IChemE

www.icheme.org/journals
doi: 10.1205/fbp.04209

0960–3085/05/$30.00+0.00

Trans IChemE, Part C, December 2005
Food and Bioproducts Processing, 83(C4): 297–305

COMPUTER SIMULATION OF THE PHARYNGEAL BOLUS TRANSPORT OF NEWTONIAN AND NON-NEWTONIAN FLUIDS

Y. MENG[1], M. A. RAO[1]* and A. K. DATTA[2]

[1]*Department of Food Science and Technology, Cornell University-NYSAES, Geneva, USA*
[2]*Department of Biological and Environmental Engineering, Cornell University, Ithaca, USA*

A computational fluid dynamics (CFD) programme was used to study dysphagia, a swallowing disorder, and demonstrated that the rheological properties of a liquid affect the pharyngeal transport of a food bolus. A fully coupled, Newton–Raphson solution algorithm was used in conjunction with the Backward–Euler scheme. Concomitant axial and radial movement of the fluid bolus was assumed, and the force exerted by the base of the tongue was assumed to be linear. Boundary conditions were based on data published in the clinical literature. The properties of three fluid types were modelled: water ($\rho = 1000$ kg m^{-3}, $\eta = 0.001$ Pa s), 250% w/v barium sulfate mixture ($\rho = 1800$ kg m^{-3}, $\eta = 0.150$ Pa s), and starch-thickened beverage (power law parameters $K = 2.0$ Pa s^n, $n = 0.7$). Results show that when the base of the tongue pushes against the throat with the same amount of force, water is transported through the pharynx at a much higher flow rate than the barium sulphate mixture, causing parts of the water bolus to flow backwards. A typical starch-thickened beverage, which is a shear-thinning non-Newtonian fluid, undergoes much lower flow rates. Furthermore, under the same conditions, a smaller volume of the non-Newtonian bolus (2 mL compared to 20 mL of the Newtonian fluids) is passed through by the end of the swallow. Values for the time to swallow a critical bolus volume, t_{cv}, show that non-Newtonian fluids increase swallowing time more effectively than Newtonian fluids and are thus safer to swallow for patients with dysphagia. These findings suggest that non-Newtonian foods may either slow down the swallowing process or trigger the subject to swallow a smaller amount, allowing the neuromuscular system more time to shut off air passages and reduce the risk of aspiration. Based on this simple CFD modelling of the swallowing process, the effects of fluid properties on bolus transit can be predicted.

Keywords: CFD; pharyngeal transport; Newtonian; non-Newtonian; shear-thinning; starch.

INTRODUCTION

The mechanisms by which a food bolus is propelled through the pharynx (throat) are still poorly understood. In particular, the effects of bolus rheology, pharyngeal pressures, swallow gesture timing and swallow duration are unclear. Studies show that an increase in bolus viscosity delays pharyngeal bolus transit and lengthens the duration of the opening of the upper esophageal sphincter (UES) (Dantas and Dodds, 1990; Dantas *et al.*, 1990; Reimers-Neils *et al.*, 1994), the outlet of the throat. More viscous materials result in slower flow through the UES (Dantas *et al.*, 1990). Pouderoux and Kahrilas (1995) report that the force of tongue propulsion increases when a bolus of greater viscosity is introduced. Kendall *et al.* (2001) suggested that taking smaller volumes of viscous liquids could also be key to a more effortless swallow.

Computer simulations allow the researcher to test many 'what-if' scenarios (Datta, 1998) for a complex problem, such as the pharyngeal phase of swallowing. In recent years computer simulations have been used to study normal and abnormal esophageal transport (Li *et al.*, 1994). Chang *et al.* (1998) used an axisymmetric geometry to model the fluid flow behaviour of a typical barium mixture given to dysphagic patients. This preliminary study demonstrates the versatility of computer-aided studies, and the need to examine more closely fluids resembling liquid foods in a dysphagia diet. Another related study (Chang *et al.*, 1999) used a three-dimensional model to simulate pharyngeal bolus movement and

**Correspondence to*: Professor M. A. Rao, Department of Food Science and Technology, Cornell University-NYSAES, Geneva, USA.
E-mail: andy_r_14456@hotmail.com

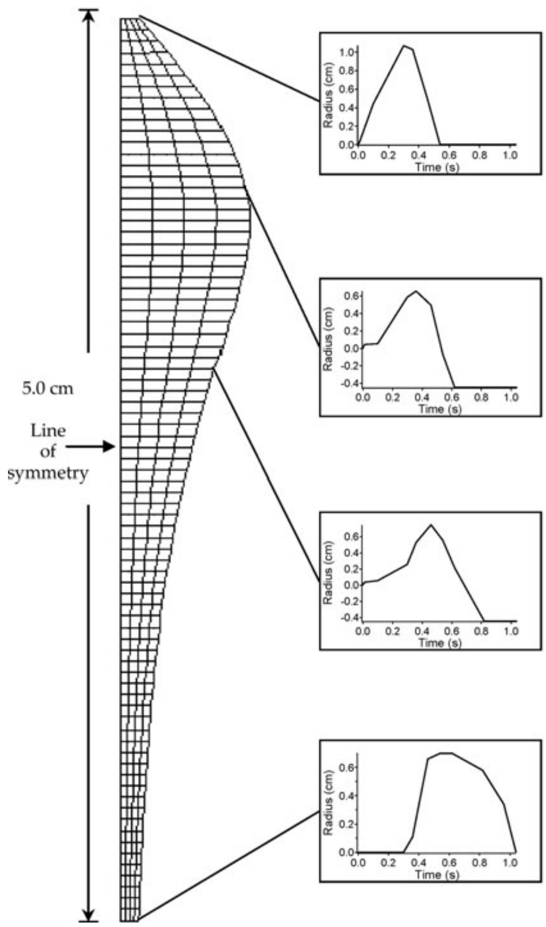
considered three volumes (5, 10 and 20 mL) of a single barium-mixed material. Neither of these studies explored the effect of non-Newtonian properties on pharyngeal swallow, which is important because thickened foods are typically not Newtonian.

The goals of this study were to: (1) simulate the pharyngeal wall movements during the transport of a liquid bolus; (2) analyse the effects of the rheological properties of Newtonian and non-Newtonian shear-thinning fluid boluses on the pharyngeal stage of the swallowing process; and (3) determine the effect of rheological parameters (i.e., consistency coefficient, flow behaviour index) on the amount of time needed to swallow a constant volume of liquid.

METHODOLOGY: PROBLEM DESCRIPTION

As a food bolus enters the pharynx, the base of the tongue pushes against the back of the throat while the pharyngeal muscle walls move in a squeezing action to further propel the bolus downward. Meanwhile, both the nasopharyngeal and laryngeal openings are shut off by neuromuscular events to prevent entrance of fluid into these areas (Langmore, 2001). The system of interest is a segment of the human throat from the glossopalatal junction (GPJ) to the UES, totalling 5.0 cm in length (Figure 1). The major assumptions in these simulations were: (1) axisymmetric geometry; (2) incompressible fluid; (3) laminar flow; (4) constant density (1800 kg m^{-3} for the barium sulphate mixture and the shear-thinning liquid, 1000 kg m^{-3} for water); (5) homogeneous fluid; (6) isothermal conditions at 37°C; (7) axial movement of the bolus with the concomitant radial opening of the pharynx; (8) linear normal force by the base of the tongue; and (9) single-phase flow. Although assumptions (1), (7)–(9) simplify the swallowing process, not enough data are currently available for a more realistic simulation.

To illustrate the swallowing process in basic terms, imagine that the human throat is an axisymmetric pipe with moveable walls. The inlet of the pipe is the GPJ, and the outlet is the UES. At the beginning of the flow process, fluid is pushed into the inlet by the base of the tongue. The diameter of the pipe is widened at the same time to accommodate the passing liquid. Soon the outlet is opened and the wall of the pipe near the inlet begins to close and further pushes the fluid toward the outlet in a squeezing action. Toward the end of the flow process, the pipe collapses completely and all of the fluid is pushed through the outlet.



Glossopalatal Junction (GPJ)

Time (s)	Boundary condition
0–0.32	σ_n = 12 mm Hg (water) σ_n =150 mmHg (all other fluids) v_z is computed
0.32–0.54	σ_n is computed v_z is computed
0.54–1.04	$\sigma_n = 0$ $v_z = 0$

Upper Esophageal Sphincter (UES)

Time (s)	Boundary condition
0–0.34	$\sigma_n = 0$ $v_z = 0$
0.34–1.04	σ_n is computed v_z is computed

Figure 1. Schematic of the segment of human throat in the resting position from the glossopalatal junction (GPJ) to the upper esophageal sphincter (UES), showing the prescribed normal stresses at the GPJ and the UES as well as prescribed displacements at the GPJ, pharyngeal wall (only two are shown), and the UES.

Governing Equations

The physics of the fluid movement in axisymmetric cylindrical coordinates is given by the continuity equation (1) and the conservation of momentum equations (2) and (3).

$$\frac{\partial \rho}{\partial t} = -\frac{1}{r}\frac{\partial(\rho r v_r)}{\partial r} - \frac{\partial(\rho v_z)}{\partial z} \tag{1}$$

$$\rho\left(\frac{\partial v_r}{\partial t} + v_r\frac{\partial v_r}{\partial r} + v_z\frac{\partial v_r}{\partial z}\right) = -\frac{\partial p}{\partial r} + \mu\left(\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial}{\partial r}(r v_r)\right) + \frac{\partial^2 v_r}{\partial z^2}\right) \tag{2}$$

$$\rho\left(\frac{\partial v_z}{\partial t} + v_r\frac{\partial v_z}{\partial r} + v_z\frac{\partial v_z}{\partial z}\right) = -\frac{\partial p}{\partial z} + \rho g_z + \mu\left(\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial v_z}{\partial r}\right) + \frac{\partial^2 v_z}{\partial z^2}\right) \tag{3}$$

Newtonian fluids such as water and apple juice are characterized by a linear relationship between the shear stress (σ) and the shear rate ($\dot{\gamma}$):

$$\sigma = \eta\dot{\gamma} \tag{4}$$

where η is the viscosity. For a non-Newtonian fluid, shear stress and shear rate are not linearly related (e.g., for a power-law fluid in simple shear):

$$\sigma = K\dot{\gamma}^{n} \tag{5}$$

where K is the consistency coefficient and n is the flow behaviour index. The interest in non-Newtonian fluids arises because starch-thickened beverages given to dysphagic patients are shear-thinning (Pfaff, unpublished data; Steele *et al.*, 2003).

Boundary Conditions

Initial conditions and boundary conditions of the pharyngeal wall movement were based on data values published in the clinical literature (Cook *et al.*, 1989; Kahrilas *et al.*, 1988, 1993) and are shown in Figure 1. All 81 nodes along the pharyngeal wall were given prescribed radial displacements with respect to time (two examples are shown). These displacement values were obtained from the clinical studies cited above. It is not clear from these clinical studies whether the augmentation of the pharyngeal radius is due to the force of the bolus on the wall alone during the swallow, or mechanisms triggered by the neuromuscular system, or a combination of both. The pushing action of the base of the tongue at the beginning of the swallowing phase and the subsequent relaxing of the tongue was simulated by a linearly decreasing normal stress (σ_n). Normal stress (gauge) at the GPJ was given a positive value at time 0 and was linearly decreased to 0 at 0.32 s, zero from 0.32 s to 1.04 s and was calculated at all other times. In this problem the time-dependent pressure gradient was used instead of normal stress in assigning boundary conditions because the latter was not possible to do in FIDAP. The normal stress at the UES was zero from 0 to 0.34 s and calculated at all other times (Figure 1) to simulate the UES being closed during the first third of the swallow and being opened at 0.34 s. Axial velocity (v_z) at the GPJ was computed from time 0 to 0.54 s and set to zero from 0.54 s to 1.04 s to calculate fluid flow through the open GPJ followed by zero flow through the closed GPJ. The velocity (v_z) at the UES was zero from 0 s to 0.34 s (to simulate zero flow through the closed UES during the first third of the swallow) and computed from 0.34 s to 1.04 s (to simulate an open UES through which fluid traverses) (Figure 1). In addition, there was a no-slip condition at the pharyngeal wall, i.e., for those 81 nodes at all time:

$$v_z = 0|_{r=R} \tag{6}$$

where R is the maximum radius of the pharynx at a particular point in time. Radial velocity (v_r) at the line of symmetry was set to 0 at all time:

$$v_r = 0|_{r=0} \tag{7}$$

There was also assumed no flow with respect to the θ-direction (symmetry):

$$\frac{dv_z}{d\theta} = \frac{dv_r}{d\theta} = 0 \tag{8}$$

Mesh Generation

The mesh was generated using GAMBIT (Version 1.3, Fluent, Evansville, IL) with 488 quadrilateral elements and 405 nodes (Figure 1). For the mesh independence test, the number of nodes was doubled from 405 to 805, and then again from 805 to 1449. As a result, the number of boundary conditions was also doubled accordingly during mesh refinement and the time needed to achieve smooth mesh movements was dramatically increased. Much time was spent doing trial-and-error analysis to ascertain that the given values of displacement boundary conditions yield a smooth contour at the pharyngeal wall.

Numerical Methods

The computational fluid dynamic software, FIDAP (Version 8.5, Fluent, Evansville, IL) was used in conjunction with a desktop computer (664 MHz Intel Pentium III microprocessor, Windows 2000 platform, 256 MB RAM) to solve the governing equations for the given boundary and initial conditions. A fully coupled solution algorithm with Newton–Raphson (N.R.) method was used. This algorithm allows the user some flexibility in structure design by adopting a mixed formulation for the pressure–velocity coupling, which discretizes the pressure variable and contributes an additional degree of freedom to the system of unknowns. A streamline upwinding scheme was used in the computation to stabilize the solution. The Backward–Euler scheme, an implicit time integration scheme with variable time increment, was used to track the transient behaviour of the solution. Because the boundary conditions at the GPJ and UES could not be translated into a single function for the entire swallow, the simulation was simplified in FIDAP by separating into three stages: (1) from 0 to 0.34 s; (2) from 0.34 s to 0.54 s; and (3) from 0.54 to 1.04 s. The last data point of each stage was used for the initial conditions for the first time step in the next stage. The results from all three stages were concatenated into one collective database for each type of fluid. For modelling non-Newtonian fluids, the PROBLEM command in FIDAP was set to NONNEWTONIAN and the VISCOSITY command was set to POWERLAW, which is defined by:

$$\mu = \begin{cases} \mu_0 K D_0^{n-1} D < D_0 \\ \mu_0 K D^{n-1} D \geq D_0 \end{cases}$$

where $D^2 = (1/2)d_{ij}d_{ij}$, $d_{ij} = 2s_{ij}$, and n may take any value. The values of μ_0, K, n and D_0 are inputted on the data record. The cut-off shear-rate value, D_0, was set to zero for all simulations because we only considered power-law fluids in simple shear. Approximate run times were 1 to 2 min for Newtonian fluids and 8 min for non-Newtonian ones.

Convergence for the fully-coupled solver, N.R., was based on the concurrent satisfaction of two convergence criteria. The first criterion was the relative error in velocity vector at iteration $i(u_i)$ compared to the true solution vector (u). The second criterion was the relative error in the residual vector at iteration $i(\mathbf{R}(u_i))$ which must tend to zero as u_i tends to u. The error tolerances for the criteria were set to 0.0001 and 0.001, respectively. The first criterion was a measure of the change in the solution between iterations, while the second criterion was a measure of how well the current solution satisfies the system of algebraic equations being solved.

RESULTS AND DISCUSSION

Mesh Independence

Mesh independence tests were conducted by refining the 405-noded mesh to 805 nodes and again to 1449 nodes (Figure 2). Simulated results using identical boundary conditions yielded very similar flowrates, volumes, and center line shear rate at the UES (Figure 3). These data showed that results from the simulation using the 405-noded mesh did in fact produce a valid solution. Although execution time was not significantly different for all three meshes, the 405-noded mesh was used for all simulations discussed in this work because it was most economical in terms of the time needed to input all the boundary conditions, which were manually applied for each node.

Mesh Movement

The mesh movements presented in Figure 4 resemble the pipe analogy mentioned in the Problem Description section above and are similar to those used by Chang *et al.* (1998).

Pressure and Flow Profiles During the Swallowing Process

Three different types of fluid were used in this study. Their properties were $\eta = 0.001$ Pa s (representing water), $\eta = 0.150$ Pa s [representing 250% w/v barium sulphate mixture with a density of 1800 kg m^{-3}, as used in Chang *et al.* (1998)], and $K = 2.0$ Pa s^n, $n = 0.7$ (representing a non-Newtonian, shear-thinning fluid obtained by thickening a beverage with starch, also with a density of 1800 kg m^{-3}). It has been found in previous studies on esophageal bolus transport (Li *et al.*, 1992) that at shear rates above 3 s^{-1}, 250% w/v barium sulphate exhibits Newtonian behaviour. Because pharyngeal bolus transport occurs at faster rates, we chose to assign a Newtonian viscosity to the barium sulphate used in our simulations and assumed any non-Newtonian behaviour at low shear to be negligible.

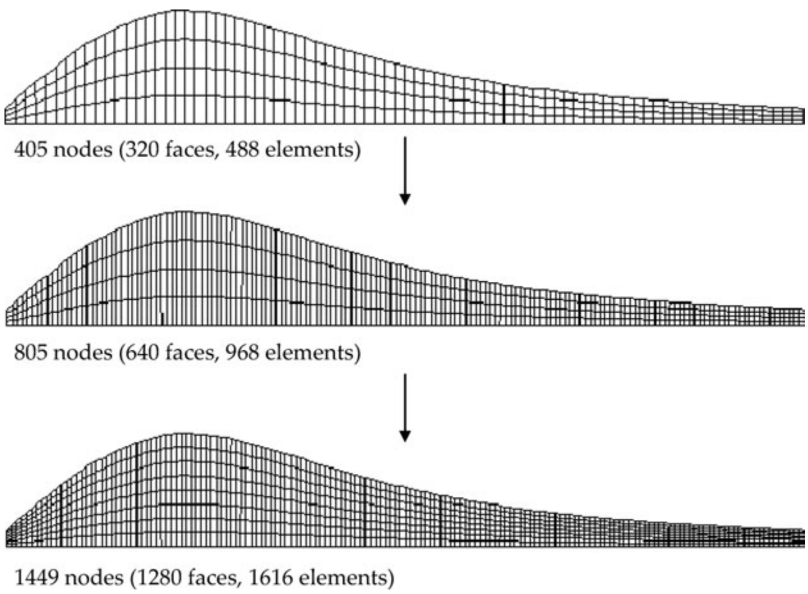


Figure 2. Initial and refined meshes generated using GAMBIT 1.3.

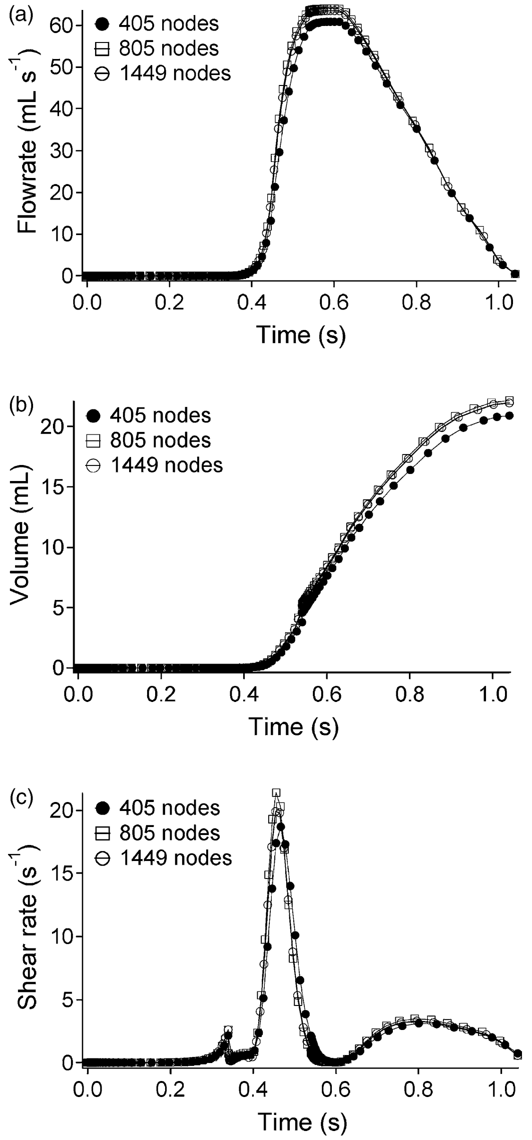


Figure 3. Effect of mesh refinement on (a) the upper esophageal sphincter (UES) flowrate, (b) the bolus volume transported through the UES, and (c) the UES shear rate as a function of time. The properties of three different types of fluid were used in this study: $\eta = 0.001$ Pa s (representing water), $\eta = 0.150$ Pa s (representing 250% w/v barium sulphate mixture), and $K = 2.0$ Pa s^n, $n = 0.7$ (representing a non-Newtonian, shear-thinning fluid obtained by thickening a beverage with starch).

The power law parameters for the starch-thickened beverage were selected because it is typical of starch-thickened beverages served at nursing homes for dysphagic patients (Pfaff, unpublished data; Steele *et al.*, 2003). The pressure profiles at both the GPJ and the UES for the barium sulphate mixture are shown in Figure 5. The overall shapes of the two plots are similar to those reported by Chang *et al.* (1998), showing a steady drop in pressure at the GPJ up until about 0.3 s (opening of the UES) and a minimum in pressures at the UES prior to the closing of the GPJ at 0.54 s. The pressure at the UES upon closing of the GPJ was less than the overall pressure of the system because a pressure gradient needs to be maintained. Since there is minimal pressure at the GPJ at that point, a pressure minimum at the outlet, the UES, ensures that the fluid would continue to flow out into the esophagus. However, these pressure minima occur about 0.1 s later than those calculated by Chang *et al.* (1998). While the boundary displacement movements are similar in both studies, the simulated results may not be exactly alike due to differences in the mesh/spine generation process, numerical methods, and the exact values of the boundary conditions. It should be noted that a higher normal stress (150 mmHg) was employed in this study for the force exerted by the base of the tongue, compared to the normal stress of 22.5 mmHg used in the work by Chang *et al.* (1998). This high value of 150 mmHg was required for the simulation to reach a flowrate that was in the same range as that published by Chang *et al.* (1998). The normal stress we used for the base of the tongue was higher, i.e., 2.0 instead of 1.25 times that recorded at the GPJ. The entire momentum of the tongue would not have been conserved, as has been shown, due to the expansion of the oropharyngeal cavity. The discrepancy between the normal stress values we used versus the Chang study was most likely due to differences in mesh construction and density. Moreover, the normal stress was assumed to be the sole contributing force of the tongue, whereas clinical data show that there is much variability depending on the thickness of the liquid given and the age of the subject (Steele and Van Lieshout, 2004). The complexity of the tongue movement would need to be addressed in a future study, but simplifications have been made for the current work.

Flowrate data through the UES (Figure 6) show a smoother curve than that of Chang *et al.* (1998), possibly due to differences in the solution algorithm employed in the simulation and their use of a less dense mesh. However, the overall shape of the flowrate curve resemble that presented by Chang *et al.* Maximum flow rate values were lower, by about 20 mL s^{-1}, possibly due to the coarser nature of their mesh. However, the total volume transported through the UES with respect to time was very similar, showing approximately a total of 20 mL of fluid had passed into the esophagus by the end of the simulation.

Effect of Fluid Rheology on the Swallowing Process

For a Newtonian water bolus with a viscosity of 0.001 Pa s and a density of 1000 kg m^{-3}, the initial normal stress at the GPJ had to be reduced by 92% (from 150 mmHg to 12 mmHg) and the duration at which the initial normal stress was held was reduced by 69% (from 0.32 s to 0.1 s) in order for the model to simulate a 20-mL swallow. Not using these corrections resulted in reverse flow (i.e., negative flowrate) at the GPJ. This was reasonable because the water bolus has a smaller viscosity than the other two liquids. Reverse flow may occur in the human throat if the pharyngeal walls are not sufficiently elastic to expand and accommodate the liquid. Such clinical data are not currently available in the literature, but would be valuable for the continuation of these studies. The computational changes may have varied the problem slightly, however the effect of rheology on the swallowing time should still remain the same.

The flowrates of the three boluses [Figure 7(a)] showed significant differences from 0.54 s to 1.04 s. The water bolus (Newtonian, 0.001 Pa s) showed a sharp increase at about 0.45 s, followed by a rapid decrease to negative

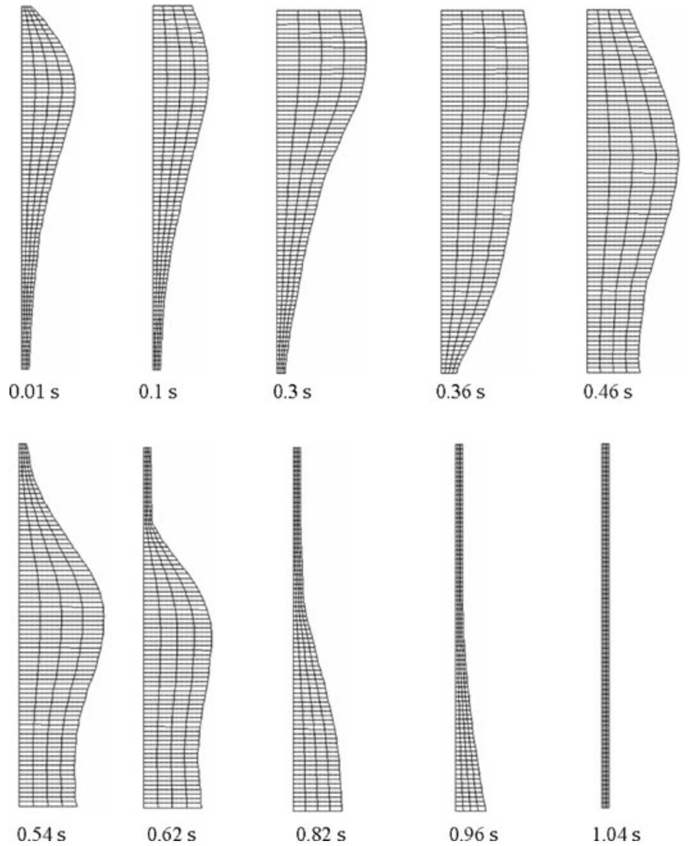


Figure 4. Finite element meshes of the pharyngeal chamber at various time steps between 0 and 1.04 s. All pharyngeal chambers are represented by axisymmetric geometries with the centreline at the left border.

values at about 0.53 s. At 0.53 s, the UES is widening, which may draw some of the fluid in the negative z direction in the case of a less viscous liquid such as water. A second maximum in flowrate was later seen at about 0.6 s followed initially by a rapid decrease to 20 mL s^{-1} at 0.7 s and then a more gradual decrease to 0 mL s^{-1} at 1.04 s [Figure 7(a)]. The barium bolus (Newtonian, 0.150 Pa s) showed a moderately rapid increase to a maximum flowrate of 60 mL s^{-1} between 0.4 s and 0.6 s, followed by a gradual decrease to zero flowrate at 1.04 s. The starch-thickened bolus (non-Newtonian) showed extremely low flowrates at all times compared to the Newtonian boluses. The difference in the shape of the flow rate curve for the water bolus indicated that there may be inertial effects due to its relatively low viscosity. The Reynolds number at the UES at the end of the simulation is 116 for the Newtonian water bolus, 4.0 for the Newtonian barium sulphate bolus, and 5.4 for the non-Newtonian bolus (data not shown).

Furthermore, the total fluid volume that passed through the UES for the shear-thinning non-Newtonian bolus was only around 2 mL [Figure 7(b)], about an order of magnitude lower than that of Newtonian boluses. This can perhaps explain why people, especially dysphagic patients, often take more than one swallow to complete the same volume of liquid when the viscosity is higher. These data

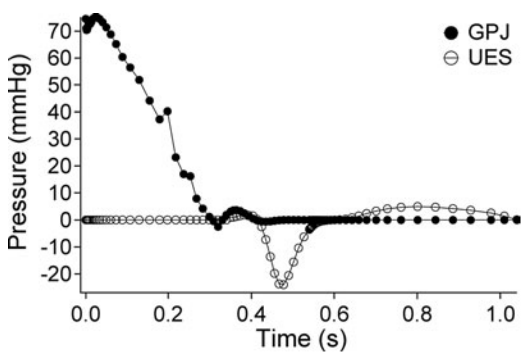


Figure 5. Pressure profile at the glossopalatal junction (GPJ) and the upper esophageal sphincter (UES) for a Newtonian barium sulphate mixture (density = 1800 kg m^{-3}, viscosity = 0.15 Pa s) calculated using a 405-noded mesh.

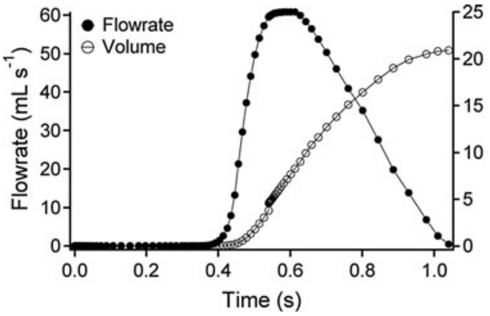


Figure 6. Flowrate and total volume passed through the upper esophageal sphincter (UES) for a Newtonian bolus (density = 1800 kg m^{-3}, viscosity = 0.15 Pa s) calculated using a 405-noded mesh.

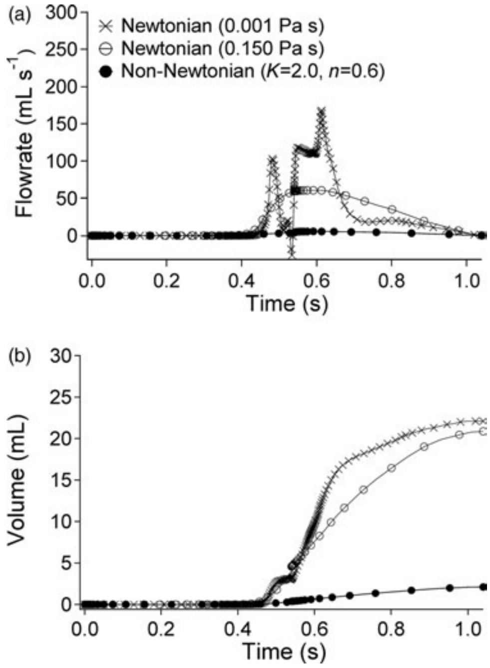


Figure 7. Effect of bolus rheological properties on (a) flowrate and (b) total volume through the upper esophageal sphincter (UES). Different inlet boundary conditions were used for water (0.001 Pa s, Newtonian) than for the other two liquids.

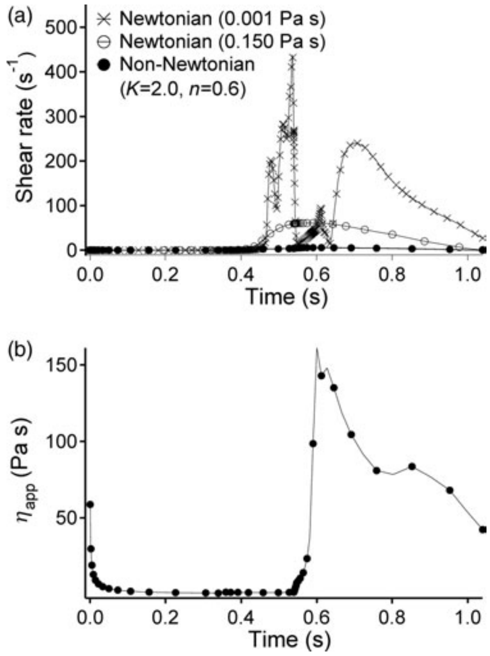


Figure 8. Effect of bolus rheological properties on (a) shear rate and (b) apparent viscosity (η_{app}) of a shear-thinning non-Newtonian bolus at the upper esophageal sphincter (UES) as a function of time.

also emphasize the importance of the non-Newtonian aspect, as starch-thickened foods in a dysphagia diet are generally shear-thinning. For this reason, it is not sufficient to model Newtonian fluids above as prepared by Chang *et al.* (1998, 1999).

The shear rates at the UES were also compared for Newtonian and shear-thinning boluses [Figure 8(a)]. Given that the pharyngeal wall movements were identical in all three cases, it can be seen that much higher shear rates were achieved for the water bolus (Newtonian, 0.001 Pa s) even though the initial normal stress at the GPJ was much lower and was sustained for a shorter duration. Perhaps a less viscous fluid such as water is sheared at a higher rate in the pharynx of a dysphagic patient because of reduced sensorimotor controls, thus resulting in greater flow and less reaction time for the muscles to close off the air passages. The apparent shear rate at the UES at the end of simulation is 0.001 s^{-1} for the non-Newtonian bolus, compared to shear rates of 0.009 s^{-1} and 27 s^{-1} for the barium and Newtonian water boluses, respectively, at the same location. These apparent shear rates and the Reynolds numbers reported above clearly indicated that the consistency of the liquid influences pharyngeal bolus transport. More specifically, the rate at which the fluid traverses through the UES is substantially greater for the water bolus than for either the barium sulphate or the non-Newtonian bolus, given the same boundary conditions (pharyngeal wall movement). The apparent viscosity (η_{app}) of the fluid at the UES in the shear-thinning non-Newtonian bolus is plotted against time [Figure 8(b)]. The value of η_{app} is calculated from K and shear rate ($\dot{\gamma}$):

$$\eta_{app} = K\dot{\gamma}^{n-1} \tag{9}$$

There was a rapid drop from an initial viscosity of 60 Pa s to about 1 Pa s between 0 and 0.2 s. The low viscosity was sustained from 0.2 s to 0.5 s, during which both GPJ and UES reopen. From 0.6 s to the end of the simulation at 1.04 s, the viscosity rose rapidly, showing a maximum at 0.6 s followed by a gradual decrease to 40 Pa s at 1.04 s.

These above data on pharyngeal bolus transport (Figures 7 and 8) suggest that perhaps one reason shear-thinning non-Newtonian liquids are safer to swallow than thin Newtonian liquids is that the fluid flow is greatly reduced during the second half of the swallowing process, thus allowing more time for air passages (e.g., entry to the trachea or the nasopharynx) to completely shut off prior to the arrival of food. As a result, the dysphagic patient does not aspirate as he or she would with a Newtonian bolus.

Effect of Rheology on Time to Swallow a Critical Volume

To further illustrate the differences in the swallowing processes of Newtonian and non-Newtonian fluids, t_{cv} was coined to represent the time to swallow a critical volume and was defined as the number of seconds needed to transport the first 1.0 mL of fluid into the esophagus. The greater the t_{cv} value, the safer is the swallow, as the muscles in the pharynx have more time to close off entryway to the air passages before food arrives. The parameter t_{cv} may be useful for characterizing the severity of deglutition in a particular patient. It may also be used as a benchmark for any improvement or deterioration in the patient. Because it would be difficult to obtain t_{cv} values clinically, computer simulations such as this one are beneficial to the understanding of dysphagia.

The effect of Newtonian viscosity (density assumed constant) on t_{cv} is shown in Figure 9(a). In general, a Newtonian bolus with a higher viscosity results in a higher t_{cv}. A linear relation was seen between t_{cv} and η at viscosities higher than 1 Pa s [Figure 9(a)]. The relationship between density and viscosity was not examined for the Newtonian bolus in our study. However, there is information in the literature (Li *et al.*, 1992) which shows a 20% variation in density in the viscosity range of 6 Pa s to 60 Pa s. Because we only examined viscosities less than 15 Pa s, we assumed density effects to be negligible.

Values of t_{cv} increase sharply with consistency coefficient K of shear-thinning non-Newtonian fluids for $K < 0.5$ [Figure 9(b)]. For K values between 0.5 and 1.0 there was a slight decrease in t_{cv}. For $K > 2$ a linear dependence on K is seen for t_{cv} [Figure 9(b)]. These data suggest that increasing the consistency coefficient of a shear-thinning fluid generally lengthens the swallowing time and may help in reducing the risk of aspiration. The effect of small values of K should be further examined for a better understanding of their effect on t_{cv}.

Values of t_{cv} showed a weak, logarithmic dependence on n for both shear-thinning ($n < 1$) and shear-thickening ($n > 1$) fluids [Figure 9(c)]. This strong dependence suggested that non-Newtonian fluids in general increase the critical swallowing time more effectively than Newtonian fluids, which underscores the importance of simulating pharyngeal swallows of non-Newtonian boluses.

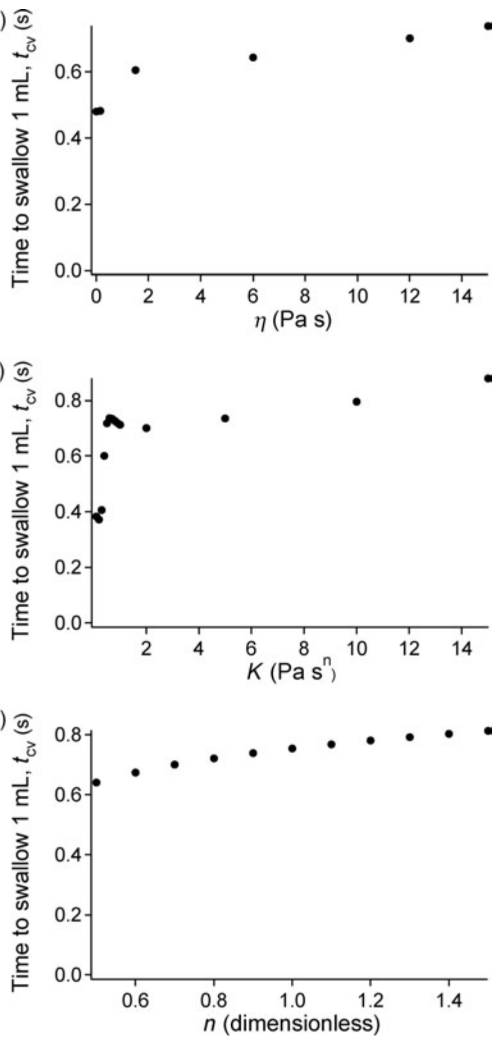


Figure 9. Effect of fluid rheology on the critical volume time (t_{cv}), where t_{cv} is defined as the number of seconds needed to transport the first 1.0 mL of fluid into the esophagus, showing (a) the effect of viscosity on t_{cv} of a Newtonian bolus, (b) the effect of the consistency coefficient (K) on t_{cv} of a shear-thinning non-Newtonian bolus (flow behaviour index $n = 0.7$), and (c) the effect of flow behaviour index (n) on t_{cv} of a shear-thinning non-Newtonian bolus (consistency coefficient $K = 2.0$).

CONCLUSIONS

It has been demonstrated that given the same boundary conditions, the pharyngeal transport of Newtonian and power law fluids are markedly different. The shear-thinning characteristics of typical starch-thickened beverages may slow down the swallowing process, thus allowing more time for airways to shut off, reducing the risk of aspiration. Using parameters such as t_{cv} may help identify the severity of dysphagia and aid in its management. Based on this simple computer model of the swallowing process, the effects of fluid properties on a pharyngeal swallow can be predicted. Such predictions may provide important clues to dysphagia and are an indispensable means of improving current treatment methods.

NOMENCLATURE

g_z	gravitational acceleration in the z-direction, m s^{-2}
K	consistency coefficient, Pa s^n
n	flow behavior index, dimensionless
p	pressure, Pa
r	radius, m
R	radius, m
R	residual vector
t	time, s
t_{cv}	time to swallow a critical volume, s
u_i	velocity vector, m s^{-1}
v_r	radial velocity, m s^{-1}
v_z	axial velocity, m s^{-1}
z	axial length, m

Greek symbols

$\dot{\gamma}$	shear rate, s^{-1}
η	viscosity, Pa s
η_{app}	apparent viscosity, Pa s
ρ	density, kg m^{-3}
σ	shear stress, Pa
σ_n	normal stress, Pa

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ACKNOWLEDGEMENTS

The authors are grateful to the Department of Food Science & Technology at Cornell University and the United States Department of Agriculture for funding this work.

The manuscript was received 9 August 2004 and accepted for publication after revision 27 June 2005.