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Relationships between shear rheology and sensory attributes of hydrocolloid-thickened fluids designed to compensate for impairments in oral manipulation and swallowing

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ABSTRACT

Thickened fluids are commonly used as a therapeutic intervention for various swallowing impairments (dysphagia). However, there is little understanding around rheological properties of thickened fluids that are relevant to dysphagia. This study compared shear rheology of thickened fluids with sensory properties during oral preparation and swallowing. Fluids were thickened with different concentrations of three hydrocolloids (xanthan gum, starch, carboxymethylcellulose gum) to provide a range of viscosities at different shear rates, and yield stresses. Perceived oral cohesiveness, propulsion effort, stickiness, and oral residue were quantitatively assessed by a specially trained sensory panel, and data correlated with rheological measurements. Very strong correlations were found between fluid viscosities at shear rates of 10 s^{-1} for oral cohesiveness (r = 0.97), and 50 s^{-1} for propulsion effort (r = 0.97). Strong positive correlations were found between viscosities at 100 s^{-1} and perceived stickiness and oral residue (r = 0.78 and 0.80, respectively). Yield stress was not a direct indicator of any sensory attribute studied.

Measurements of fluid viscosity at representative shear rates 10, 50 and 100 s^{-1} provide a sound basis for investigating the impact of a 2.5 mL bolus size on sensory performance of thickened fluids during oral preparation and propulsion. Different hydrocolloids produce differing sensory profiles, providing important consideration for selecting thickeners for dysphagia.

1. Introduction

Dysphagia is a medical condition characterized by impairments in the transfer of food or fluids from the mouth to the stomach (Groher, 1997), and is estimated to affect 8% of the population worldwide (Cichero et al., 2013). Acute health consequences of dysphagia include misdirected transfer of the food or drink into the airway and lungs (aspiration), leading to asphyxiation or chest infection.

Swallowing is a complex dynamic process but can be described in stages, including the oral preparatory stage, oral stage, and pharyngeal stage (Logemann, 1984). Oral preparatory stage involves use of the tongue to contain the fluid bolus in a position suitable for swallowing (Clarkson, 2011; Dodds, 1989). Impairments in this stage include reduced tongue movement (Logemann, 1984) and impaired sensory awareness (Penman and Thomson, 1998), which may delay swallowing and risk premature leakage of fluid into the pharynx (Ekberg, 1997), where misdirection into the airway can occur. Oral stage is a rapid transition where sequential contact between the tongue and hard palate propels the bolus from the mouth into the pharynx (Logemann, 2014). Impairments in this stage commonly involve reduced tongue strength or mobility, causing weakened propulsion and incomplete bolus clearance from the oral cavity (Logemann, 1984; Steele and Cichero, 2014). Fluid residue in the oral cavity may subsequently experience leakage into the pharynx and potential misdirection into the airway.

Thickening dietary fluids is a common intervention to assist safe consumption with dysphagia (Newman et al., 2016; Steele et al., 2015), and is believed to compensate for dysfunctions by slowing the fluid's rate of flow, alleviating the oral control required, and providing more time to safely prepare for swallowing (Coster and Schwarz, 1987; Steele et al., 2015). Hydrocolloids commonly used to thicken dietary fluids

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generally display non-Newtonian flow (Casanovas et al., 2011; O'Leary et al., 2010), but different types and concentrations of hydrocolloids will result in varying rheological profiles depending on molecular weight and conformational differences (Chan et al., 2007). For example: Xanthan gum solutions form a weak gel-like structure at under low stress, but become highly shear-thinning beyond their yield points (Fagioli et al., 2019); Starch solutions also display shear-thinning flow profiles (Chan et al., 2007), with weak gel-like behavior at higher concentrations (Youn and Rao, 2003); Carboxymethylcellulose solutions have more dominant viscous than elastic properties under both low and high-shear deformation, being mildly pseudoplastic but characterized as either dilute or concentrated solutions rather than gels (Vais et al., 2002).

Rheological properties of thickened fluids are paramount for swallowing safety (Brito-de la Fuente et al., 2017; Engmann and Burbidge, 2013), yet comprehensive literature reviews by Steele et al. (2015) and Newman et al. (2016) have highlighted the paucity of rheological data characterising bolus flow during normal and impaired swallowing. Shear deformation is believed to dominate the swallowing process, though elongational flow may also be involved, especially during pharyngeal transit (Brito-de la Fuente et al., 2017). Shear rates during the entire swallowing process are believed to span from 1 to 1000 s^{-1} (Brito-de la Fuente et al., 2017), and Steele et al. (2015) proposed that apparent viscosities at shear rates of 1, 10, 30, 50 and 100 s^{-1} would provide a generally sound basis for comparing thickened fluids for dysphagia. How these shear rate ranges relate to stages of the swallowing process is yet to be elucidated. Yield stress has also been postulated as important for a fluid's ability to be swallowed efficiently, particularly as a force that needs to be overcome for propulsion of the bolus from the mouth into the pharynx (Cichero et al., 2000; Cichero and Lam, 2014; Hadde et al., 2016), though no data could be found in the literature to verify this.

Sensory analysis is a well accepted approach to research that is less invasive than clinical trials, and quantitatively scaling the intensity of sensory attributes is amenable to correlation with instrumental tests (Bourne, 2002). Historically, sensory studies in the literature had explored relationships between rheology and perception of fluid thickness as measures of palatability (Stanley and Taylor, 1993). More recent studies have attempted to compare rheology and sensory attributes in the context of swallowing function, including overall perceived 'swallowing ease' (Nakauma et al., 2011; Nyström et al., 2015; Yamagata et al., 2012), fluid stickiness or slipperiness (Nakauma et al., 2011; Ong et al., 2018; Vickers et al., 2015), and normal perception of bolus viscosity in the mouth (Ong et al., 2018; Smith et al., 1997; Steele et al., 2014a; Yamagata et al., 2012). These studies focused on the pharyngeal stage of swallowing, or normal oral manipulation, even though impairments in oral preparatory stage of swallowing also require intervention to prevent fluid misdirection into the airway (Ekberg, 1997; Logemann, 1984; Penman and Thomson, 1998).

To address this gap in the literature, the objective of this study was to explore correlations between shear rheology and sensory performance of fluids that are thickened with hydrocolloids to compensate for impaired oral function. It was hypothesized that shear rate ranges could be differentiated between physiological scenarios involving impaired oral manipulation and oral propulsion. The impact of yield stress as a force to be overcome during oral propulsion, and role of perceived stickiness during oral propulsion and post-swallow, were also discussed.

2. Materials and methods

2.1. Thickened fluid samples

Samples were prepared using one of three different food thickeners: Xanthan gum (XG) (KELTROL® T-PLUS; CP Kelco, China); sodium carboxymethylcellulose gum (CMC) (CEKOL® 30000 P; CP Kelco, Finland); and modified tapioca starch (ST) (Thick-flo®; Ingredion™, Thailand), each at a range of concentrations (Table 1). These thickeners were specifically chosen for their high clarity in solution, bland flavor, and differing viscosity profiles at increasing shear rates. It was anticipated from the literature (Fagioli et al., 2019; Vais et al., 2002), that xanthan solutions would be highly shear-thinning beyond their yield point, whereas carboxymethylcellulose solutions would be substantially less shear-thinning, approaching Newtonian flow characteristics. Starch solutions were anticipated to display shear-thinning flow profiles between that of xanthan and carboxymethyl cellulose (Waqas et al., 2017), with a potential yield point at higher concentrations (Youn and Rao, 2003).

Table 1
Sample codes corresponding to thickeners and their concentrations used for preparing the sample fluids.

Sample Code	Thickener	% w/w of Thickener in sample
XG-0.4	Xanthan gum	0.40
XG-0.7	Xanthan gum	0.70
CMC-0.55	Sodium carboxymethylcellulose gum	0.55
CMC-0.7	Sodium carboxymethylcellulose gum	0.70
CMC-0.85	Sodium carboxymethylcellulose gum	0.85
CMC-1.0	Sodium carboxymethylcellulose gum	1.00
CMC-1.15	Sodium carboxymethylcellulose gum	1.15
CMC-1.3	Sodium carboxymethylcellulose gum	1.30
ST-3.0	Modified tapioca starch	3.00
ST-3.5	Modified tapioca starch	3.50
ST-4.0	Modified tapioca starch	4.00
ST-4.5	Modified tapioca starch	4.50

All samples had added sucrose (10% w/w), citric acid ($< 0.32\%$), and sodium citrate ($< 0.10\%$) to give a standardized palatable flavor that masked any taste contribution from the thickener. The sugar and acidity levels (pH 3.8 $\pm$ 0.2) used are comparable to a fruit juice drink. Samples were prepared by dissolving pre-weighed ingredients in ambient tap water using an overhead stirrer (IKA® RW20 Digital, Germany) and 4 × 50 mm stainless steel impeller. Pre-weighed thickener was added and dispersed using a hand-held blender (Dynamic™ MD95, France). Blended samples were heated to 75 °C for gums and 85 °C for starch on an electric hotplate (Breville® BHP150, Australia) to ensure full hydration of the starch and gums and pasteurize the mixtures. Samples with any air bubbles incorporated during preparation were de-aerated using a single stage rotary vane vacuum pump (Joysun® X-20, China). Finally, solutions were portioned into plastic containers while still above 65 °C, hermetically sealed with a heat-sealed plastic-foil film, and left at room temperature until used for analyses. A single batch of each sample was made and used for all rheological and sensory analyses to avoid variability from replicate batch manufacture.

Categorisation of samples based on their viscosity/texture and reference to existing dysphagia standards e.g. the International Dysphagia Diet Standardisation Initiative (Cichero et al., 2013), U.S. National Dysphagia Diet (National Dysphagia Diet Taskforce, 2002) or Australian national standards (Dietitians Association of Australia and The Speech Pathology Association of Australia, 2007) were purposefully excluded from this paper; the findings and discussion transcend existing categorisation and are intended to guide development of more meaningful ranges and objective testing methods. For comparison, however, thickener concentrations were used to create samples representative of 'nectar'/'mildly thick' to 'honey'/'moderately thick' fluids under the above mentioned standards.

2.2. Sensory analysis

Four sensory attributes were selected for evaluation, based on prior literature (Ekberg, 1997; Hiss et al., 2004; Logemann, 1984; Steele et al., 2015; Steele and Cichero, 2014). The sensory attributes aimed to

Table 2
Sensory attribute descriptions and assessment methods used by the trained sensory panel, and their relevance to common swallowing impairments.

Sensory attribute name	Assessment definition	Assessment method {Descriptor anchors for 0–100}	Relevance to swallowing impairments
Oral cohesiveness	How well the bolus holds together on the tongue	Place 1 spoonful (2.5 mL) of sample onto your tongue and hold for a maximum of 4 s; maintain an upright posture with level chin and relaxed tongue. Assess cohesiveness. {None-High}	Impaired oral manipulation
Propulsion effort	The ability of the tongue to move the bolus in order to initiate the swallow	Move the bolus toward the back of the tongue and then initiate the swallow. Assess propulsion effort. {Requires little effort - requires great effort}	Impaired oral propulsion
Stickiness	Stickiness of the sample when depressed between the tongue and roof of mouth and then swallowed; felt in the oral cavity, tongue and/or lips	Place an additional 1 spoonful (2.5 mL) onto your tongue and depress between roof of mouth and tongue, then swallow. Assess stickiness. {None-High}	Impaired oral clearance
Oral residue	Amount of residue detected in the mouth after swallowing	Following swallow from stickiness assessment, assess oral residue. {None-High}	Impaired oral clearance

represent common physiological impairments present with dysphagia during oral preparatory and oral stages of the swallow (Table 2). Although healthy panellists were used, they were specially educated and trained (described below) to orally manipulate the fluids in a manner that emulated a person with compromised tongue mobility, and sense attributes during oral propulsion and post-swallow which are relevant to oropharyngeal dysphagia. This approach allowed many of the variables typically associated with sensory evaluation to be minimized, such as reliance on subject's individual oral processing techniques, or variation in type and severity of symptoms if using subjects with dysphagia (Nyström et al., 2015).

An experienced sensory panel (n = 12, age 26–64 years, 9 female) void of all health concerns including oral health and swallowing impairments, undertook the sensory evaluation. Each panellist had been selected from comprehensive recruitment process during which they were screened for their sensory acuity as well as their ability to describe and differentiate between various food and beverage products. The panellists all had three years experience in sensory evaluation covering a variety of products and evaluation techniques, and over this time had been continually tested and assessed on their performance, and trained accordingly. The sensory panel then undertook nine 2-h training sessions led by the sensory scientist, during which panellists were exposed to each of the samples, and performed tasks and training exercises with the focus on accurately quantifying each sample with regards to the four sensory attributes. Panel discussions were held throughout to ensure all panellists were in agreement on the terms and descriptions used. Prior to formal evaluations, the panel carried out three practice evaluations under controlled conditions in sensory booths, and panellist performance was assessed to verify agreement and accuracy between all panellists.

Formal evaluations were held under controlled conditions in isolated sensory booths. A 25 mL aliquot of each sample was served in a clear plastic pot labelled only with a random three digit code. Plastic teaspoons of 2.5 mL capacity were used for sample delivery, and panellists were trained to deliver consistent volumes with each spoonful. Although 2.5 mL represents a relatively small bolus size, fluid bolus volumes as small as 1–3 mL have been used during research and diagnostic procedures for dysphagia (Bisch et al., 1994; Clavé et al., 2006; Dantas et al., 1990; Kendall et al., 2016; Nishinari et al., 2011). It was determined during panel training that this volume allowed optimum resolution and accuracy between samples, however interpretation of results is limited to a bolus size of 2.5 mL, and further work will be required to understand the changes in sensory perception or fluid flow behavior during swallowing of larger bolus sizes.

Samples were stored and served at 20 ± 2 °C, but measurements of sample temperatures following 4 s in the mouth were taken from each panellist and found to be 25.1 ± 1.2 °C (raw data not shown).

The twelve samples (Table 1) were quantitatively evaluated for all four sensory attributes on a 0–100 sliding scale, with upper and lower anchor point descriptors (Table 2). FIZZ version 2.50 a278 sensory software (Biosystèmes, France) was used to collect the data. Each panellist evaluated all twelve samples in each of four separate sessions. A 12 × 12 Latin square design was used for each session that ensured the products were evaluated in random order within the session and in different orders between sessions. Palate cleansers of green apple, still and sparkling water were provided for mandatory use along with a 5 min forced wait between each sample.

The statistical analysis of each of the four sensory attributes was performed using analysis of variance (ANOVA). The dataset had a total of 144 observations (i.e. averaged session data for 12 panellists x 12 samples). The model included a term for panellist (equivalent to block), a term for sample, and a random error term. Examination of the residual plots from the ANOVA for each attribute did not indicate severe deviations from the assumptions of normality and homoscedasticity. Mean comparisons of the samples were performed using the least significant difference (LSD) test. Correlations between the sensory attributes were obtained using the Pearson correlation coefficient. The level of significance was set at 0.05 for all statistical tests performed. Statistical analyses were performed using GenStat® 16 (VSN International Ltd, United Kingdom).

2.3. Rheological analysis

Rheological analysis was performed on an SR5 universal stress rheometer (Rheometric Scientific™, Piscataway, NJ) using a 40 mm cone and plate geometry. Steady stress ramps were performed following a 60 s delay for the fluid sample to relax and re-equilibrate, to generate shear rate sweeps from 1 to 1000 s^{-1}. The temperature of samples was controlled at 25 ± 0.1 °C using a peltier plate. A temperature of 25 °C was chosen since it matched the average temperature that samples were found to reach in the mouths of the sensory panel during the sensory evaluation exercises. The temperature of thickened fluids affects their rheological properties (Nyström et al., 2015). It is, therefore, important to match sample temperatures when comparing sensory and objective test results.

Yield stresses were determined by performing dynamic stress sweeps (0.06–60 Pa) using a 40 mm cone and plate geometry, temperature controlled at 25 ± 0.1 °C using a peltier plate. Samples which exhibit a yield stress have a higher elastic modulus than viscous modulus (G' > G″) under very low amounts of applied stress, until a point where the stress becomes enough to deform the material structure so much that it begins to flow, and the liquid-like characteristics thereafter dominate (G' < G″). Using this technique, the yield stress is qualified by the stress (Pa) at which the value of G' and G" become equal before they cross over.

Sample densities were measured gravimetrically by weighing 10 mL of fluid in a sterile disposable 10 mL slip-tip syringe (BD™, Singapore). Densities of all samples were matched as closely as possible using the same fluid base composition, and were measured as 1.04 ± 0.02 g/mL (raw data not shown). Due to the very small variation in sample density, this parameter was not included in further analyses.

Twelve thickened fluid samples were tested following a randomized complete block design with three replicates that balanced order of testing across the three blocks. Different designs were generated for testing steady stress ramps, dynamic stress sweeps, and densities.

A linear mixed model with smooth polynomial lines (splines) (Verbyla et al., 1999) was fitted to the decadic logarithm of viscosity (mPa.s) across the decadic logarithm of shear rate (for shear rates ranging 1-1000 s^{-1}) for the twelve samples of thickened fluids. This model included fixed effects for sample, log of shear rate, and their interaction, and random effects for an overall spline term, individual spline terms for each sample, and their deviations. From this model, predicted average flow curves (from now on referred to as flow curves) were obtained for each sample. Analyses were performed using the package ASReml-R (Butler et al., 2009).

Apparent viscosities of each sample at discrete shear rates of 1, 10, 30, 50 and 100 s^{-1} were calculated using the power law equation (Waqas et al., 2017) derived using the rheometer's 'RSI Orchestrator' software. The power law equation was found to give a better fit than other mathematical models (e.g. Herschel-Bulkley) across the shear rate range 1–100 s^{-1}. The aforementioned shear rates were chosen because prior literature has proposed that they would provide a sound basis for characterizing thickened liquids intended for therapeutic use with dysphagia (Steele et al., 2015).

3. Results

3.1. Sensory analysis

The perceived intensity of all sensory attributes increased as thickener concentrations increased, though different trends between sensory attributes were observed between each thickener type, as depicted in Fig. 1. Analysis of variance determined that there was significant effect of sample for all sensory attributes. Mean sensory scores and LSD test results for each sensory attribute are presented in Table 3, with XG samples highlighted to serve as standard references for comparison with CMC and ST samples.

Samples thickened with CMC showed a clear increasing trend in perceived intensity for all sensory attributes from lowest to highest concentration (CMC-0.55 to CMC-1.3) (Fig. 1). Most CMC samples were significantly different from each other for oral cohesiveness, propulsion effort and stickiness (Table 3).

Samples thickened with ST displayed a concomitant increasing trend between oral cohesiveness and propulsion effort as ST concentration increased (Fig. 1), with samples generally significantly different from each other (Table 3). Perceived stickiness and oral residue

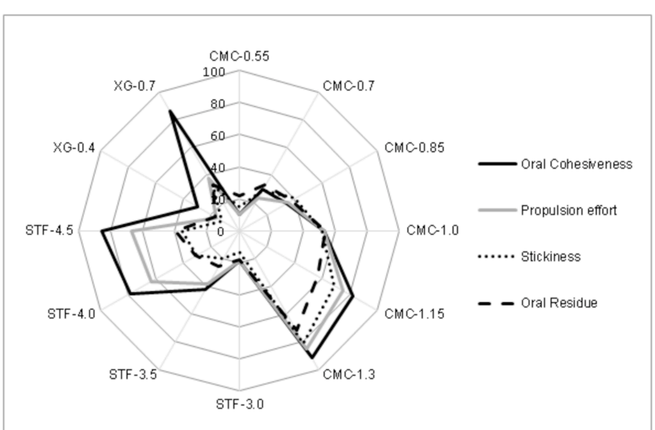

Fig. 1. Average scores of sensory attributes for all thickened fluid samples on 0–100 anchored sliding scale (0 = least intense, 100 = most intense).

also increased as ST concentration increased, but unlike for the CMC samples these attributes did not increase at the same perceived rate as oral cohesiveness and propulsion effort (Fig. 1), and show fewer significant differences between the samples (Table 3).

The most notable property of samples thickened with XG was their perceived oral cohesiveness relative to the other three sensory attributes (Fig. 1). Both XG samples were significantly different from each other for all sensory attributes (Table 3). The sharpest increase with XG concentration was observed for perceived oral cohesiveness (Table 3).

Inclusive of samples from all three thickeners, all four sensory attributes had positive significant correlations (Table 4). A particularly strong correlation was found between the sensory attributes stickiness and oral residue (r = 0.99).

3.2. Comparison of sensory and rheological analyses

Apparent viscosities of fluids (from now on referred to as viscosities) increased with increasing thickener concentration for all thickener types, and all fluids displayed some degree of shear-thinning flow behavior. Shear-thinning profiles (flow curves) are presented separately for CMC and ST thickened samples (Figs. 2 and 3) for ease of comparison with the standard reference XG samples. The thickeners and concentrations used provided an array of viscosities and shear-thinning profiles that allowed their flow curves to cross each other within the shear rate range of 1–1000 s^{-1}. It was anticipated that the order of magnitude of sample sensory scores could be matched to the shear rates, or regions along the x-axis of the flow curves, where sample viscosities had the same relative order of magnitude as the sensory attributes. In this way, shear rate regions relevant to each sensory attribute could be identified.

To illustrate the concept, the region along the x-axis (Fig. 2) where intersecting flow curves displayed sample viscosities that align with the statistically significant differences of CMC and XG samples for oral cohesiveness (Table 3) has been highlighted, and correspond to shear rates that spanned approximately 5–30 s^{-1} for the samples used in this study. Similar regions were identified for the other sensory attributes and each spanned a range of shear rates that generally tilted towards lower shear rates for higher viscosity samples, namely approximately 30–90 s^{-1} for propulsion effort; 90-150 s^{-1} for stickiness, and 200-250 s^{-1} for oral residue.

Sensory scores and shear rate regions of XG and ST-thickened samples (Fig. 3) showed similar trends to the XG-CMC sample subset (Fig. 2). For example, the perceived oral cohesiveness of fluids corresponded with lower shear rates (approximately 1.5–15 s^{-1}) and propulsion effort with slightly higher shear rates (approximately 40–200 s^{-1}), and regions for each sensory attribute tilted strongly towards lower shear rates for higher viscosity fluids. Shear rate regions along the flow curves corresponding to stickiness and oral residue involved lower shear rates (approximately 3–200 s^{-1}) compared with those for the XG-CMC sample subset (Fig. 3).

The shear rates 1, 10, 30, 50 and 100 s^{-1} proposed by Steele et al. (2015) were generally present within the shear rate regions highlighted in Figs. 2 and 3. Correlations between mean viscosities at these shear rates (Table 5) and mean sensory scores (Table 3) are presented in Table 6.

Oral cohesiveness presented the strongest correlation with viscosity at shear rate 10 s^{-1} (r = 0.97), with weaker correlations at lower or higher shear rates (Table 6). Very strong positive correlations were found between perceived intensity of propulsion effort and viscosities at shear rates 30, 50 and 100 s^{-1} (r = 0.95 to 0.97), with the strongest correlation at shear rate 50 s^{-1} (Table 6). Perceived intensity of stickiness and oral residue both had similarly strong positive correlations with viscosities at shear rates 30, 50 and 100 s^{-1} (r = 0.75 to 0.80), with the strongest positive correlations at shear rate 100 s^{-1} (Table 6).

Only five of the twelve thickened fluid samples exhibited a

Table 3
Mean sensory scores for thickened fluid samples in decreasing order of intensity on 0–100 anchored sliding scale. Values in each column denoted with different letters are significantly different ($p < 0.05$) according to the Least Significant Difference (LSD) test.

Oral cohesiveness		Propulsion effort		Stickiness		Oral residue	
Sample	Score	Sample	Score	Sample	Score	Sample	Score
CMC-1.3	91.9^{h}	CMC-1.3	85.0^{g}	CMC-1.3	80.9^{f}	CMC-1.3	71.5^{f}
XG-0.7	**86.6^{gh}**	CMC-1.15	75.0^{f}	CMC-1.15	68.9^{e}	CMC-1.15	57.0^{e}
ST-4.5	85.4^{fgh}	ST-4.5	67.2^{ef}	CMC-1.0	51.8^{d}	CMC-1.0	53.8^{e}
CMC-1.15	82.0^{fg}	ST-4.0	63.5^{e}	CMC-0.85	40.3^{c}	ST-4.5	39.7^{d}
ST-4.0	78.5^{f}	CMC-1.0	53.0^{d}	ST-4.5	35.6^{c}	CMC-0.85	37.5^{d}
CMC-1.0	53.6^{e}	ST-3.5	38.7^{c}	**XG-0.7**	**32.4^{c}**	CMC-0.7	32.9^{cd}
ST-3.5	42.1^{d}	**XG-0.7**	**38.0^{c}**	ST-4.0	30.5^{bc}	**XG-0.7**	**32.8^{cd}**
CMC-0.85	34.5^{cd}	CMC-0.85	35.4^{c}	CMC-0.7	29.4^{bc}	ST-4.0	31.3^{bcd}
XG-0.4	**30.2^{c}**	CMC-0.7	23.6^{b}	ST-3.5	19.8^{ab}	ST-3.5	25.8^{abc}
CMC-0.7	29.7^{c}	ST-3.0	18.6^{ab}	CMC-0.55	15.2^{a}	CMC-0.55	22.0^{ab}
ST-3.0	18.5^{b}	**XG-0.4**	**16.3^{ab}**	ST-3.0	13.3^{a}	ST-3.0	17.8^{a}
CMC-0.55	10.0^{a}	CMC-0.55	10.4^{a}	**XG-0.4**	**12.6^{a}**	**XG-0.4**	**16.9^{a}**
LSD	7.65	LSD	8.29	LSD	11.05	LSD	10.72

Table 4
Pearson correlation coefficients between pairs of sensory attributes (n = 12, upper triangle) and p-values for testing their significance (lower triangle).

	Oral cohesiveness	Propulsion effort	Stickiness	Oral residue
Oral cohesiveness	–	0.89	0.69	0.68
Propulsion effort	< 0.001	–	0.85	0.85
Stickiness	0.014	< 0.001	–	0.99
Oral residue	0.015	< 0.001	< 0.001	–

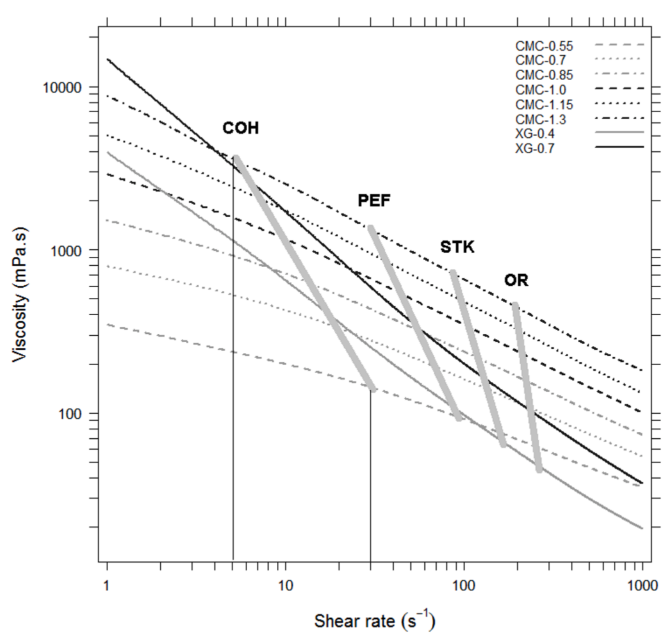

Fig. 2. Flow curves of samples thickened with CMC and XG displayed as log viscosity versus log shear rate. Thick grey lines indicate shear rate regions where relative order of sample viscosities matches their order of magnitude of perceived sensory attributes: Oral cohesiveness (COH), propulsion effort (PEF), stickiness (STK), and oral residue (OR). Vertical black lines illustrate the approximate shear rate range corresponding with perceived oral cohesiveness, as an example.

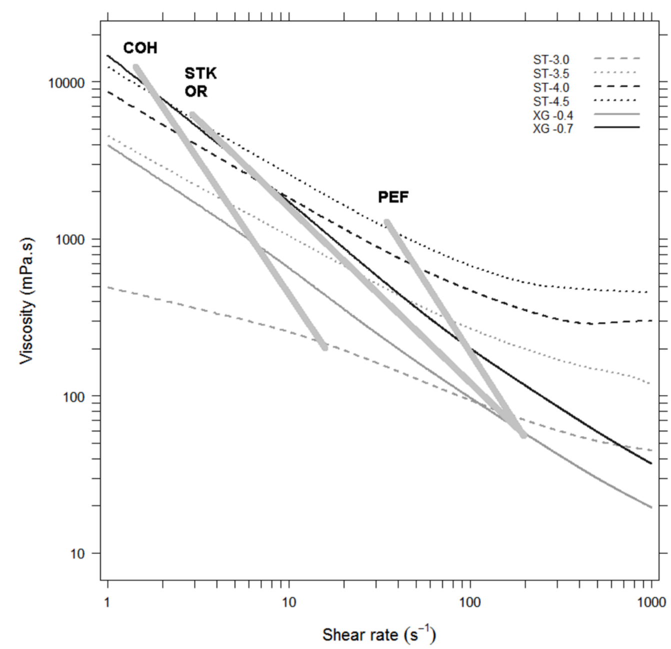

Fig. 3. Flow curves of samples thickened with ST and XG displayed as log viscosity versus log shear rate. Thick grey lines highlight shear rate regions where relative order of sample viscosities matches their order of magnitude of perceived sensory attributes: Oral cohesiveness (COH), propulsion effort (PEF), stickiness (STK), and oral residue (OR).

measurable yield stress (Table 5). Yield stress increased with increasing thickener concentration for XG and ST samples. All samples thickened with CMC, and the lowest concentration of ST, possessed negligible yield stresses which were below the sensitivity limit of the rheometer (i.e. < 0.06 Pa).

4. Discussion

4.1. Oral cohesiveness

Fluids exhibiting oral cohesiveness, as defined in this study (Table 2), would assist the formation and maintenance of a bolus where tongue control is impaired and/or the swallowing reflex is delayed. Samples generally formed perceptibly more cohesive boluses as thickener concentrations and viscosities increased. The strongest positive correlation ($r = 0.97$) found between perceived oral cohesiveness and viscosities of thickened fluids was at a shear rate of 10 s^{-1} (Table 6). The shear rate 10 s^{-1} is, in practical terms, a fairly low rate of deformation and results from relatively low magnitudes of applied stress. This makes sense when considering impaired control of a fluid bolus. Where little or delayed oral manipulation occurs, the fluid would be subject to very low levels of applied stress by the tongue, possibly as little as gravity alone.

Table 5
Mean viscosities (mPa.s) ± standard deviation at different shear rates, and mean yield stress ± standard deviation of thickened fluid samples.

Sample	Shear rates:					Mean yield stress (Pa)
	$1\ s^{-1}$	$10\ s^{-1}$	$30\ s^{-1}$	$50\ s^{-1}$	$100\ s^{-1}$	
XG-0.4	4311 ± 200	665 ± 11	273 ± 1	180 ± 1	103 ± 2	5.9 ± 0.5
XG-0.7	14964 ± 922	1694 ± 87	599 ± 28	369 ± 16	192 ± 8	15.2 ± 1.0
CMC-0.55	256 ± 18	173 ± 7	143 ± 4	131 ± 3	117 ± 3	NM
CMC-0.7	844 ± 30	397 ± 20	277 ± 16	235 ± 15	187 ± 13	NM
CMC-0.85	1680 ± 59	703 ± 16	464 ± 7	382 ± 5	294 ± 3	NM
CMC-1.0	3615 ± 142	1164 ± 34	678 ± 17	527 ± 13	375 ± 9	NM
CMC-1.15	6136 ± 105	1732 ± 31	947 ± 17	715 ± 13	489 ± 9	NM
CMC-1.3	9493 ± 156	2496 ± 31	1319 ± 14	981 ± 10	656 ± 6	NM
ST-3.0	355 ± 9	221 ± 14	177 ± 19	160 ± 20	139 ± 21	NM
ST-3.5	4344 ± 166	1043 ± 29	528 ± 15	385 ± 11	250 ± 8	4.4 ± 0.5
ST-4.0	7219 ± 417	1764 ± 10	901 ± 23	659 ± 25	432 ± 24	8.8 ± 0.3
ST-4.5	8706 ± 465	2359 ± 89	1266 ± 39	947 ± 26	640 ± 15	12.7 ± 0.8

NM = No measurable yield stress (< 0.06 Pa).

Table 6
Pearson correlation coefficients between sensory attribute mean scores and mean viscosities of thickened fluid samples at representative shear rates (n = 12). Unless otherwise denoted, all correlations were significantly different from zero ($p < 0.05$).

Sensory attribute	Correlation coefficient with viscosities at shear rates:				
	$1\ s^{-1}$	$10\ s^{-1}$	$30\ s^{-1}$	$50\ s^{-1}$	$100\ s^{-1}$
Oral cohesiveness	0.87	0.97	0.91	0.87	0.80
Propulsion effort	0.57	0.92	0.96	0.97	0.95
Stickiness	0.39^{ns}	0.68	0.75	0.77	0.78
Oral residue	0.38^{ns}	0.69	0.77	0.79	0.80

^{ns} Correlation not significantly different from zero ($p > 0.05$).

The single shear rate 10 s^{-1} was not a clear delineation when sensory and rheology results were compared, but was found to be a suitable representative shear rate within the regions identified for oral cohesiveness on the flow curves (Figs. 2 and 3). These shear rate regions agreed quite well between the thickener types, and spanned shear rates of approximately 1.5–30 s^{-1} when incorporating all samples used in the study. Shear rate regions also trended towards lower shear rates for higher viscosity fluids. The existence of regions rather than discrete points is expected, due to the spectrum of fluid viscosities assessed. Shear rates are proportional to the shear stress applied, but inversely proportional to fluid viscosity. Since the sensory panel was highly trained to perform evaluation tasks consistently, each sample bolus would have been subject to levels of stress as reasonably consistent as possible during human evaluation. Under equal applied stress, a fluid with higher viscosity will have greater resistance to flow and hence experience a lower shear rate than a less viscous fluid. As indicated by the data (Figs. 2 and 3) samples with higher thickener concentrations and viscosities trended towards lower shear rates than the thinner fluid samples. Shear rates also vary within a bolus based on its volume, slipperiness, and distance from the surfaces generating propulsion (Nicosia, 2013), which would also contribute to the existence of ranges.

It should be noted that although elongational stress would likely occur under normal physiology when fluid is held between the tongue and hard palate, the specific sensory tests conducted in this study aimed to mimic impaired oral manipulation (Table 2), and hence avoided compression or elongational stress. As a result, flow would have been primarily due to shear stresses, making viscosities across the shear rate range 1.5–30 s^{-1} a relevant indicator of bolus cohesiveness when hydrocolloid-thickened fluids of 2.5 mL volume are administered to consumers with delayed oral manipulation.

Yield stresses of samples increased with increasing thickener concentration, except for CMC-thickened fluids where no measurable yield stress existed at any concentration (Table 5). Perceived oral cohesiveness of samples increased as concentration of all thickener types increased; therefore, yield stress did not appear to be relevant to the flow properties of thickened fluids used in this study during impaired oral manipulation. Yield stress can be an indicator of intrinsic structure within a fluid relative to properties of the hydrocolloid thickener system (Nakauma et al., 2011), and fluid elasticity is usually correlated to its degree of cohesiveness, and ability to remain intact, especially during extensional flow (Brito-de la Fuente et al., 2017). Future work should investigate if elastic properties of fluids become more relevant as bolus volumes and/or hydrocolloid concentrations increase, and oral processing involves extensional as well as shear stresses.

The compensatory performance of thickened fluids during impaired oral preparation has received very little attention in the literature. Published studies that have focused on the oral preparation of thickened fluid boluses have used healthy consumers to utilize their normal oral manipulation and sensory functions to judge how viscous fluid samples felt in the mouth (Ong et al., 2018; Smith et al., 1997; Steele et al., 2014a; Yamagata et al., 2012). These physiological actions would be expected to involve a significant degree of inter-subject variability in both the directions and magnitudes of stresses applied (Nyström et al., 2015), and more importantly may not be reflective of a common symptom of oropharyngeal dysphagia during the oral preparatory stage of swallowing (Ekberg, 1997; Logemann, 1984; Penman and Thomson, 1998).

Based on the range of samples used in this study, viscosity at 10 s^{-1} may indicate a fluid's inherent ability to form and maintain an intact bolus during impaired oral manipulation, where higher viscosities will theoretically better compensate for more severe dysfunction. Future work should investigate the applicability of this measurement for increases in bolus volumes above 2.5 mL, and the impacts of elongational deformation and elastic properties of fluids during oral processing.

4.2. Propulsion effort

Thickened fluids are designed to resist flow and may thus require greater propulsion effort to initiate the swallow (Hiss et al., 2004; Steele et al., 2015). This exacerbates the risks of swallowing inefficiency for consumers who already have reduced tongue strength and/or mobility (Logemann, 1984). In apparent contradiction to the viscosity and cohesiveness desired during impaired oral preparation, the compensatory role of thickened fluids during oral propulsion is to flow more easily under the attenuated physical propulsive forces present.

At increasing concentrations, each hydrocolloid thickener achieved higher levels of oral cohesiveness with concomitant higher viscosities at 10 s^{-1}. The relative impact that each thickener had on the other three sensory attributes, however, became more pronounced as concentrations increased (Fig. 1). At thickener concentrations where equivalent levels of oral cohesiveness were achieved, XG samples had significantly lower perceived propulsion effort than solutions thickened with either ST or CMC (Table 3). XG solutions were more shear-thinning than ST or CMC solutions, and hence experienced lower resistance to flow as shear rates increased. It follows, then, that viscosities at shear rates greater than 10 s^{-1} may be indicative of oral propulsion effort.

Comparison between sensory scores for perceived propulsion effort and fluid viscosities showed the highest correlation at shear rate 50 s^{-1} (r = 0.97, Table 6). Oral propulsion involves rapid movement of the fluid bolus, so it is conceivable that shear rates of this magnitude may be developed during such dynamic events (Cichero et al., 2000). Furthermore, there is some published evidence that viscosity at 50 s^{-1} translates to differences in swallow physiology. Steele et al. (2014b) used xanthan-thickened fluids to measure tongue-palate pressure amplitudes in healthy adults. Apparent viscosities at 50 s^{-1} of the fluid stimuli utilized by Steele et al. (2014b) were very similar to samples XG-0.4, ST-3.0, CMC-0.7, and XG-0.7, ST-3.5, CMC-0.85, in the present study. Statistical differences ($p < 0.05$) identified between sample sets agree perfectly when comparing swallowing pressure amplitudes measured by Steele et al. (2014b) and intensities of perceived propulsion effort in the present study.

Some authors have hypothesized that yield stress affects the amount of tongue pressure required to initiate flow of the fluid for swallow reflex initiation (Hadde et al., 2016), and individuals with poor tongue strength may have greater difficulty initiating flow of a bolus with higher yield stress (Cichero et al., 2000). More viscous fluids have been shown to elicit higher tongue pressures during swallowing (Miller and Watkin, 1996; Steele et al., 2014b), but no published evidence could be found to substantiate the proposition that the material property responsible is yield stress. The trained sensory panel in the present study found significant differences in perceived propulsion effort across the twelve thickened fluid samples (Table 3), but the intensities of perceived propulsion effort did not align with the presence nor magnitudes of yield stress (Table 5).

Furthermore, assessment of commercial thickened fluids in Australia has shown yield stresses can range from 2.7 Pa for categorized ‘mildly thick’ fluids, up to 18.3 Pa for ‘extremely thick’ fluids (Hadde et al., 2016). Anterior and posterior tongue pressures of elderly subjects (n = 78, mean age = 77.3 years) have been measured as low as 270 and 220 mmHg (35997 and 29330 Pa), respectively, when swallowing thin fluids (Butler et al., 2011). The tongue pressures generated for thin fluids within this elderly cohort are still more than one thousand times the stress required to initiate flow in the aforementioned ‘extremely thick’ fluids. Therefore, data from published literature and the present study do not support the postulation that yield stress is a critical factor to be overcome during oral propulsion.

Perceived stickiness and propulsion effort had a strong positive correlation in the present study (r = 0.85, Table 4), and their relative intensities based on thickener type and concentration can be seen in Fig. 1. Intensity ratings for these two sensory attributes increased proportionately with each other as concentration of the least shear-thinning fluid (CMC) and most shear-thinning fluid (XG) increased. For fluids thickened with ST, however, propulsion effort and stickiness were very closely aligned at lower concentrations but did not increase proportionately as concentration increased. This indicates there are hydrocolloid-dependent parameters other than shear viscosity profiles and yield stress that affect both these sensory attributes but could not be discerned within the scope of this study.

Based on the range of samples used in this study, viscosity at 50 s^{-1} may be useful in indicating the amount of propulsion effort required for 2.5 mL fluid boluses within approximate ‘mildly thick’ to ‘moderately thick’ consistency ranges. More research is required to identify and understand any hydrocolloid-specific factors that impact propulsion effort of thickened fluids, including at higher concentrations and with larger bolus volumes.

4.3. Oral residue and stickiness

Fluid viscosities at shear rate 100 s^{-1} showed the strongest positive correlations with perceived intensities of both oral residue and stickiness, compared with lower shear rates (r = 0.86, 0.80 and 0.78, for each sensory attribute, respectively) (Table 6). In addition, the least shear-thinning CMC solutions displayed significantly greater perceived stickiness and oral residue as thickener concentrations increased, compared with XG and ST solutions (Table 3).

Several published studies show agreement with the present findings, where shear-thinning profiles of solutions and viscosities at shear rates greater than 50 s^{-1} appeared to be related to perceptions of stickiness. A sensory study using solutions of fifteen different hydrocolloids (Vickers et al., 2015) showed that highly shear-thinning fluids had lower intensities of perceived stickiness, adhesiveness and mouth coating, and required fewer swallows to cleanse the palate. Ong et al. (2018) found that concentrated xanthan solutions displayed greater perceived slipperiness when squeezed between the tongue and hard palate, compared to less shear-thinning guar and carboxymethylcellulose solutions. Fluids were matched for apparent viscosity at 50 s^{-1}, so the authors concluded that perceived slipperiness was affected more by the type of hydrocolloid and shear-thinning behavior of the solutions, than viscosity at a single shear rate of 50 s^{-1}. Nakauma et al. (2011) found highly shear-thinning xanthan gum solutions were perceived to be less adhesive in the pharynx during swallowing than less shear-thinning LBG solutions. Although not discussed by the authors, apparent viscosities of all ten xanthan and LBG solutions at 100 s^{-1} displayed the same relative order of magnitude as their sensory scores for adhesiveness. In clinical evaluations using subjects with oropharyngeal dysphagia, xanthan-thickened fluids have shown reductions in the prevalence and severity of aspiration compared with guar-gum thickened fluids (Nishinari et al., 2011), with no significant increase in post-swallow residue as xanthan concentrations increase (Bogaardt et al., 2007).

Notable differences between thickener types were also observed regarding yield stress and perceived stickiness and oral residue. Only samples thickened with XG, or ST at higher concentrations (ST-3.5, 4.0, 4.5) exhibited a measurable yield stress (Table 5). These samples all had relatively low levels of perceived stickiness and oral residue relative to their oral cohesiveness, unlike the remaining ST-3.0 and all CMC solutions which did not exhibit a yield stress (Table 3). The presence of a yield stress indicates more structure within a fluid, which may promote a more coherent bolus and facilitate more efficient clearance during swallowing (Nakauma et al., 2011; Taniguchi et al., 2008).

The very strong positive correlation found in the present study between perceived stickiness in the oral cavity and perceived oral residue (r = 0.99) (Table 4), indicates that surface adhesiveness properties of the bolus at the mucosa interface may also be an important consideration for post swallow residue. Notwithstanding the incorporation of saliva, sensory qualities such as slipperiness, smoothness, and mouth coating are associated with friction-lubrication properties (tribology) of the fluid surface (Chojnicka-Paszun et al., 2014; Malone et al., 2003; Stokes et al., 2013), and these properties also hold some interdependence with rheological parameters like shear-thinning flow behavior and viscosity at very high shear rates e.g. 10^4 s^{-1} (De Vicente et al., 2006; Stokes et al., 2011).

Viscosity at higher shear rate i.e. 100 s^{-1} may give an adequate indication of bolus stickiness and potential for post-swallow oral residue, and yield stress may indicate greater bolus coherence, but these measurements alone do not appear to provide a complete indication of stickiness and potential for oral residue. Future work should continue to investigate degree of shear-thinning behavior and tribological properties of hydrocolloid-thickened solutions.

5. Conclusions

This study demonstrated that oral processing and measurement of relevant rheological parameters can be focused into separate stages of the swallow, and trained sensory panels can be utilized to mimic voluntary aspects of swallowing impairments in lieu of invasive clinical trials. Using this approach, very strong positive correlations were found between apparent viscosities of fluids at representative shear rates between 1 and 100 s^{-1} and perceived intensities of specific sensory attributes related to impaired oral manipulation and oral propulsion.

These findings not only verify that different rheological parameters need to be measured during various physiological events in swallowing, but also contribute to elucidating the measurable steady shear properties of fluids that are relevant during impaired oral manipulation and oral propulsion. Xanthan solutions displayed the most suitable oral cohesiveness relative to their perceived oral propulsion effort, stickiness, and oral residue compared to starch or carboxymethylcellulose solutions. Fluids which are highly shear-thinning and possess a yield stress may, therefore, provide more beneficial flow properties when used as therapeutic interventions to improve swallowing safety and efficiency in consumers with dysphagia.

Institution where work was performed

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Declaration of interest

This project was co-funded by Flavour Creations Pty Ltd (Australia), which has a commercial interest in the production of thickened fluids and thickening agents. Authors A. Ross and B. Eriksen are paid employees of Flavour Creations. No Flavour Creations or competitors' products were used in the study.

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