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

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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 ($\rho = 1000\,\mathrm{kg\ m^{-3}}, \eta = 0.001\,\mathrm{Pa\ s}$), 250% w/v barium sulfate mixture ($\rho = 1800\,\mathrm{kg\ m^{-3}}$, $\eta = 0.150\,\mathrm{Pa\ s}$), and starch-thickened beverage (power law parameters $K = 2.0\,\mathrm{Pa\ s^n}$, $n = 0.7$). 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

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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.

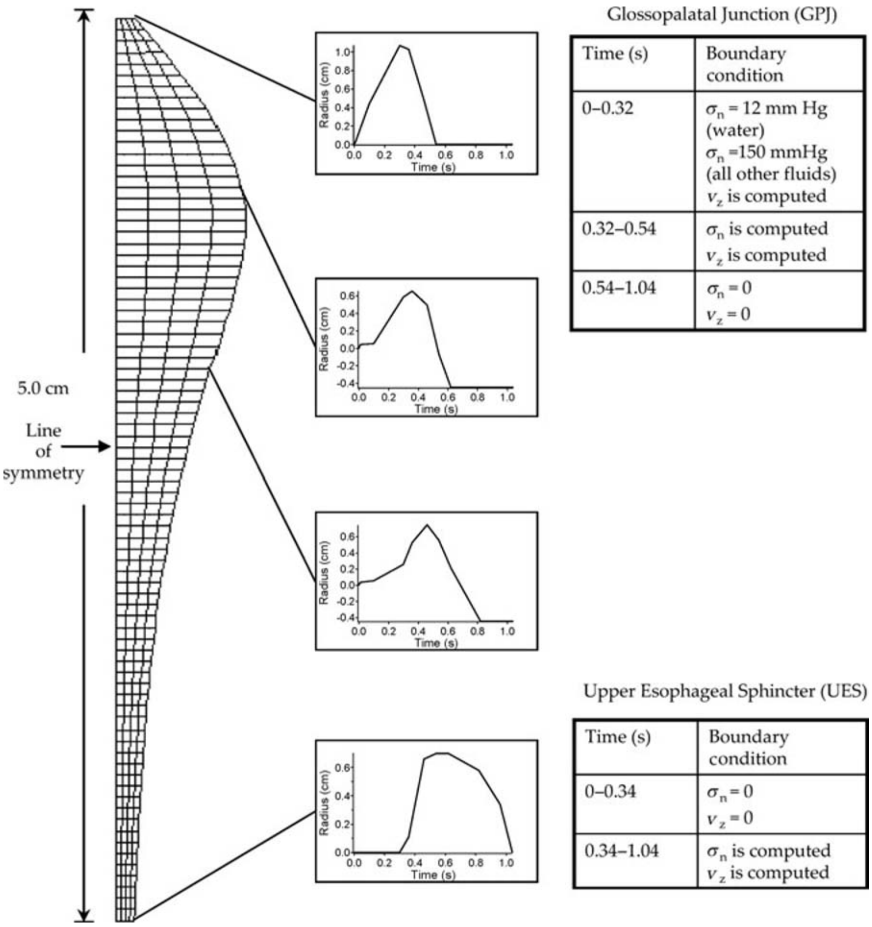

Figure 1. Schematic of the segment of human throat in the resting position from the glossopalatal junction (GPJ) to the upper esophageal sphincter (UES), showing the prescribed normal stresses at the GPJ and the UES as well as prescribed displacements at the GPJ, pharyngeal wall (only two are shown),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