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The rheology and processing behavior of starch and gum-based dysphagia thickeners

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Synopsis

The addition of a starch or gum-based thickener to patient fluids with dysphagia is commonly carried out, but the mechanism behind the efficacy of this treatment is not fully understood. This paper describes the rheological behavior of two commercially available thickening powders and an additional xanthan gum solution with a view to explaining the efficacy of thickened fluids in terms of their rheology. Both linear viscoelastic and steady shear data were obtained for the fluids together with filament extensional stretch, decay, and breakup data. In order to follow the behavior of the fluids in a processing situation, a mechanical “Cambridge Throat” was designed and tested. The action of the tongue was modeled using a constant torque cam that forced fluid contained within a flexible membrane through a model throat. Movie photography captured images of the fluid behavior and showed that for a constant tongue torque, the transit time within the model throat increased with increasing fluid viscosity, with implications for the time available for the successful function of the larynx, throat muscles, and epiglottis. © 2013 The Society of Rheology.

I. INTRODUCTION

Dysphagia is a general term used for drinking and eating disorders that can be present in a range of diseases and in particular elderly people [see, for example, Seo et al. (2007); Germain et al. (2006)]. The complexity of how different fluid properties influence swallowing is difficult to quantify; however, it is widely accepted that aspiration resulting from some swallowing difficulties can be alleviated by using thickened fluid additives [see, for example, Bisch et al. (1994); Sopade et al. (2007, 2008)], although the exact mechanism by which this occurs still remains elusive. Amongst other factors, it is believed that improvement can result from a longer residence time within the throat, thereby giving a longer reflex response time when the fluid enters the pharynx [Logemann (1983); Reimers-Neils et al. (1994)]. Figure 1 of this current paper illustrates the main features of the throat that are involved with swallowing. Fluid, or a bolus of fluid and food, is initially held in the mouth and the tongue then forces the fluid into the back of the throat toward the pharynx. The epiglottis is a flexible diaphragm that either

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directs air into the trachea, or fluid and food into the esophagus. The time scales for the whole process can be between milliseconds to several seconds. A recent paper by Smith et al. (2006) gives a useful summary of factors that influence the swallowing of fluids including the human perception of viscosity changes.

The process of liquid swallowing in humans can be strongly influenced by the action of the tongue. The tongue provides a complex moving surface that in turn provides a driving force to the fluid which is then passed to the back of the throat. In rheological terms, the first order action of the tongue in the throat acts like a constant stress device. The muscles in the tongue can generate a certain level of force that causes the tongue to move. The tongue driving force amongst other processes can provide the peristaltic process of moving fluid or a bolus down the esophagus; the whole swallowing process can take up to 20 s. Yoshioka et al. (2004) reports that the normal tongue pressure required to swallow liquids is around 150 mmHg, or 0.2 bar, and the maximum tongue pressure that can be applied is around 600 mmHg, or 0.8 bar, for young adults and 450 mmHg, or 0.6 bar, in elderly. The tongue driving pressure decreases with age and can be a contributor to swallowing difficulties.

This paper is concerned with characterizing the rheology of certain commercial dysphagia thickening fluids and establishing how in particular viscosity affects the way in which thickened fluids influence the swallowing process in a model throat. In order to do this, a simple model “Cambridge Throat” has been designed and constructed in order to mimic some of the processing behavior of a human throat. The geometry is highly idealized; however, the main elements of the action of a “tongue” forcing fluid through a flow constriction are captured, together with an approximation of the flow in the region of the epiglottis.

The rheology of thickened liquids and in particular dysphagia drink thickeners can be complex, and this paper examines in some detail the linear viscoelastic behavior of the test fluids together with both their steady shear and extensional behavior. The exact percentage of each component of the test commercial thickeners was not known, although corn starch is used in both and is an extensively used viscosity enhancing component. In order to have an additional quantifiable reference, xanthan gum solutions were also tested and also a “Smoothie” drink, which is sometimes used as an alternative to a powder prepared dysphagia thickener (see, for example, http://www.lyonsreadycare.com/smoothie-plus.html). Xanthan gum has received extensive rheological research in the past [see, for
example, Whitcomb and Macosko (1978); Sopade et al. (2007); Song et al. (2006)], and aqueous xanthan gum solutions are characterized by significant viscosity enhancement with increasing concentration and a high level of shear thinning at high concentrations.

II. THICKENER FORMULATIONS

Three different thickeners were used: Nutilis, “Resource ThickenUp” (abbreviated to ThickenUp in this paper), and xanthan gum. In each case, the powdered thickeners were added to reverse osmosis filtered water to make a thickened solution. Comparison experiments were also performed with just reverse osmosis filtered water and also with an Innocent “Pineapple, Blueberry and Ginger Smoothie.”

In order to make up the thickened solutions, 50 ml of reverse osmosis filtered water was used for each sample and the powder was added to the water at a consistent rate over a short period of time. The solution was stirred with an Aerolatte™ milk frother for 45 s from the point of starting to add the powder or until the frother could no longer move in the solution. The solution was then left to stand for 6 min in accordance with the manufacturer’s instructions to leave the solution to thicken for a few minutes before use and also to allow air entrainment within the fluid to disperse. Dewar and Joyce (2006) have shown that rheology of Dysphagia thickeners can vary over periods of several hours; however, all experiments carried out in this paper followed the set time of a 6-min time lapse between preparation and being used.

Nutilis, http://www.nutilis.com is produced by Nutricia and contains modified cornstarch, malto dextrin, corn flour, xanthan gum, and guar gum. The recommended range of concentrations for use was equivalent to 2.9–6.5 wt. %. ThickenUp is produced by Nestlé, http://www.nestlehealthscience.us, and contains modified cornstarch. The ThickenUp manufacturer recommends an operational range of between 4.8 and 8.3 wt. %. Figure 2 shows optical micrographs for Nutilis [2(a)] and ThickenUp [2(b)], and both micrographs indicate that the solutions are highly heterogeneous with swollen corn floor granules visible within the solutions. This heterogeneity is to be anticipated and is often unavoidable when starch-based solutions are prepared, particularly under the conditions described in this paper.

Xanthan gum supplied by Sigma Aldrich was used as a comparison. The quantities tested were 0.6, 1.0, and 1.4 wt. %. Concentrations higher than this proved extremely difficult to mix to create a homogeneous solution and therefore were not used. In contrast to

![Optical microscope images](a) Nutilis 4.8 wt. % (b) ThickenUp 4.8 wt. %

FIG. 2. Optical microscope images of (a) 4.8 wt. % Nutilis and (b) 4.8 wt. %ThickenUp.
Nutilis and ThickenUp, the xanthan gum solutions were optically transparent and without any optically observable microstructure. In terms of sample preparation, it should be noted that the cation composition of the water, the exact form of mixer used, and the duration of mixing will all affect the final rheology of the test fluids.

III. LINEAR VISCOELASTIC AND STEADY SHEAR RHEOLOGY

A TA ARES rheometer, http://www.tainstruments, was used to obtain simple shear oscillatory viscoelastic and steady shear apparent viscosity data. Measurements were carried out at 25°C using parallel plate geometry (diameter = 50 mm, gap = 1 mm) for all experiments apart from very low concentrations which necessitated a Couette cell. For each sample, the tests run were (in order) oscillatory dynamic strain sweep, oscillatory dynamic frequency sweep (strain control), and then steady shear rate sweep. The strain sweep was carried out at $\omega = 10$ rad/s and covered the strains from 0.001 to 1. After the strain sweep, the frequency sweep was carried out from 0.1 to 100 rad/s at a suitable strain so that $G'$, $G''$, and $\eta^*$ were still within the linear region. $G'$ the storage modulus, $G''$ the loss modulus, and $\eta^*$ the complex viscosity are standard viscoelastic properties. The $G'$, $G''$ data were expressed in terms of a series of Maxwell elements described by Eqs. (3.1)–(3.3) [see, for example, Mackley et al. (1994)] and computed for 12 modes using TA Ares “orchestra” software

\[
G'(\omega) = \sum_i \frac{g_i(\omega^2 \lambda_i^2)}{1 + \omega^2 \lambda_i^2},
\]

\[
G''(\omega) = \sum_i \frac{g_i(\omega \lambda_i)}{1 + \omega^2 \lambda_i^2},
\]

\[
\eta^* = \sum_i \frac{g_i \lambda_i}{(1 + \omega^2 \lambda_i^2)^{1/2}}.
\]

The rate sweep was performed at shear rates of 0.1–100/s. Data were obtained at a rate of 10 points per decade. We have found experimentally that in general parallel plate rheometry gives more reliable data than using a cone and plate, particularly when highly viscoelastic fluids are used. There are a number of correction procedures for steady shear parallel plate data analysis which give different results; however, we have chosen to use uncorrected data.

The complex viscosity results of the strain sweeps are shown in Fig. 3 for different solutions prepared at different concentrations. The results show a consistent trend with the low shear rate viscosity increasing with increasing concentration within a viscosity range of between 0.5 and 100 Pas. The Nutilis solutions [Fig. 3(a)] show a typical characteristic of a Newtonian plateau at low strains followed by a nonlinear decay in viscosity from about 0.01 strain. The ThickenUp [Fig. 3(b)] showed an unexplained shear thickening before also shear thinning. The xanthan gum [Fig. 3(c)] exhibited nonlinear strain thinning and the Smoothie fruit drink [Fig. 3(c)] exhibited the greatest degree of nonlinearity of all solutions.

Three representative oscillatory frequency sweeps are shown in Fig. 4 for [4(a)] 4.8% Nutilis, [4(b)] 6.5% ThickenUp, and [4(c)] 1% xanthan gum solution. All show the same
characteristic features, namely, $G'$ dominance over the frequency range tested and a power law decay of the complex viscosity $\eta^*$. Figure 4 also shows the best fit multimode modeling of the viscoelastic response, and the computed values for the $g_i$ modes are shown in Fig. 5.

In all, 12 modes were chosen to cover the time domain of the frequency data. The magnitude of the relaxation modes for each solution is similar and the long relaxation modes have a significantly high weighting. The dip in mode strength for all samples in
The region of $\dot{\lambda} = 12$ s is thought to be an artifact of the fitting procedure. The presence of dominant long modes in the spectra is consistent with the fluids containing a gel-like structure for these small strain measurements. The overall observed response is unlike most polymer melt and concentrated polymer solutions where the magnitudes of the relaxation moduli usually decay with increasing relaxation time [see, for example, Mackley et al. (1994)].

The steady shear rate response of the test solutions are shown in Fig. 6, and again, each solution has a similar response with a power law shear thinning behavior over the range of shear rates tested. The shear rate at the rim of parallel plate was taken as the applied apparent shear rate, and no modification was used for the variation of shear rate with radial distance for using parallel plates. None of the data shows a low shear rate

FIG. 4. Oscillatory frequency sweeps for (a) 4.8% Nutilis, (b) 6.5% ThickenUp, and (c) 1% xanthan gum together with best fit multimode Maxwell fit.
Newtonian plateau; however, there is a systematic increase in apparent viscosity at any shear rate with increasing concentration for all three solutions. Figure 7 shows a Cox Merz plot (Cox et al., 1958) for the complex and apparent viscosity data. In a rather similar way to many polymer melt solutions and melts, the Cox Merz rule of equivalence is approximately obeyed. The Cox Merz plot highlights that from both small and large strain measurements, all the fluids tested were highly “shear thinning” although all fluids had gel-like strong $G'$ dominance at small strains.

The effect of overall concentration on viscosity for the solutions is shown in Fig. 8. Because no zero shear viscosity could be established, a somewhat arbitrary choice of 1 rad/s oscillatory frequency was chosen for complex viscosity measurements and this is displayed in Fig. 8. In all cases, the viscosity increases with concentration. Xanthan gum shows a steady increase in viscosity in the range of 10 Pas for concentrations of order 1%. Nutilis viscosity enhancement was recorded between 2% and 8%, and the data show that ThickenUp requires a higher concentration than Nutilis and xanthan gum in order to reach the same level of viscosity.

From both the similar oscillatory linear viscoelastic response and nonlinear steady shear behavior that has been presented so far, it might be expected that all of the tested solutions would have a similar processing behavior for the same overall level of viscosity. The extensional processing behavior of the solutions is described in Sec. V of this paper, and then their processing behavior in a model throat is described in Secs. V and VI.

**IV. EXTENSIONAL DEFORMATION BEHAVIOR**

A Cambridge Trimaster [Vadillo et al. (2010)] was used to evaluate information about the rheological behavior of the test solutions in extensional deformation. The Trimaster is a twin piston filament stretching device that can rapidly stretch a test fluid initially held between the pistons and then optically interrogate the stretch, filament thinning, and subsequent break up. A schematic diagram of the geometry is shown in Fig. 9. The two pistons of 1.2 mm diameter started at a separation ($L_0$) of 0.6 mm. Samples were loaded

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**FIG. 5.** Maxwell multimode relaxation spectra for 4.8% Nutilis, 6.5% ThickenUp, and 1.0% xanthan gum. Data fit shown in Fig. 3.
between the pistons and manipulated into a cylindrical form. The pistons were then rapidly moved apart to a final distance ($L$) of 2.2 mm in a time of 0.011 s. The filament stretching and subsequent filament thinning behavior of the sample were captured with a high speed camera (Photron Fastcam 1024 PCI) and the data were analyzed using TriVision Analysis V1_1.

Representative photographic sequences for the solutions of the filament stretch and decay are shown in Fig. 10. Figure 10(a) shows the behavior of a 4.8% Nutilis.

**FIG. 6.** Apparent viscosity as a function of shear rate for (a) Nutilis, (b) ThickenUp, and (c) xanthan gum for different concentrations. Reference Smoothie is included in (c).
Comparison with other homogeneous solutions that have been tested with similar geometries [see, for example, Liang and Mackley (1994); McKinley (2005); Vadillo et al. (2010)] indicate that the filament deformation is nonuniform and this is almost certainly due to the nonuniform nature of some formulations. The long lifetime final filament decay of the Nutilis filament, say after 50 ms, does however have the discernable characteristic of a polymer solution [Liang and Mackley (1994)], although the near macroscopic presence of swollen starch granules influences the final breakup behavior. The situation for the 4.8% ThickenUp solution shown in Fig. 10(b) is even more extreme than the Nutilis. The ThickenUp solution, which is essentially swollen corn starch granules, stretches in a very nonhomogeneous manner before prematurely breaking even in

**FIG. 7.** Cox Merz plot of apparent viscosity and complex viscosity for Nutilis, ThickenUp, xanthan gum, and Smoothie.

**FIG. 8.** Complex viscosity at 1 rad/s as a function of concentration for Nutilis, ThickenUp, and xanthan gum. Smoothie is a reference.
FIG. 9. Schematic diagram of Cambridge Trimaster geometry with starting and finishing dimensions.

![Schematic diagram of Cambridge Trimaster geometry with starting and finishing dimensions.]

- $D_0 = 1.2\text{mm}$
- $L_0 = 0.6\text{mm}$
- $L_f = 2.2\text{mm}$

FIG. 10. High speed photographs of Trimaster filament stretching experiments for (a) 4.8% Nutilis.

![High speed photographs of Trimaster filament stretching experiments for (a) 4.8% Nutilis.]

- (Piston stops)
- (Filament breakage)

- (Filament breakage)
- (Piston stops)

- (Piston stops)
- (Filament breakage)
advance of the piston motion stopping. Finally, the 1.0% xanthan gum solution shown in Fig. 10(c) exhibits a very much more uniform deformation and also a long lifetime thread decay. Breakup behavior for different hydrocolloids solutions in silicon oil suspensions have been recently reported by Desse et al. (2011) and their findings also demonstrate the sensitivity of formulation to overall break up behavior.

Figure 11 shows the centerline time evolution for each of the three fluids and highlights the differences of the three solutions. ThickenUp exhibits a fast decay, Nutilis some filament thinning, and xanthan gum an extended filament lifetime. These extensional observations appear to be related to the homogeneity of the respective test solutions and whether or not dissolved polymer was present. The ThickenUp is essentially swollen starch and as such is a highly heterogeneous fluid and susceptible to filament break up. Nutilis contains some xanthan gum which helps “bind” the starch granules and extend the filament stretching ability of the fluid. Xanthan Gum behaves as a classic dissolved polymer solution with extended filament thinning ability. However, the breakup time is shorter than expected for Newtonian fluids with similar low shear viscosity. The result observed here indicates an acceleration of the necking typical of shear thinning fluids [Clasen et al. (2012)]. The observed very different extensional behavior of these three fluids contrasts markedly with their very similar simple shear rheological behavior reported in Sec. III.

Trimaster extension rates for the whole duration of the experiment are variable depending on both time and the profile of the fluid. The initial experimental filament stretch strain rate $\dot{E}$ when the pistons are separating can however be computed using the equation below [Anna et al. (2001)]

$$
\varepsilon_L = \ln \left( \frac{L_f}{L_0} \right) = \dot{E} t_s,
$$

where $\varepsilon_L$ is the filament stretching Hencky strain and $t_s$ is the stretching time. Using the values previously given, a value $\dot{E} = 118 \text{ s}^{-1}$ was obtained for the experiments described in this paper.

![FIG. 11. Trimaster centerline filament thickness decay for 4.8% Nutilis, 4.8% ThickenUp, and 1.0% xanthan gum.](image-url)
V. THE CAMBRIDGE THROAT, DESIGN AND OPERATION

In order to evaluate the processing behavior of the thickened solutions in a geometry and condition similar to that experienced in a human throat, a model Cambridge Throat was designed and constructed. The Cambridge Throat is shown schematically in Fig. 12(a) and as a photograph in Fig. 12(b). The geometry of the throat was modeled as a 2D channel in optically transparent Perspex that resembled the upper throat, pharynx, and epiglottis. There were a number of aspects considered in the design of a physical model throat to test the thickened fluids. The model was designed to be life-sized and match the approximate profile of the human throat as can be seen in Fig. 12. The throat was projected to a depth of 29 mm, as this was comparable to the width of a human throat. The model has a static “throat” and features, such as the epiglottis, are included in the overall shape and consequently the epiglottis does not move. The action of the tongue

FIG. 12. (a) Schematic diagram of the Cambridge Throat with main dimensions. (b) Photograph of apparatus showing pulley and weight to create a controlled torque on the tongue.
was mimicked by the use of a roller at the end of a lever arm. The tongue was activated by releasing a weight on a pulley wheel which generated a constant torque action of the roller. The weight used was 190 g as this equated to an estimated pressure of around 0.1 bar applied to the fluid by the tongue which is comparable to that expected for a human tongue when swallowing liquids [Yoshioka et al. (2004)]. This pressure approximation was calculated from the torque due to the weight on the pulley and then converting this to a force applied by the roller. The area over which this force was applied has been assumed to be approximately the cross-sectional area of the fully open tubing and thus the pressure applied to the fluids has been calculated. The “mouth” section required a tube to contain the fluid so that it could be forced around by the roller. There were two main options considered for this tubing: Silicon tubing and dialysis tubing. Silicon tubing had the advantages of being translucent and flexible. It was also able to hold its shape and thus could be attached in a permanent or semipermanent manner. Unfortunately, silicon tubing was relatively stiff and thus required a significant force to compress it. As a result, the difference in behavior of the different fluids was masked, as the majority of the force was going into compressing the tubing. The alternative use was dialysis tubing which is transparent, very flexible, and requires very little force to flatten the tube. Thin flexible dialysis tubing was attached to the top of the Perspex throat, and colored thickened solution was injected into the front of the dialysis tubing. Activation of the tongue was started by releasing the weight on the pulley which allowed the tongue roller to force, in a peristaltic action, the fluid around the throat within the dialysis tube and eject upstream of the epiglottis. A photographic sequence of the throat action is shown in Fig. 13 for a 6.5% Nutilis solution.

To perform experiments in the throat, the front face was unscrewed and 25 mm diameter dialysis tubing was fixed with double sided adhesive tape to the roof of the mouth.

FIG. 13. Photographic sequence showing representative motion of the tongue. The blue dyed bolus is for 6.5 wt. % Nutilis® displaying every fourth frame. Images taken at 30 fps. Time taken as 0 for the frame before roller movement is observed.
The front face of the model was then replaced and screwed into position and a pin used to hold the tongue mechanism in position. A 5 ml sample of thickened solution was syringed into the tubing free end. The sample was then manipulated manually through the tubing until it was all in the path of the roller. Then the pin was removed. Images were taken from the time of pin release until the fluid had stopped moving through the throat. For the images that captured the roller movement, a Canon Ixus 55 camera was used at 30 fps. For the images that captured the detailed fluid flow, a QICAM FAST 1394 camera was used at 15–17 fps. Ground glass diffuse illumination was provided from behind the throat.

VI. OPTICAL OBSERVATION AND RESIDENCE TIME MEASUREMENTS FOR CAMBRIDGE THROAT EXPERIMENTS

The representative overall movement of a thickened 6.5% Nutilis solution within the dialysis tubing is shown as a photographic sequence in Fig. 13. At \( t = 0.013 \) s, the rotating roller comes in contact with the stationary Nutilis fluid bolus which has been dyed blue to enhance contrast. Subsequently, the bolus moves ahead of roller and within the dialysis tube. At \( t = 0.8 \) s, the bolus has reached the end of the dialysis tube and then falls under the influence of gravity toward the epiglottis. Repeat experiments for the same fluid composition, and initial conditions were reproducible within the photographic accuracy available.

From photographs of the type shown in Fig. 13, it is possible to determine the transit time for roller motion for different fluids within the dialysis tube for essentially the same initial conditions and applied torque of the tongue. Results are shown in Fig. 14 and indicate as expected, the transit time is very dependent on thickener concentration. Water is also included in the graph, and here the transit time was significantly less than 1 s and of order 0.13 s. For the same concentration of Nutilis and ThickenUp, the transit time was not significantly different, and depending on concentration, ranged from 0.13 s to nearly 10 s at high concentration. Clearly thickener concentration and the fluids viscosity have a significant effect on the transit time particularly above 5% concentration.

FIG. 14. Time to complete roller motion for Nutilis and ThickenUp as a function of concentration. Data for water and 1% xanthan gum included.
For this part of the throat motion, the xanthan gum transit time was similar to that of water alone.

Subsequent flow of the test fluids through the throat is given as photographic series in Figs. 15–17. These photographs show the passage of fluid after the point where the tongue roller motion had stopped, for example, in the case of Nutilis, Fig. 15(a), $t = -61$ ms, to when the fluid reached the epiglottis, Fig. 15(a), $t = 0$, and then subsequently to the divide point of the throat between the esophagus and airway, Fig. 15(a), $t = 54$ ms. For each of the three concentrations shown in Fig. 15 for Nutilis, it can be seen that when the fluid reaches the epiglottis, there is bridging of the fluid between the epiglottis and the back of the throat. The transit time between the stopping of the roller motion and time to reach the epiglottis increases with concentration. For the case of the 6.5% Nutilis solution, Fig. 15(c), the fluid remains stationary at the epiglottis and does not reach the airway divide. The ThickenUp shown in Fig. 16 has a slightly different

**FIG. 15.** Flow of Nutilis through the Cambridge Throat: (a) 2.9 wt. % solids, (b) 4.8 wt. % solids, (c) 6.5 wt. % solids.
response. In this case at lower concentration 4.8%, Fig. 16(a), the fluid does not bridge at the epiglottis and runs down the back of the throat. At the higher concentrations, Figs. 16(b) and 16(c), bridging does occur and again at the highest concentration, Fig. 16(c), the fluid does not pass the epiglottis.

Finally, the flow behavior of 1% xanthan gum and water is shown in Fig. 17. For the case of xanthan gum, the flow is dominant at the back of the throat with a small amount of bridging at the epiglottis shown in Fig. 17(a), $t = 0$ ms. For the case of water, Fig. 17(b), the flow is totally along the back of the throat.

From photographic sequences of the type shown in the Figs. 15–17, it is possible to determine transit times for the fluid, and these are plotted in Fig. 18 for the transit time between the roller stopping and reaching the epiglottis and in Fig. 19 for the time from the epiglottis to the flow divide. Both show similar trends of increasing transit times with higher thickener concentration. Two different cameras were used to capture images and
the differences between the two sets of data give some idea of the precision of the results; the high resolution camera can, however, be expected to give more accurate results for the low concentration, short transit time data.

Figures 15–17 do show that different thickeners have different flow behavior in the “unconstrained” region after the fluid has left the dialysis tubing. Extensional
components of the flow are present and differences detected from the Trimaster experiments become relevant.

VII. DISCUSSION AND CONCLUSIONS

The shear thinning rheology results reported in this paper for thickened dysphagia fluids are consistent with shear thinning results already reported for these fluids by, for example, Sopade et al. (2007). The additional viscoelastic results reported in this paper extend the data set and also rank the fluid rheology and throat behavior against xanthan gum solution. Taken together, the shear rheology of the all tested fluids appears similar with the Cox Merz rule approximately obeyed for each fluid. It was however discovered that the Trimaster extensional stretch, thinning, and breakup behavior for the fluids were very different in spite of their shear rheology being similar. The heterogeneous ThickenUp solutions that contained no polymer binder deformed in a very nonuniform manner and the stretching filament broke up at a very early stage of deformation. The Nutilis solutions, that contained some xanthan gum polymer, extended the filament lifetime and the pure xanthan gum solutions showed a classic polymer behavior with a long lasting filament lifetime. From these results alone, it is clear that shear rheology characterization, even with linear viscoelastic data, is not sufficient to characterize the full deformation behavior of the type of fluids studied here.

The design and development of the Cambridge Throat involved incorporating many simplifications to the real action of a human throat. The mechanical throat did however enable the behavior of thickened fluids to be studied in a flow geometry that bore some resemblance to the action of human swallowing. The use of a roller at the end of an arm was effective in mimicking the action of the tongue and a simple weight and pulley arrangement enabled a constant torque rheometer to be developed. The use of dialysis tubing to contain the fluid proved to be effective as this provided negligible resistance to the roller movement without the fluid being present. It was discovered that the transit

FIG. 19. Time from epiglottis to divide for Nutilis and ThickenUp as a function of concentration. Data for water and 1% xanthan gum included. HR denotes results observed using the higher resolution camera.
time within the dialysis tubing increased with increasing concentration above a threshold concentration of about 3%. The effect is consistent with the belief that thickened fluids increase transit time for swallowing in humans, and this presumably provides more time for muscles in the back of the throat and the epiglottis to adjust from breathing air to consuming fluid. It was found the same fluid viscosity of different fluid formulations gave similar transit times in relation to transit times within the dialysis tubing.

Different formulations did however behave in a different manner for the flow in the back of the throat. Water traveled down the back wall of the throat and as the viscosity of the thickened fluid increased, bridging between the back of the throat and the static model epiglottis was detected. The flow behavior of the Nutilis and ThickenUp solutions became different with increasing concentration suggesting that the differences could be linked to the differences seen in the Trimaster extensional fluid testing.

In a related study by Thien and Liu (private communication), attempts were made to estimate typical wall shear rates that occurred within the Cambridge Throat. A model was developed in order to predict the angular displacement of the rotating arm as a function of time. Various forces including viscous friction within a capillary flow were estimated, and for the conditions described in this paper, an estimate of wall shear rate of $50 \text{s}^{-1}$ for a power law fluid that fitted the experimental data was obtained. This of course only gives a crude estimate of the complex flow and associated complex range of shear rates that occur during the action of the roller forcing fluid within the flexible tubing during rotation around the throat.

Overall the Cambridge Throat represents a very simple first order mechanical model of a human throat that can be used and improved to examine different fluids under different conditions. Clearly the Cambridge Throat does not capture the full delicate complexity of the human throat where deformable muscular action at all the internal walls of the throat results in a very complex motion. The Cambridge throat is essentially a two-dimensional device and all the wall boundary conditions except the moving tongue are static. Given these limitations, the Cambridge Throat does however provide a useful device where the rheological effect of fluid substances can be tested. Additional variables that should be explored in future work include different, tongue torque levels, fluid bolus volumes, dialysis tube inner surface coatings, and other fluid additives. Experimental results should also be compared with human trials on the same range of fluids.

There are relatively few papers published on modeling of different aspects associated with the swallowing process, see, for example, Brasseur (1987), Nicosia (2007), and Nicosia et al. (2000). The peristaltic action of a rotating roller forcing rheologically complex fluid within flexible tubing does not appear to have been addressed in the literature, and this could provide valuable insight in relation to human fluid digestion as well as other peristaltic flow action in pumps and even toothpaste.

Whilst the experiments described in this paper clearly show that thickened fluids delay the transport of fluid to the back of the throat, the exact reason as to why this could be beneficial to dysphagia sufferers remains uncertain. The overall complexity of the human action of swallowing has been greatly simplified by the use of a static channel, and inevitably, muscle movements during the action of swallowing will have a significant effect on both transit times and flow trajectory, which is not captured by the Cambridge Throat. In the future, in situ videofluoroscopic experimental experiments of the type already reported by Groher et al. (2006) and MRI experiments can be expected to provide further insight on details of human response.
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