ARTICLE IN PRESS

Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
www.JBiomech.com

In vivo observations and *in vitro* experiments on the oral phase of swallowing of Newtonian and shear-thinning liquids

S. Mowlavi [a], J. Engmann [b], A. Burbidge [b], R. Lloyd [d], P. Hayoun [c], B. Le Reverend [b], M. Ramaioli [d,*]

[a] *Department of Mechanical Engineering, Massachusetts Institute of Technology, 77 Massachusetts Av., Cambridge, MA02139, USA*
[b] *Nestlé Research Center, Route du Jorat 57, 1000 Lausanne 26, Switzerland*
[c] *CNRS/UPMC/ESPCI ParisTech-PSL Research University, UMR 7615, Laboratoire SIMM, 10 Rue Vauquelin, 75231 Paris, France*
[d] *Department of Chemical and Process Engineering, Faculty of Engineering and Physical Sciences, University of Surrey, Guildford GU2 7XH, United Kingdom*

ARTICLE INFO

Article history:
Accepted 9 October 2016

Keywords:
Bolus
Flow
Swallowing
Tongue
Ultrasound
Viscosity
Thickener
Rheology
Fluid mechanics
Oral cavity
Palate
Peristalsis

ABSTRACT

In this study, an *in vitro* device that mimics the oral phase of swallowing is calibrated using *in vivo* measurements. The oral flow behavior of different Newtonian and non-Newtonian solutions is then investigated *in vitro*, revealing that shear-thinning thickeners used in the treatment of dysphagia behave very similar to low-viscosity Newtonian liquids during active swallowing, but provide better control of the bolus before the swallow is initiated. A theoretical model is used to interpret the experimental results and enables the identification of two dynamical regimes for the flow of the bolus: first, an inertial regime of constant acceleration dependent on the applied force and system inertia, possibly followed by a viscous regime in which the viscosity governs the constant velocity of the bolus. This mechanistic understanding provides a plausible explanation for similarities and differences in swallowing performance of shear-thinning and Newtonian liquids. Finally, the physiological implications of the model and experimental results are discussed. *In vitro* and theoretical results suggest that individuals with poor tongue strength are more sensitive to overly thickened boluses. The model also suggests that while the effects of system inertia are significant, the density of the bolus itself plays a negligible role in its dynamics. This is confirmed by experiments on a high density contrast agent used for videofluoroscopy, revealing that rheologically matched contrast agents and thickener solutions flow very similarly. *In vitro* experiments and theoretical insights can help designing novel thickener formulations before clinical evaluations.

1. Introduction

Swallowing disorders (dysphagia) can be caused by several conditions such as stroke, dementia, neurological diseases or head and neck cancer. Dysphagia is considered the main cause of post-stroke pneumonia that affects about 20% of stroke patients (Scheitz et al., 2015) and causes more than 10% of post-stroke deaths (Koennecke et al., 2011). More generally, in elderly dysphagia can result in food and drink avoidance leading to malnutrition and dehydration.

Several approaches exist to manage dysphagia, one of the most popular being the use of thickeners to increase the viscosity of thin drinks, resulting in shear-thinning liquids. A review of their efficacy and limitations can be found in Newman et al. (2016). Despite the clinically proven efficacy of thickeners, it remains unclear, at least from a mechanistic perspective, exactly why they are effective and what role is played by their shear-thinning rheology. Consequently it is difficult to either develop better thickeners, or to identify which patients are likely to respond to which level of viscosity other than by trial and error and there is a strong ongoing debate within the medical community about what represents best practice. Some would argue that prescribing overly thickened beverages can lead to excessive residues in the pharynx and oral cavity, which, although providing a safe initial swallow, are likely to provide post-swallow complications.

Clearly, the physical act of forming and then swallowing a liquid bolus is exquisitely complicated and requires precise coordination of many muscles in order to avoid catastrophic failure. From the mechanistic standpoint, the kinematics and dynamics of single muscles involved in mastication and/or swallowing are still the object of active research (Weickenmeier et al., 2016) and it is a formidable challenge to describe realistically all organs and tissues moving during these food oral processes.

---

[*] Corresponding author.
E-mail address: m.ramaioli@surrey.ac.uk (M. Ramaioli).

http://dx.doi.org/10.1016/j.jbiomech.2016.10.011
0021-9290/© 2016 Elsevier Ltd. All rights reserved.

Please cite this article as: Mowlavi, S., et al., *In vivo* observations and *in vitro* experiments on the oral phase of swallowing of Newtonian and shear-thinning liquids. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.10.011

The clinical observation of subjects is usually carried out by one of two popular techniques: fiberoptic endoscopic evaluation of swallowing (FEES, see Hiss and Postma, 2003), which involves insertion of an instrumented catheter through the nose, or videofluoroscopic swallowing study (VFFS, see Logemann, 1998), which is an X-ray based video technique. Both of these techniques are cumbersome and invasive: insertion of a catheter will certainly perturb the flow, and likely the physiology, and radiation exposure limits repeats and studies on healthy individuals. There are several other techniques available, but they also have significant drawbacks. For this reason, the concept of *in vitro* swallowing experiments is beguiling, and many things can be learned from this approach, despite the difficulty of matching the biophysical reality exactly. In this article an *in vitro* 'swallowing simulator' is presented, which mimics some aspects of the *in vivo* swallow, and enables quantitative measurements and comparisons of the oral flow of different types of liquids. To be absolutely clear, this should not be considered as an alternative to clinical research. However, judicious use of in vitro experiments like those detailed here could allow for improved understanding of the relative significance of different effects, leading to stronger and tighter focused hypotheses that can subsequently be tested *in vivo*.

To put our current findings into context, we first present a very short review of the most relevant literature.

A simple and mechanistic theory of the oral phase of swallowing was initially proposed by Nicosia and Robbins (2001). This theory considered the transient motion of two approaching parallel plates as a model for the tongue and the palate. De Loubens et al. (2010, 2011) later introduced an *in vitro* pharyngeal peristalsis simulator and a theory to study the thin film left on the pharyngeal mucosa after a swallow, this time using two rolling cylinders to model the peristaltic action of the tongue against the pharyngeal wall.

The above studies only considered the flow of Newtonian liquids and did not address the behavior of thickened solutions. Popa Nita et al. (2013) used rotational rheometry to characterize the rheology of aqueous solutions of Resource® ThickenUp™ Clear (TUC), a common dysphagia thickener, and demonstrated that their steady state viscosity is close to that of Bracco™ E-Z-PAQUE, a common video fluoroscopy contrast agent. However, their study did not discuss the relevance of using steady state rheological properties for a transient, fast flow such as swallowing.

Mackley et al. (2013) used different techniques to characterize the rheology of several dysphagia thickeners and introduced for the first time a qualitative, '*in vitro* swallowing simulator' mimicking the oral phase of swallowing. Building upon this first device, Hayoun et al. (2015) proposed a more quantitative *in vitro* experiment, devised a theoretical model and applied both to studying the flow of Newtonian liquids.

This study extends the scope of the latter by using *in vivo* observations to determine an appropriate value of the mechanical inertia of the *in vitro* swallowing simulator. The behavior of shear-thinning liquids is then investigated in the calibrated device and compared to that of Newtonian liquids. Finally, the theoretical model is extended and refined and a novel mechanistic interpretation of the experimental results is proposed through the identification of two dynamical regimes. This interpretation also leads to a novel explanation for the role played by the shear-thinning rheology of thickened fluids in managing dysphagia.

This study is presented as follows. In Section 2 we describe the experimental device, select test fluids and the *in vivo* experiments used to calibrate the swallowing simulator. Section 3 describes the full theory and a simplified model. Section 4 describes the results obtained, the implications of which are then discussed in Section 5, before drawing some conclusions in Section 6.

2. Materials and methods

2.1. *In vitro* swallowing simulator

During this study we further developed a mechanical, *in vitro* device designed to study and understand the flow of a liquid induced by the movement of the tongue during the oral phase of swallowing. This device, shown in Fig. 1, is based on a mouth-sized *in vitro* experiment initially designed by Mackley et al. (2013) and later improved by Hayoun et al. (2015). Without having the ambition of reproducing faithfully the *in vivo* process, the objective of this study was to capture two essential features of the mouth and tongue. A thin and flexible polyethylene membrane is attached to the "palate" and contains the liquid, representing the oral cavity. A roller attached to a rotating arm is driven by a weight and mimics the driving pressure applied by the tongue to the bolus, propelling the liquid through the oral cavity. The effect of gravity on the rotating arm is cancelled out by a counterweight. Different driving forces F lead to different pressures applied on the liquid, which can be computed as illustrated in Hayoun et al. (2015).

A significant improvement made to the model experiment in this current study, with respect to the experiment used in Hayoun et al. (2015), consists of the possibility of varying the total moment of inertia I_{tot} of the rotating arm, roller and counterweight assembly. To that effect, two radially opposed rods, each carrying an offset mass, can be attached to the rotating arm. In the physiological context, I_{tot} accounts for the combined inertia of all the tissues and organs involved in a swallow, including the tongue, the larynx, the hyoid bone and the associated muscles and soft tissues. Due to the non-rigid body motion, the inertia of the tissues is difficult to estimate and we take the approach of calibrating I_{tot} using *in vivo* observations, as described later in Section 4. Other improvements to the *in vitro* device include the use of an inert polyethylene film instead of a porous dialysis tube, and the use of an inextensible steel string to hold the weight.

The time evolution of the position of the liquid during an *in vitro* experiment was quantified by measuring the angle θ between the roller and the horizontal direction, as shown in Fig. 1. To carry out an artificial swallow experiment, a closed flexible membrane was first attached to the "palate" along the path of the roller. 6 ml of liquid were then injected into the front opening of the membrane and the liquid was manually pushed through the membrane until it reached its starting position, shown in Fig. 1. A pin initially held the roller in its starting angular position $\theta_0 = 45°$. Releasing the pin

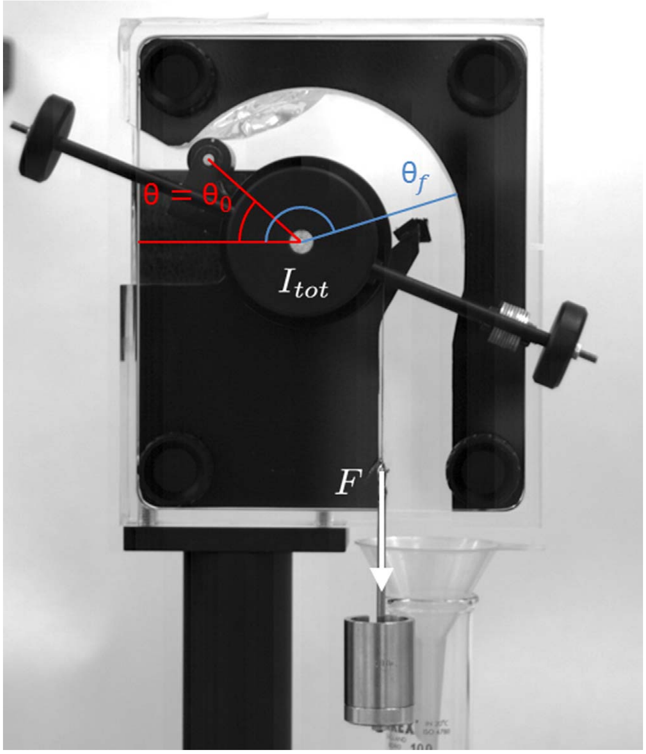

Fig. 1. The *in vitro* experiment showing the roller at the initial position $\theta = \theta_0$ and the two radially opposed offset masses to vary the moment of inertia I_{tot} of the rotating arm, roller and counterweight (in this image $I_{tot} = 1.15 \cdot 10^{-3}$ kg m^2). The weight imposes a driving force F represented by the white arrow.

Please cite this article as: Mowlavi, S., et al., *In vivo* observations and *in vitro* experiments on the oral phase of swallowing of Newtonian and shear-thinning liquids. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.10.011