Rheology and Dysphagia: An Overview

Críspulo Gallegos[1,2], Lida Quinchia[1], Gabriel Ascanio[3], Martín Salinas-Vázquez[4] and Edmundo Brito-de la Fuente[1]

[1] I&D Centre Complex Formulations, Fresenius Kabi Deutschland GmbH, Bad Homburg, Germany.
[2] Departamento de Ingeniería Química, Universidad de Huelva, Huelva, Spain
[3] Centro de Ciencias Aplicadas y Desarrollo Tecnológico, UNAM, México DF, México
[4] Instituto de Ingeniería, UNAM, México DF, México

ABSTRACT

Eating and drinking are essential activities of human beings. Swallowing is a complex mechanism involving many muscles and nerves aiming to transport bolus into the stomach. Boluses may have several solid-like consistencies and drinks different viscous levels. Consequently, rheology plays an important role in the swallowing process, being of paramount importance to better understand dysphagia or swallowing impairment.

INTRODUCTION

Dysphagia, or abnormal swallowing of foods and/or liquids, affects people of all ages from the newborn to the elderly. It is usually a consequence of neurological diseases, several forms of cancer, or stroke[1]. Dysphagia is usually related to a reduced oral intake that easily leads to malnutrition and dehydration.

The most efficient assessment of these abnormalities is still under discussion within the medical community[2]. In any case, the main objective is to avoid food aspiration (food to enter into the airway passing the vocal folds), because this may lead to pneumonia. Aspiration and penetration, this last defined as the passage of materials into the larynx, depend on clinical status as well as food/liquid flow properties (e.g., viscosity, consistency, adhesiveness, cohesiveness) and bolus volume[3].

Management of dysphagia is commonly done by the prescription of texture-controlled diets. The rationale behind altering or modifying the consistency of foods and/or drinks is to change the rate at which food is transported through the pharynx and, thus, to reduce the risk of aspiration. Although the most appropriate modification of food consistencies should follow from a clear assessment of the swallowing problem, this is not possible in all cases and quite often health care professionals relay on National guidelines for the dietary management of dysphagia patients.

In this sense, the National Dysphagia Diet (NDD)[4], published in 2002 by the American Dietetic Association, aims to establish standard terminology and practice applications of dietary texture modification in dysphagia management. The proposed terms for liquids and correlating viscosity ranges, at 25°C and a single shear rate of 50 s^{-1}, are: (1) Thin: 1-50 cP; (2) Nectar-like: 51-350 cP; (3) Honey-like: 351-1750 cP; (4) Spoon-thick: >1750 cP. There is no scientific evidence or rationale given by NDD on the temperature and shear rate chosen for this scale. On the

Table 1. Some kinematic data for analysis of dysphagia.

Reference	Bolus Transit Velocity	Comments
A) Pharyngeal phase	cm/s	
Nguyen et al.[9]	37.1 ± 1.1	Bolus head traversing the pharyngeal region. Data from Multiple Intraluminal Impedance (MII)
	28.3 ± 2.1	Bolus head velocity decreases as viscosity increases
	9.6 ± 1.0	Mean pharyngeal propulsion velocity of bolus body
Williams et al.[10]	42	Bolus head entering into the UES. Data from high-resolution manometry
Bardan et al.[11]	37.6 ± 8.1	Bolus head traversing the pharyngeal region. Datafrom videofluoroscopy
	10.3 ± 3.0	Bolus tail average velocity as it traversed the pharynx and passed through the UES
Reference	*Bolus Transit Velocity*	*Comments*
B) Esophageal phase	cm/s	
Nguyen et al.[9]	9.6 ± 1.4	Head liquid bolus (low viscosity); subjects in supine position. Data from MII
	14.2 ± 2.2	Head liquid bolus (low viscosity); subjects in upright position
	6.3 ± 0.8	Head high viscosity bolus (yogurt); subjects in supine position
	5.0 ± 0.4	Body liquid bolus (low viscosity); subjects in supine position
	5.2 ± 0.8	Body liquid bolus (low viscosity); subjects in upright position
	4.0 ± 0.2	Body high viscosity bolus (yogurt); subjects in supine position
	4.1 ± 0.1	Tail liquid bolus (low viscosity); subjects in supine position
	4.7 ± 0.2	Tail liquid bolus (low viscosity); subjects in upright position
	4.1 ± 0.2	Tail high viscosity bolus (yogurt); subjects in supine position

other hand, these scales only consider viscous properties; elasticity is not even mentioned. Further similar National guidelines have been proposed in UK and Australia.

In summary, most of the available information regarding the rheological properties of ready-to-use diets/foods used for dysphagia management is mainly focused on viscosity. However, the need for more comprehensive rheological information on ready-to-use products for dysphagic patients has been recently highlighted by different authors[5,6].

The aim of this paper is to present an overview on recent advances concerning fluid dynamics analysis of the swallowing process and the role of rheology in product design for dysphagia nutritional support.

FLUID DYNAMICS, SWALLOWING AND DYSPHAGIA

Dysphagia may be analysed from both medical and fluid kinematics/dynamics point of views. This last one may be considered as the "dysphagia engineering approach". A kinematic/dynamic analysis of dysphagia aims to gain insight into the mechanisms of bolus and liquid flow during swallowing.

The velocity spectrum of bolus flow in the pharynx and esophagus has been determined using different techniques. So far, videofluoroscopy has been the most frequently used. Other non-radiological techniques, i.e. high-resolution manometry[7] and ultrasonic pulse Doppler analysis[8], have been more recently proposed.

Regardless of the technique used for kinematic analysis of dysphagia, it is clear that bolus transit time and, consequently, velocity are highly dependent on patient's medical conditions and bolus rheological properties.

Some literature kinematic data for dysphagia analysis are shown in Table 1. As can be observed, bolus transit velocity is considerable higher for the pharyngeal phase than for the esophageal phase. On the other hand, as bolus viscosity increases, bolus transit velocity decreases, as expected.

Using as a basis some of the information given in Table 1, and assuming only shear deformation, an estimation of the shear rates involved in the swallowing process in presented in Table 2. As the results clearly suggest, shear rate during the swallowing process is higher for the pharyngeal phase than for the esophageal phase. In general, shear rate for the whole swallowing process varies from 1 to 1000 s^{-1}. This is in-line with previous estimations[12]. In this sense, Meng et al.[13] estimated a shear rate of 400 s^{-1} for water, quite reasonable value as compared with those shown in Table 2.

Table 2. Estimated swallowing shear rates from bolus transit velocities

Swallowing Phase	Liquid Bolus kinematic velocity, V^c (cm/s)	Estimated Shear rate, $\dot{\gamma}^d$ (1/s)
Pharyngeal		
bolus head (max)[a]	35.5	931.7
bolus tail (average)[a]	10	262
Esophageal		
from Bolus Transit Time (BTT = 6.12 s)[b]	2.94	4.7

[a] Anatomy – Data from Battagel et al.[14]
[b] Data based on Multichannel Intraluminal Impedance (MII) from Srinivasan et al.[15]
[c] Kinematics – Data from Bardan et al. [11]
[d] From capillary and peristaltic flow equations

A systematic kinematic study with well-defined bolus rheological properties is still not available in the literature. Thus, it is apparent that elongational flows are also involved in the deformation of food bolus, as clearly seen from videofluoroscopy and real-time magnetic resonance imaging[16,17]. The shape of the deformed bolus is typical of that produced under elongational stretching. This is in line with the fact that many boluses exhibit extensional properties[5]. Unfortunately, little attention has been paid to the role of elongational flows for swallowing disorders assessment. So far, viscous properties are the only considered and with still too many limitations.

NUMERICAL ANALYSIS OF THE SWALLOWING PROCESS

Different approaches can be found in the literature concerning numerical analysis of the swallowing process. Most of them are 2D simulations[13,18]. Brito-de la Fuente et al.[19] are currently developing a 3D simulation of the bolus flow along the pharynx.

It is well-known that bolus travels along the pharynx under peristaltic flow conditions. A numerical analysis of such a flow has been carried out from the glossopalatal junction (GPJ) to the upper esophageal sphincter (UES). Three-dimensional meshes have been built based on two dimensional axisymmetric geometries available in the literature[20]. Such 2D meshes were generated by considering 21 points along the symmetry line. Therefore, in order to increase the 3D mesh density, intermediate points were obtained by linear interpolation. Because simulation with sliding meshes is a complex task, immersed boundary conditions were used. For that purpose, a marker was used in a Cartesian mesh. Such a marker was set to zero in regions without fluid (solid) and it was set to one in zones where the fluid can flow. Regions with value of zero located near to nodes with value of one are known as phantom zones and they must be carefully handled in order they accomplish wall boundary conditions. A Cartesian mesh having a resolution of 150 x 109 x 109 nodes ($1.2 \cdot 10^6$ nodes) was built. The working fluid was Newtonian with a dynamic viscosity of 0.15 Pa·s and density of 1800 kg/m^3. The bolus volume flowing through the pharynx was fixed at 20 mL with a previous volume of 2.7 mL. In order to solve the Navier-Stokes equations, a high-order finite differences method (4 in space and 2 in time) was used. This method approaches the fluid incompressibility from the artificial compressibility method, with the advantage of avoiding the resolution of any Poisson equation, resulting in a faster calculation and allowing the flawlessly use of inner boundaries.

Following the transit time reported elsewhere[8], the total simulation time was fixed to 1.04 s, which was divided into the three following periods:

- 0 s to 0.34 s: GPJ open and UES closed (intake flow is calculated as a function of pharynx volume increase)
- 0.34 s to 0.54 s: GPJ and UES both open (both flows are obtained from a mass balance and pharynx volume change)
- 0.54 s to 1.04 s: GPJ closed and UES open (outtake flow is calculated as a function of pharynx volume decrease)

Two different cases were simulated by varying the maximum contact pressure of the peristaltic wave: 3600 Pa (≈27 mm Hg) y 1800 Pa (≈13.5 mm Hg).

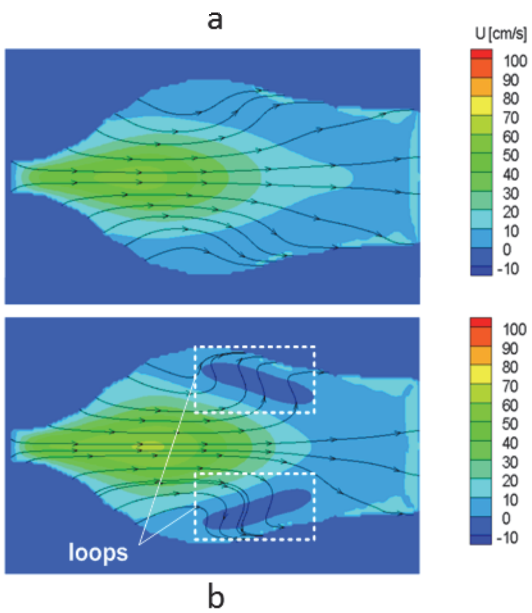

Figure 1. Axial velocity fields: (a) 1.8 kPa; (b) 3.6 kPa

Fig. 1 displays the axial velocity profiles, at 0.54s, as a function of the pressures investigated. As can be observed in Fig. 1a, a central stream, with a maximum speed of 0.5 m/s, is generated. However, as pressure increases (see Fig. 1b), which could be considered as an additional effort that a patient makes for swallowing, the central stream persists but two symmetrical loops are also formed. Looking at the streamlines, it is observed that the flow in such regions tends to go back, which could be an indication of a swallowing pathology.

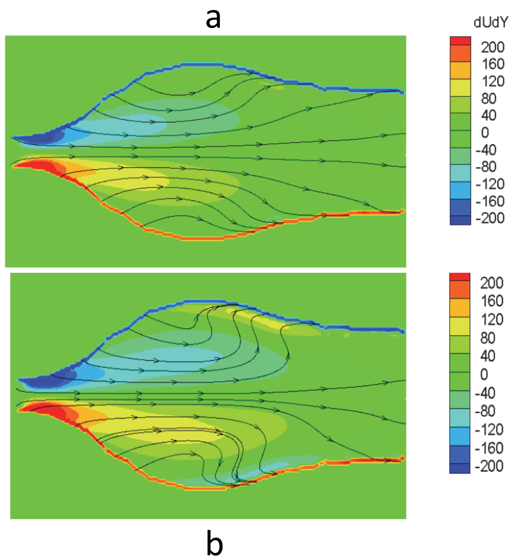

Figure 2. Shear rate distribution in the pharynx (1/s): (a) 1.8 kPa; (b) 3.6 kPa

Fig. 2 shows the shear rate fields with streamlines in the pharynx, at 0.6 s. It is observed a region of high shear rate (about 200 s^{-1}), which is formed along the walls. On the other hand, a region of almost zero-shear-rate is formed in the central stream. As Fig. 2b demonstrates, two symmetrical loops, denoted by streamlines, tend to form close to the walls as the maximum pressure increases, which could be an indication of a possible swallowing malfunction.

RHEOLOGY AND DYSPHAGIA

As previously mentioned, control of food (or bolus) viscous flow properties is part of several strategies to address patient's swallowing disorders. An important alternative is the use of ready-to-use oral nutritional supplements specially designed, from a rheological point of view, for the nutritional support at different stages of dysphagia.

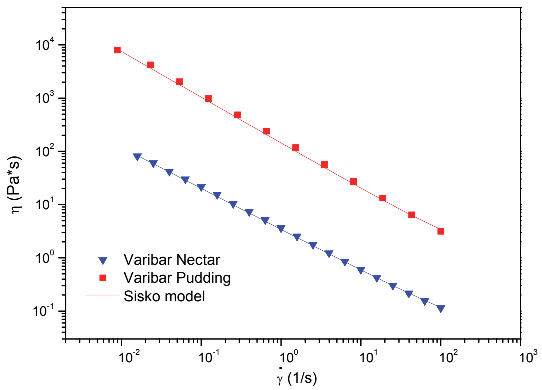

Figure 3. Steady-state viscous flow curves for Varibar® Nectar and Varibar® Pudding, at 25°C.

On the other hand, rheology and swallowing are connected at the diagnosis level. The most usual technique is videofluoroscopic swallowing study (VFSS). The swallowing process can be visualized using videoradiography, by using either ready-to-use commercial contrast medium or by mixing food with barium sulphate, making it radiopaque. Unfortunately, there is not standardisation to perform VFSS. For example, in USA, it is common to use commercial ready-to-use contrast media, but this is not the case in Europe. This lack of standardisation leads to variability in practice and results, and encourage individual speech pathologist, dieticians and dysphagic food manufacturers to determine their own dietary consistencies. Fig. 3 shows viscous flow curves corresponding to two different commercial contrast fluids (Varibar® Nectar and Varibar® Pudding), which correspond to two different levels of dysphagia. As can be observed, both of them show a shear-thinning behaviour in the whole range of shear rates studied (0.01-100 s^{-1}). The Sisko model fits the experimental results obtained fairly well (see Eq. 1):

$$\eta = K_s \dot{\gamma}^{n-1} + \eta_\infty \qquad (1)$$

where K_s is a consistency index, n is a flow index, and η_∞ is the high shear rate limiting viscosity.

However, it is important to mention that the rheological properties of the radiopaque bolus, usually resulting from previous mixing of standard food and barium sulphate, are quite different from the normal food used for dysphagic patients. Consequently, if VFSS results are extrapolated to dietary recommendations using the same food preparation, then there may be a severe problem.

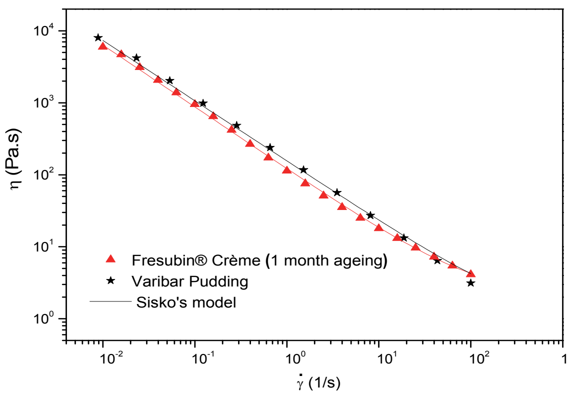

Figure 4. Steady-state viscous flow curves for Varibar® Pudding and Fresubin® Crème, at 25°C.

Aiming to save this issue, Brito-de la Fuente et al.[21] have proposed a rheological similarity approach by closing the gap with VFFS fluids rheological properties, for the design of oral nutritional supplements having complex formulations. In this sense, Fig. 4 displays the viscous flow curves for Varibar® Pudding and Fresubin® Crème (after 1 month ageing), at 25°C. The approximate composition of Fresubin® Crème is as follows: 59.0%wt. water; 10.0%wt. proteins; 7.2%wt. fats; 21.0wt% carbohydrates; 2.8%wt. flavours, minerals and vitamins. As can be observed, the viscous flow curves are quite similar in the whole shear rate range studied. On the other hand, Fig. 5 gathers the evolution of the linear viscoelasticity functions with frequency, for the above-mentioned samples. The behaviour is typical of a "weak-gel", with values of the storage modulus larger than the viscous modulus in the whole frequency range studied. As can be observed, the linear viscoelastic behaviour for both samples is also quite similar.

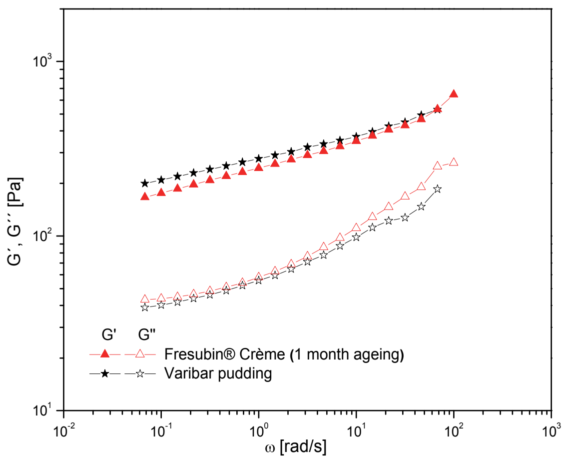

Figure 5. Evolution of the linear viscoelasticity functions with frequency for Varibar® Pudding and Fresubin® Crème, at 25°C.

CONCLUDING REMARKS

Dysphagia, or abnormal swallowing of foods and/or liquids, is a combination of symptoms affecting a person's ability to swallow. Management of dysphagia is commonly done by the prescription of texture-controlled diets, specially designed, from a rheological point of view, for the nutritional support at different stages of dysphagia. The rationale behind these products is to change the rate at which liquids and boluses are transported from the mouth into the stomach.

An overall kinematic/dynamic analysis of dysphagia, aiming to gain some insight into the mechanisms of bolus and liquid flow during swallowing, has been presented in this paper. In this sense, it is apparent that bolus transit velocity is significantly higher for the pharyngeal than for the esophageal phase of the swallowing process. In general, the shear rate range during this process varies from 1 to 1000 s^{-1}. Unfortunately, most of the literature is focused on shear flow, whilst little attention has been paid to the role of elongational flows in dysphagia.

In addition, early results on 3D simulation of the bolus flow along the pharynx, using a Newtonian fluid with similar viscosity to some thickened fluid used for some dysphagic patients (dysphagia stage 1, nectar-like) have been presented. Thus, axial velocity and shear rate profiles, as a function of pressure, have been calculated. The obtained profiles remark the influence of pressure on the development of swallowing disorders.

Rheology and swallowing are also connected at the diagnosis level. The most common technique is a videofluoroscopic swallowing study (VFSS). The swallowing process can be visualized using videoradiography by employing either ready-to-use commercial contrast medium or by mixing food with barium sulphate, making it radiopaque. Aiming to close the gap with VFFS fluids, a rheological similarity approach has been presented for the design of new pudding-like products for the nutritional management of dysphagic patients.

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