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Shear and extensional rheology of commercial thickeners used for dysphagia management

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Abstract

People who suffer from swallowing disorders, commonly referred to as dysphagia, are often restricted to a texture-modified diet. In such a diet, the texture of the fluid is modified mainly by the addition of gum or starch-based thickeners. For optimal modification of the texture, tunable rheological parameters are shear viscosity, yield stress, and elasticity. In this work, the flow properties of commercial thickeners obtained from major commercial suppliers were measured both in shear and extensional flow using a laboratory viscometer and a newly developed tube viscometry technique, termed Pulsed Ultrasound Velocimetry plus Pressure Drop (PUV+PD). The two methods gave similar results, demonstrating that the PUV+PD technique can be applied to study flow during the swallowing process in geometry similar to that of the swallowing tract. The thickeners were characterized in relation to extensional viscosity using the Hyperbolic Contraction Flow (HCF) method, with microscopy used as a complementary method for visualization of the fluid structure. The gum-based thickeners had significantly higher extensional viscosities than the starch-based thickeners. The rheological behavior was manifested in the microstructure as a hydrocolloid network with dimensions in the nanometer range for the gum-based thickeners. The starch-based thickeners displayed a granular structure in the micrometer range. In addition, the commercial thickeners were compared to model fluids (Boger, Newtonian and Shear-thinning) set to equal shear viscosity at 50s^{-1} and it was demonstrated that their rheological behavior could be tuned between highly elastic, extension-thickening to Newtonian.

Practical applications

Thickeners available for dysphagia management were characterized for extensional viscosity to improve the understanding of these thickeners in large scale deformation. Extensional deformation behavior was further explained by using microcopy as corresponding technique for better understanding of structure/rheology relationship. Moreover the major challenge in capturing human swallowing process is the short transit times of the bolus flow (<1 second). Therefore the ultrasound based rheometry method; PUV-PD which measures the real-time flow curve in ~50ms was used in addition to classical shear rheometry. The two methods complimented each other indicating that the PUV-PD method can be applied to study the transient swallowing process which is part of our future research, where we are studying the flow properties of fluids in an *in-vitro* swallowing tract.

1. Introduction

Dysphagia, which refers to swallowing disorders in general, has various causes, such as brain damage, post-stroke complications, Parkinson´s disease, and trauma (Clavé *et al.*, 2006). Approximately 8% of the global population suffers from dysphagia(Steele, 2015). Dysphagia is a growing concern in the developed world due to the aging population. Currently in Europe, about 17% of the population is ≥65 years of age. This segment of society has increased by 28% during the past 10 years, as compared to the remainder of the population, which has increased only 0.8%. It is estimated that in general, 30% of individuals who are ≥65 years of age and 40% of persons who are registered at care facilities suffer from dysphagia (Ekberg *et al.* (2002). Thus, there is an urgent need for research into new therapies for swallowing disorders.

During normal swallowing, rapid transfer of food or drink from the mouth to the stomach takes place without misdirection into the airways (Bülow, 2003). Dysphagics are challenged by the fast and turbulent flow of liquids through their oropharynx (Cichero, 2013), and they have been reported to aspirate when the velocity of water in the pharynx increases to 0.5 m/s (Tashiro *et al.*, 2010). This makes texture modification an important consideration for reducing the fast flow of fluid through the pharynx. A thickened diet is a common food-based strategy to manage dysphagia. The underlying idea is that a viscous food bolus travels with lower velocity, thereby providing more time for the oropharyngeal apparatus to close (Moret-Tatay *et al.*, 2015; Steele, 2015; Tashiro *et al.*, 2010). However, highly viscous liquids require the exertion of more force by the tongue to push the bolus through which may increase the chances of post-swallow residues (Clavé *et al.*, 2006; Steele, 2015). A recent White Paper published by the European Society for Swallowing Disorders suggests that more rheological parameters should be investigated as part of the bolus modification strategy, such as extensional viscosity and yield stress (Newman *et al.*, 2016). Thickener-based powders, which can be either gum or starch-based, are available in the market (Mackley *et al.*, 2013). These thickeners are added to liquids to thicken the texture and promote ease of swallowing (Tatay *et al.*, 2015). Gum-based and starch-based thickeners differ in the way that they absorb water. Starch-based thickener swells, while a gum-based thickener creates a network that entraps water upon hydration. Gum-based thickeners are less susceptible to viscosity modification during oral processing, whereas starch-based thickeners are modified by the amylase enzyme in the saliva resulting in reduced viscosity (Leonard *et al.*, 2014).

Thickeners need to be classified to provide guidelines to healthcare professionals for the preparation of foodstuffs with different consistencies. Different countries have developed their scales for the consistency ranges of thickened products for treating dysphagia. The protocol is set in the US by the National Dysphagia Diet (NDD), in Australia by the Dietitians and Speech Pathology Associations, and in the UK by the British Dietetic Association (Popa Nita *et al.*, 2013). The NDD guidelines, which are the most widely used, consider the shear rate of 50 s^{-1} (as being relevant for swallowing) and a temperature of 25°C as reference. Moreover, the NDD guidelines categorize the food products on the basis of apparent shear viscosity at 50 s^{-1} on the range from as thin as water (1-50 cP) to the consistency of pudding

(>1750 cP). Alternative scales rely on subjective terms, such as nectar-like and pudding-like and are not so popular (Quinchia *et al.*, 2011). The NDD scale has been criticized for not considering the shear rate-dependence and the extensional properties of the food (Zargaraan *et al.*, 2013), the latter referring to the ability of a material to resist extensional flow. Studies have shown that a food bolus is subject to both shear and extensional flow during swallowing, and also when the bolus is compressed between the tongue and the soft palate (Chen *et al.*, 2011; Hasegawa *et al.*, 2005; Salinas-Vázquez *et al.*, 2014). The swallowing literature refer to this as cohesiveness of the bolus, and there is some confusion whether the mechanism is fluid elasticity as expressed by the extensional viscosity or if there could also be an effect of the yield stress. A cohesive food fluid has been concluded to resist disintegration during swallowing reflux, thereby reducing the risk of post-swallowing residues (Chen *et al.*, 2011; Ishihara *et al.*, 2011). However, unlike the shear response , the extensional rheology of the food has been largely neglected (Chen, 2009). The main reason being the lack of appropriate experimental techniques (Chen, 2009). A general challenge in extensional flow is to achieve a steady state (Petrie, 2006), and the measured extensional viscosity is in reality always transient. A measurement system such as the Hyperbolic Contraction Flow (HCF) technique, has been developed which is suitable for medium-viscosity fluids (Stading *et al.*, 2001; Wikström *et al.*, 1999a). This technique has been applied to various food systems such as dough/dairy products (Andersson *et al.*, 2011), bread (Oom *et al.*, 2008) and ketchup (Berta *et al.*, 2016) as well as to polymer melts (Köpplmayr *et al.*, 2016).

The technique utilizes a flow through a hyperbolic nozzle designed to have constant extension rate. The calculation of the extensional viscosity from the measured force on the nozzle and the given extension rate assumes a Power-law fluid (Debbaut & Crochet, 1988). The contribution of shear is small for a shear-thinning fluid and is subtracted from the total measured stress (Wikström *et al.*, 1999a). The HCF method gives the transient extensional viscosity for a given extension rate at fixed Hencky strain. A precise determination of the extensional flow in the hyperbolic nozzle requires comparative simulations, but the simplified determination using the assumption of a Power-law fluid has proven to be good (Nyström *et al.*, 2012). The method has also recently been validated against other methods for polymer melt samples (Köpplmayr *et al.*, 2016).

The human pharynx has a complex geometry that ranges in shape from tubular to elliptical, with dimensions 5–6 cm and 2.8–3.0 cm (Walsh *et al.*, 2008). Since swallowing is a dynamic process, it is imperative to study it in real-time and in the context of a relevant geometry. In-line Pulsed Ultrasound Velocimetry (PUV) combined with Pressure Drop (PD) is an advanced version of tube viscometry. Originally developed to study human blood flow, this technique has subsequently been applied successfully in many food applications (Reinhardt Kotzé *et al.*, 2013; Wiklund *et al.*, 2008). Examples of applications include: chocolate tempering (Dufour *et al.*, 2007), dairy products/xanthan gum (Wiklund *et al.*, 2008); and improving the flow of tomato ketchup (Dogan, 2002). An advantage as compared to rotational viscometers is the real time determination of the flow curve which is measured approximately every 50 ms. In the present study, we apply the technique for the first time towards characterizing the thickeners used in dysphagia management, as well as the model fluids.

The main aim of this study was to characterize commercial thickeners for dysphagia management for clinically relevant rheological parameters, such as shear viscosity, extensional viscosity and yield stress. We further compared existing laboratory rheometry to advanced tube PUV+PD viscometry, which mimics the nearly tubular geometry present in the swallowing tract. The thickeners were also characterized for microstructural properties. The results from the rheological analyses of the commercial thickeners were compared with model fluids serving as a reference in the current study since they were standardized for elasticity and viscosity. The present study is the first in a series aimed at the construction of a laboratory-based human swallowing tract that could be used to study the flow properties of model fluids, dysphagia products, and general foodstuffs in a pharyngeal swallowing geometry using the PUV+PD method.

2. Materials and Methods

2.1 Materials

Five commercially available thickener products designed for patients with dysphagia were kindly provided by the suppliers: Nutilis powder from Nutricia Nordic AB, Stockholm, Sweden (denoted herein as Nutilis); Fresubin® Clear thickener from Fresenius Kabi GmbH, Bad Homburg, Germany (Fresubin Clear); Findus thickener from Findus Sweden AB (Findus); Nestlé Resource® Thicken-up™ (Nestlé Thicken-up); and Nestlé Resource® Thicken-up™ Clear (Nestlé Clear) from Nestlé Health Science Center, Stockholm, Sweden. The syrup used in the study was Lys Syrup (84% sugar) from Dan Sukker, Malmö, Sweden, the xanthan gum (Grinsted Xanthan CLEAR 80) was supplied by Danisco France SAS (Melle, France), and the poly(acrylamide) (PAA) was supplied by ACROS Organics.

2.2 Sample preparation

A large volume of the thickener solution (~2 liter) was prepared by mixing the sample with tap water following the manufacturer's guidelines to achieve a honey-like consistency (according to the NDD scale) using a magnetic stirrer until complete homogenization was achieved (about 1 hour). The thickeners are used in elderly care centers to thicken fluid food and therefore are expected to be highly soluble. Shear viscosity was adjusted within the honey consistency range (0.35-1.75 Pa.s) specifically to 0.55±0.03 Pa.s (Table 1) at a shear rate of 50 s^{-1}. The amounts of powder that were used to achieve the desired shear viscosities (Pa.s) are listed in Table 1. The model Newtonian, Boger, and shear-thinning fluids were made by diluting the syrup with water to achieve the targeted viscosity of 0.55 Pa.s at a shear rate of 50 s^{-1}, with subsequent mixing (in the case of the Boger and shear-thinning fluid) with a concentrated solution of either the xanthan gum or PAA polymer (Table 1). Finally all the samples mixed were degassed before mixing using a vacuum pump, D-82178 from ASF-THOMAS: Munich, Germany.

[Table 1 here]

Separate sample preparation was performed for microscopy. The given thickeners were dispersed in deionized water on % w/w basis in different concentrations depending upon the thickener structure visualization (table 1) and stirred constantly for 4 to 8 hours until they were dissolved completely. All the samples were mixed at room temperature (~25°C) except for Findus where higher temperature (~65°C) was used since it was not easily soluble at room temperature.

3. Rheological measurements

3.1 *Shear rheology measurement (Flow curves and yield stress)*

The shear rheology of the samples was measured for shear rates ranging between 1 to 1000s^{-1} to cover the entire shear rate range mentioned in the literature, using an ARES-G2 (TA Instruments, New Castle, DE, USA) equipped with a cone and plate geometry with a diameter of 40 mm and cone angle of 0.04 rad. The yield stress was measured using the Reologica Stresstech HR (Reologica AB, Lund, Sweden) stress-controlled rheometer. Flow measurements were performed by the continuous increase of the shear stress. The stress value at which the two tangents crossed was considered as the yield stress value (Moller *et al.*, 2006). The yield stress was also determined from the flow curve by curve fitting of the Hershel-Bulkley model

$$\tau = \tau_0 + K(\dot{\gamma})^n \qquad (1)$$

where τ denotes the shear stress, τ_0 the yield stress, $\dot{\gamma}$ the shear stress while 'K' and 'n' are constants. Stresstech instrument was equipped with concentric cylinders (bob and cup geometry) with the cup radius,R_c=13.5 mm and bob radius, $R_{b=}$12.5 mm. All the rheological measurements were performed at 25°C as recommended by the NDD standards.

3.2 *Advanced tube viscometry, PUV+PD (Flow curves and yield stress)*

The real-time velocity profile was monitored with advanced tube viscometry using PUV+PD measurement to acquire the flow curve (Flow-Viz, Gothenburg, Sweden). The method and the system are described in detail elsewhere (R Kotzé *et al.*, 2015; Wiklund *et al.*, 2007; Wiklund *et al.*, 2008). In the present study, the sample was mixed in the product tank with an agitator (Fig. 1).

[figure 1 here]

Flowing of the sample was initiated by the positive displacement pump through a stainless steel pipe. The shear stress (τ) at the wall and the radial shear distribution inside the tube are determined from the pressure drop (Δp) across a fixed length (*l* =0.6m) and radius (r=0.011 m) of the tube (Fig. 1) using the relationship:

$$\tau = \frac{r\Delta p}{2l} \qquad (2)$$

Two ultrasound sensors were used to capture the velocity profile. The shear rate was calculated from the gradient of the measured velocity profile. The PUV+PD software measures the complete inline viscosity profile. Moreover, the software can post-process the data and measure the yield stress from the pressure drop and plug radius data as

$$R = 2I\tau_0/\Delta P \qquad (3)$$

where *R* is the radius of the plug, and *l* is length of the pipe in which the fluid is flowing. Thus, real time estimation of the yield stress can be performed with PUV+PD.

3.3 *Extensional rheology measurement using Hyperbolic Contraction Flow*

The transient extensional viscosity of the thickened solutions was determined by the HCF method using an Instron 5542 (Instron Corp., Canton, USA). The method used is thoroughly described elsewhere (Nyström *et al.*, 2012; Stading *et al.*, 2001; Wikström *et al.*, 1999a). The hyperbolic nozzle used for the measurement had an inlet radius of 10 mm and outlet radius of 0.78 mm. The maximum Hencky strain was in the range of 3.6–8.7 depending on the fluid tested. The power law parameters (K and n) from equation 4

$$\sigma = K\dot{\gamma}^n \qquad (4)$$

Required to subtract the contribution of shear stress σ to the total measured stress were determined from the flow curves measured in the ARES-G2 by fitting the data to the Power law model. Each measurement was performed in triplicate and the relative standard deviation was <3.7% between measurements for all samples tested.

3.4 Microstructural characterization

3.4.1 *Mica sandwich technique and transmission electron microscopy (TEM)*

The microstructure of a diluted thickener (Table 1) was determined using the Mica Sandwich Technique described in detail by Barreto et al. 2013 (Barreto *et al.*, 2013). TEM was used to analyze the replicas under the LEO 706E microscope (LEO Electron Microscopy Ltd., Cambridge, England).

3.4.2 *Light microscopy (LM)*

The starch-based thickeners, Nestlé Thicken-up and Findus, were analyzed using light microscopy, revealing that they had structure at micro-meter scale compared to nano-meter scale for the xanthan-based thickeners. Two staining methods were used: Lugol’s iodine solution for starch; and a mixture of Lugol’s iodine and Light Green solution (1:1) for both starch and protein. Lugol’s iodine stains amylopectin a pink-to-brownish color and amylose purple, whereas Light Green stains proteins green. The light microscope used was a Nikon Microphot-FXA (Nikon, Tokyo, Japan), together with an Olympus Altra 20 color camera connected to a computer and operated using the Olympus cellSens Dimension software (Olympus Soft Imaging Solutions GmbH, Münster, Germany).

4. Results and Discussion

4.1 Microstructure

TEM and LM were used to visualize the fine structures of the xanthan gum and starch in the commercial thickeners (Fig. 2). The xanthan gum-based thickeners, Fresubin (Fig. 2A and D), Nestlé Clear (Fig. 2B and E) and Nutilis (Fig. 2C and F), formed transparent solutions which meant that no microstructure could by observed by LM due to the limiting resolution of about 1 µm. With TEM at high magnification, a main mesh-like network structure was observed (Fig. 2A, B and C). At even higher magnification thin filaments were observed as shown in the micrographs (Fig. 2D, E and F). The main component of the gum based thickeners is xanthan gum, while the manufacturers do not specify other biopolymers present. The thin filaments correspond well with the structure of xanthan helices previously visualized with the same microscopy technique (Lundin *et al.*, 1995). The starch-based thickeners were analyzed at a lower magnification using LM to accommodate the starch-based microstructure. They were not visualized by TEM because the microstructure is too heterogeneous. In Nestlé Thicken-Up (Fig. 2G), only slightly swollen starch granules were noticed. Most of the granules stained light-brown, indicating that they contain amylopectin, and a few starch granules stained purple, which indicates that amylose had leached out. The granule structure was at largely retained indicating a low degree of gelatinization. The Findus sample showed some starch granules that stained purple and a protein network that stained green (Fig. 2H). Moreover, unstained fat droplets were observed in the sample. The Findus thickener is not a single thickener-based product, in addition to the starch, protein and fats contribute to the microstructure and fluid consistency.

[Figure 2 here]

4.2 Shear rheology by viscometry and PUV+PD

The thickeners and the model fluids were characterized using laboratory-based viscometry as well as advanced tube viscometry (PUV+PD) with tube dimensions that resemble those of the pharynx. The latter was mainly included in the study to demonstrate to the clinical dysphagia community that a flow in a tube, such as the pharynx can be evaluated with both methods, as well as a basis for our future studies of flow in the pharynx using the ultrasonic techniques where we want to utilize the real time ability to determine flow curves in transient flows.

4.2.1 Flow curves in shear rheology (Lab-based and PUV+PD)

Thickeners used for dysphagia management and model fluids were characterized using laboratory-based viscometry as well as advanced tube viscometry (PUV+PD) with tube dimensions that resemble those of the pharynx. Figure 3(A–C) and Table 2 show that the flow curves derived from the two methods overlapped well with similar power-law K and n values for all the thickener-based and model fluids. The gum-based thickeners were the most shear-thinning (Fig. 3A), with the lowest shear thinning indices noted for Nestlé Clear (n=0.19) and Fresubin Clear (n=0.19), followed by Nutilis (n=0.33). The starch-based thickeners (Fig. 3C), Nestlé Thicken-up and Findus, were the least shear-thinning, showing higher n values of 0.39 and 0.61, respectively. The shear thinning index for the Newtonian and Boger fluids was as expected 1 for both the methods. The model fluids (shear thinning with either PAA or xanthan gum) were not measured using the PUV+PD method due to the limited capacity of the pump used in the current study to propel such highly viscoelastic fluids.

[Figure 3 here]

[Table 2 here]

The results show that the PUV+PD method in a clinically relevant geometry gives the same results as classical viscometry. Furthermore, the PUV+PD method gives a complete flow curve in 0.19-1.35 ms and can thus be used in fast transient flows such as for a bolus passing the pharynx in about a second. The main limitation of the method is that air may be introduced during pumping thus transforming a surface active fluid to foam.

The flow behavior index for the model shear-thinning xanthan gum polymer was n=0.22 and for the shear-thinning PAA was n=0.79, as assessed by the laboratory viscometry. The model fluids used in the study serve as a reference, since they are based on a single elastic polymer (PAA or xanthan gum) and a Newtonian fluid (either syrup or water) system, thereby eliminating the interference effects of other polymers used in the commercial powders. In addition to the food-grade elastic polymer xanthan gum, PAA was also used in the model fluids (PAA). The PAA is not a food grade polymer but is much more elastic than xanthan gum (Jones *et al.*, 1989). The use of PAA allows the study of high-level elastic effects. These model fluids are also planned to be used in the future to study the influence of high extensional viscosity in relation to swallowing.

All the fluids used in the present study were thickened to syrup consistency (range, 0.35–1.75 Pa.s), as recommended by the NDD, and more precisely to a viscosity of 0.55±0.03 Pa.s at a shear rate of 50 s^{-1} for the reason mentioned earlier. Gum-based xanthan solutions are strongly shear-thinning owing to their rigid-rod polymer conformation in solution. This means that a xanthan-based thickener is perceived as being less thick as the shear rate increases during oral processing. It should also be noted that starch-thickened foods are susceptible to reductions in thickness during oral processing through the action of the amylase in saliva, thus reducing the effective viscosity during swallowing. Moreover, less xanthan gum than starch was needed to acquire the set viscosity of 0.55 Pa.s in the current study.

It should be noted that shear-thinning is less pronounced in PAA-based model fluids. This is because PAA is a highly compact molecule with very strong intramolecular bonding, and the shear flow, which is considered to be a “weak flow”, is not sufficient to stretch the polymer. Hence large extensional deformation, as applied in the present study, is needed to study the flow properties of PAA in detail.

4.2.2 Yield stress in shear rheology (Viscometry and PUV+PD)

Yield stress for the thickeners and model fluids was considered during measurements since previous publications (Marcotte, 2001; Steele, 2014) have proposed yield stress as a contributing factor to bolus cohesiveness and therefore yield stress has to be considered in addition to other parameters to alleviate aspiration. The yield stress values were determined by viscometry and the PUV+PD method and are presented in Table 2. Figure 4 presents an example of determination of yield stress with laboratory rheometer for the sample having the highest yield stress value; Fresubin Clear. The value is taken at the stress value when two tangent lines intersect each other at the point of sudden drop in shear viscosity and the consequential increase in shear rate. The two methods gave similar values and the small differences were not statistically significant ($P>0.05$).

[Figure 4 here]

Generally the samples composed of xanthan gum had higher values for the yield stresses in the order Fresubin Clear>Nestlé Clear>Nutilis and no or negligible yield stress was detected in the starch-based thickeners (Nestlé Thicken-up and Findus). The yield stress depends on the structure of the thickener fluid and the exact composition of the commercial fluids is not known. However, from the microscopy images in Fig. 2 it is clear that the gum-based thickeners have a well-developed network structure at rest.

The model xanthan gum fluid had a yield stress of 13 Pa which is similar to the reported value of 10 Pa by Marcotte and coworkers (Marcotte, 2001). Furthermore the yield stress noticed in model xanthan-gum system confirms observed yield stresses noticed in the gum-based thickeners. The yield stresses of the PAA based model fluids (Boger and shear thinning) were negligible and similar results were reported by Yang (Yang, 2001). Yield stress has been proposed to be responsible for the "binding properties" of xanthan gum in dysphagia management (Marcotte, 2001). In the swallowing context, this binding property is expected to promote a cohesive bolus structure, thereby reducing the risk of premature disintegration of the bolus during swallowing. The pressure gradient created as the bolus is squeezed between the tongue and palate is essential for causing the bolus to flow across the oropharynx (Steele, 2014). Therefore, the higher the yield stress, the greater the force needed to initiate the flow. This means individuals with weak swallowing reflux may suffer from post-swallow residues in case they swallow food of very high yield stress or they have reduced capacity to generate appropriate tongue pressure as mentioned by the group of Becker (Becker *et al.,* 2015). However, during oral processing and swallowing, the bolus is never static and therefore the overall stress required exceeds the yield stress at the levels measured by Steele and coworkers (Steele, 2014). While it has been shown by Alsanei and Chen (Alsanei *et al.*, 2014) that the average maximum tongue pressure generation capacity decreases with growing age, the study conducted by Steele (Steele, 2014) noted that the senior citizens (aged 70 years) still can generate enough tongue pressure to handle a honey-thick consistency bolus at the shear rate of 50 s^{-1} studied herein. Therefore we believe the yield stresses noticed in the present work is less likely to influence the swallowing process overall. While the yield stresses measured with two different methods gives relatively identical values, the PUV-PD method has the advantage of being independent of any possible wall slip, since the yield stress is determined from the radius of the plug not in direct contact with the wall. Moreover PUV-PD mimics the flow geometry of the pharynx.

Yield stress is an important characteristic in many food systems such as in ketchup and mayonnaise, (Berta *et al.*, 2016) however the measurement of yield stress is not straight forward. Many difficulties such as wall slippage arise during measurement and a detailed discussion on these difficulties has been discussed elsewhere. (Barnes, 1995; Walls *et al.*, 2003). In the current work, bob and cup geometry was used since the results matches better with the ones from PUV-PD method and we believe the PUV-PD method addresses the wall slip condition in a better way.

4.3 Extensional flow

The HCF method was applied to measure the extensional viscosity of the given products. Extension rates were varied from 1–100 s^{-1} (Fig. 5) for all the fluids. The extensional viscosity of the thickeners (Fig. 5A) was measurable even at an extension rate <10 s^{-1}, which was not the case for the model fluids. The thickener-based and model fluids behaved differently in extensional flow. The xanthan-based thickeners were more elastic than the starch-based thickeners, while the model fluids (Fig. 5 b) made with PAA (Boger and shear-thinning) showed extension-thickening, whereas 2% xanthan gum exhibited extension-thinning behavior. The extensional viscosity corresponds well with the presence of the xanthan dominated network structure shown in Figure 2A-F.

[Figure 5 here]

We have previously shown that the extensional viscosity of xanthan gum fluids promotes safe swallowing, which means that extensional viscosity is an important parameter to consider while designing fluid foods for persons with dysphagia (Nyström *et al.*, 2015). In the labeling information for the thickeners, the precise amount of xanthan gum is not given, although it is reasonable to assume that with a higher level of xanthan gum, greater elasticity is achieved, as previously observed (Choi *et al.*, 2014). The extension-thinning behavior noticed for the xanthan-based model fluids is consistent with a xanthan gum based commercial fluid. This is likely due to the semi-rigid rod-like conformation of the xanthan gum. The extension-thickening behavior of PAA is due to its coiled structure and the polymer uncoils and aligns in the stretching direction (Ferguson *et al.*, 1990).

The fact that xanthan gum solutions both in the commercial thickeners and in water behaves extension-thinning at higher extension rates possibly suggests that they are perceived less slimy in the context of swallowing than PAA. While assigning a fixed shear rate during swallowing of 50 s^{-1} is an over-simplification, extension rates during swallowing have not been described to date in the literature to the best of our knowledge. This makes predictions about extensional viscosity with respect to swallowing even more complicated, and therefore prompts further research. As noticed in TEM, the structure of network is more pronounced in Fresubin and Nutilis than in Nestlé clear. It is however not possible to relate the nature of the network to the individual components since the exact thickener composition is not known.

In the current study, we have characterized commercial thickeners and model fluids to understand flow properties. However, further studies are required to determine the appropriate level of elasticity and type of polymer to promote safe and easy swallowing, as well as to define the most dominant shear and extension rates. Trouton ratio $Tr = \frac{\eta_{\dot{\varepsilon}}}{\eta_{\dot{\gamma}}}$ estimates the departure of ratio of extensional to shear viscosity from its Newtonian counterpart, which is estimated around 3 (Sochi, 2010) for the Newtonian equivalent. Trouton ratios for the gum-based thickeners were: Fresubin =~40, Nestlé Clear=~45 and Nutilis =~68 and for starch-based thickeners: Nestle thicken-up=41.9 and Findus=~152. The ratio is higher than three for all the fluids which confirms the elastic nature of the samples.

5. Conclusions

This study shows that the xanthan-based commercial thickeners used for dysphagia management are slightly more shear-thinning and have considerably higher extensional viscosities than starch-based thickeners. Moreover, with microstructural characterization using light and electron microscopy, we further elucidated how the network structure of xanthan gum influences the rheology in a different way than starch does. Model fluids can be designed to mimic commercial thickeners as well as to set the upper limit for maximum elasticity that will be tested in clinical studies in the future. The shear viscosity measured using laboratory viscometry and the newly developed PUV+PD method gave similar results, which means by using the PUV+PD method the flow curve and yield stress can be acquired in less than 1.4 ms which is important for the short time scales involved in human swallowing. Only low yield stresses were detected, considerably lower than expected to occur during swallowing.

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Ethical statements

The author declares no conflict of interest for this study, while this study does not involve any animal or human testing.

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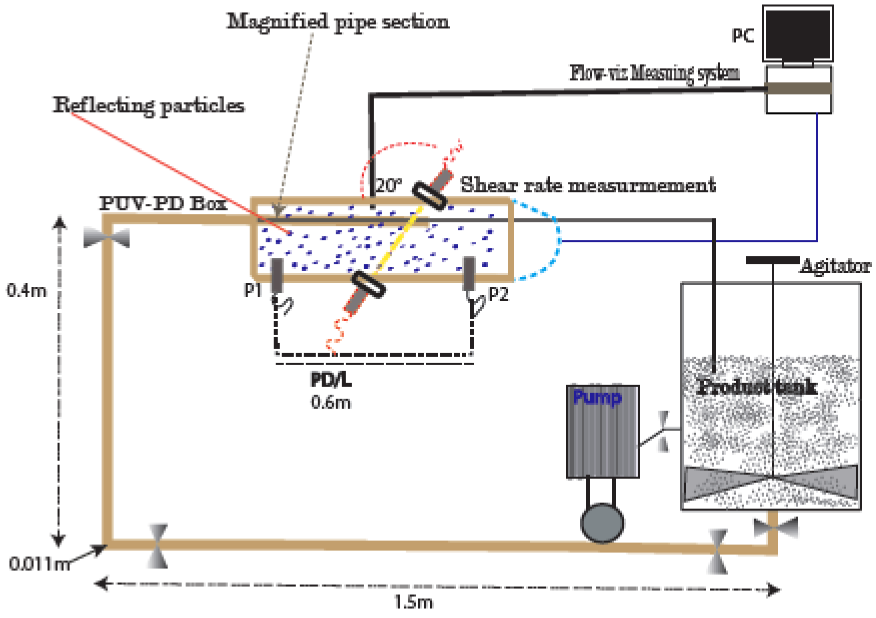
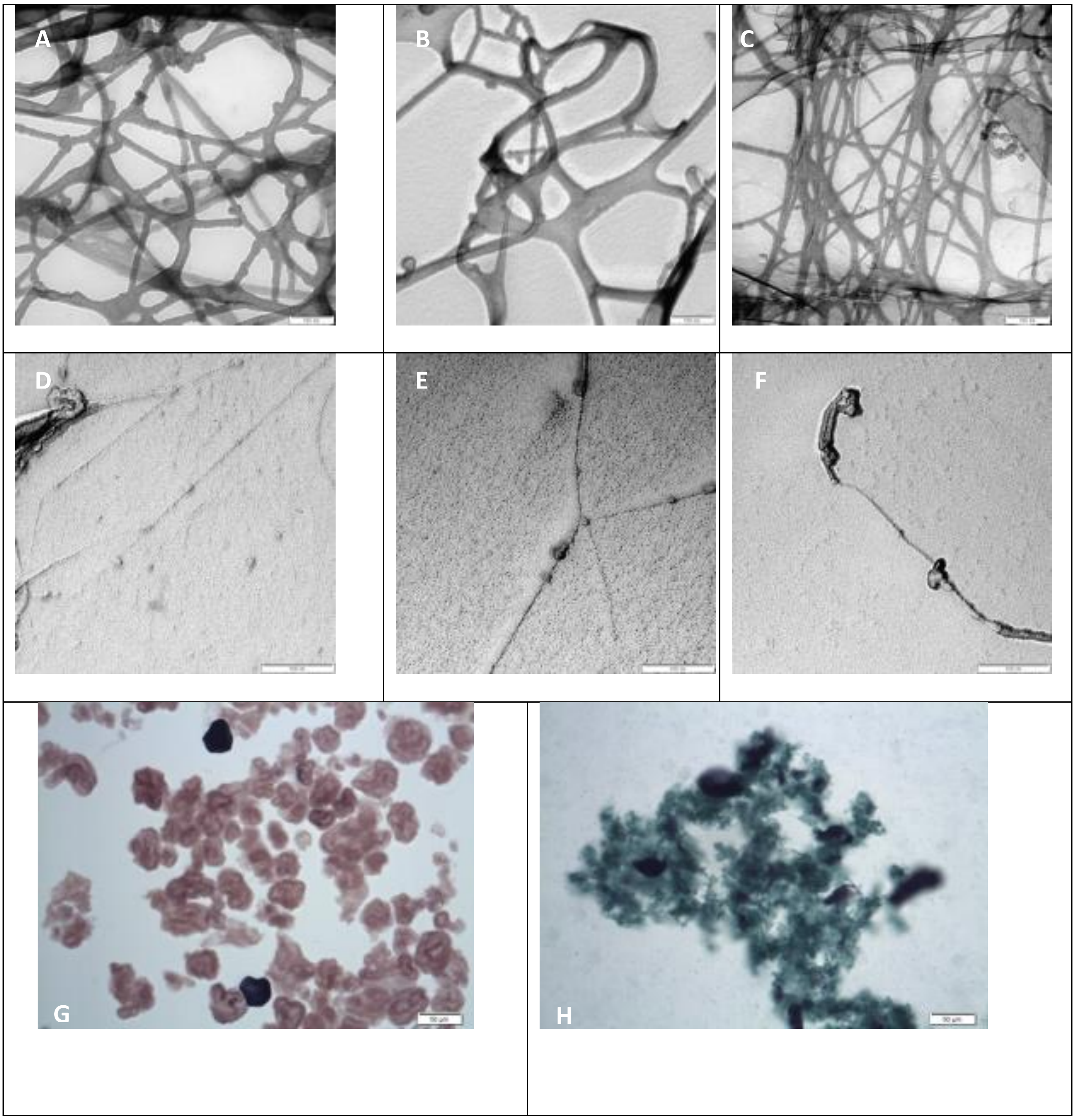


Figure 1: Schematic illustration of how the inline shear viscosity was measured using PUV+PD method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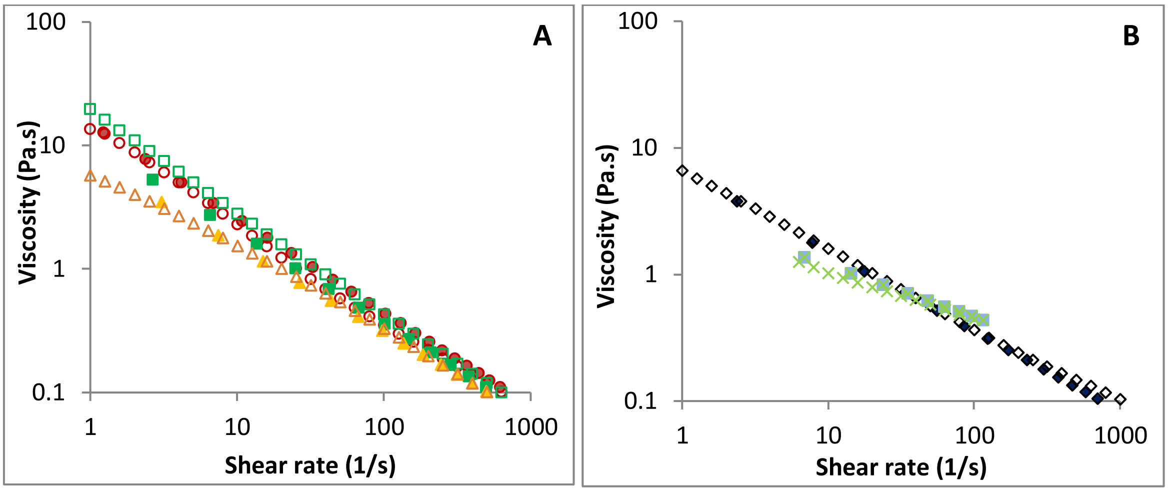

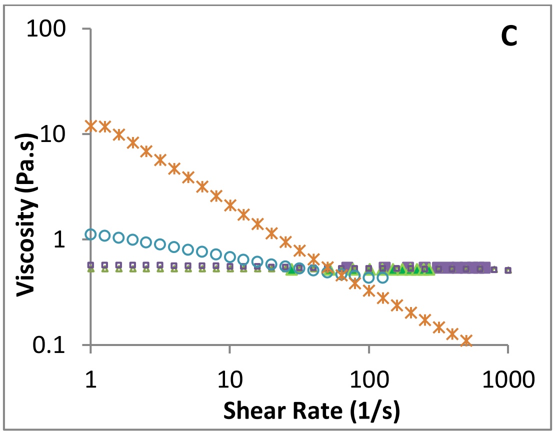

Figure 3. **A**: Shear viscosities (Pa.s) of xanthan gum-based thickeners in water: Fresubin Clear□; Nestlé Clear ○; Nutilis Δ; open symbols: laboratory-based rheometry; filled symbols: tube viscometry PUV+PD method. **B**: Shear viscosity (Pa.s) of starch-based thickener in water: Findus × Nestlé Thicken-up ◇. Open symbols: laboratory-based rheometry; filled symbols: tube viscometry PUV+PD method. **C**: Shear viscosity of model fluids: shear-thinning (PAA) ○; shear-thinning (xanthan gum); ✳ Boger □; Newtonian Δ; open symbols: laboratory-based rheometry; filled symbols: tube viscometry PUV+PD method. The laboratory-based viscosities for all samples were adjusted to 0.55±0.03 Pa.s at a shear rate of 50 s^{-1} with maximum standard deviation of 0 to 0.1 at 50 s^{-1} for all the samples at 25°C.

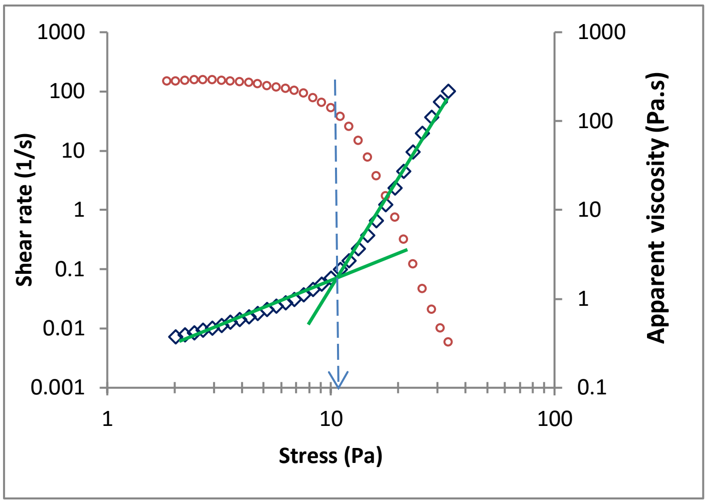

Figure 4: Flow curve showing the apparent viscosity O and shear rate ◇ a function of increasing stress. The decrease in apparent viscosity causes a sudden jump of the shear rate curve. The stress at which this change occurs is the yield stress and it was calculated by the intersection of two linear fitting curves.

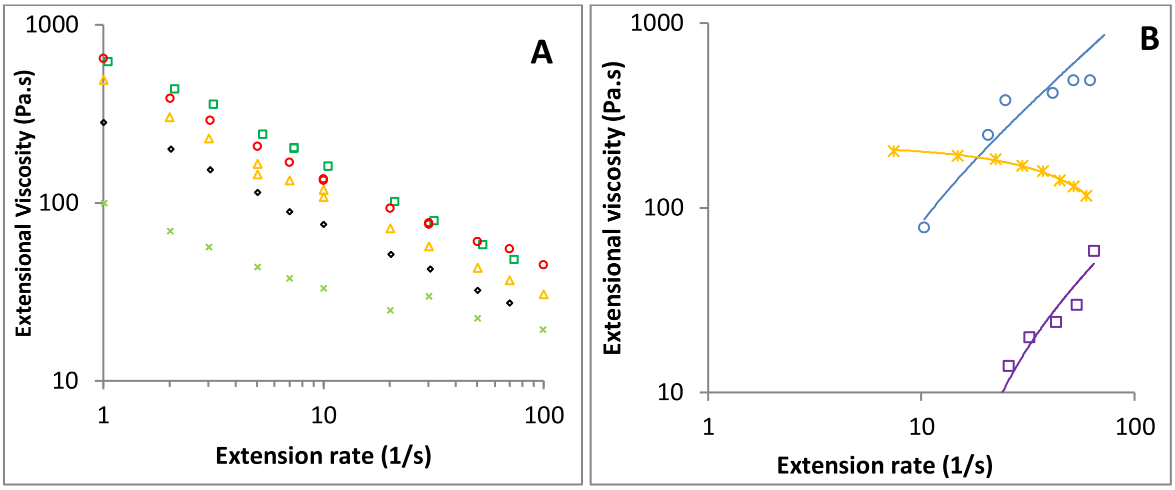

Figure 5. **A**: Extensional viscosities (Pa.s) of thickener-based dysphagia fluids in water: Fresubin Clear□; Nestlé Clear○; Nutilis △; Nestlé Thicken-up ◇; Findus ×; and the model fluids, **B**: Boger □ (0.015% PAA in syrup), 2% xanthan gum in water (shear thinning) ✳; and 0.2% PAA in syrup (shear thinning) ○.