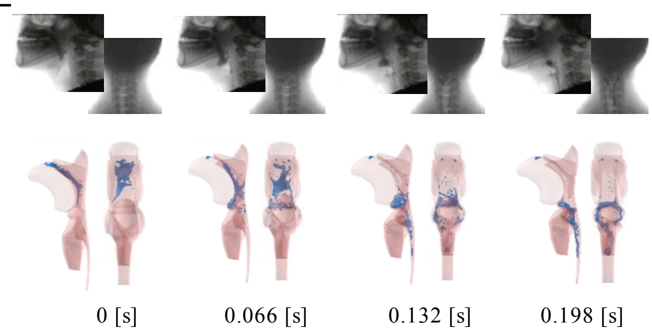

Figure 3. Comparison between VF image and results of 3D MPS method (From oral stage to pharynx stage)

As shown in Fig. 2, the brightness of the focusing area changed as time elapsed. The normalized brightness evaluated these changes numerically. The simulated and VF images were compared at all time steps.

IV. Results and Discussion

A. Qualitative evaluation of the swallowing behavior in the 3D swallowing simulator

To evaluate the accuracy of the 3D swallowing simulator, the swallowing configurations were compared at each time step as shown in Fig.3. The liquid bolus broke up and small splash particles were generated. It is difficult to observe these small particles in the normal VF image and we suggest that the 3D simulator could allow more detailed observations of the swallowing behavior than the VF image. It was also clear that the epiglottis went down when most of the liquid bolus entered the vallecula. In the simulated and VF images, small amounts of the liquid bolus moved over the epiglottis before the epiglottis went down, but no particles flowed into the respiratory tract. All the images were fairly similar at all steps. Thus, we confirmed that the 3D swallowing simulator based on the MPS method was qualitatively correct.

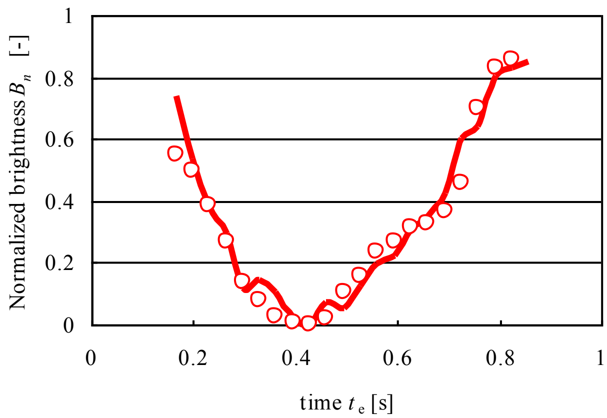

Figure 4. Comparison of normalized brightness between experiment and 3D simulation

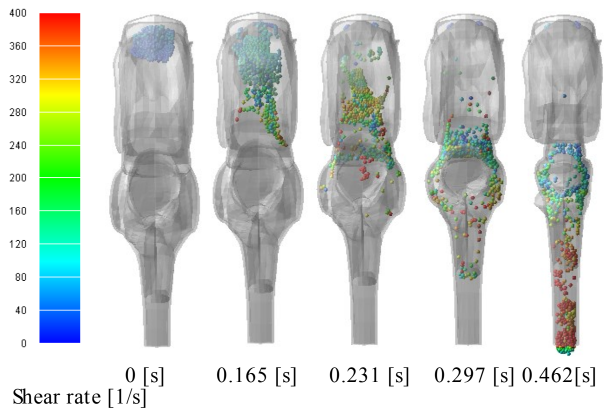

Figure 5. Variation in share rate of liquid food bolus

B. Quantitative evaluation of the accuracy of the 3D swallowing simulation

In the numerical evaluation of the validity of the accuracy of the 3D swallowing simulator, the normalized brightness was compared. Fig. 4 shows comparisons of the normalized brightness for the simulated and VF images. It is obvious that the normalized brightness in the 3D simulation was the same as that in the VF images throughout the swallowing process. This result confirmed that the 3D swallowing simulator was highly accurate based on this quantitative comparison.

C. Variations of the shear rate during the swallowing process

The 3D swallowing simulator could extract several physical properties. The shear rate could be obtained during the swallowing process. For a non-Newtonian fluid, the viscosity of the product also changed when the shear rate changed. Most liquid food products have non-Newtonian properties and the shear rate during the swallowing process is very important for developing good food products for elderly people who have difficulty with swallowing and patients with dysphasia. Fig. 5 shows the variation in the shear rate during the swallowing process. Higher shear rates were observed at the entrance of the middle pharynx and the esophagus. The shear rate at the entrance of the pharynx was approximately 300 s^{-1}. This was similar to the values reported in previous studies [10].

V. Conclusion

In this study, we confirmed the accuracy and validity of a 3D swallowing simulator using the 3D MPS method. Most previous numerical simulations of the swallowing action were carried out using FEM and the MPS method was rarely used. Previous studies also performed simulations using 2D models. In the present study, we developed a 3D swallowing simulator using the MPS method, which could handle liquid splashes and the transformations of free surfaces with liquid and air. We demonstrated that our simulation could estimate the food configuration with high accuracy.

This simulation did not consider the negative pressure in the lower zone of pharynx, which is caused by the rapid opening of the esophagus. A consideration of this negative pressure effect is required in the next step.

We developed a 3D human swallowing simulation using the 3D MPS method based on an accurate living model, which considered forced structure changes with time. The accuracy of the simulation was confirmed using qualitative and quantitative methods. This simulation could be used to develop appropriate food products for elderly people who have difficulty in swallowing and patients with dysphasia

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