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RESEARCH ARTICLE

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Rheological, textural, and swallowing characteristics of xanthan gum-modified Riceberry porridge for patients with dysphagia

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Abstract

The incidence and prevalence of dysphagia worldwide are increasing yearly requiring a change in food texture to avoid malnutrition, dehydration, or sever complications. Riceberry porridges fortified with protein hydrolysate (1.5%), bio-calcium (589 mg), and thickened with xanthan gum (XG) of varying concentrations (0%, 0.255, 0.50%, 0.75%, 1.0%, and 2.0%) showed suitability for use in enriching diets of these patients. Porridges were examined using specified tests from the International Dysphagia Diet Standardization Initiative (IDDSI) and National Dysphagia Diet (NDD), and coupled with rheological, textural analyses, in vitro swallowing simulator and sensory analysis performed by a trained panel. Porridges with 0%–0.25% and 0.50%–2.0% XG were classified as IDDSI level 3 and 4, respectively, and apparent viscosities of porridges showed samples with XG displayed shear thinning behavior beneficial for patients with dysphagia. Increasing XG concentrations increased the consistency coefficient and decreased the flow behavior index ($p < .05$) with positive correlation of XG concentration with textural properties including firmness, consistency, cohesiveness, adhesiveness, and stickiness values. The relationship between instrumental measurements, in vitro and in vivo swallowing behavior showed high correlations with regards to XG concentration ($r = .995$). The findings indicate Riceberry porridges containing XG have significantly improved textural properties over those without XG for patients with dysphagia.

KEYWORDS
dysphagia, Riceberry rice porridge, texture analysis, xanthan gum

1 | INTRODUCTION

Dysphagia is a condition that makes it difficult for a person to swallow, which affects the safety and quality of eating and drinking. Dysphagia is associated to complications including aspiration pneumonia, choking, malnutrition, dehydration, and weight loss and can occur in all age groups but is most common among elderly populations. Physiological changes affecting the nutritional status of the elderly consist of decreasing basal metabolic rate, sensory perception, efficiency and function of body systems and their ability to chew and swallow (number of teeth, saliva secretion, and tongue pressure). Specific oral cavity changes that impact on the bolus preparation stage include tooth loss, flattening of the crown of the chewing teeth, tongue weakness, fatigue, and decreased salivation. (Alsanei & Chen, 2013, Matsuo & Fujishima, 2020).

In many Asian countries, rice porridge is commonly consumed and is given to people who are unwell and older people because of its ease of swallowing and digestion. However, a simple traditional rice porridge lacks the essential vitamins, minerals, and proteins that are needed for healthy living. Riceberry rice is a deep purple whole grain of the *Oryza sativa* L. family, which has a unique aroma and is gluten-free, rich in minerals and antioxidants. It has low to medium Glycemic Index (GI) which measures how quickly a consumed carbohydrate affects postprandial serum glucose levels over a specific time (Suttireung et al., 2019) and other health-promoting effects such as anti-inflammatory, anticancer, anti-hyperlipidemic, and anti-hypoglycemic properties. Riceberry porridge offers a more nutritious alternative to traditional rice porridge with more desirable properties.

Protein and calcium are essential nutrients required in the human body to maintain healthy muscles and bones. Both affect the efficiency and function of bodily systems, including skin, renal, musculoskeletal, cardiovascular, and gastrointestinal systems. However, diets may not contain enough calcium as calcium deficiency is a worldwide issue, particularly so in older populations, leading to osteoporosis, reduced bone mass and in turn a decreased quality of life. Moreover, calcium deficiency is linked to dysphagia as low serum levels of calcium are associated to irritability of autonomic ganglia (Anne & Dolores, 2016). The dietary recommendations for daily calcium supply have been thoroughly studied and determined in various countries, for example, in Thailand, the recommended daily intake (TRDI) of calcium is 800 mg/day (Jaisaard et al., 2021). Ingestion of pure calcium is less effective in absorption compared to calcium contained in peptides as the peptides can chelate calcium, which prevents its precipitation in the intestinal environment thereby increasing the amount of soluble calcium available for absorption (Benjakul et al., 2017). In addition, protein hydrolysates are in itself health-promoting ingredients rich in biologically active peptides and essential amino acids such as glutamic acid, aspartic acid, and glycine (Idowu et al., 2018). Therefore, protein and calcium fortification is a useful approach to provide essential nutrients for porridges consumed by those with dysphagia.

Xanthan gum (XG) is a mild-flavored gum that is stable in many different matrices under a wide range of pH, temperature and is used widely to manipulate the viscosity and functional properties of fluids for a person with impaired swallowing (Ong et al., 2018). For example, XG is added to foods to increase transit times during swallowing, enhance viscosity and cohesiveness between food particles and to improve consumer/patient perception of foods (Seo & Yoo, 2013). It has been shown that the addition of XG as a thickening agent improves the consistency for dysphagia management compared to low viscosity thin rice porridge without thickeners (Syahariza & Yong, 2017).

Textural and rheological characteristics of foods are fundamental factors for dysphagia management as these characteristics are affected directly during the swallowing progression of the bolus. The International Dysphagia Diet Standardization Initiative (IDDSI) and National Dysphagia Diet (NDD) testing are intended to confirm the flow or textural characteristics of food substances and to create a standardized framework to guide the development of appropriate new-modified foods and thickened liquids. The NDD standard utilizes a rheometer to determine the viscosity values of food and liquids as the basis for categorizing into each NDD level. Meanwhile, the IDDSI testing uses common eating/everyday utensils, that is, fork, spoon, and syringe, to evaluate the flow and texture properties of food and liquids. Even though NDD and IDDSI have some similar content, a comparison of NDD and IDDSI levels of various thickened drinks studied by An et al. (2023) revealed that the thickened drinks of NDD levels differed from those of IDDSI levels.

In addition to the NDD and IDDSI frameworks, swallowing characteristics of food and liquids can be assessed using in vivo sensory analysis. Human sensory perception provides descriptions, perceived intensity, and comparison between various foods/modified foods, providing useful data on products' suitability and consumer's preference. Another useful technique is in vitro swallowing stimulator, for example a previously published "Cambridge Throat" which imitates swallowing technique and allows the characterization of the bolus velocity, transit time, and cohesive properties during swallowing (Patel et al., 2020).

In this study, Riceberry rice porridge fortified with 1.5% protein hydrolysate and 589 mg bio-calcium with varying XG concentrations were compared, and investigated by measuring the rheology (NDD measurements), flow and texture characteristics (IDDSI tests), in vitro swallowing (the Cambridge Throat) and developing the lexicon of human perception with sensory evaluation.

2 | MATERIALS AND METHODS

2.1 | Fortified Riceberry rice porridge preparation

Riceberry rice (*Oryza sativa* L., Mah Boonkrong Rice Brand, Patum Rice Mill and Granary Public Company Limited, Thailand) was washed, soaked, drained, and sieved through mesh sieve no. 10 to collect particles with size less than 2.0 mm. The grounded rice with a rice to water ratio of 1:10 was boiled for about 45 min until water had completely evaporated, added chicken soup, 1.5% w/w protein hydrolysate powder, 589 mg bio-calcium produced following the method developed by Idowu et al. (2018). XG powder was added slowly to the Riceberry rice porridge to obtain varying XG concentrations (0% (control), 0.255, 0.50%, 0.75%, 1.0%, and 2.0%) (Chemipan Corporation Co., Ltd, Bangkok, Thailand), heated to a simmer for 5 min while stirring continuously using a blender to ensure thorough mixing and dispersion of the XG particles until the powder was completely dispersed. The resultant Riceberry rice porridges obtained a level of sterilization. Porridges were stored at ambient temperature in sealed containers to be reheated before analyses.

2.2 | Sample preparation for analysis

The porridge samples were reheated by pouring individual samples (10 mL) into beakers, covering with aluminum foils and immediately putting the beaker into a water bath (Grant Instruments™) maintained at 60°C for 9 min. After heating, the porridge samples were cooled to room temperature (25.3 ± 0.5°C) for 19 min.

2.3 | Particle size measurement

Porridge samples (1 mL) were placed onto a standard microscope slide and a thin glass was used to spread the sample evenly covering the surface of the slide. The mean particle size of a sample was determined using a microscope with a LED lights (GXM L3230, GT Vision Ltd, United Kingdom). Samples were measured via 5× objective nosepiece (N.A. = 0.12) with the number of particles measured for each sample being $n = 600$ to determine the average length and width for each sample.

2.4 | IDDSI tests

IDDSI was developed as a standard framework for specific, objective measurements of food textures and thickness. The IDDSI tests categorize foods and drinks by levels using the syringe flow test or IDDSI funnel test based on the rate of flow; the fork drip test was used to check the thickness and cohesiveness and the spoon tilt test was used to determine the stickiness of foods (adhesiveness) and the ability of the food to hold together (cohesiveness). The IDDSI systematic reviews suggested that liquids and food should be classified in the context of the physiological processes involved in oral processing, oral transport, and flow initiation. IDDSI tests were performed on porridges with different XG concentrations (0% (control), 0.255, 0.50%, 0.75%, 1.0%, and 2.0%) following IDDSI classification for thickened liquids using a DDSI funnel, fork drip test, and spoon tilt test (IDDSI, 2016).

2.5 | Rheological measurement

Rheology of porridges was performed using a 1500 EX control-stress rheometer (TA instruments Ltd, United Kingdom) with a 40 mm diameter of parallel plate geometry at a gap of 1000 μm. Shear viscosity at shear rate of 50 s^{-1} (NDD) were measured under a continuous shear rate ramp from 0.1 to 100 s^{-1} at 25°C with the equilibrium step. Flow curves obtained were fitted to power-law model (Equation 1).

$$\tau = K \times \dot{\gamma}^{n}, \quad (1)$$

where τ is the shear stress (Pa), $\dot{\gamma}$ is the shear rate (Pas), K is consistency coefficient, and n is the flow behavior index. The dynamic yield stress was determined as the minimum shear stress in the flow curve with a steady-state flow condition.

2.6 | Textural measurement

Back extrusion test and adhesive test were conducted using a TA-XT2 texture analyzer (TA.XT. Plus, Stable Microsystems, United Kingdom) with slight modification from Aussanasuwannakul et al. (2022) and Peh et al. (2021). For the back extrusion method, the disk was positioned centrally over the container holding 100 mL sample and penetrated the sample to a depth of 20 mm at 10.0 mm s^{-1} test speed. A 10.0 g surface trigger was attained. The extracted data were analyzed using the Exponent Stable Micro Systems software (version 3.0.5.0; Stable Micro System Ltd., Godalming, Surrey, U.K.). The maximum force was taken as a measurement of firmness (*N*). The area under the curve up to this point is taken as a measurement of consistency (*N* s). The maximum negative force, in the negative region of the graph produced during the probe return, was taken as an indication of the cohesiveness (*N*) of the sample. The area of the negative region of the curve refers to as the work of cohesiveness or adhesiveness (*N* s). The adhesive test was analyzed using a 40-mm flat-ended aluminum cylinder mounted to the Texture Analyzer equipped with a 5 kg load cell. The sample was contained in a Petri dish (10.0 cm depth) and placed centrally on the base under the probe. The maximum force required to separate the sample was recorded as the surface stickiness (*N* s). The distance the probe moved away from the sample surface before the force dropped to 2.5 g was recorded as the stringiness (in millimeters).

2.7 | In vitro swallowing behavior

An in vitro swallowing device, "Cambridge Throat" (Figure A1), was designed and modified by Mackley et al. (2013) and Patel et al. (2020). The sample (5 g) was held within a 25 mm wide dialysis tube with molecular weight cut off (MWCO) 3500 Daltons (Medicell Membranes Ltd, United Kingdom) attached to the curved top of the model. The in vitro oral transit time (in vitro OTT) and bolus length (BL) of samples were measured following the methods of Patel et al. (2020). The in vitro OTT were calculated as the time taken by the roller to reach an angle of 120°. BL measured as the length of the bolus from front to tail by captured first images via ImageJ (Fiji) image processing software in the model cavity, which represented the juncture of the pharynx and larynx, before exiting the tubing. Both parameters were applied to characterize the swallowing behavior of porridges.

2.8 | Sensory evaluation

Multisampling difference test was performed using 13 trained panelists aged between 20 and 40 years (male = 6, female = 7) recruited from Hatyai, Songkhla Thailand. Research ethical approval was obtained from the Health Science Human Research Ethics Committee of Prince of Songkla University, Thailand (HSc-HREC: 63-037-1-1). Sensory evaluation was conducted immediately following training using descriptive analysis procedures described by Kim et al. (2017). The panelists attended weekly 1 h training session for a total training time of 10 h. Initially, the definition of slipperiness and viscosity

TABLE 1 Sensory attributes for training of sensory evaluation of rice porridge.

Attributes	Definition/evaluation	Reference
Slipperiness	Degree of slippery or sample being pushed away between tongue and the top part of mouth. Evaluation technique was placed half a spoon in the middle of tongue. When compressing once food toward the palate after putting on the tongue, rate the degree of slipping tongue.	Sour cream (Aro, Siam Makro Plc.) = 5.0 Mayonnaise (HEINZ Good Mayonnaise (HEINZ Company, Pittsburgh, PA)) = 8.0 Instant vanilla pudding (Jell-o, Kraft Heinz foods company, Chicago, USA) = 10.0 Rice porridge(rice porridge with 0.25% XG, Hydrolysate 1.5% and bio-calcium 589 mg) = 12.0 Jelly carrageenan with konyakku powder, Vitamin B, C and 8% Yuzu Juice, Yuzu flavor = 14.0
Viscosity	Evaluation technique was considered in two steps. Step 1, "flow rate" and "flow characteristic" were considered when pouring a spoonful of a sample (5 g) into a cup. Step 2, "resistant force" was evaluated by the tongue. A spoonful of sample was poured onto the panelist's tongue, and then slowly pushed toward the palate. The panelists gently swept the sample and considered the resistance and the force required to move the sample across the tongue.	Porridge A = 5.75 (Boiled rice*:water = 1:1) Porridge B = 7.5 (Boiled rice*:water = 1.5:1) Porridge C = 10.5 (Boiled rice*:water = 2:1) Porridge D = 13.5 (Boiled rice*:water = 3:1) Porridge E = 15.0 (Boiled rice*) *Jasmine rice 200 g, water 1000 g, 100°C, 12 min (100%Thai Hom Mali Rice, new crop of special sort rice, Mah Boonkrong Rice Brand, Patum Rice Mill and Granary Public Company Limited, Thailand)

attributes was generated and agreed by the panelists. The reference samples were presented to the panelists (Table 1). Panelist were also trained on the use of a 15 cm line scale, anchored with the words "low" and "high" 1.5 cm from each end, and was used to rate the intensity of each attribute. The six Riceberry rice porridges of 20 ± 2 g were presented in identical plastic cups at 25°C covered with aluminum foils and labeled with three-digit random numbers to avoid any bias during evaluation. The order of presentation of the samples was randomized according to "balance order and carry-over effects design." All sensory testing was carried out in partitioned booths under white light and at a maintained room temperature (25 ± 2°C). Room temperature water was provided for the panelists to cleanse their palates for 10 min after testing each sample. The tests were then replicated on different days. Panelists recorded their responses on a 15 cm intensity line scale.

2.9 | Data analysis

All experiments (IDDSI test, Rheology, texture, in vitro swallowing test, and sensory evaluation) for the development of rice porridge formulation were run a minimum of five times and reported as mean ± standard deviation. Comparison of means carried out by Duncan's multiple range tests at a significant level $p < .05$. For in vitro swallowing test, the in vitro OTT and BL were presented as mean ± 95% confidence interval (CI) and the Shapiro–Wilk test—normal distribution was used to test the normality of the data. It was confirmed that the data were normally distributed. The statistical software SPSS package (SPSS version 10.0 for window, SPSS Inc., Chicago, IL, USA) was used to conduct normality tests and the Pearson's product–moment correlation between XG concentration levels and instrumental/sensory parameters.

3 | RESULTS

3.1 | Particle size of rice porridges

Particles of Riceberry porridge were of consistent size and shape regardless of XG concentrations. The two-dimensional irregular shapes of the porridge particles as seen in Figure 1a were found to have an average width of 91.72 ± 31.23 μm and an average length of 150.95 ± 39.15 μm.

3.2 | International dysphagia diet standard initiative levels

The funnel (syringe flow) test showed that the control sample (no XG) and thickened porridge at 0.25% XG were at IDDSI level 3 with less than 10 mL sample remaining in the syringe, whereas samples with 0.50%–2.0% XG concentrations were at level 4 (Figure 1b). The same results were confirmed by the fork drip test (Figure 1c). For the thickened porridges with 0.50%–2.0% XG, most samples were sat in a mound above the fork, form a short tail below the fork prongs and little amount was left on the spoon. This further confirms that samples with 0.50%–2.0% XG were at IDDSI level 4.

3.3 | NDD and rheological characteristics

The porridges were defined by viscosity as nectar-level (51-350 cP) (no. XG), honey-level (351-1750 cP) (0.25%, 0.50%, and 0.75% XG), and spoon-thick (>1750 cP) (1.0% and 2.0% XG) as depicted in Table 2. As expected, the viscosity of porridges increased with increasing XG concentrations. Statistically, viscosity values of

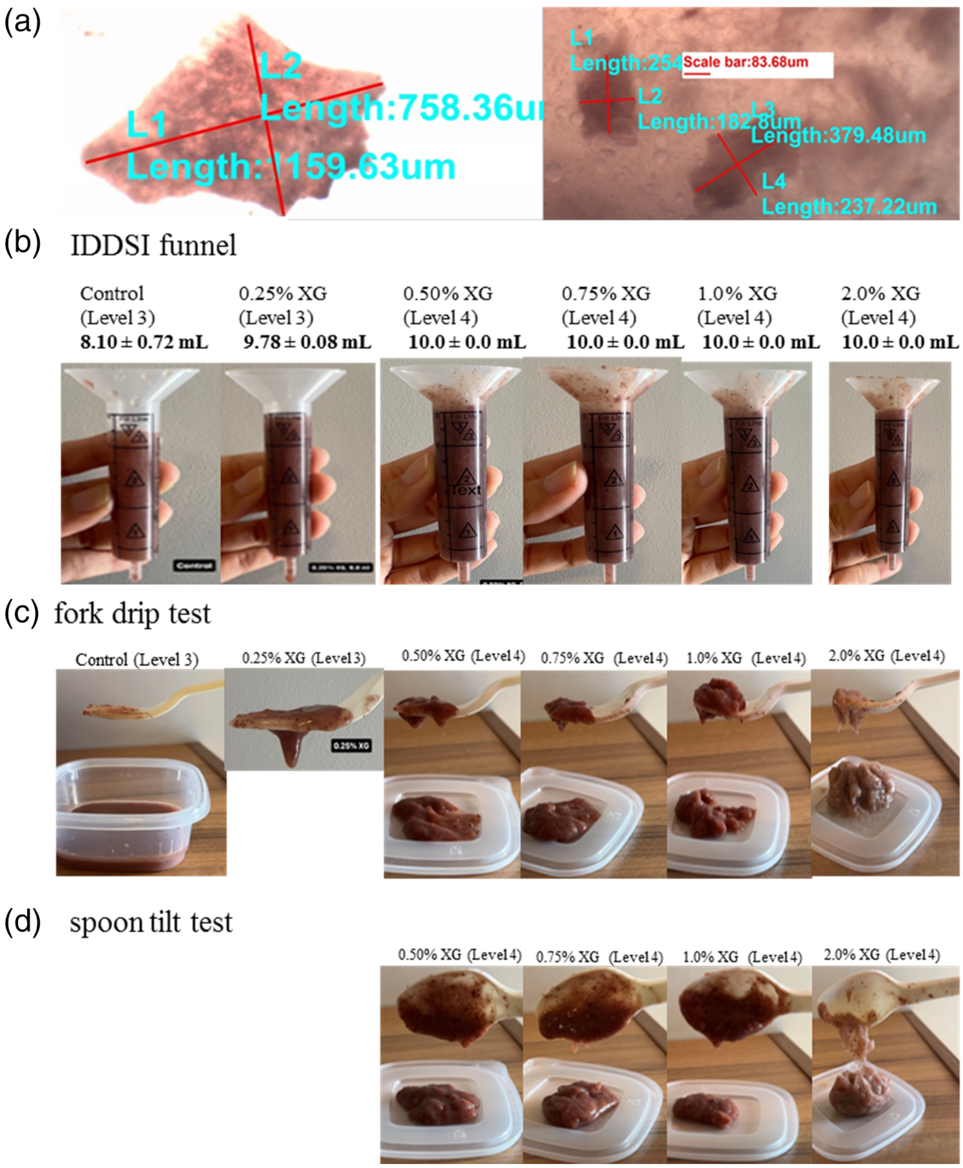

FIGURE 1 Particle sizes of Riceberry rice porridge (a) and International Dysphagia Diet Standardization Initiative (IDDSI) tests of Riceberry rice porridges with various xanthan gum concentrations including IDDSI funnel (b), fork drip test (c) and spoon tilt test (d).

porridges with 1.0%–2.0%, with 0.755–1.0% and with 0.255–0.75% XG were significantly different ($p < .05$). The log–log plot of apparent viscosity as a function of shear rate for Riceberry rice porridge with various XG concentrations was shown in Figure 2; the close to linear curve log–log indicates a pseudoplastic behavior. All samples were presented pseudoplastic characteristics with a yield stress and demonstrated shear-thinning behavior The flow behavior index (n value) or degree of shear thinning were below 1 for all samples and decreased with increasing XG concentration (indicating higher degrees of shear thinning). The n value was statistically different for increased XG concentrations ($p < .05$). Moreover, the consistency coefficient (K) and yield stress values with steady-state flow and flow continue ramp step increased with in XG concentration and were significantly different ($p < .05$). The porridge with 2.0% XG had the highest degree of shear thinning behavior, the highest K value indicating internal stable structure and the highest yield stress, which were forces to areas both flow stopping and starting.

3.4 | Texture characteristics

Textural parameters were defined by back extrusion (firmness, consistency, cohesiveness, adhesiveness) and adhesive test (surface stickiness, stringiness) for the porridge samples. Firmness referred to the force required to compress a food sample to a specified percentage of its original height. It reflects the hardness or resistance of the sample to deformation under compression. Consistency was a measure of how the force needed to deform the sample changes over successive compressions. It indicates the degree of structural integrity and stability of the sample during repeated deformation. Cohesiveness measured how well the sample holds together during compression and subsequent release. It quantifies the extent of internal bonding or stickiness within the sample. Adhesiveness measured the force required to overcome the attractive forces between the sample and the surface of the probe during the first compression. It quantifies the stickiness of the sample.

TABLE 2 Rheological and textural characteristics for Riceberry rice porridges containing different xanthan gum concentrations.

Samples	NDD levels	Viscosity (mPa s) at shear rate of 50 s^{-1}	Consistency coefficient, *K* ($Pa.s^n$)	Flow behavior index, *n*	Yield point (Pa)		Firmness (N)	Consistency (N s)	Cohesiveness (N)	Adhesiveness (N s)	Surface stickiness (N)	Stringiness (mm)
					Flow steady-state step	Flow continuous ramp step						
Control	Nectar	187.6 ± 1.7^{d}	3.114 ± 0.181^{e}	0.299 ± 0.007^{a}	$1.5. \pm 0.3^{f}$	4.9 ± 0.7^{f}	0.132 ± 0.029^{f}	1.104 ± 0.020^{f}	0.069 ± 0.001^{f}	0.076 ± 0.003^{f}	0.060 ± 0.000^{f}	12.0 ± 0.0^{c}
0.25% XG	Honey-like	663.0 ± 15.4^{cd}	12.560 ± 1.626^{e}	0.233 ± 0.010^{b}	6.8 ± 0.1^{e}	15.5 ± 0.4^{e}	0.144 ± 0.004^{e}	1.310 ± 0.014^{e}	0.106 ± 0.001^{e}	0.150 ± 0.005^{e}	0.090 ± 0.002^{e}	12.6 ± 0.1^{c}
0.50% XG	Honey-like	1180.0 ± 70.7^{c}	29.680 ± 1.386^{d}	0.181 ± 0.009^{c}	16.0 ± 1.0^{d}	32.3 ± 1.1^{d}	0.376 ± 0.009^{d}	3.112 ± 0.036^{d}	0.413 ± 0.007^{d}	0.400 ± 0.010^{d}	0.208 ± 0.009^{d}	16.2 ± 0.8^{ab}
0.75% XG	Honey-like	1542.0 ± 94.8^{bc}	46.415 ± 0.007^{c}	0.147 ± 0.001^{d}	29.2 ± 1.4^{c}	52.4 ± 1.1^{c}	0.483 ± 0.012^{c}	3.852 ± 0.069^{c}	0.413 ± 0.007^{c}	0.537 ± 0.017^{c}	0.250 ± 0.010^{c}	15.7 ± 0.7^{b}
1.0% XG	Spoon-thick	2275.5 ± 300.5^{ab}	89.405 ± 9.963^{b}	0.102 ± 0.019^{e}	45.2 ± 3.9^{b}	89.9 ± 3.1^{b}	0.719 ± 0.022^{b}	5.399 ± 0.141^{b}	0.555 ± 0.022^{b}	0.667 ± 0.023^{b}	0.279 ± 0.010^{b}	17.0 ± 1.4^{a}
2.0% XG	Spoon-thick	2694.0 ± 847.1^{a}	170.350 ± 11.667^{a}	0.051 ± 0.008^{f}	104.6 ± 3.8^{a}	194.8 ± 2.3^{a}	0.984 ± 0.040^{a}	7.020 ± 0.161^{a}	0.625 ± 0.016^{a}	0.744 ± 0.026^{a}	0.336 ± 0.017^{a}	16.6 ± 1.3^{ab}

Note: All values are means ± standard deviation ($n = 9$). [a–f] In the same column with different xanthan gum concentrations addition, mean values followed by the different superscripts are significantly different ($p < .05$).

Surface stickiness referred to the stickiness or tackiness of the sample's surface, specifically when a force is applied to it. It quantifies the degree to which the surface of the sample adheres to a contacting surface or probe. Stringiness measured the ability of the sample to form string-like structures when subjected to deformation or shearing forces. It reflects the elongation and thinning of the sample into strands or strings. Stringiness is usually quantified by observing the length and thickness of the strands formed during testing.

Porridges having different XG concentrations showed significant differences ($p < .05$) in these characteristics as shown in Table 2. The porridge with the highest XG concentrations (2.0% XG) had the highest firmness, consistency, cohesiveness (~0.984 *N*, 7.020 *N*s, and 0.625 *N*, respectively), adhesiveness (~0.744 *N* s), and surface stickiness as expected. It indicates that the porridge at this XG concentration needs to be consumed and breakdown with the highest muscle forces to compress to achieve deformation. In addition, the porridge bolus has the highest internal and external bonding which affects how the bolus holds together and between the palate surfaces during compression and being released that allow for swallowing. However, the stringiness of porridges with 0.50%, 0.75%, 1.0%, and 2.0% XG were not significantly different ($p \geq .05$). This shows that the ability of the samples to form string-like structure is independent of the XG concentration.

3.5 | In vitro swallowing behavior

Using the in vitro swallowing device, or "Cambridge throat", the velocity or transit time and cohesion of the bolus flow were assessed through the in vitro OTT and BL, respectively. The in vitro flow effects of the varying XG concentrations in the porridges on the transit time and on the BL are summarized in Figure 3. As the XG concentrations of the porridge increased, the in vitro OTT lengthened and BL shortened. Significant differences in vitro OTT and BL were observed between the levels of XG ($p < .05$). The porridge with 2.0% XG has the longest of the in vitro OTT ($p < .05$), whereas BL was similar to the porridge with 1.0% XG.

3.6 | Sensory evaluation

The participants perceived samples, which were pushed between tongue and the roof of the mouth. In Figure 3, rice porridge with no XG additions had the highest degree of slipperiness. However, additions of 0.25% and 0.50% XG were not significantly different from control ($p \geq .05$) as their lower concentrations could make it hard for the panelist to detect a noticeable difference between samples. On the other hand, among samples XG concentrations from 0.75%–2.0% there were significantly differences ($p < .05$) observed when compared to the control. Therefore, at concentrations higher than 0.75% XG, the slipperiness of the porridge decreased which helps to slow the velocity of bolus for safer swallowing.

The viscosity perceptions of porridge with XG additions were significantly different from the control ($p < .05$). Increased XG levels in samples increased their resistance with greater force being required to move the sample across the tongue, implying that the bolus should flow slower through the pharynx during swallowing with XG.

4 | DISCUSSION

Under microscope rice fragments or damaged starch granules were shown in the fortified Riceberry rice porridge post preparation. Riceberry rice requires a high temperature and a relatively long time to process due to its high amylose content (17.52%) which inhibited the swelling of starch granules during cooking (Juemanee et al., 2018). The grinding and heating processes involved in the production of the porridge could cause the release of protein, starch granules, and other substances and produce an aggregation of particles.

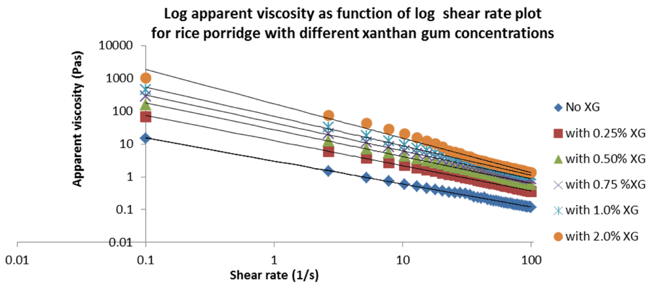

FIGURE 2 Log–log plot of apparent viscosity as a function of shear rate for Riceberry rice porridge with various xanthan gum concentrations.

The thickness levels with IDDSI tests and the accurate apparent viscosity values at shear rate of 50 s^{-1} ($\eta_{a,50}$) for NDD standards are both routinely used to monitor foods for patient with dysphagia. For the fortified Riceberry rice porridges, the results of the IDDSI tests and the apparent viscosity values (NDD test) were not statistically different at corresponding XG concentrations ($p \geq .05$). As the concentration of XG increased, the apparent viscosities (NDD test) and the thickness levels of the IDDSI tests increased due to the higher degrees of XG intermolecular interactions (Seo & Yoo, 2013).

A high positive relationship between XG concentration and apparent viscosity was demonstrated by a high Pearson's correlation coefficient (full details of Pearson's correlations coefficients between XG concentrations and instrumental measurements are shown in Table 3). The viscosity of XG in porridges arises predominantly from physical entanglement of conformationally disordered random polymeric coils. When XG is dispersed in the liquid component of porridge, its molecules form a network through physical entanglement. This entanglement occurs due to the long, flexible, and branched structure of XG molecules. XG molecules exist as long chains with a random coil conformation. This means that the molecular chains are not rigidly structured but rather adopt a flexible and disordered arrangement. These conformationally disordered coils allow XG molecules to move and interact with each other in a tangled manner. The main source of viscosity in porridges containing XG is this physical entanglement of conformationally disordered random polymeric coils. As the porridge is stirred or mixed, the XG molecules form a network that impedes the flow of the liquid phase, resulting in increased viscosity or thickness. Physical entanglement is a significant contributor to viscosity, other factors such as concentration of XG, temperature, and shear forces (mixing or stirring) also influence the final viscosity of XG-containing porridges. The

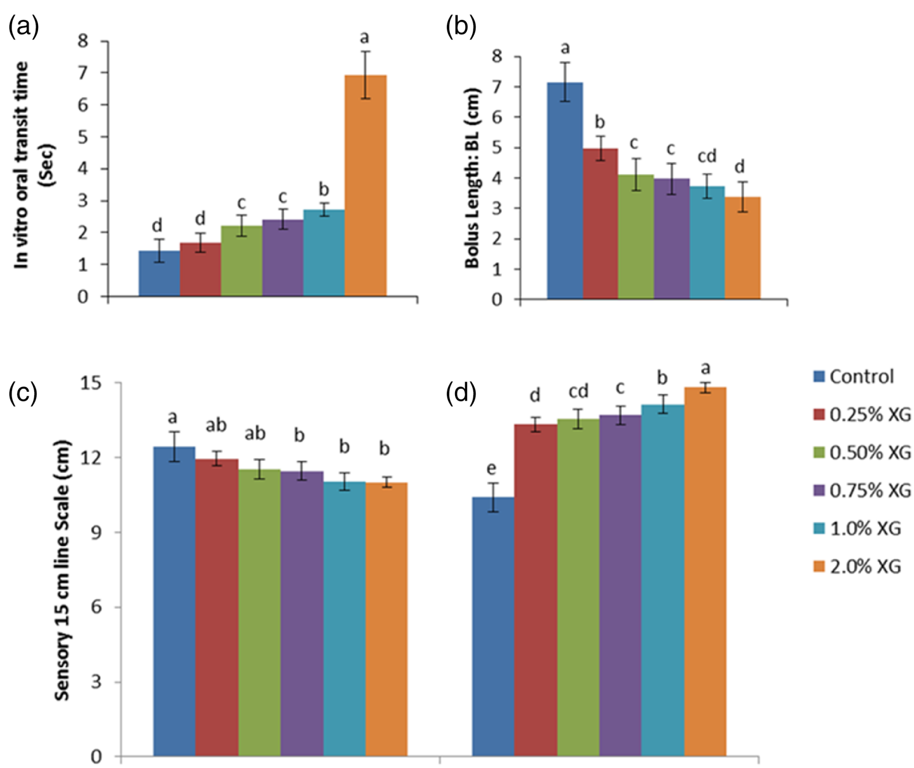

FIGURE 3 In vitro oral transit time (in vitro OTT) (a), bolus length (BL) (b) and mean scores of slipperiness (c) and viscosity attributes (d) in Riceberry rice porridges with different xanthan gum concentrations. A and B are evaluated using the in vitro throat model; C and D are collected by human sensory panel. Bars represent standard deviation (in vitro OTT (a) and BL (b)) ($n = 15$), slipperiness (c) and viscosity attributes (d) ($n = 13$). Different letters within the same parameter denote significant difference.

TABLE 3 Pearson's correlation coefficients between characteristics of Rice berry rice porridge with different xanthan gum concentrations.

		Texture characteristics						Rheological characteristics					In vitro swallowing		In vivo swallowing	
	Concentration	Firmness	Consistency	Cohesiveness	Adhesiveness	Surface stickiness	Stringiness	Viscosity	Consistency coefficient	Flow behavior index	Yield stress 1	Yield stress 2	Bolus length	Oral transit time	Slipperiness	Viscosity
Concentration	1	.978	.984	−.984	−.988	.975	.809	.995	.922	−.994	.901	.841	−.824	.903	−.408	.834
Firmness	.978	1	.998	−.970	−.963	.950	.769	.977	.969	−.963	.953	.898	−.777	.920	−.720	.748
Consistency	.984	.998	1	−.981	−.975	.963	.796	.982	.955	−.971	.936	.879	−.796	.922	−.725	.763
Cohesiveness	−.984	−.970	−.981	1	.996	−.985	−.859	−.982	−.884	.976	−.858	−.799	.830	−.896	.738	−.792
Adhesiveness	−.988	−.963	−.975	.996	1	−.989	−.851	−.984	−.877	.980	−.852	−.795	.845	−.897	.728	−.811
Surface stickiness	.975	.950	.963	−.985	−.989	1	.847	.965	.864	−.974	.849	.803	−.861	.895	−.725	.819
Stringiness	.809	.769	.796	−.859	−.851	.847	1	.801	.632	−.827	.609	.565	−.731	.663	−.532	.738
Viscosity	.995	.977	.982	−.982	−.984	.965	.801	1	.921	−.985	.895	.834	−.833	.928	−.725	.826
Consistency coefficient	.922	.969	.955	−.884	−.877	.864	.632	.921	1	−.905	.991	.932	−.704	.900	−.672	.697
Flow behavior index	−.994	−.963	−.971	.976	.980	−.974	−.827	−.985	−.905	1	−.887	−.830	.881	−.920	.728	−.882
Yield stress 1	.901	.953	.936	−.858	−.852	.849	.609	.895	.991	−.887	1	.946	−.690	.885	−.638	.685
Yield stress 2	.841	.898	.879	−.799	−.795	.803	.565	.834	.932	−.830	.946	1	−.661	.845	−.591	.643
Bolus length	−.824	−.777	−.796	.830	.845	−.861	−.731	−.833	−.704	.881	−.690	−.661	1	−.702	.415	−.892
Oral transit time	.903	.920	.922	−.896	−.897	.895	.663	.928	.900	−.920	.885	.845	−.702	1	−.318	.750
Slipperiness	−.408	−.720	−.725	.738	.728	−.725	−.532	−.725	−.672	.728	−.638	−.591	.415	−.318	1	−.226
Viscosity	.834	.748	.763	−.792	−.811	.819	.738	.826	.697	−.882	.685	.643	−.892	.750	−.226	1

Note: Interpreting the size of a correlation coefficient including $r = .90$ to 1.00 (−.90 to −1.00) = very high positive (negative) correlation; $r = .70$ to .90 (−.70 to −.90) = high positive (negative) correlation; $r = .50$ to .70 (−.50 to −.70) = moderate positive (negative) correlation; $r = .30$ to .50 (−.30 to −.50) = low positive (negative) correlation; $r = .00$ to .30 (.00 to −.30) = negligible correlation.

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porridges with high viscosity ($r = .995$) as shown in Table 3 have high intermolecular interactions, requiring more force for propulsion of bolus from the mouth into the pharynx (Hadde et al., 2021).

The *n* values of porridges showed a tendency to decrease with increasing XG concentrations (indicating increasing degree of shear thinning). The shear thinning behavior is due to rearrangements in the porridge microstructure in the plan of applied shear, implying that higher viscosity at lower shear rates was beneficial in controlling swallowing in the oral cavity of those suffering from dysphagia (e.g., applying low force during oral preparation phase of swallowing). When the boluses were swallowed, they underwent a high shear rate during the pharynx phase of swallowing, where their viscosity was lowered and able to flow through the pharynx (Hadde et al., 2021). A study by Nishinari et al. (2011) investigated the oral and pharyngeal residue and risk of aspiration in healthy persons and patients with dysphagia using videofluorographic observation. Some patients with dysphagia aspirated the sample boluses with increased risk of aspiration at decreased bolus viscosity at low shear rates. Therefore, determining the apparent viscosity and flow behavior index (*n* values) assists in the understanding of risk of aspiration of the porridge samples.

Furthermore, the consistency coefficient values (*K* values) via power law model using shear rheological analysis of thickened porridges were higher in those containing increased XG concentrations. The *K* value is determined by the intermolecular spacing and the hydrogen-bond strength in the sample. This implied that increasing XG concentration decreased the ability to suspend and disperse particles indicating the viscous nature of the porridges. Intrinsic structures within thickened porridges were indicated by the yield stress, which is the degree of the shear stress related to the state of microstructural changes in the porridges. The porridges yield stress increased with increasing XG concentrations indicating a high stability and elasticity which are correlated to the degree of cohesiveness ($r = .858$) as shown in Table 3. The most stable porridge in this regard at 2.0% XG was resultant from the rigid structure of XG and internal binding forces that contribute to the formation of a more coherent bolus and facilitate more efficient clearance during swallowing (Nakauma et al., 2011).

As correspond to textural data, the bolus textures showed high forces at the point of contact between the probe surface and sample surface implying that would assist in the formation and maintenance of a bolus where tongue control is impaired and/or the swallowing reflex is delayed (Ross et al., 2019).

A very high correlation between firmness and consistency of the thickened porridges ($r = .998$) with XG concentrations were demonstrated. Consistency of thickened porridges is dependent on the interparticle interactions of rice cell walls, the XG in the continuous phase and the possibility of thickener-porridge particle interactions (Peh et al., 2021). The firmness is associated with XG network structure enhanced by the polysaccharide chains in the presence of the rice particles within the product matrix. However, it is worth noting that the extent of differences in the firmness measured by instrumental methods was not always linearly perceived in the mouth by human subjects because human perception is limited to samples that can be confined between the tongue and palate or the teeth.

Adhesiveness of the porridge correlated well with the cohesiveness ($r = .996$) and consistency ($r = .975$) values as shown in Table 3. The hydroxyl and carboxyl polar groups of XG in the porridges undergo intramolecular and intermolecular hydrogen bonding interactions in aqueous solutions. As associated with attraction between the molecules surface, XG resided on the starch surface affected the adhesiveness. Due to high molecular weight and substantial hydrogen bonding interactions, an aqueous solution of XG exhibits high adhesiveness even at low concentrations. Porridges with XG addition showed a higher level of adhesiveness compared to its cohesiveness, whereas without the addition of XG, the porridge had adhesiveness values close to their cohesiveness values. XG has known mucoadhesive properties; when a XG based system is added to a mucus and mucosal rich environment such as the oral cavity and the pharynx, it is able to stick and retain (Jadav et al., 2023). Mucoadhesion holds the carrier to the biological site by interfacial forces; the high adhesive nature of the sample indicates its prolonged retention in the upper gastrointestinal tract especially its post peaks duration of anterior tongue activity during swallowing in the upright, inclined and supine position (Salgado et al., 2022). These help to release flavor and deliver protein especially hydrolysate from the porridge. However, prolonged retention of food residue accumulated in the oropharynx may lead to aspiration so a balance in the porridges adhesive and cohesive properties is required.

The time duration of swallowing is an important criterion for dysphagia food management. The in vivo OTT which was defined as the time between the incision and the passage of the last portion of the bolus by the jaw were 1.0 s in young adults with a thin liquid consistency, and 1.5 s in the elderly, respectively (Tamin et al., 2022).

In vivo evaluation of foods is invasive and costly, whereas a simulation of in vitro swallowing showed that thickened porridges slowed the bolus flow with a long in vitro OTT. This correlates with the rheological and texture properties of the samples, for example, cohesiveness, firmness, adhesiveness, surface stickiness and stringiness, corresponding to binding forces between particles of the bolus. The long in vitro OTT and the associated decrease in elongation of bolus (short BL) indicate that porridges with XG decrease risk of post-swallowing aspiration in people with dysphagia.

The BL performed in the in vitro swallowing tests showed a high relationship with surface stickiness ($r = -.861$) and stringiness ($r = -.731$), respectively. Surface stickiness involves a combination of adhesive and cohesive forces, and stringiness is defined as the extension of the filament. They are influenced by intrinsic factors such as surface tension and viscoelastic properties of the bolus. The BL decreased with increased XG concentrations ($r = -.824$) as shown in Table 3. At no XG concentration (nectar-like), porridge produced the significantly long BL. Boiling rice in a great deal of water breaks down rice particles into a consistency, which was developed by swollen starch granules. This consistency does not show sufficient cohesiveness for safe swallowing. Porridges with 0.50% and 0.75% XG produced significantly shorter BL than 0.25% XG, despite the same NDD level (honey-like). This is supported by the stringiness values; as the XG concentration increased, the filament-thinning rate and the porridge deformation uniformly decreased (Hadde et al., 2019).

For human perceptions, the addition of high XG concentrations had a low negative relationship ($r = -.408$) with perceived slipperiness and a high positive relationship ($r = .834$) with perceived viscosity, respectively, whereas perceived viscosity showed negligible correlation with perceived slipperiness ($r = -. 226$) as shown in Table 3. Perceived viscosity was detected at the beginning of the oral processing relating to the flow rate and resistant force (shear force) in the porridges. Increased viscosity with increased XG concentrations was perceived with high pouring and pushing forces toward the palate. The perceived slipperiness associates to the subsequent stages of oral processing via compressing the porridge bolus toward the palate after putting on the tongue. Slipperiness perception is resultant from a mixture of frictional and viscous components related to lubrication in the mouth. It was reported that there is a reduction in friction with more viscous porridges (Blok et al., 2020), caused by a thin, immobile layer of thicken bolus between tongue and palate surface stopping the relative movement of the contacting surfaces. In the current study, we found that the rating for slipperiness of porridges at IDDSI level 3 was higher than in those at level 4, reflecting the reduction in friction at higher viscosity levels. Furthermore, the perceived slipperiness was dependent on the viscosity of the porridges at below a certain viscosity level and above this threshold; the slipperiness becomes dependent on shear-thinning behavior of the sample. The shear-thinning profiles of porridges with *n* values measured in the rheological tests had a high relationship with perceived viscosity ($r = -.882$) and with perceived slipperiness ($r = .728$), respectively. Highly shear thinning porridges (low in *n* values) were rated high perceived viscosity and low perceived slipperiness intensities.

This was in agreement with the work of Szcesniak and Farks (2006) who have shown that XG displayed slipperiness-inducing behavior relating to its shear-thinning behavior.

When rice porridge is consumed and mixed with amylase in the oral cavity, it breaks down, which decreases the porridge's viscosity and increases bolus flow velocity leading to aspiration risk in patients with dysphagia. The thickened porridges promote adequate oral intake due to a consistency appropriate for swallowing and propelling the resulting bolus from the mouth to the stomach. This is because the immobile molecule of XG becomes entangled in high-order networks and cause an increase in the viscosity and thickness of porridges (Duangsai & Gawborisut, 2022).

Through the investigation of this study, correlation between the data from rheology, texture properties, IDDSI and artificial throat of the porridges can be drawn. Rheology deals with the flow and deformation behavior of the porridges, including viscosity and shear stress, whereas texture parameters of the porridges reveals their mechanical properties. Both textural data and rheological data are dependent on the internal molecular structure of the porridge mainly affected by the addition of XG. IDDSI is a framework for categorizing consistency of food and drink applicable to practical safety and suitability for individuals with dysphagia, which in turn is fundamentally determined by the rheological and textural properties of the porridge align with the recommended texture levels for dysphagia management. The artificial throat simulates swallowing conditions in the oral cavity, evaluating more realistically how easily and safely the porridge can be swallowed compared to other instrumental measurements and providing a more holistic understanding of the relationship between the physical properties of the porridge and its swallowing safety.

This study, for the first time, demonstrates the correlations of physical properties, measured by various instrumental tests, and swallowing behavior, and safety of XG fortified Riceberry rice porridges. It provides valuable understanding for optimizing the porridge formulation (and any other food types consumed by patients with dysphagia) to achieve desired texture, flow properties, and swallowing safety for individuals with dysphagia.

5 | CONCLUSION

This study demonstrated that instrumental measurement of relevant rheological, textural, and in vitro parameters could be used to demonstrate the oral stages of swallowing, and trained panelists can be utilized for the perception of various NDD and IDDSI levels of thickened Riceberry rice porridges with XG concentrations related to impaired oral manipulation. XG-based thickener provides beneficial swallowing characteristics correlated to binding force between porridge particles and interfacial forces between the tongue or palate and the porridge during swallowing. Overall, correlating data from rheology, texture analysis, IDDSI testing, and artificial throat evaluations provided a comprehensive understanding of the textural and flow characteristics of XG-based porridge and its implications for dysphagia management. This information provides reliable data to producers to develop safe foods for elderly and dysphagia patients.

AUTHOR CONTRIBUTIONS

Pakanun Charoensri: Investigation; writing–original draft; writing–review and editing; methodology; validation; formal analysis; data curation. **Sam Aspinall**: Investigation; writing–original draft; methodology; writing–review and editing; supervision; formal analysis. **Fang Liu:** Supervision; investigation; writing–review and editing; methodology. **Kongkarn Kijroongrojana:** Conceptualization; investigation; funding acquisition; writing–review and editing; writing–original draft; methodology; visualization; project administration; supervision.

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CONFLICT OF INTEREST STATEMENT

The authors declare that they do not have any conflict of interest.

DATA AVAILABILITY STATEMENT

Raw data were generated at the Prince of Songkla University & University of Hertfordshire. Derived data supporting the findings of this study are available from the corresponding author on request.

ETHICS STATEMENT

Ethical approval for this study was approved by the Health Science Human Research Ethics Committee of Prince of Songkla University, Thailand (HSc-HREC: 63-037-1-1).

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APPENDIX A

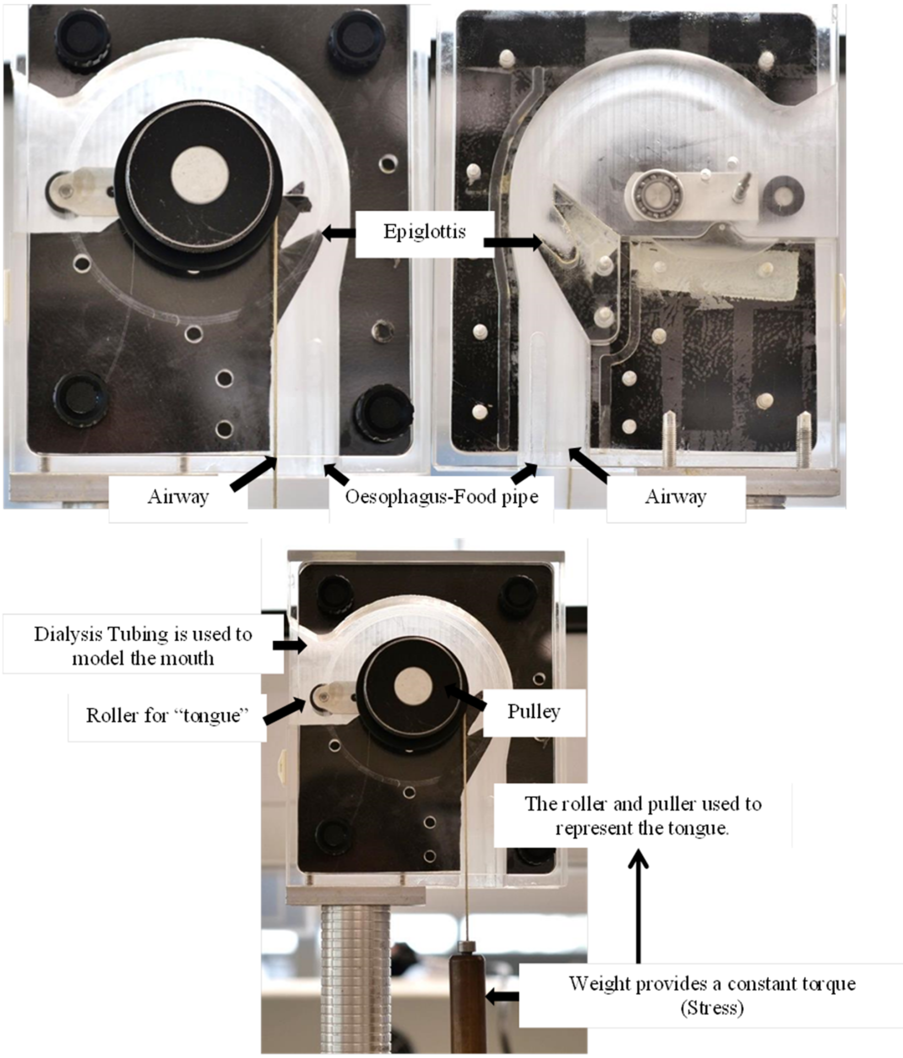

FIGURE A1 Compositions of in vitro swallowing device or "Cambridge Throat."