Journal of Biomechanics xxx (2018) xxx–xxx

Contents lists available at ScienceDirect

Journal of Biomechanics

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

An experimental model to investigate the biomechanical determinants of pharyngeal mucosa coating during swallowing

Vincent Mathieu [a,*], Clément de Loubens [a,b], Chloé Thomas [a], Maud Panouillé [a], Albert Magnin [b], Isabelle Souchon [a]

[a] UMR GMPA, INRA, AgroParisTech, Université Paris-Saclay, 78850 Thiverval-Grignon, France
[b] Univ. Grenoble Alpes, CNRS, Grenoble INP (Institute of Engineering Univ. Grenoble Alpes), LRP, 38000 Grenoble, France

ARTICLE INFO

Article history:
Accepted 3 March 2018
Available online xxxx

Keywords:
Swallowing
Lubrication
Biofluid mechanics
Food bolus
Dysphagia
Sensory perceptions

ABSTRACT

The development of innovative experimental approaches is necessary to gain insights in the complex biomechanics of swallowing. In particular, unraveling the mechanisms of formation of the thin film of bolus coating the pharyngeal mucosa after the ingestion of liquid or semi-liquid food products is an important challenge, with implication in dysphagia treatment and sensory perceptions.

The aim here is to propose an original experimental model of swallowing (i) to simulate the peristaltic motions driving the bolus from the oral cavity to the esophagus, (ii) to mimic and vary complex physiological variables of the pharyngeal mucosa (lubrication, deformability and velocity) and (iii) to measure the thickness and the composition of the coatings resulting from bolus flow. Three Newtonian glucose solutions were considered as model food boli, through sets of experiments covering different ranges of each physiological parameter mimicked.

The properties of the coatings (thickness and dilution in saliva film) were shown to depend significantly on the physical properties of food products considered (viscosity and density), but also on physiological variables such as lubrication by saliva, velocity of the peristaltic wave, and to a lesser extent, the deformability of the pharyngeal mucosa.

The biomechanical peristalsis simulator developed here can contribute to unravel the determinants of bolus adhesion on pharyngeal mucosa, necessary both for the design of alternative food products for people affected by swallowing disorders, and for a better understanding of the dynamic mechanisms of aroma perception.

1. Introduction

While propelling the food bolus from oral cavity to the esophagus, the sequence of swallowing leads to the formation of a thin film of bolus coating the pharyngeal mucosa (Buettner et al., 2001). Unraveling the biomechanical phenomena involved in the formation of these coatings is critical both for healthcare and welfare considerations.

From a public health perspective, the applications deal with an improved prevention of swallowing disorders (dysphagia), due to multiple origins like perturbations of muscles coordination or alteration of salivary glands functioning (Clavé and Shaker, 2015). The consequences of dysphagia may be dramatic for the patients: risks of choking, lung infections and in a longer perspective, avoidance of some categories of food and drink products, leading to dehydration and malnutrition issues (Rommel and Hamdy, 2015). In this regard, understanding the mechanisms of bolus adhesion during swallowing is essential in order to design appropriate alternative food products combining health and pleasure for patients affected by dysphagia.

From a sensory point of view, the swallowing sequence has been shown to play a crucial part in the dynamics of aroma perception of food (Doyennette et al., 2011; Linforth and Taylor, 2000). Due to their location at the crossroads between bolus trajectory and respiratory airways, the exchange surfaces between pharyngeal coatings (consecutive to swallowing) and respiratory flows promote the transport of aroma compounds to the olfactory receptors. As a consequence, a better understanding of the biomechanical determinants of pharyngeal coatings' formation could be helpful for an improved control of food aromatic qualities and/or defects.

* Corresponding author at: Laboratory of Food Process Engineering and Microbiology (GMPA UMR 782), Joint Research Unit INRA AgroParisTech, Bâtiment CBAI, 1, avenue Lucien Brétignières, 78850 Thiverval-Grignon, France.
E-mail address: vincent.mathieu@inra.fr (V. Mathieu).

https://doi.org/10.1016/j.jbiomech.2018.03.006
0021-9290/

Different biomedical technologies (video-fluoroscopy, endoscopy, esophageal manometry, ultrasound imaging) are clinically used *in vivo* for the diagnosis of dysphagia (Cook, 2008; Gao et al., 2013; Gao and Kohyama, 2014). However, due to resolution issues, these techniques are not suitable for the characterization of coatings. Moreover, the complexity of swallowing process (with important inter-individual variabilities) represents additional barriers for the rigorous investigation of coatings' formation with *in vivo* approaches. Several original *in silico* and *in vitro* studies were thus conducted to describe in controlled conditions the fluid mechanics of food bolus during tongue-palate compression and swallowing (Hayoun et al., 2015; Mowlavi et al., 2016; Nicosia and Robbins, 2001).

Theoretical models of pharyngeal peristalsis have also been proposed (de Loubens et al., 2011, 2010), based on the assumption that during swallowing, at the most occluded point, pharyngeal walls can be considered as being in rotation to each other. The relative motions between pharyngeal membranes have thus been described with lubrication theory following the forward roll coating configuration (see Fig. 1a) (Cohu and Magnin, 1997;Coyle, 1988). These models have shown the importance of the complex interactions between the flow of the food bolus and the film of saliva lubricating the deformable mucosa (de Loubens et al., 2011, 2010). To our knowledge, such a configuration with double lubrication (saliva and food bolus) in forward roll coating has not been tackled in an experimental framework. The development of experimental approaches is thus necessary in order to better understand the mechanisms arising from these complex conditions.

In the present work, an original biomechanical set-up was developed in order (i) to mimic through a forward roll coating configuration the pharyngeal peristaltic motions occurring during swallowing and (ii) to measure the thickness of the coatings resulting from the bio-mimicking swallowing sequences. The aim of the study is to characterize and to quantify the potential respective contributions (i) of food bolus physical properties (viscosity and density) and (ii) of swallowing physiological parameters, on the formation of pharyngeal coatings. To do so, model boli made of glucose syrup Newtonian solutions were swallowed in the pharyngeal peristalsis simulator, making it possible to consider the variability of different properties of pharyngeal walls (lubrication, stiffness and velocity).

2. Material and methods

2.1. Model food boli

Three Newtonian solutions of glucose syrup were considered (referred to as G0, G40 and G50 for their dry matter fraction), composed of mixing ratios between a commercial glucose syrup (Caullet, Erquinghem-Lys, France) and water (concentration in glucose syrup $c_m(glu)$ respectively of 0, 49 and 67 wt%). Table 1 summarizes the values of dry matter, mass density and viscosity measured in triplicate at 20 °C for each solution. Viscosity measurements were carried out on a rheometer RheoStress RS 600 (Haake, Vreden, Germany) equipped with a 2° cone/plate geometry and have shown a Newtonian behavior up to 2000 s^{-1}. All experiments were carried out at 20 °C.

2.2. Pharyngeal peristalsis simulator

The pharyngeal peristalsis simulator consists in two contra-rotating rigid cylinders (radius R = 35 mm, length L = 80 mm) covered by a layer of soft gelatin and driven by electric motors (see Fig. 1b and c). The activation of muscles during pharyngeal peristalsis is mimicked by the force applied by a spring dynamometer (tension set to 2 N) between the axes of the rigid cores of the two cylinders. This force is then transmitted to the external layer of the cylinders, made of soft gelatin and playing the role of pharyngeal mucosa deformed by the effect of muscles during peristalsis. The thickness of the gelatin layer retained to mimic pharyngeal tissues in the present study (e_g = 5 mm) was chosen in accordance with the few data available for similar tissues: 1–4 mm for skin (Diridollou et al., 2000), 0.3–6.7 mm for oral mucosa (Chen et al., 2015). Slot coating systems were designed to lubricate the surfaces

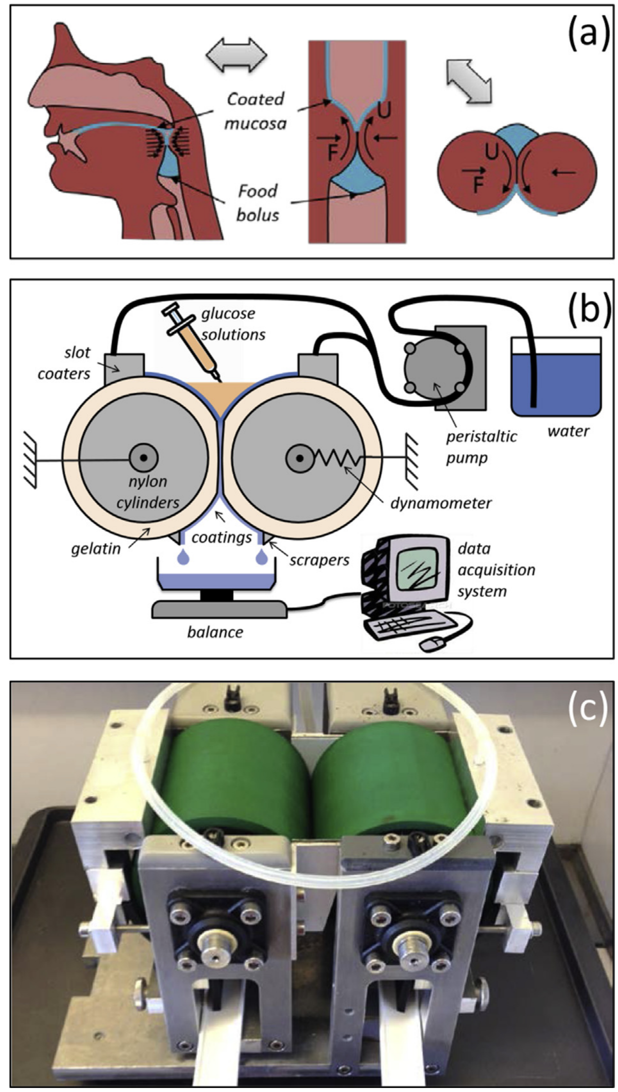

Fig. 1. Schematic representation of pharyngeal peristalsis during swallowing (a): in the most occluded point, pharyngeal walls (force F, velocity U) can be considered in rotation, and modeled by the forward roll coating configuration. Schematic representation (b) and photograph (c) of the pharyngeal peristaltic simulator.

Table 1
Characteristics of the glucose solutions considered to mimic food bolus.

Reference	G0	G40	G50
Glucose syrup concentration c_m(glu) (wt.%)	0	49	67
Dry matter (g per gram of solution)	0.00 ± 0.00	38.98 ± 0.03	53.88 ± 0.06
Viscosity (mPa s)	1.2 ± 0.2	10.2 ± 0.2	57.4 ± 1.8
Mass density (kg m^{-3})	996.3 ± 0.1	1172.5 ± 0.2	1253.0 ± 0.3