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A model experiment to understand the oral phase of swallowing of Newtonian liquids

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ABSTRACT

A model experiment to understand the oral phase of swallowing is presented and used to explain some of the mechanisms controlling the swallowing of Newtonian liquids. The extent to which the flow is slowed down by increasing the viscosity of the liquid or the volume is quantitatively studied. The effect of the force used to swallow and of the gap between the palate and the roller used to represent the contracted tongue are also quantified. The residual mass of liquid left after the model swallow rises strongly when increasing the gap and is independent of bolus volume and applied force. An excessively high viscosity results in higher residues, besides succeeding in slowing down the bolus flow. A realistic theory is developed and used to interpret the experimental observations, highlighting the existence of an initial transient regime, at constant acceleration, that can be followed by a steady viscous regime, at constant velocity. The effect of the liquid viscosity on the total oral transit time is lower when the constant acceleration regime dominates bolus flow. Our theory suggests also that tongue inertia is the cause of the higher pressure observed at the back of the tongue in previous studies.

The approach presented in this study paves the way toward a mechanical model of human swallowing that would facilitate the design of novel, physically sound, dysphagia treatments and their preliminary screening before *in vivo* evaluations and clinical trials.

1. Introduction

Swallowing occurs about one thousand times per day to transport subconsciously saliva and to transport voluntarily food from the mouth to the stomach (Dodds, 1989). Swallowing disorders, also known as dysphagia, can be the consequence of several pathologies, such as throat and neck cancer, stroke, dementia, or other neurodegenerative conditions. The higher prevalence among elderly subjects justifies increased attention in countries with aging populations. Dysphagia management is crucial for providing adequate nutrition and hydration while minimizing the risk of choking, aspiration and resulting pulmonary diseases.

Despite such importance, swallowing is still not fully understood, because it involves the complex, coordinated contraction of different muscles located in and around the tongue, larynx, pharynx and oesophagus. The bolus flow starts in the mouth under the pressure produced by the tongue surface, moving toward the hard palate. The pressure and the total work provided by the tongue during the squeezing action of different jelly-type foods was recently studied (Yokoyama et al., 2014) and maximum pressures were measured in the range 5–40 kPa. Other groups (Nicosia et al., 2000; Youmans and Stierwalt, 2006) reported previously similar figures and highlighted also that pressure varies along the tongue position and is higher at the back. The mean peak tongue pressure was also found to remain similar across different age groups, although maximum tongue strength was found to decrease with age (Youmans and Stierwalt, 2006; Utanohara et al., 2008). Clavé et al. (2006) showed that brain damage or neurodegenerative conditions result in decreased tongue pressure, decreased bolus kinetic energy and increased transit time.

The volume of the bolus swallowed was shown to vary with the viscosity of the food (Adnerhill et al., 1989). For thin liquids, the volume ranges from 1 mL (saliva bolus) to 20 mL (cup drinking), and decreases when drinking hot fluids or sipping.

A simple theory, considering the transient motion of two rigid plates as a model for the tongue and the palate, has been proposed to describe the fluid mechanics of bolus ejection from the oral cavity by Nicosia and Robbins (2001). This theory has highlighted that liquid density can potentially play an important role in swallowing. However, in that simple system, the tongue and the palate are separated by a spatially uniform gap that decreases with

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time and an infinite time is needed to complete the ejection of the bolus. In turn, it is extremely difficult to perform any direct comparison with *in vivo* data.

To bridge the gap between theory and *in vivo* experiments in the field of mastication, Woda et al. (2010) developed an artificial masticator and studied in a controlled way the effect of the different process parameters, while overcoming the difficulties linked to *in vivo* observations. Similarly, De Loubens et al. (2010, 2011) proposed a simple pharyngeal peristalsis simulator and a numerical analysis to study the flow and the resulting coating thickness.

Numerical simulations were recently used to reproduce mastication and human swallowing, but the complexity of this free surface flow requires non-conventional algorithms such as SPH (Ho et al., 2014) or MPS (Kikuchi et al., 2015).

Mackley et al. (2013) characterized the rheology of dysphagia thickeners and proposed for the first time a qualitative model experiment replicating tongue peristalsis. Our study proposes a quantitative model experiment to understand swallowing and in particular the effect of bolus physical properties on the bolus transit time and the residues left during the oral phase of swallowing.

2. Materials and methods

2.1. Materials

Aqueous glycerol solutions are used in this study because they allow a wide viscosity variation, while showing a simple Newtonian rheology. The liquid viscosity of the aqueous glycerol solutions was characterized using a rheometer Physica MCR-500 by Anton Paar, under simple shear with a concentric cylinder geometry. The water concentration was varied in the range of 0, 2, 5, 20, 50% wt (0–440 g/L), to obtain a viscosity range from $\mu = 1.185$ Pa s to $\mu = 0.006$ Pa s at 22° C. A red dye powder was added for enhancing contrast in the images, with no impact on the rheological properties of the liquids.

2.2. Methods

To simulate the oral phase of human swallowing, we developed and optimized the mechanical model designed initially by Mackley et al. (2013). The model experiment used in this study is shown in Fig. 1. The top rigid wall is a bidimensional approximation of a human palate, with a constant curvature along θ.

This experimental setup simulates two main actions of the tongue during swallowing. A roller, attached to a pivoting arm, mimics the contracted part of the tongue, propelling the bolus. Its position during the experiment is defined by the angle θ (see Fig. 1). A thin, compliant tubing made of a dialysis membrane mimics the ability of the tongue at rest to hold the fluid in mouth. When this is empty and flat, its width is $w_T = 23$ mm and its thickness is 0.1 mm, including the adhesive tape. We define h the gap between the roller and the palate and h' the initial gap between the roller and the tube, the difference being the membrane thickness. Before each experiment, the soft membrane is glued on the top rigid surface. The bolus is fed into the dialysis membrane via a syringe and pushed manually until the starting position.

The experiment used in the study by Mackley et al. (2013) was improved in several ways: a counterweight to equilibrate the arm weight and an adjustable gap between the roller and the palate were introduced. Furthermore the initial angular position of the roller ($\theta_i = 45^o$) is chosen to mimic the contact between the tongue tip and the bolus before an *in vivo* swallow.

The arm is initially blocked by a pin and different weights can be used to apply a range of torques to the arm. Once the pin is released, the weight pulls the arm and the roller, propelling the bolus inside the membrane. The applied force and bolus physical properties determine the resulting acceleration and the evolution of bolus angular position with time. The roller travels to the final position $\theta_f = 165^o$, as depicted in Fig. 1 and the liquid flows in the membrane until it reaches the open end and flows out. Although the epiglottis is schematically represented in the model, it is not considered in this work.

In order to measure quantitatively the arm and liquid motion, this is recorded using a Photron FastCam SA3 high speed camera, at a frame rate of 500 frames/s. Image analysis is used to extract the angular position of the roller (bolus tail), the bolus front and the transit time. Finally, the residual liquid mass in the system is obtained by weighting.

Exploiting the advantages provided by the model swallowing experiment, the process parameters were varied independently to elucidate their effect on the liquid motion. In particular we considered the effect of the liquid viscosity μ, the driving force F, the liquid volume V and the gap between the roller and the membrane h', see Table 1.

The force and the pressure applied by the roller on the bolus increase during an experiment because of the transient motion and the inertia of the system. This will be discussed after introducing the theory. The maximum driving force at the roller F_R and the pressure applied on the bolus $P_{(R/bolus)}$ can be estimated from a torque balance on the system at steady state:

$$F_R = \frac{r_C}{r_A + r_R} F = \frac{r_C}{r_A + r_R} mg = P_{(R/bolus)} S \qquad (1)$$

F is the driving force generated by the mass m, r_R is the roller radius (8 mm). r_C is the distance from the center of rotation of the point of application of the driving force (28 mm), while r_A (47 mm) is the distance of the center of the roller from the

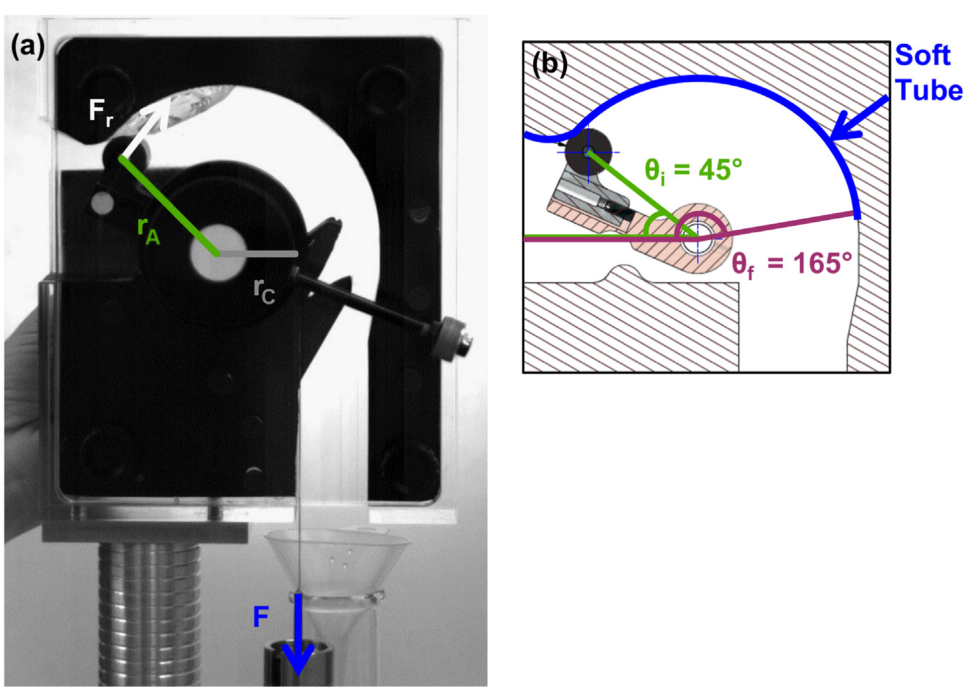

Fig. 1. Artificial swallowing experiment : (a) overview of the experimental setup, (b) detailed drawing of the arm and roller without liquid.

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