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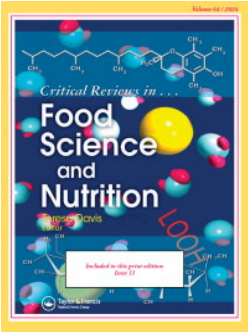

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REVIEW ARTICLE

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Polysaccharide–dextrin thickened fluids for individuals with dysphagia: recent advances in flow behaviors and swallowing assessment methods

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ABSTRACT

The global aging population has brought about a pressing health concern: dysphagia. To effectively address this issue, we must develop specialized diets, such as thickened fluids made with polysaccharide–dextrin (e.g., water, milk, juices, and soups), which are crucial for managing swallowing-related problems like aspiration and choking for people with dysphagia. Understanding the flow behaviors of these thickened fluids is paramount, and it enables us to establish methods for evaluating their suitability for individuals with dysphagia. This review focuses on the shear and extensional flow properties (e.g., viscosity, yield stress, and viscoelasticity) and tribology (e.g., coefficient of friction) of polysaccharide–dextrin-based thickened fluids and highlights how dextrin inclusion influences fluid flow behaviors considering molecular interactions and chain dynamics. The flow behaviors can be integrated into the development of diverse evaluation methods that assess aspects such as flow velocity, risk of aspiration, and remaining fluid volume. In this context, the key *in-vivo* (e.g., clinical examination and animal model), *in-vitro* (e.g., the Cambridge Throat), and *in-silico* (e.g., Hamiltonian moving particles semi-implicit) evaluation methods are summarized. In addition, we explore the potential for establishing realistic assessment methods to evaluate the swallowing performance of thickened fluids, offering promising prospects for the future.

KEYWORDS

Polysaccharide dextrin; thickened fluids; dysphagia food; rheological properties; swallowing behaviors; tribological properties

1. Introduction

In the current landscape, the global population is grappling with the challenges posted by the aging demographic. According to *the United Nations' World Population Prospects: The 2019 Revision*, it is projected that the elderly population will comprise approximately 16% of the world's total by the year 2050 (source: https://www.un.org/zh/global-issues/aging). Among the issues faced by older individuals, dysphagia stands out, representing the difficulty in smoothly moving food from the mouth to the stomach (Abu-Ghanem, Chen, and Amin 2020). Dysphagia also affects specific groups dealing with various medical conditions, such as sarcopenia, neurological disorders, cancer, and inflammation-related ailments (e.g., stroke, Parkinson's, and dementia) (Smukalla et al. 2017). It is noteworthy that over 50% of patients with acute illnesses and nursing home residents aged 65 or older may experience symptoms of dysphagia (Forster et al. 2011). In particular, older individuals may exhibit reduced chewing ability, decreased saliva production, and delayed closure of the epiglottis, leading to dysphagia symptoms like aspiration and choking during food swallowing (Rodd, Tas, and Taylor 2022; Vivanti et al. 2009; Pae, Meydani, and Wu 2012). Additionally, dysphagia can cause issues like dehydration, malnutrition, pneumonia, and other respiratory ailments, elevating hospitalization rates and mortality among affected patients (Ebihara et al. 2016).

To enhance the quality of life for individuals grappling with dysphagia, a range of specialized diets has been developed, including thickened fluids (e.g., water, milk, juices, and soups) and texture-modified foods (TMFs) (e.g., vegetables, fruits, pork, and chicken), have been developed. Among these options, thickened fluids are favored by people with dysphagia, as they require less chewing effort during swallowing compared with TMFs (Hadde and Chen 2021). It has been observed that the presence of a thickening agent in fluids can elevate viscosity and cohesiveness, thereby reducing flow velocity. This, in turn, affords more time for muscle regulation and the closure of the epiglottis in individuals with dysphagia, mitigating the risks associated with dysphagia, such as aspiration and choking (Methacanon et al. 2021; Kongjaroen, Methacanon, and Gamonpilas 2022; Hadde and Chen 2019; Marconati and Ramaioli 2020).

Dysphagia fluids are typically thickened using various polysaccharides, such as xanthan gum (XG), guar gum (GG), konjac glucomannan (KGM), locust bean gum (LBG), κ-carrageenan (KC), methylcellulose (MC), sodium carboxymethylcellulose (CMC), and modified starch (Ross et al. 2019). These polysaccharide chains exhibit entanglement and

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interactions (e.g., hydrogen bonding) within the fluid matrix, resulting in remarkable thickening effects that play a crucial role in the swallowing performance of these fluids, affecting aspects like aspiration risk and residual amount (Evageliou 2020). To ensure the dissolution, dispersion, and thickening properties of polysaccharides at room temperature, binder components, typically dextrins, are commonly incorporated. The addition of dextrins, such as maltodextrin and cyclodextrin, enhances the surface adhesion of polysaccharide particles within the fluid matrix. This, in turn, facilitates the collision and binding of wetted particles, ensuring instant dispersion at room temperature (Lee and Yoo 2021; Jeong, Bak, and Yoo 2019). Consequently, this leads to alterations in the chain interactions and thickening characteristics of the resultant polysaccharide–dextrin fluids. Furthermore, dextrin serves as a functional component with a significant role in enhancing immune system function, stabilizing blood sugar and lipid levels, and providing nutritional supplementation (Farhangi et al. 2018; Gentilcore et al. 2011; Slavin et al. 2009). Over time, extensive efforts have been dedicated to crafting polysaccharide–dextrin-thickened fluids tailored to exhibit specific flow behaviors and optimized swallowing performance (Kim, Kim, and Yoo 2017; Aguilera and Park 2016). Also, these dysphagia fluid diets can be easily prepared using a variety of commercial thickeners that combine polysaccharides and dextrin, such as Nestlé ThickenUp Clear (TUC), Nutricia Nutilis Powder, and Hormel Thick & Easy (Kongjaroen, Methacanon, and Gamonpilas 2022).

In recent years, significant attention has been devoted to understanding and optimizing the flow properties (e.g., shear viscosity, yield stress and extensional modulus) of polysaccharide–dextrin-thickened fluids. This focus extends to the development of evaluation methods that incorporate these flow characteristics to ensure the safety of fluid swallowing, including *in-vivo* methods (e.g., videofluoroscopy method and animal models), *in-vitro* techniques (e.g., the Cambridge Throat and the Gothenburg Throat), and *in-silico* simulations (e.g., the semi-implicit motion particle method) ones, as illustrated in Figure 1.

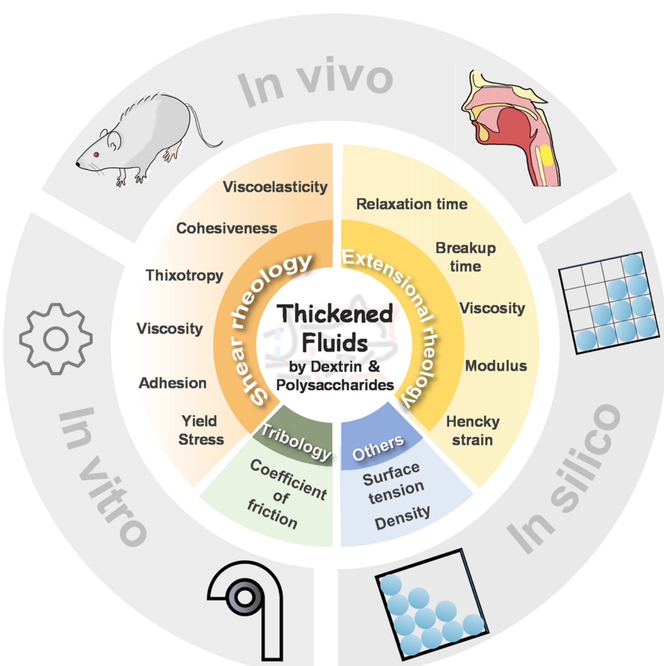

Figure 1. Flow behaviors and swallowing features of thickened fluids by polysaccharides with dextrin.

Given that polysaccharide–dextrin-thickened fluids undergo pronounced shear and extensional deformations throughout the oral cavity, pharynx, and esophagus during swallowing, the flow properties, both shear and extensional, as well as tribological properties, assume pivotal roles in determining their safety and performance during ingestion (Waqas et al. 2017). A systematic overview of the flow behaviors and associated swallowing evaluation methods for polysaccharide–dextrin-thickened fluids hold great significance in the development of special fluid diets tailored to the preferences and needs of individuals coping with dysphagia.

To date, some reviews have explored the impact of polysaccharides on shear rheological properties and swallowing behaviors. For instance, Schmidt et al. (2021) showed the influences of polysaccharides (XG, GG, and KGM) on the viscosity, viscoelasticity, and sensory attributes of special dysphagia diets. Also, researchers reviewed the importance of rheology and tribology in specific polysaccharide fluids (e.g., starch and XG) in the context of oropharyngeal dysphagia, emphasizing the need for further research into the nutritional implications arising from interactions between thickeners and food ingredients (Methacanon et al. 2021). However, a comprehensive review of the flow characteristics of polysaccharide–dextrin-thickened fluids and the concurrent advancements in swallowing assessment methods remains outstanding. This knowledge is essential for the development and verification of thickened fluid formulations tailored to individuals experiencing dysphagia symptoms.

This present review delves into the influence of dextrin supplementation on the shear and extensional rheological properties, along with tribological properties, of polysaccharide-based fluids, intimately connected with their swallowing performance and safety. Additionally, it explores various *in-vivo*, *in-vitro* and *in-silico* models that incorporate flow characteristics to assess crucial aspects like oropharyngeal flow velocity, risk of aspiration, and remaining fluid volume in polysaccharide–dextrin-thickened fluids. This understanding is of paramount importance in the design of fluid-based diets that enhance the quality of life for individuals afflicted by dysphagia.

2. Basic aspects of dysphagia and thickened fluids

2.1. Overview of fluid food swallowing and dysphagia

Swallowing food boluses represents a complex physiological process within the human body (Clavé and Shaker 2015), divided into three distinct stages: the oral stage, the pharynx stage, and the esophagus stage. The swallowing process for fluid foods is illustrated in Figure 2.

During the oral stage (Figure 2a), unlike the case of solid foods, fluid foods do not require chewing and can be mixed directly with saliva to form a bolus (Rommel and Hamdy

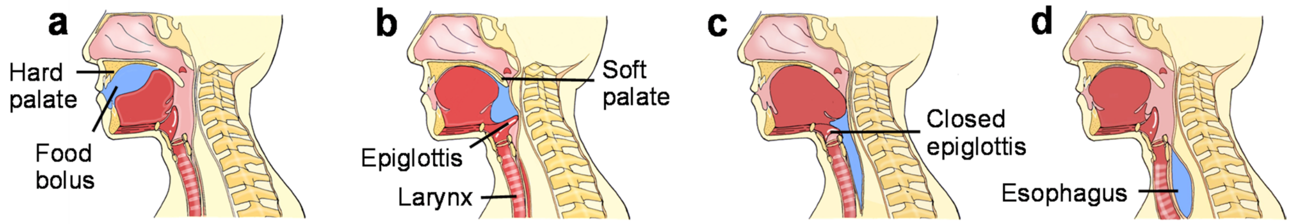

Figure 2. Human swallowing process. (a) The tongue lift pushes the bolus into the oropharynx. (b) The raised soft palate closes the opening of the nasal cavity as the bolus enters the pharynx. (c) The bolus is advanced through the pharynx through the closed epiglottis and the upper esophageal sphincter into the esophagus. (d) The bolus travels through the esophagus to the stomach *via* peristaltic waves.
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2016; Smukalla et al. 2017). A food bolus is positioned at the front part of the tongue under the influence of the soft palate. With the muscles of the base of the tongue and the floor of the mouth in action, the tongue is pushed upwards against the hard palate and then moved backward to propel the bolus.

In the pharyngeal stage (Figure 2b), the entry of the food bolus into the pharynx and the base of the tongue initiates a swallowing reflex, which includes the closure of the airway by the soft palate and the epiglottis cartilage near the airway, the peristalsis of the pharynx, and the opening of the upper esophageal sphincter (UES) to allow passage of the ingested food. As the pharynx contracts, the esophagus begins to move in a primary peristalsis wave, and the bolus enters the esophagus (Figure 2c). This action stretches the esophageal wall, triggering the secondary peristalsis of the esophagus.

In the final esophageal stage (Figure 2d), the striated and smooth muscles in the esophagus generate peristaltic waves under the control of central control mechanisms and local reflexes, respectively. These waves propel the fluid bolus into the stomach. The soft palate and tongue relax, and the epiglottis opens, allowing resumption of resume breathing (Rommel and Hamdy 2016; Smukalla et al. 2017).

The elderly and patients, particularly those afflicted by neurological diseases, often experience muscle weakness, reduced saliva production, impaired tongue-jaw coordination, and incomplete or slow epiglottis closure. These factors can result in boluses entering the trachea or nasal cavity, leading to symptoms such as choking, aspiration, esophageal reflux, chest pain, and more. This condition is known as dysphagia, which can be categorized into oropharyngeal dysphagia and esophageal dysphagia (Jean 2001).

Compared to esophageal dysphagia, oropharyngeal dysphagia exhibits a higher prevalence, more severe symptoms, an increased risk of complications, and greater associated mortality (Clavé and Shaker 2015). Oropharyngeal dysphagia can stem from a variety of aging and disease factors. Symptoms of oropharynx dysphagia, including decreased saliva production, delayed epiglottis closure, and neurological impairments, can affect bolus formation and result in reflux into the nasal cavity or trachea (Sasegbon and Hamdy 2017). Oropharyngeal dysphagia commonly causes choking, aspiration, malnutrition, dehydration, and pneumonia.

On the other hand, esophageal dysphagia is often related to reflex-based causes and can be triggered by intrinsic and extrinsic mechanical causes, primary or secondary neuromuscular diseases, or inflammatory processes affecting the lower esophageal sphincter (LES) and the esophagus (Clavé and Shaker 2015; Nikaki et al. 2019). Esophageal dysphagia typically manifests as symptoms like slow food passage and temporary food entrapment.

2.2. Overview of features of thickened fluids for individuals with dysphagia

Developing special diets has been proven effective at managing dysphagia symptoms and enhancing the quality of life for individuals afflicted with dysphagia. To prevent severe complications, individuals with dysphagic are often recommended to include TMFs (semi-solid and gel forms) and thickened fluids in their dietary plans (Steele et al. 2015). Within these specialized dietary options, thickened fluids, such as water, milk, juices, and soups, have gained widespread utilization for addressing dysphagia-related challenges such as choking and aspiration. In long-term-care facilities, TMF accounts for 15–30% of use, while thickened fluids are more extensively used (Cichero et al. 2013). The inclusion of thickeners, primarily polysaccharides, serves to decelerate the flow of the fluid bolus during swallowing, providing the epiglottis with ample time to maneuver and safeguard against food entering the trachea, ultimately alleviating the symptoms of dysphagia (Poursani, Razavi, and Norouzi 2021). However, the reduced flowability in the mouth due to excessive viscosity may result in the accumulation of food residues during swallowing, thereby heightening the risk of choking and aspiration (Steele et al. 2015; Ullrich and Crichton 2015).

Polysaccharides such as XG, GG, KGM, and LBG are commonly employed in the thickening of fluid diets for individuals with dysphagia (Jo, Bak, and Yoo 2018). However, pure polysaccharides have a propensity to form clumps when dissolved at room temperature due to their small particle size, which can impede their instantaneous and complete dissolution in fluids (Lee and Yoo 2021). Meet the demands of fluid thickening typically necessitates the inclusion of binder components to improve the dispersion, dissolution, and thickening properties of the polysaccharide components. Dextrins are the most commonly used binders, and they have minimal impact on the nutritional values and functions of foods. They play a pivotal role in enhancing the surface adhesion of polysaccharide particles, facilitating the collision and adhesion of wetted polysaccharide particles. This process results in the formation of larger agglomerates, ensuring their instant dispersion (Lee and Yoo 2021; Jeong, Bak, and Yoo 2019). In addition, the inclusion of dextrins can reduce the cost of production, and alter the rheological properties (e.g., viscosity) of fluids (Jeong, Bak, and Yoo 2019). Dextrins are already integral components of various commercial thickeners, such as TUC, Nutricia Nutilis Powder, and Hormel Thick & Easy. Consequently, substantial endeavors have been dedicated to creating thickened fluids by combining polysaccharide with dextrins to facilitate dysphagia management. Representative polysaccharides and dextrin structures used for fluid thickening are illustrated in Table 1.

Dysphagia fluid diets, including those thickened by polysaccharide–dextrin, can be classified into different grades in different countries (Table 2). Wood (1968) initially proposed that the assessment of fluid thickness in the oral context takes place at a shear rate of approximately $50\,s^{-1}$. Subsequently, this criterion for viscosity at this specific shear rate was adopted by the United States and other countries as a standard for grading dysphagia-friendly foods. Line-spread test (LST) and Bostwick concentration meters are also commonly employed for this purpose. Furthermore, the International Dysphagia Diet Standardization Initiative (IDDSI) introduced a comprehensive framework for the identification and categorization of food consistencies, employing user-friendly methods to promote the global circulation of food commodities (Figure 3a) (Cichero et al. 2017). To facilitate clinical treatment, researchers have attempted to correlate IDDSI ratings with dysphagia assessments, such as the IDDSI Functional Diet Scale (Figure 3b) and dietary recommendations based on the Water Drinking Test (Steele et al. 2018; Su et al. 2018). And, the Ball-Back Extrusion (BBE) cell coupled with a texture analyzer has been introduced as a means to quantitatively characterize the IDDSI thickened fluid framework using apparent stress (Hadde et al. 2022). This method offers an approach to grading the swallowing properties of fluid based on their flow behavior in industrial production. The use of fluid flow for precise, objective correlation with dysphagia and clinical standards holds significant importance in the realm of industrial production.

Considering this, several methods have been devised to encompass a broader range of flow parameters for fluids, including those thickened by polysaccharide–dextrin, in order to enhance the evaluation of their swallowing performance.

3. Flow behaviors of polysaccharide–dextrin thickened fluids for individuals with dysphagia

Throughout the process of swallowing, a fluid thickened with polysaccharide–dextrin experiences deformation and flow phenomena within the oral cavity, pharynx, and esophagus. Comprehending the flow characteristics of these thickened fluids holds immense significance in the development of corresponding swallowing assessment techniques and, consequently, the creation of fluid diets tailored for individuals with dysphagia. This section summarizes the recent advances in the shear and extensional flow characteristics of polysaccharide–dextrin-thickened fluids, including viscosity, modulus, loss tangent (tan δ), yield stress (τ_0), thixotropy, adhesion, cohesion, and other parameters. Additionally examined are the tribological properties of these composite fluids.

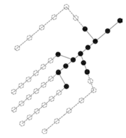
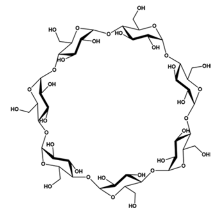
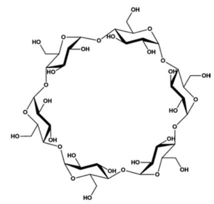
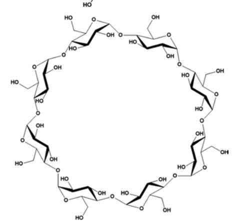
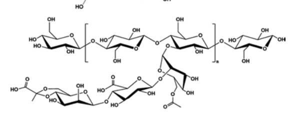
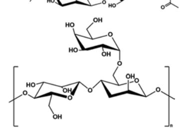
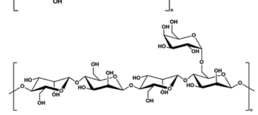
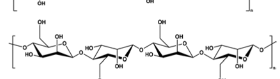
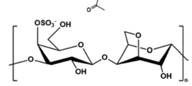
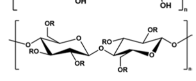
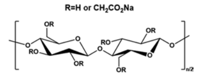
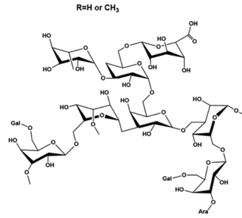
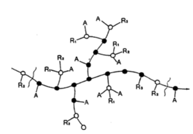
3.1. Rheology

Rheology is the science about the intricate dynamics of matter deformation and flow. A fluid's rheological equation, as elucidated by the relationship between stress (force per unit area), strain (alteration in position along the flow direction), and strain rate (change in strain over time), is pivotal in understanding its behavior (Alghooneh, Razavi, and Kasapis 2020).

Swallowing, a complex process, subjects the fluid to both shear and extensional deformations. Shear deformation prompts layers of molecules to move relative to each other, a phenomenon explored through rheometers. These devices are instrumental in examining parameters like viscosity, the ratio of shear stress to shear rate. The choice of geometry for rheological measurements, be it concentric cylinders, parallel plate-plate, or cone-plate, depends on the viscosity of the thickened fluid. It is noteworthy that most thickened fluids used in dysphagia management exhibit non-Newtonian, shear-thinning behavior. As shear rate increases during swallowing, the viscosity of thickened fluids decreases due to the disentanglement and orientation of polysaccharide chains (Xie 2023).

Furthermore, certain thickened fluids exhibit solid-like behavior under low stresses and transform into flowing states under high stresses, and this critical point is known as yield stress (τ_0). The yield stress is believed to be linked to the tongue pressure required for effective swallowing. Considering the viscoelastic or thixotropic time factor, the fluid's stress response evolves during flows (Li et al. 2023). These two time-dependent characteristics are distinguished from the relaxation of stress after the end of flow and elasticity. Thixotropy is typically associated with rapid relaxation and viscosity, while viscoelasticity manifests as slow and elastic behavior (Larson and Wei 2019; Bui and Ho 2020). Viscoelasticity, based on the type of response, branching into small-amplitude oscillatory shear (SAOS) and large-amplitude oscillatory shear (LAOS). A nuanced understanding of these time-dependent characteristics proves invaluable in assessing the swallowing efficacy of thickened fluids (Alghooneh, Razavi, and Kasapis 2020; Li et al. 2023). In contrast to shear deformation, extensional deformation involves the removal of molecules within the fluid. Extensional viscosity, filament break-up time, and cohesiveness serve as representative indices of filament deformation with time. The elasticity of thickened fluids is considered to correlate with extensional viscosity and the first normal stress difference (N_1, the difference between the normal stress in the direction of flow (σ_{11}) and the normal stress perpendicular to the flow (σ_{22}) (Xie, Halley, and Avérous 2012). While the

Table 1. Polysaccharides and dextrins for fluid thickening.

Name	Molecular formula	Structure	Solution conformation	Electrostatic charge	References
Maltodextrin (MD)	$(C_6H_{10}O_5)_n$	Starch hydrolysis products with DE ≤20	——	Neutral	——
Branched limit dextrins (BLD)	$(C_6H_{10}O_6)_n$	——		——	(Wang et al. 2018)
β-Cyclodextrin (β-CD)	$C_{42}H_{70}O_{35}$		——	Neutral	——
α-Cyclodextrin (α-CD)	$C_{36}H_{60}O_{30}$		——	Neutral	——
γ- Cyclodextrin (γ-CD)	$C_{48}H_{80}O_{40}$		——	Neutral	——
Xanthan gum (XG)	——		Ordered helical	Anionic	——
Guar gum (GG)	——		Random coil	Neutral	——
Locust bean gum (LBG)	——		Random coil	Neutral	——
Konjac Glucomannan (KGM)	——		Random coil	Neutral	——
κ-Carrageenan (KC)	——		Random coil	Anionic	——
Carboxymethyl cellulose (CMC)	——		Random coil	Anionic	——
Methylcellulose (MC)	——		Random coil	Neutral	——
Gum Arabic (GA)	——			Anionic	(Islam et al. 1997)

Notes: Putative molecular structure for *A. senegal* gum (GA). A = arabinosyl; ● = 3-linked Galp (Galp attached); ○ = 6-linked Gal*p* (Gal*p* or Glc*p* attached), or end-group; R_1 = Rha → 4GlcA (Rha occasionally absent, or replaced by Me, or by Ara*f*); R_2 = Gal →→3Ara; R3 = Ara →3 Ara → 3 Ara.

Table 2. Fluid grading standards of various countries, regions, and organizations.

Country/Region/Organization	Grade 1	Grade 2	Grade 3	Grade 4	Grade 5
Australia (Fork drip testing)	Regular	Level 150 Mildly thick (95–200 mPa·s)[a]	Level 400 Moderately thick (260–550 mPa·s)[a]	Level 900 Extremely thick (670–1040 mPa·s)[a]	
America (NDD)	Thin (1–50 cP)[a]	Nectar-like (51–350 cP)[a]	Honey-like (351–1750 cP)[a]	Spoon-thick (>1750 cP)[a]	
Britain	Thin	Stage 1	Stage 2	Stage 3	
Europe	Normal	Syrup/slightly thick	Nectar	Honey	Pudding
Ireland	regular/normal	Grade 1 very mildly thick	Grade 2 mildly thick	Grade 3 moderately thick	Grade 4 extremely thick
Japan	Thin	Mildly thick (50–150 mPa·s)[a]	Moderately thick (150–300 mPa·s)[a]	Extremely thick (300–500 mPa·s)[a]	
Japan (LST)		36–43 mm	32–36mm	30–32 mm	
Québec, Canada (Bostwick consistometer, 8C)	Clair/thin (16–24 cm/30 s)	Nectar (13–15 cm/30 s)	Miel/Honey (7–9 cm/30 s)	Pudding (3–5 cm/30 s)	
IDDSI	Slightly thick (1–4 mL after 10 s)	Mildly thick (4–8 mL after 10 s)	Moderately thick (>8 mL after 10 s)	Extremely thick (None, fork test)	

[a]Shear viscosity at a shear rate of $50\,s^{-1}$.

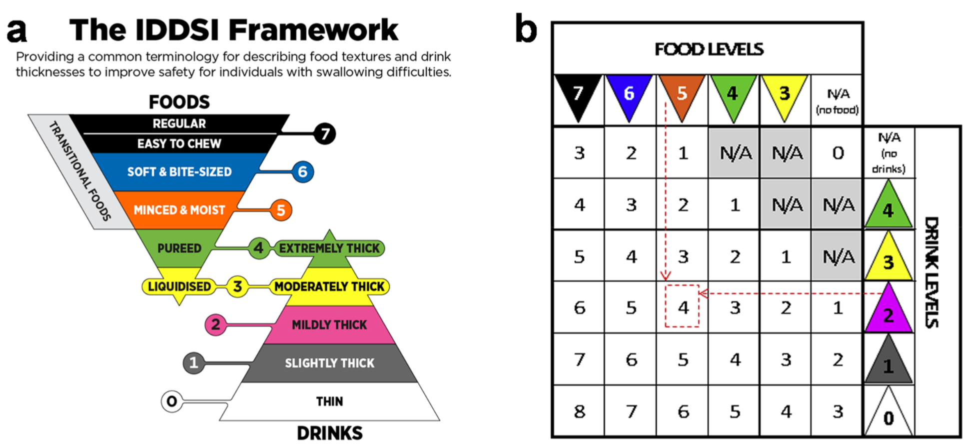


Figure 3. (a) The international dysphagia Diet standardisation initiative (IDDSI) 2019 classification and (b) IDDSI Functional Diet Scale. IDDSI Functional Diet Scale is a scoring chart for a patient to determine the IDDSI-FDS score (the numbers in intersecting cells of columns show the patient's food texture recommendation, and rows indicate the patient's drink consistency recommendation).
(a) is reprinted from https://iddsi.org/framework/ Licensed under the CreativeCommons Attribution ShareAlike 4.0 License. (b) is reprinted from Ref. (Steele et al. 2018) with permission from Elsevier, Copyright 2018.

measurement of extensional viscosity is challenging due to fluid breakage before stabilization, current instruments, like CaBER (HAAKE CaBER1), typically gauge apparent extensional viscosity (Gallegos et al. 2021).

3.1.1. Viscosity

Viscosity is a key factor in assessing fluid foods for individuals with dysphagia as it characterize the material's resistance to flow. This parameter has been adopted by standards such as the National Dysphagia Diet (NDD) of the American Dietetic Association and the Japanese Diet for Dysphagia (JDD) of the Japanese Society for Dysphagia Rehabilitation (JSDR) (Newman et al. 2016; Seo and Yoo 2013; Ross et al. 2019). While the steady-state viscosity is typically measured using Brookfield viscometers, contemporary rheometers offer a broader range of insights into fluid behavior (Zargaraan et al. 2013). It is widely acknowledged that elevating the shear viscosity of thickened fluids, such as those with nectar-like and honey-like consistencies, enhances their cohesiveness and decelerates their flow. This deliberate slowing effort affords the epiglottis ample time to function, safeguarding against the entry of fluid food into the trachea, ultimately diminishing the likelihood of aspiration and choking incidents.

The inclusion of dextrin into polysaccharide-thickened fluids has the capacity to modulate their steady-state viscosities. It is revealed that the presence of dextrin influences the hydrogen bonding and chain entanglement of polysaccharides in thickened fluids, thereby altering their rheological properties under shear conditions (Pourmohammadi et al. 2018; Witczak et al. 2010; Kim, Kim, and Yoo 2017; Habibi and Khosravi-Darani 2017; Rao, Ramadevi, and Sirisha 2014). For most polysaccharides (e.g., starch, XG, and GG), the addition of dextrin elevates shear viscosity (Hadde, Nicholson, et al. 2020; Newman et al. 2016) and can contribute to improving swallowing safety. However, in certain instances, the introduction of dextrin can lead to a reduction in shear viscosity, as observed in fluids thickened by KGM (Wei et al. 2021). The reasons will be mentioned later in this section.

More specifically, the thickening effect of starch depends on the hydrogen bonding between amylopectin and amylose or hydrate bridging (Dewar and Joyce 2006). In the case of starch-thickened fluids, different dextrins can yield different effects by vying for water and altering the interactions between starch chains. Typically, the inclusion of branched limit dextrin (BLD), a low-molecular-mass dextrin with an amylopectin core, competes for water with maize starch, reducing the mobility of starch chains and subsequently increasing viscosity (Wang et al. 2018). In contrast, adding maltodextrins (MDs) limits starch's accessibility to water molecules, resulting in reduced viscosity within the system due to limited gelatinization (Pourmohammadi et al. 2018; Witczak et al. 2010).

In addition, the shear viscosities of thickened fluids with non-starch polysaccharides and dextrin have been investigated. For instance, the thickening effect of XG is intricately tied to the formation of a physical network through the combination of *O*-acetyl groups and pyruvate residues, which is upheld by chain hydrogen bonding and chain entanglements (Kumar, Madhusudana Rao, and Han 2018). While XG has the ability to transition from an ordered helical structure to a coiled (disordered) structure, thereby augmenting viscosity (Habibi and Khosravi-Darani 2017), MD inclusion enhanced the disordering and entanglement of XG molecule chains, resulting in increased fluid viscosity (Kim, Kim, and Yoo 2017).

Furthermore, viscosity reductions were observed in fluids thickened with non-starch polysaccharide–dextrin. Notably, the inclusion of MD with a low dextrose equivalent (DE) (especially DE ≤ 6) significantly reduced the viscosity of galactomannan systems (e.g., KGM, GG, and LBG), and a high MD concentration (10% w/w) made the flow behaviors of galactomannan matrices (1% w/w) resemble that of an MD system (Tha Goh, Sui Mei Wee, and Hemar 2013). This effect can be attributed to the phase separation between two polysaccharides (as summarized in Table 1). Compared to the high mixing entropy observed when anionic polysaccharides (e.g., XG) are mixed with MD, the mixing entropy is lower for two neutral polysaccharides, making phase separation more likely and resulting in reduced system viscosity (Boyd et al. 2009). It was disclosed that MD could function as a plasticizer within a polysaccharide matrix (e.g., KGM), hindering chain associations and the formation of entangled networks due to steric hindrance, ultimately leading to a significant reduction in viscosity (Wei et al. 2021). Additionally, as the hydrophobic cavity of CD, which can accommodate the hydrophobic tails of polysaccharides and partially deactivate hydrophobic associations, resulted in reduced apparent viscosity in polysaccharide systems like methylcellulose (MC) and sodium carboxymethylcellulose (CMC) (Rao, Ramadevi, and Sirisha 2014; Tha Goh, Sui Mei Wee, and Hemar 2013; Beheshti et al. 2007) when β-cyclodextrin (β-CD) was introduced. Likewise, the presence of CD decreased the viscosity of a fluid thickened with KC when compared to the counterpart with KC alone (Yuan, Ritzoulis, et al. 2018).

Other than shear viscosities, the extensional rheological behaviors of polysaccharide–dextrin-thickened fluids have been assessed. At present, CaBER and hyperbolic contraction flow equipment can be applied to the measurement of extensional viscosity, with the former holding greater popularity. It is noteworthy that thickened fluids with identical shear viscosities can exhibit significantly different extensional characteristics (Kongjaroen, Methacanon, and Gamonpilas 2022; Hadde and Chen 2019; Marconati and Ramaioli 2020). This was substantiated by the alterations observed in commercial polysaccharide thickeners containing dextrin (Figure 4a–b). Using an extensional rheometer, an apparent extensional viscosity (η_E) and a Hencky strain (ε) can be calculated based on equations (1) and (2) (Figure 4d).

$$\eta_E = (2X-1)\frac{\sigma}{-\frac{dD_{mid}(t)}{dt}} \tag{1}$$

$$\varepsilon = 2\ln\left(\frac{D_0}{D_{mid}(t)}\right) \tag{2}$$

In these equations, σ is surface tension, D_0 is the initial sample diameter (before stretch), and D_{mid}(t) is the mid-filament diameter at any given time. X is the geometry coefficient that accounts for the deviation of the filament shape from a uniform cylinder due to both inertia and gravity effects (Kongjaroen, Methacanon, and Gamonpilas 2022).

The extensional-rheological study has been corroborated using different polysaccharide–dextrin thickeners with the same viscosity in $50\,s^{-1}$ and grade of IDDSI (Figure 4b) (Kongjaroen, Methacanon, and Gamonpilas 2022). The filaments break-up time showed variations attributable to the assortment of polysaccharides and other components introduced. It is noted that the influence of additional components (e.g., MD, ascorbic acid, potassium) on XG as a natural anionic polyelectrolyte (TUC, Thick-It Clear Advantage (TIC), and QuikThik (QT)) was more evident than neutral polysaccharides like talar gum and guar gum (Supercol (SP) and Purathick (PT)) (Kongjaroen, Methacanon, and Gamonpilas 2022). Thickened fluids with a high extensional viscosity usually exhibit strong cohesion, which refers to the internal bonds that hold the product together, and these fluids tend to resist breaking into small droplets during swallowing, thereby improving swallowing behaviors (Hadde and Chen 2019; Hadde, Chen, et al. 2020). However, excessive extensional viscosity can result in heightened resistance to extensional deformation, especially for individuals with dysphagia who may have low tongue pressure (Hadde and Chen 2019).

3.1.2. Modulus

Modulus is yet another vital parameter that mirrors the flow characteristics of fluid matrices thickened with polysaccharide–dextrin, and it holds a significant connection to the safety of swallowing these fluids. Typically, the thickened fluids display viscoelastic behavior, demonstrating both elastic characteristics (indicated by storage modulus G') and viscous features (reflected by loss modulus G''). The ratio of G'' to G' gives rise to the loss factor, tan δ. An increase in G' signifies that the fluid possesses a more extended deformation range, as manifested by increased extensional viscosity and cohesion (Schmidt et al. 2021). The tan δ value in the range of 0.1 to 1 is employed to indicate weak gel properties in foods and has been proposed as a criterion for foods that can be safely swallowed by individuals with dysphagia (Sharma et al. 2017). As depicted in Figure 4c, the G'' values of the majority of polysaccharide–dextrin-thickened

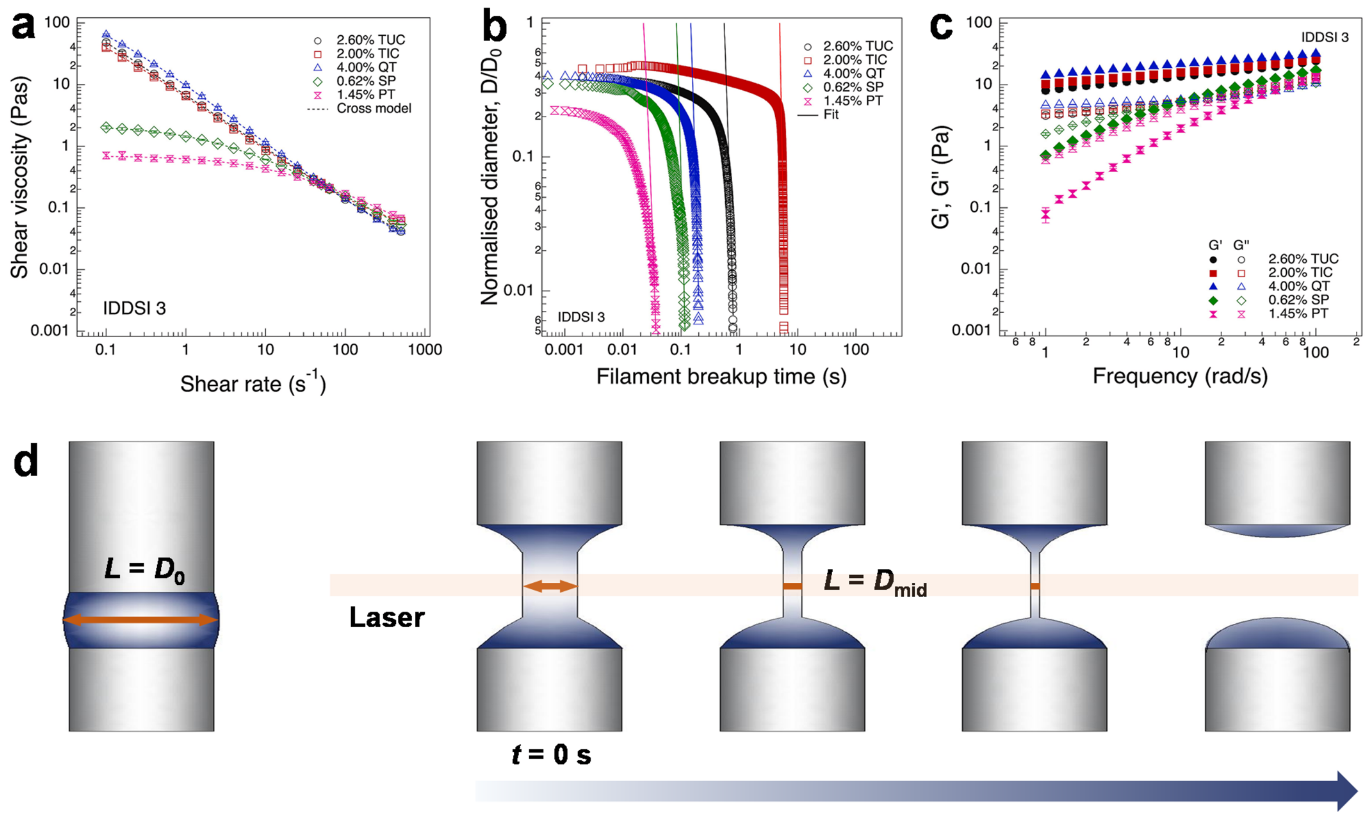


Figure 4. Rheological characteristic of IDDSI grade 3 fluids thickened by different commercial thickeners containing maltodextrin (MD). (a) shear viscosity; (b) variation in filament diameter during extension; (c) storage modulus G′ and loss modulus G″; (d) schematic diagram of extensional rheology.
(a), (b), and (c) are adapted from Ref. (Kongjaroen, Methacanon, and Gamonpilas 2022) with permission from Elsevier, Copyright 2022.
Notes: TUC represents is Resource Thickenup clear by Nestlé, composed of xanthan gum (33%), MD (66.4%), and potassium chloride (0.6%); TIC represents Thick-It Clear Advantage by Kent Precision Foods Group, composed of xanthan gum, MD, and ascorbic acid; QT represents QuikThik by Dr. MacLeod's Medical food, composed of xanthan gum, MD, dextrose, and tricalcium phosphate (anticaking agent); SP represents Supercol by Supercol Australia, composed of guar gum (100%); PT represents Purathick by Parapharma Tech, composed of Tara gum, MD, and calcium carbonate.

fluids, especially those primarily composed of xanthan gum, were lower than the G' value (i.e., tan $\delta < 1$), indicating the presence of weak gel properties (Kongjaroen, Methacanon, and Gamonpilas 2022).

Polysaccharide–dextrin-thickened fluids can exhibit different moduli compared to those thickened solely with non-dextrin polysaccharides. Kim, Yoo, and Yoo (2014) and Yoon and Yoo (2017) found that for pudding-like fluids thickened using two different thickeners containing XG and dextrin, G' consistently exceeded G''. In contrast, when MD was introduced into carboxymethylated curdlan (CMCD) and XG solutions, both G' and G'' increased (Wei et al. 2021), a trend also observed for GG- and LBG-thickened fluids in the presence of MD (Lee and Yoo 2021). This was attributed to MD enhancing the polysaccharide network, thereby boosting G' (Wei et al. 2021; Kim, Kim, and Yoo 2017). Likewise, the use of indigestible dextrin (IDD), BLD, or CD heightened the viscoelasticity of KC-thickened fluid, linked to the enhanced helical structures of KC and the arrangement of random coils (Yuan et al. 2020; Yuan, Ritzoulis, et al. 2018). Compared to IDD, BLD, with its higher molar mass and branched structure, more effectively promoted the rearrangement of polysaccharide chains' random coils, resulting in a more rapid increase in viscoelasticity (Yuan et al. 2020).

The aforementioned studies collectively demonstrate that dextrin inclusion enhances the viscoelasticity of polysaccharide-thickened fluids, thereby promoting ease of swallowing. Conversely, some instances have shown a reduction in G' following the addition of dextrin to polysaccharide-thickened fluids. This effect was observed when a modified high-molar-mass dextrin (MWS-1000) (from waxy maize) was introduced, which suppressed starch retrogradation by increasing steric hindrance between starch chains. This, in turn, led to a reduction in G' (and an increase in tan δ), rendering the system softer and more liquid-like (Sumida et al. 2021). The fluids containing KGM and MD exhibited lower G' values compared to the pure KGM-thickened fluid, as the steric hindrance induced by MD reduced the physical entanglement of KGM, consequently diminishing the mechanical resistance to strain (Wei et al. 2021). In addition, the excessive addition of dextrin tended to sterically hinder the aggregation of polysaccharide chains and reduce G'. Research showed that the G' value of a KC-thickened fluid decreased when too much IDD and BLD (3% w/w and 5% w/w, respectively) were included (Yuan et al. 2020).

Extensional modulus (G), categorized as an elastic modulus, assume a critical role in preserving the structural integrity of thickened fluids during the act of swallowing. Utilizing the fitting equations (1) and (2) for tensile viscosity, the tensile modulus and relaxation time can be derived through the following equation fitting (Yuan, Ritzoulis, et al. 2018):

$$\frac{D}{D_0} = \left(\frac{GD_0}{\sigma}\right)^{\frac{1}{3}} e^{\frac{-t}{3\lambda}} \tag{3}$$

In this equation, G is the extensional modulus, D_0 is the initial filament diameter, and λ is the relaxation time.

Surface tension serves as an independent variable for fitting the extensional modulus and relaxation time. The parameter λ signifies the initiation of chain stretching in thickened fluids (Kongjaroen, Methacanon, and Gamonpilas 2022). Significantly, there has been a concerted effort to comprehend the extensional modulus in various fluid contexts, including those thickened with polysaccharides. For example, Yuan, Ritzoulis, et al. (2018) determined the tensile modulus of okra mucilage by fitting the surface tension and filament diameter data. Further research is required to establish the suitability of the tensile modulus as a characterization parameter for polysaccharide–dextrin-thickened fluids for individuals with dysphagia. This is crucial for the evaluation and enhancement of dysphagia diets with improved swallowing performance.

3.1.3. Large amplitude oscillatory shear (LAOS) features

The modulus mentioned above is acquired through SAOS testing. SAOS is conducted within the linear viscoelastic region (LVR), representing the undisturbed structure of a fluid, describing its initial structural properties. On the other hand, LAOS testing assesses the viscoelastic modulus of a fluid beyond the LVR, simulating the disruption of the fluid's structure, which closely resembles the conditions during oral food processing (Sukkar et al. 2018). The LAOS analysis protocol developed by Ewoldt, Hosoi, and McKinley (2008) determines the nonlinear viscoelastic properties during LAOS measurements by utilizing the Fourier transform of higher-order harmonics. In addition, Ewoldt, Hosoi, and McKinley (2008) defined two new viscoelastic moduli (minimum strain elastic modulus, G'_M, and maximum strain elastic modulus, G'_L) and two new instantaneous viscosity at minimum shear rate (instantaneous viscosity at minimum shear rate, η'_M, and instantaneous viscosity at maximum shear rate, η'_L). These parameters can be viewed in the Lissajous-Bowditch diagram (Figure 5a). The relevant content is introduced in detail elsewhere (Melito, Daubert, and Foegeding 2013). Joyner (2021) and Wang and Selomulya (2022) have summarized the recent application of LAOS in the food industry, with a specific focus on the analysis techniques and findings obtained from LAOS studies conducted on various food products. It is anticipated that LAOS will find increasing application in the study of the relationships between food structure, function, texture, and sensory attributes. Research in the food industry has started to recognize the value of LAOS measurements.

On the basis of Ewoldt, Hosoi, and McKinley (2008), Anvari, Tabarsa, and Joyner (2018) used a Lissajous-Bowditch plot and phase angle to characterize the effect of temperature and concentration on *A. holocarpum* seeds gum influence LAOS behavior (Figure 5b). In the LVR, the Lissajous-Bowditch plot turns out to be a perfect ellipse. Under large deformation, the ellipse morphs into a parallelogram. This suggests that the sample transitions from a predominantly elastic behavior to a predominantly viscous behavior. This is also confirmed by the increase of the phase angle at high strain and the change in the ratio between the third-order harmonic data (G'_3/G'_1), the elastic modulus (G'_L/G'_M), and the instantaneous viscosity (η'_L / η'_M) from the output stress wave (refer to the paper of Melito, Daubert, and Foegeding (2013) for analysis). These behavioral changes are related to permanent deformation and flow caused by gel network failure at high strain. High concentration and high temperature caused greater stability or smaller permanent deformation of polysaccharides under LAOS, respectively (Anvari, Tabarsa, and Joyner 2018). In addition, there was no significant difference in the XG's flow behavior within the LVR with the presence of NaCl, but differences became apparent outside the LVR (Carmona et al. 2014). While the significance of LAOS in the oral processing of thickened fluids for dysphagia has been underscored, there is limited research on LAOS in the oral processing of polysaccharide-dextrin fluids.

3.1.4. Yield stress

Yield stress (τ_0) represents the minimum stress required for a fluid to flow. In an ideal situation, a simple yield stress fluid is considered to be non-thixotropic and inelastic, i.e., the shear stress depends only on the applied shear rate. Therefore, Bingham, Herschel-Bulkley, Casson and other models are often used to calculate the yield stress of thickened fluids (Frigaard 2019). Dinkgreve et al. (2016) used steady shear measurements method (Herschel–Bulkley model), oscillatory measurement, stress growth experiment, and creep experiment to measure the yield stress of simple yield stress fluid and thixotropic fluid. Among them, the yield stress obtained by Herschel–Bulkley model is considered to be reliable.

There remains limited research on the yield stress of dysphagia fluids. Hadde, Ann Yvette Cichero, and Michael Nicholson (2016) posited that yield stress was associated with the tongue pressure during the swallowing reflex, suggesting that fluids with higher yield stress demanded greater tongue pressure. However, this view was refuted by Ross et al. (2019), who uncovered that, despite significant variations in the perceived propulsion force among samples, there were no noteworthy differences in yield stress. Observations indicated that the addition of dextrin altered the yield stress of polysaccharide-thickened fluids. Specifically, the presence of MD increased the yield stress of XG and CMCD-containing fluids but decreased it in the case of KGM-thickened fluids (Wei et al. 2021). Yuan et al. (2020) applied the Herschel-Bulkley model to fit the stress of a KC-thickened fluid. They found that the yield stress of the KC-thickened fluid containing IDD or BLD was higher than that of the KC-thickened counterpart when the dextrin concentration was below 5% and 7% w/w, respectively. The appropriate addition of dextrin can significantly reduce the yield stress

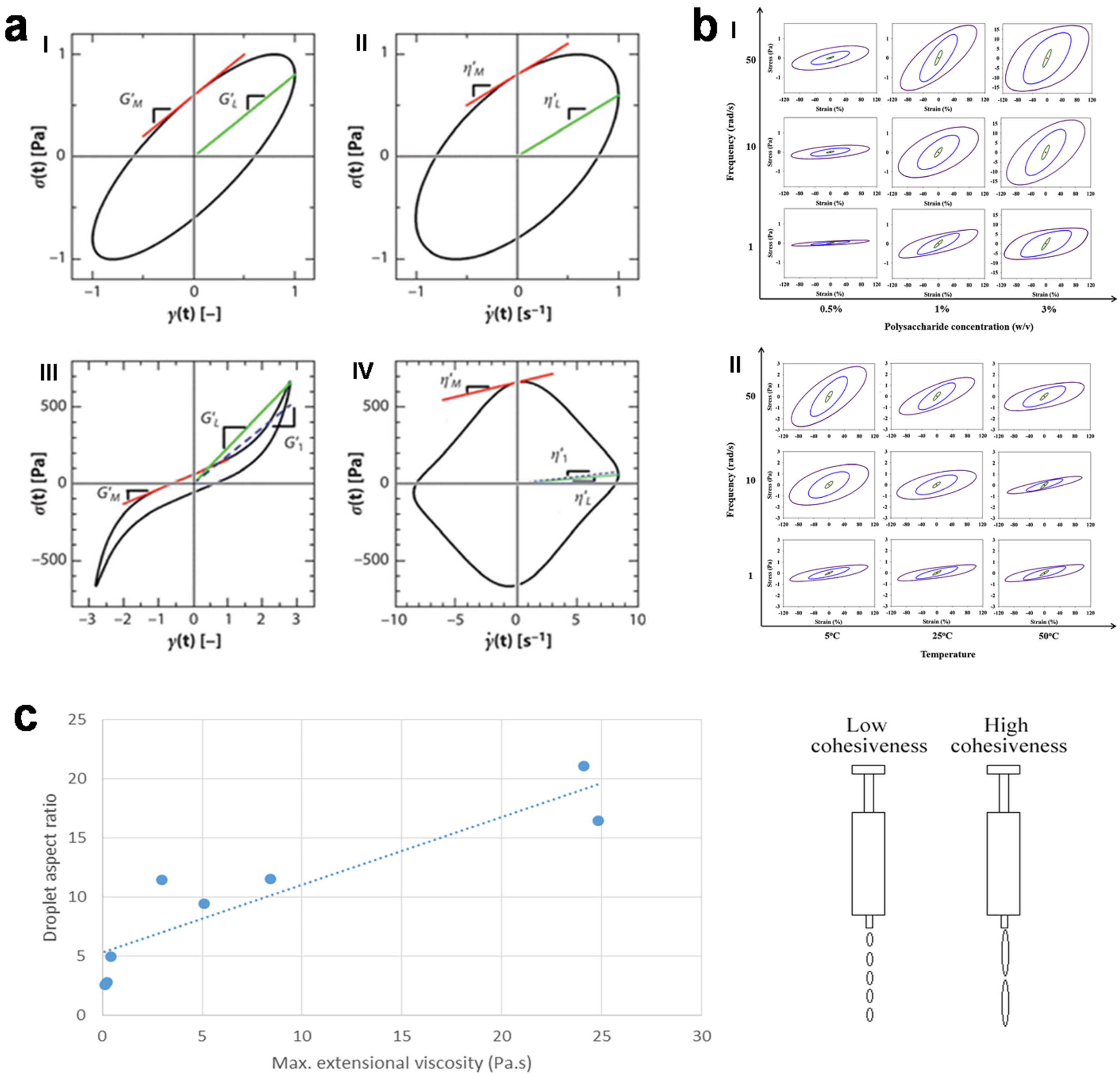


Figure 5. (a) Example plots of Lissajous-Bowditch curves showing the determination of G'_M, G'_L, η'_M, and η'_L under SAOS (I, II) and LAOS (III, IV) testing. (b) Lissajous plots for A. homolocarpum seed gum aqueous dispersions treated at (I) different concentrations (at 25 °C) and (II) temperatures (at 1% w/v). Line colors indicate different strains: red- 0.1%, green- 10%, blue- 50%, and purple- 100%. (c) Correlation between droplet aspect ratio and maximum extensional viscosity.
(a), (b) and (c) are adapted with permission from Ewoldt, Hosoi, and McKinley (2008) with permission from The Society of Rheology, Copyright 2008, Anvari, Tabarsa, and Joyner (2018) with permission from Elsevier, Copyright 2018 and Hadde, Chen, et al. (2020) with permission from Elsevier, Copyright 2020, respectively.

(IDD and BLD content 5%) with less variation in consistency coefficient (K, namely zero-shear-rate viscosity). This suggests that a lower tongue pressure was required for swallowing, making it more suitable for older adults.

3.1.5. Thixotropy

Polysaccharide–dextrin-thickened fluids typically exhibit time-dependent characteristics. Thixotropy serves as an indicator of how time affects the viscosity of fluid foods, with methods such as hysteresis loops and three interval thixotropy tests (3ITT) being employed for assessment (Li et al. 2023). The primary approach is 3ITT, encompassing static, shear and structural recovery stages (i.e., low shear rate, high shear rate, and then low shear rate again). This method allows for both rotational (viscosity) and oscillatory tests.

Thixotropy imparts distinct viscosity behavior to thickened fluids at rest compared to when subjected to shear, a factor closely tied to the fluid's safety for swallow (Dewar and Joyce 2006). Individuals managing dysphagia should consider the timing effect when consuming thickened fluids. Dewar and Joyce (2006) conducted tests examining the thixotropic behavior of corn starch and MD systems in dysphagia treatment. Their findings revealed the thixotropic nature of the corn starch system, while the MD system was not thixotropic, and dextrin-based thickened matrices exhibited a Newtonian flow regime (Dewar and Joyce 2006). Further research is essential to comprehend whether including dextrin in polysaccharide-based fluids influences hydrogen bonding and chain entanglements, leading to variations in thixotropic behavior.

3.1.6. Cohesiveness and adhesiveness

The significance of cohesiveness and adhesiveness in the context of swallowing thickened fluids cannot be overlooked, although there is currently no universally accepted quantification standard (Nishinari et al. 2019). Cohesiveness signified the degree of the intermolecular attraction within a food and the cohesion of its particle components. Increasing cohesiveness contributes to the formation of a well-bound, lubricated bolus, which in turn aids in averting aspiration. The swallowing perception test confirmed a robust positive correlation between the cohesiveness of food during swallowing and the extensional viscosity (Nishinari et al. 2019). At the shear rate of $10\,s^{-1}$, the perceived cohesion had the strongest correlation with the viscosity of the thickened fluid ($r = 0.97$) (Ross et al. 2019). Hadde, Chen, et al. (2020) proposed a strong relationship between the maximum extensional viscosity of a fluid and the filament breaking time, both of which are closely linked to the cohesiveness of visual perception during swallowing (Figure 5c). In addition, the droplet aspect ratio, determined using the syringe extrusion flow behavior technique, serves as a quantifiable measure of cohesiveness. High cohesiveness materials exhibit greater elongation before breaking down into droplets compared to materials with low cohesiveness (Hadde, Chen, et al. 2020). Adhesiveness pertains to a sticky food's capacity to adhere to the lining of the mouth. Elevated adhesiveness typically demands increased tongue pressure, thereby heightening the risk of suffocation. Vickers et al. (2015) showed that fluids exhibiting a higher degree of shear thinning (low n and high K) are typically associated with reduced adhesiveness. Swallowing is observed when the act of chewing produces an optimal food particle size, and the cohesiveness and adhesiveness between these particles in the subsequent bolus formation reach their maximum levels (Sun-Waterhouse et al. 2021). Quantification of cohesiveness and adhesiveness will help to investigate the behavior of thickening fluid during swallowing.

3.2. Tribology

Tribology is the science of friction, wear, and lubrication of surfaces in relative motion, finds significance in oral processing, where it is termed oral tribology. This specific term refers to the study of the interaction between food and the internal surface of the mouth during food consumption (Methacanon et al. 2021). As a burgeoning technology, oral tribology addresses the limitations of sensory testing in assessing swallowing rheology and safe swallowing. For example, the coefficient of friction plays a role in the astringency of food (Pradal and Stokes 2016), and the easy of swallowing may be related to the lubricating properties of food (Araiza-Calahorra et al. 2023).

In the journey of swallowing, the perception of food transitions from rheology to tribology (You, Murray, and Sarkar 2021). The Stribeck curve categorizes the lubrication states of fluids in the oral environment into boundary lubrication, mixed lubrication, and fluid lubrication. In the process of fluid lubrication, rheology is dominant, and the thickness of the fluid is enough to separate the friction contact surface. Fluid lubrication corresponds to the beginning of food oral processing. The oral lubrication film formed by food and saliva separates the tongue from the palate, with the texture perception primarily influenced by the rheological properties of the food, such as viscosity. Moving into mixed lubrication, tribological factors progressively assume a more significant role. As oral processing advances, the contact between the tongue and the palate's surface intensifies, impacting oral friction, which, in turn, shapes the texture perception of food (You, Murray, and Sarkar 2021).

The measurement of bolus friction behavior stands out as a pivotal challenge in tribology. To simulate the soft properties of the tongue, deformable material like polydimethylsiloxane (PDMS) are often used, mimicking the tongue's elasticity (Sarkar et al. 2021). Frosted glass, with appropriate surface roughness, emulates a hard palate (Funami and Nakauma 2021). Several devices, including friction tester, mounted tribological device, mini-traction machine, have been employed to measure food tribology (Sethupathy, Moses, and Anandharamakrishnan 2020). Sarkar et al. (2021) suggested techniques such as small angle X-ray scattering (SAXS), quartz crystal microbalance with dissipation monitoring (QCM-D), and atomic force microscopy (AFM) to complement the friction properties of foods, enhancing the study of food tribology.

The "lubricating" property of the fluid, an opposite factor to the fluid's friction coefficient, plays a pivotal role in bolus formation and swallowing (Laguna and Sarkar 2017). The lubrication properties of fluids are affected by particles. For example, Ji et al. (2022) demonstrated that the lubrication properties of starch suspensions are affected by particle size and swelling. Better swelling capacity correlates with larger, round starch particles having a lower friction coefficient. The presence of starch particles provides sufficient dynamic force to eliminate boundary lubrication, enhancing the overall lubricating effect (You, Murray, and Sarkar 2021). Notably, the presence of saliva mitigates friction differences caused by particles (Ji et al. 2022). Additionally, viscosity affects the lubrication properties of fluids. In the presence of artificial saliva, the coefficient of friction decreased at high slip speeds compared to pure starch-based thickeners (ambiguous and refined commercial thickeners). The XG thickeners mixed with starch consistently exhibited the highest coefficient of friction, which was considered to be influenced by viscosity (Baixauli et al. 2023). Gum-based thickeners (e.g., flaxseed gum and XG) were found to possess superior lubricating properties compared to starch with equivalent viscosity (Vieira et al. 2021; Gamonpilas, Kongjaroen, and Methacanon 2023). Baixauli et al. (2023) observed that consumers preferred fluids with smooth texture (low coefficient of friction), tasteless, and refreshing properties, endorsing gum-based thickeners and dispersed-starch thickeners over starch-containing particles. Furthermore, differences in the adsorption properties of polysaccharides on soft elastomer surface (e.g., PDMS) suggested varied ways in which polysaccharides are adsorbed in the oral cavity, impacting fluid film maintenance between surfaces, achieving ultra-low friction (Rodrigues et al. 2021).

In recent years, tribology has emerged as a crucial tool in uncovering sensory aspects that influence food swallowing. The confirmation of bolus swallowability hinges on reaching threshold values for particle size, cohesiveness, and lubrication (Malone, Appelqvist, and Norton 2003). The preliminary judgment of the swallowing characteristics of thickened fluids through the measurement of the coefficient of friction holds significant implications for the development of thickeners for dysphagia.

3.3. Other characteristics

Additional flow characteristics associated with polysaccharide–dextrin-thickened fluids include density and surface tension, both of which are linked to the swallowing dynamics of these fluids.

Density is intricately linked to the fluid quality and exhibit a positive correlation with swallowing velocity (Steele and Cichero 2008; Mizunuma, Sonomura, and Shimokasa 2020). Following Newton's second law, the acceleration of the bolus, indicative of the rate of velocity change, can be influenced by mass, a factor linked to density. Therefore, with a fixed volume and force applied to the bolus, density consistently influences the bolus's entry into the oral cavity and its acceleration into the pharynx. As viscosity increases, the flow tends to simplify into a theoretical type of lubrication, with density playing a diminished role. Fluid dynamics in oral processes are primarily governed by fluid density, viscosity, and tongue pressure. In the case of low-viscosity boluses (< ~100 cP), density significantly dictates fluid dynamics, while for high-viscosity boluses (> ~1000 cP), system viscosity takes prevalence (Nicosia and Robbins 2001).

Moreover, the effects of surface tension on the extensional rheological parameters of thickened fluids have attracted significant attention (Nishinari et al. 2019; Gallegos et al. 2021; Hadde, Nicholson, et al. 2020). The formation of a fluid bolus is related to its surface tension, and a higher surface tension makes the bolus more cohesive (related to extensional rheology), which causes a reduced flow rate in the mouth and pharynx (being friendly to people with dysphagia) (Lucas et al. 2002). It was reported that XG- and carrageenan-thickened fluids at high concentrations showed an increased surface tension, presumably due to increases in viscosity and gelation (Poursani, Razavi, and Norouzi 2021; Huang, Kakuda, and Cui 2001). However, a lower surface tension does not mean a lower viscosity.

Higher thickener concentration can lead to a reduction in surface tension. For instance, elevating the concentration of a polysaccharide–dextrin-based thickener (such as TUC and TIC) was found to reduce the surface tension of the thickened fluid by mitigating the cohesion resulting from the buildup of the biopolymers on the surface. This effect could be counteracted by increasing the extensional viscosity (Hadde, Nicholson, et al. 2020; Kongjaroen, Methacanon, and Gamonpilas 2022).

In addition, the choice of measurement method can impact the relationship between concentration and surface tension. As reported by Lee et al. (2012), for thickened fluids by sodium alginate, carboxymethyl cellulose (CMC), XG, and pectin, the surface tension from the DuNouy ring method increased as the solid concentration rose, but the drop weight method showed an opposite trend. This discrepancy arises because the du Nouy ring is affected by the viscous force of the thickened fluid during surface tension measurement, causing variations in the force required for the ring to detach from the liquid surface of the sample or the maximum weight it can support, leading to significant errors. Despite the need for some corrections, the drop weight method is considered more appropriate for measuring the surface tension of thickened fluids due to its consistency with surface thermodynamic theorems (Lee et al. 2012). This finding hints to us that for establishing assessment criteria for dysphagia fluid diets, both the surface tension and the flow characteristics should be considered to precisely regulate the swallowing performance of thickened fluids.

Therefore, significant efforts have been devoted to understanding the flow characteristics of fluids thickened with polysaccharides and dextrin. This research is invaluable for the assessment and enhancement of dysphagia-friendly fluid foods. While some flow parameters like shear viscosity and modulus have received substantial attention, others, such as extensional rheological behaviors, tribology and the interactions between polysaccharide and dextrin, remain insufficiently explored. To enhance the precise control of flow behavior during swallowing, further research is imperative to establish correlations between the polysaccharide–dextrin interplay and the flow properties of polysaccharide–dextrin-thickened fluids. This aims to enable more accurate regulation of fluid behavior at the molecular level. Furthermore, extending this technique to the investigation of polysaccharides and other substances (e.g., polysaccharides–polysaccharides, polysaccharides–proteins, polysaccharides–lipids) is crucial. This extension will contribute to the development of more effective evaluation methods for assessing the swallowability of dysphagia diets.

3.4. Influences of environmental factors

Thickeners commonly encounter a range of complex challenges. Environmental factors (pH, dispersion medium, temperature and ionic strength) and saliva can affect the rheological properties of polysaccharide–dextrin-thickened fluid, consequently altering swallowing behavior.**pH.** Thickeners encounter varying pH environments. Normally, food tends to be acidic (pH = 3–7). This means that testing only in water (approximately neutral) is not appropriate when considering the effect of dysphagia thickeners. Yoon and Yoo (2016) examined the flow behavior of thickened fluids using a commercial thickener based on XG–GG–dextrin and another one based on starch–LBG–dextrin at different pH values (pH = 3, 4, 5, 6, and 7). At pH 3, both thickeners exhibited a low K value and a high n value at pH 3. As the pH increased, the XG–GG–dextrin thickener exhibited an escalating K value while n, G', and G'' decreased. While XG is typically recognized for its ability to maintain high viscosity across a broad pH spectrum, it is important to note that XG molecules can degrade, and experience suppressed electrostatic action at extreme pH levels. In such conditions, the molecular structure becomes more compact, leading to a reduction in viscosity. The flow behavior of starch-based thickeners remained relatively stable within the pH range of 4–7, and K decreased significantly at pH 3. In contrast, Hadde, Nicholson, and Cichero (2015) found that the viscosity, yield stress, and thickening kinetics of an XG-based thickener did not change significantly in carbonated beverage (pH 2.75) and herbal tea (pH 9.50). The difference between these studies may arise from the different sources of XG. When utilizing polysaccharide–dextrin thickeners, it is crucial to identify the pH range for stable thickening effects and ensure that the thickened fluid reaches the appropriate swallowing grade.

Dispersing media. Dispersing media include protein, fat, pigment, salt and other substances, which can impact the thickening effect of polysaccharides. These different dispersion media were studied. Kongjaroen, Methacanon, and Gamonpilas (2022) investigated the shear and stretching behaviors of XG (with dextrin and KCl) and GG in water, milk, and apple juice. In all dispersion media, XG and GG exhibited higher zero-shear viscosity than water, but at high shear rates (especially $50\,s^{-1}$), their viscosity equalized. Furthermore, XG dissolved in apple juice and milk, as well as GG in milk, displayed more pronounced viscoelastic solid-like behavior than water. Particularly noteworthy are the differences in extensional characteristics, with XG showing a lower filament break time and extensional viscosity than water in both milk and apple juice. The extensional properties of GG were enhanced in milk and decreased in apple juice. Sopade et al. (2007, 2008a, 2008b) studied the flow properties of different thickeners across a range of liquids, including water, raspberry cordial, homogenized and pasteurized full cream, skim milk, ultra-high-temperature or ultra-heat-treated full cream, and different fruit juices (apple, orange and pineapple). Notably, the viscosity, density, and yield stress of skimmed milk after thickening were found to be significantly higher than those of whole milk, contrary to the findings of Hadde, Nicholson, and Cichero (2015), which suggested a direct correlation between milk fat content and viscosity. However, the juices showed no significant changes in density, yield stress, and viscosity after thickening. Karataş and Aydoğmuş (2023) compared the flow behavior of XG and pectin when dispersed in lemon juice. Lemon juice, in comparison to water, displayed reduced surface tension after thickening and expedited dissolution of the polysaccharides, resulting in higher viscosity. These findings underscore the importance for consumers to have clear guidelines regarding the dosage and application range of polysaccharide-dextrin-based thickeners in various dispersion media.

Temperature. Temperature plays a crucial role in influencing the rheological properties of fluids, especially thickened fluids. Lower temperatures are associated with increased viscosity in the thickened fluid (Adeleye and Rachal 2007). Hadde, Nicholson, and Cichero (2015) showed that the viscosity and yield stress of high-concentration Resource ThickenUp Clear (which is XG-based) remained stable, whereas the thickener's viscosity and yield stress decreased as the temperature increased at a low concentration. Hong et al. (2012) assessed the flow characteristics of an XG-based thickener at temperatures of 5, 25, 35, and 50 °C. The results indicate that the flow characteristics of the XG-based thickener remained relatively stable within the range of 5–35 °C, but there was a notable decrease in η_{50} (viscosity at $50\,s^{-1}$) and K at 50 °C. Furthermore, it is important to note that both temperature and taste are significant factors influencing swallowing. By employing cold and acidic simulation, it is possible to reduce the pharyngeal passage time in patients with oropharyngeal dysphagia, thus serving as an adjuvant therapeutic approach (Cola et al. 2012).

Ionic strength. Adding minerals to thickeners can not only enhance their nutritional value but also alter their flow characteristics. However, in the realm of commercial thickener research, ionic strength remains a relatively understudied factor when compared to other influential variables. Cho, Yoo, and Yoo (2015) found that different thickeners based on XG and other polysaccharides exhibited varying flow behaviors with NaCl concentrations (0.3%, 0.6%, 0.9%, and 1.2%). Low NaCl concentrations (0.3%) showed synergy with XG, while high NaCl concentrations (>0.3%) reduced K, yield stress, and η_{50}. This phenomenon may arise from Na^+ ions shielding the side chain groups of XG, leading to viscosity reduction. Moreover, the addition of 0.6–1.2% NaCl reduced shear thinning and increased n, improving taste. Notably, when 0.6% NaCl was added, the combination of XG, GG, and dextrin consistently exhibited a synergistic effect on G' within the tested Na^+ concentration range. In contrast, the complex of XG, CMC, GG, and dextrin showed lower G' at high NaCl concentrations. Other thickeners also experienced inhibition at high concentrations but higher G' values than without NaCl. Kongjaroen, Methacanon, and Gamonpilas (2022) suggested that the presence of cations like K or Na in milk (Na 41.7 mg/100g) and apple juice (Na 12.5 mg/100g) could mitigate repulsive interactions between polyelectrolyte chains. These chains then interact and form hydrogen bonds, thereby increasing their viscosity, especially at low shear rates. In essence, a low concentration of ions in combination with polysaccharides demonstrates a synergistic effect, and an appropriate increase of ionic strength is conducive to achieving better thickening effects.

Saliva. Saliva plays a vital role in oral hygiene, oral wear and lubrication, and the processing of food in the mouth (including the formation and movement of boluses and the transmission of odors) (Mu and Chen 2023). It accounts for a significant difference between simulated swallowing and actual mouth conditions. When swallowing occurs, saliva fills the gaps between particles, enhancing cohesion and lubrication, ultimately reaching the threshold for triggering the swallowing reflex (Mosca and Chen 2017). This process facilitates bolus formation and movement. Furthermore, the interaction between saliva and the bolus contributes to food digestion, as saliva contains salivary amylase. The presence of starch mixed with saliva results in the decomposition of macromolecules and a notable reduction in viscosity. Vallons et al. (2015) subjected a starch-thickened fluid (1315 ± 364 mPa·s) and a gum-based thickened fluid (1,376 ± 252 mPa·s) to various durations of oral treatment to assess changes in fluid viscosity. Following oral treatment for 10 s, the viscosity of the starch-thickened fluid decreased to 383.6 mPa·s, while the gum-base thickened fluid decreased to 901.1 mPa·s. After 20 s, the starch-thickened fluid transitioned from a honey-like viscosity to a nectar-like viscosity, while the viscosity of the gum-based thickened fluid remained unchanged. Turcanu et al. (2018) showed that salivary amylase significantly reduced the axial force of a starch-thickened fluid (by about 15 mN) but did not significantly impact a gum-based thickener. The effect of saliva on starch can be reduced by combinations of different polysaccharides or within an acidic environment (pH < 3.6) (Hanson, Cox, et al. 2012). Hanson, O'Leary, et al. (2012) compared the viscosity between a starch-based thickener and that added with gum under saliva. Their study revealed that saliva reduced the viscosity of both thickened fluids. While the starch-based thickened fluid underwent complete decomposition, the compound thickener retained a certain level of consistency. In contrast, no measurable reduction in viscosity was observed for thickened orange juice (pH 3.8).

Hence, examining the flow characteristics of polysaccharide–dextrin systems in diverse environments expands the dietary options for dysphagia patients, aiding in reducing resistance to eating and addressing malnutrition. The thickening effect of polysaccharide–dextrin thickeners varied with pH, dispersion medium, temperature, and ionic strength. Sourness, coldness, and appropriate temperature play a beneficial role in encouraging patient swallowing. Within the pH range of 4–7, at low temperatures and reduced ionic strength, most polysaccharide–dextrin-thickened fluids demonstrate stable and effective thickening. When saliva is present, gum-based thickeners exhibit more stability compared to starch. However, it is worth noting that the influence of low pH (<3.6) on saliva decomposition should not be overlooked.

Subsequent studies should delve into the interconnections among shear and extensional behaviors, tribology, and inherent fluid properties (e.g., density and surface tension), and their correlation with swallowing. Building on this foundation, there should be a concerted effort to simulate the clinical conditions of dysphagia diets. This involves a meticulous examination of the rheological changes of the fluid under substantial large deformation, considering both extensional and frictional properties. Additionally, it is essential to select temperature, pH, and salt concentrations that align with the specific requirements of a patient's diet. Further investigations ought to concentrate on unraveling the link between molecular interactions, facilitating a systematic evaluation of the characteristics of polysaccharide–dextrin mixtures (or polysaccharides mixed with other substances) in the context of swallowing.

4. Methods to evaluate swallowing of polysaccharide–dextrin-thickened fluids for individuals with dysphagia

By incorporating the flow characteristics discussed above, a range of evaluation methods have been developed to realistically simulate the swallowing attributes (e.g., flow velocity, risk of aspiration, and residual amount) of polysaccharide–dextrin-thickened fluids. These advancements are fundamental in crafting specialized fluid diets for individuals with dysphagia. This section provides an overview of various swallowing assessment methods (*in-vivo*, *in-vitro*, and *in-silico*) developed in recent years for thickened fluid systems.

4.1. In-vivo evaluation methods for fluid swallowing behaviors

4.1.1. Clinical examination

Different clinical methods, such as videofluoroscopy swallowing study (VFSS), endoscopy, swallowing acoustics, surface electromyography (sEMG), and computed tomography (CT)., have been employed to examine the swallowing characteristics (e.g., flow velocity and aspiration risk) of fluids thickened with polysaccharide-based thickeners (Koyama et al. 2021).

VFSS is considered a standard method to judge the swallowing status (Pavithran et al. 2020). This technique based on X-ray enables us to visualize the swallowing behaviors of thickened fluid boluses in the oral phase (e.g., food spillage), pharyngeal phase (e.g., fluid residue and aspiration), and esophagus phase (e.g., food stagnation and reflux) (Palmer et al. 1993). Utilizing VFSS images, it becomes possible to ascertain how the flow characteristics (e.g., shear viscosity) of polysaccharide–dextrin-thickened fluids impact their swallowing safety (Steele et al. 2019; Bolivar-Prados et al. 2019; Vilardell et al. 2016). Bolivar-Prados et al. (2019) employed VFSS to evaluate Nutilis Clear (containing MD, XG, and GG)-thickened fluids with varying shear viscosities (ranging from 150 to 2000 mPa·s). It was noted that the swallowing safety of these fluids predominantly hinged on their viscosity, while the roles of other rheological attributes (e.g., elasticity, adhesion, cohesion, and tensile viscoelastic characteristics) warrant further scrutiny (Bolivar-Prados et al. 2019). Similar findings have been reported in other investigations (Steele et al. 2019; Vilardell et al. 2016).

However, there are certain limitations associated with VFSS examinations. Typically, a contrast medium (e.g., barium) is introduced to enhance the visualization, resulting in alterations to the rheological properties of fluid boluses, rendering them more viscous (Park, Yoo, and Yoo 2019; Barbon and Steele 2019; Park and Yoo 2021). Furthermore, the presence of barium leaves a coating on the mucous membranes of the pharynx and esophagus, thereby obscuring the inherent nature of the fluid (Steele et al. 2013). Additionally, to accurately capture muscle forces acting on the fluid bolus, VFSS necessitates coordination with invasive endoscopic examinations, such as fiberoptic endoscopic evaluation of swallowing (FEES) and high-resolution manometry (HRM). These endoscopic methods entail catheter insertion into the body, which can impede and disrupt the flow of the fluid bolus flow during swallowing (Koyama et al. 2021).

In light of this, a noninvasive clinical approach, sEMG, has been employed to examine the swallowing characteristics of thickened fluids. This method gauges the electrical signals emanating from muscle activities associated with fluid ingestion (Zhu et al. 2017), as different fluids elicit varied muscle responses during swallowing (Vaiman and Eviatar 2009). Koyama et al. (2021) reported that thickened fluids containing 2% dextrin exhibited longer muscle activity durations compared with water, indicating a reduced fluid flow velocity (and, consequently, diminished aspiration risk) during swallowing. Additionally, it was observed that augmenting the shear viscosity of sesame paste could prolong the swallowing cycle (Zhu et al. 2017). Another noninvasive method for assessing fluid bolus swallowing is swallowing acoustics, which involves analyzing the sounds generated within the organs (Enz et al. 2021; Nakauma et al. 2011). Nakauma et al. (2011) disclosed that XG (0.3% to 0.9%)-thickened fluids exhibited a more coherent flow pattern (as opposed to a scattered flow) when compared to thickened counterparts with LBG (ranging from 0.5 to 0.8%). Despite these advancements, it is imperative to integrate these noninvasive methods with VFSS to gain a comprehensive understanding of how the remaining attributes of polysaccharide–dextrin-thickened fluids affect their swallowing behaviors.

CT, as another new evaluation mode, addresses the limitations of VF through dynamic three-dimensional observation. Typically, the patient ingest a fluid containing a contrast agent, facilitating a multi-phase scan of the 3D image to capture a dynamic swallowing image. This approach enables detailed measurements and a broader quantification of swallowing dynamics. Notably, CT introduced a groundbreaking visualization of vocal cord closure (the last line of defense during swallowing), allowing, for the first time, the laryngeal closure (glottis closure, laryngeal vestibular closure, and epiglottic inversion) processes safeguarding the airway to be independently observed and measured. The movement of the upper esophageal sphincter (UES) was also distinctly observable in this technique (Inamoto, González-Fernández, and Saitoh 2022; Inamoto, Ueha, and Gonzalez-Fernandez 2023). Besides, 3D-CT excels in accurate structural measurement and time recording. As a result, CT gained widespread adoption in the study of swallowing since 2011. For example, Inamoto et al. employed 3D-CT to scrutinize the movement of 10 mL of honey concentrated barium (5% v/w) and thin barium (5% v/w) in a 45° inclined position. The findings revealed that for thin fluids, the bolus reached the lower pharynx earlier and remained longer in the lower pharynx compared to thickened fluids (Inamoto et al. 2013). The use of CT scanning of the human body will be more beneficial to construct a model of the swallowing process and better simulate the flow of thickened fluids.

Clinical examinations tend to prioritize the assessment of physiological processes during the ingestion of polysaccharide-thickened fluids. While the methods offer insights into the correlations among flow parameters of polysaccharide–dextrin-thickened fluids and their swallowing traits, conducting such investigations within the human body presents ethical and economic challenges. To aid the development of dysphagia diets, there is a need to establish animal models, as well as *in-vitro* and *in-silico* approaches, to authentically evaluate the swallowing dynamics of polysaccharide–dextrin-thickened fluids with diverse flow characteristics.

4.1.2. Animal model

Animal models (e.g., rodent, pig, and dog) can serve as valuable tools for assessing the swallowing characteristics of thickened fluids, including those employing polysaccharide–dextrin systems. These models offer the advantage of fewer ethical issues and reduced individual variabilities. Utilizing these animal models for swallowing assessments of thickened fluids provide a means to validate their efficacy in dysphagia management (Au-Lever et al. 2015; German et al. 2017; Lammers et al. 2020; Harris et al. 2017; DeLozier et al. 2018). To date, a range of animal models with dysphagia have been established, such as elderly, nerve injury, Parkinson's disease, stroke, amyotrophic lateral sclerosis, and Down syndrome (Russell et al. 2013; Cullen et al. 2018; Cullins and Connor 2019; Sugiyama et al. 2014; Osman et al. 2020; Glass, Twadell, et al. 2019; Glass, Valmadrid, et al. 2019; Wang et al. 2017; Welby et al. 2020; Gould et al. 2018). Kletzien, Cullins and Connor (2019) conducted VFSS examinations on aging rodents and disclosed that the aging process altered the swallowing biomechanics of peanut butter (IDDSI level 4) and influenced the bolus flow behavior (Kletzien, Cullins and Connor 2019). In an aging dysphagia dog model, Harris et al. (2017) showed that thin fluids were ingested more rapidly than purees matrices, aligning with VFSS findings in humans. Additionally, research indicated that higher viscosity in XG-thickened fluids resulted in prolonged retention in the lungs, potentially leading to more severe lung injuries (Araie et al. 2020; Nativ-Zeltzer et al. 2018).

Nonetheless, to date, there is a lack of sufficient understanding of whether animal models can provide a comprehensive swallowing assessment of the swallowing properties of polysaccharide–dextrin-thickened fluids, taking into account the influence of various flow parameters. Further research is required to validate the efficacy of thickened fluids utilizing polysaccharide-based thickeners through animal models, particularly with regard to their relevance to the human body.

4.2. In-vitro evaluation methods for fluid swallowing behaviors

To address ethical concerns and enhance data reproducibility, *in-vitro* simulations have been developed to visually and realistically assess the swallowing performance of polysaccharide–dextrin-thickened fluids under varying fluid flow parameters (Marconati, Engmann, et al. 2019).

Using *in-vitro* modeling methods could capture the swallowing performance of diverse thickened fluid matrices (Table 3),

Table 3. *In-vitro* methods assessing fluid swallowing behaviors.

Equipment	Obtained parameters	Verification methods	Remark	References
Cambridge Throat (Severe difficulty swallowing in the throat area)	• Oral swallowing time; • Bolus residue; • Bolus stretch length; • Bolus position;Bolus flow velocity;	**Non-Newtonian fluids:** *(a)* ThickenUp Clear (0.6–3.6, 1.2, 2.4, 3.6% w/w); *(b)* ThickenUp (4.8, 8.3 % w/w); *(c)* E-Z-PAQUE (41% w/w); *(d)* Thick & Easy (4.5, 6.75, 9% w/w); *(e)* Nutilis powder (2, 4, 6, 2.9–6.5% w/w); *(f)* Xanthan gum (0.25, 0.5, 0.6, 1.0, 1.4% w/w); *(g)* Carboxymethyl cellulose (0.5, 1, 1.5% w/w); *(h)* Ski strawberry yoghurt; *(i)* Polyethylene oxide (1, 3% w/w); **Newtonian fluids:** *(a)* Molasses and glycerol (viscosities: 6 to 1185 mPa·s); *(b)* Water;	**Viscous non-Newtonian fluids:** *(a)* Reduced flow velocity; *(b)* Increased swallowing time; *(c)* Better tensile properties; *(d)* Smoother and denser bolus; *(e)* Increased pharyngeal residual volume;	(Lavoisier et al. 2021; Mowlavi et al. 2016; Hayoun et al. 2015; Mackley et al. 2013; Patel et al. 2020; Marconati, Lopez, et al. 2019)
Gothenburg Throat (Normal swallowing of the pharynx and models of various swallowing disorders)	• Bolus velocity; • Shear rate; • *In-vitro* manometry analysis (accuracy <6% in the range of 1–48 kPa);	**Non-Newtonian fluids:** *(a)* Nutricia Nordic AB (0.5, 1, 1.5, 2 Pa·s at 50 s^{-1}); *(b)* Fresubin Clear (0.65 Pa·s at 50 s^{-1}); **Newtonian fluids:** Rapeseed oil (0.063 Pa·s at 50 s^{-1});	*(a)* First noninvasive manometry; *(b)* Increasing viscosity increased pressure peak duration; *(c)* Increasing bolus volume increased pressure; *(d)* A broad range of shear rates should be considered;	(Stading et al. 2019; Qazi et al. 2019)
Tongue-Palate Compression Mechanical Simulator (Oral)	• Bolus pressure; • Bolus velocity; • Internal shear rates for bolus calculated with the velocity profile;	**Non-Newtonian fluids** • Thick & Easy Clear (0.47 Pa·s at 50 s^{-1}); • Thick & Easy (0.47 Pa·s at 50 s^{-1});	*(a)* Viscosity at 50 s^{-1} cannot represent the fluid oral flow; *(b)* Gum- and starch-based flow behaviors show differences; *(c)* Higher tongue pressure is required to remove oral residue;	(Redfearn and Hanson 2018)
Swallow Safe model (From the mouth to the pharynx into the esophagus)	• Extrusion force; • Lip and deformation resistance;	**Non-Newtonian fluids** *(a)* Xanthan gum (1, 1.25, 1.5, 1.75, 2% w/w); *(b)* Gelatin gels of different hardness (Gelita 125, 150, 175, 200, and 250 blooms); *(c)* Glass ballotini (between 510 and 750 microns) mixed with different amounts of xanthan gum solution of varied cohesion;	*(a)* "Slip Extrusion Test" adapted from the squeeze test; *(b)* Deformation resistance measurements relate to gel hardness; *(c)* Slip resistance measurements relate to solution viscosity;	(Ng et al. 2017)
***In-vitro* dynamic VFSS simulation system** (Throat)	• VF image; • Residual ratio; • Time required for test food to move down; • Food residual area in side and front images; • Gray density of images;	*(a)* Barium (7 J/m^3); *(b)* Barium-containing thickener (30 J/m^3); *(c)* Barium-containing cream pudding (10 J/m^3); *(d)* Iodine-containing rice porridge (200 J/m^3);	*(a)* A bolus with high viscosity is easy to remain in the pharynx; *(b)* A thin bolus remains less but is more likely to be sucked;	(Noh et al. 2011)
Swall-E Robot (Throat)	• The absence or presence of aspiration in the trachea; • Pharyngeal residue Scale;	Nutricia Power, Nutilis (IDDSI grade 3);	Weak bolus propulsion and lack of lubricity result in residues of bolus;	(Fujiso et al. 2018)

with several models discussed below. The Cambridge Throat model is the most commonly used *in-vitro* model in laboratory settings (Figure 6a) (Mackley et al. 2013). This model combines tongue pressure and fluid flow parameters (e.g., viscosity) to illustrate the oropharynx phase of swallowing thickened fluids (Patel et al. 2020). Using the Cambridge Throat, various polysaccharide-based thickeners, such as Nutilis (including XG, GG and MD), TUC (containing MD and XG), THU (containing modified starch), XG, and CMC, have been assessed. It allows for the collection of data on parameters, such as swallowing time, stretch length, and bolus position. Increasing the thickener concentration has been linked to longer swallowing times, indicative of enhanced swallowing safety. Also, this model reveals the role of extensional behaviors of thickened fluids during swallowing. It is noteworthy that this model simulates a scenario where the epiglottis is impaired, and the bolus, driven by gravity, traverses the esophagus, which differs from peristaltic esophageal transport (Marconati, Lopez, et al. 2019; Mowlavi et al. 2016; Mackley et al. 2013; Patel et al. 2020).

On the other hand, the Gothenburg Throat model has the capability to incorporate shear rate and pressure, which are significant factors in assessing the dynamic swallowing of various flowing thickened fluids (Figure 6b) (Qazi et al. 2019). The model can replicate the velocity and shape of a fluid bolus and its movement into the pharynx, UES, and nasopharynx (Stading et al. 2019). It was employed to analyze rapeseed oil and a thickened fluid using Fresubin Clear

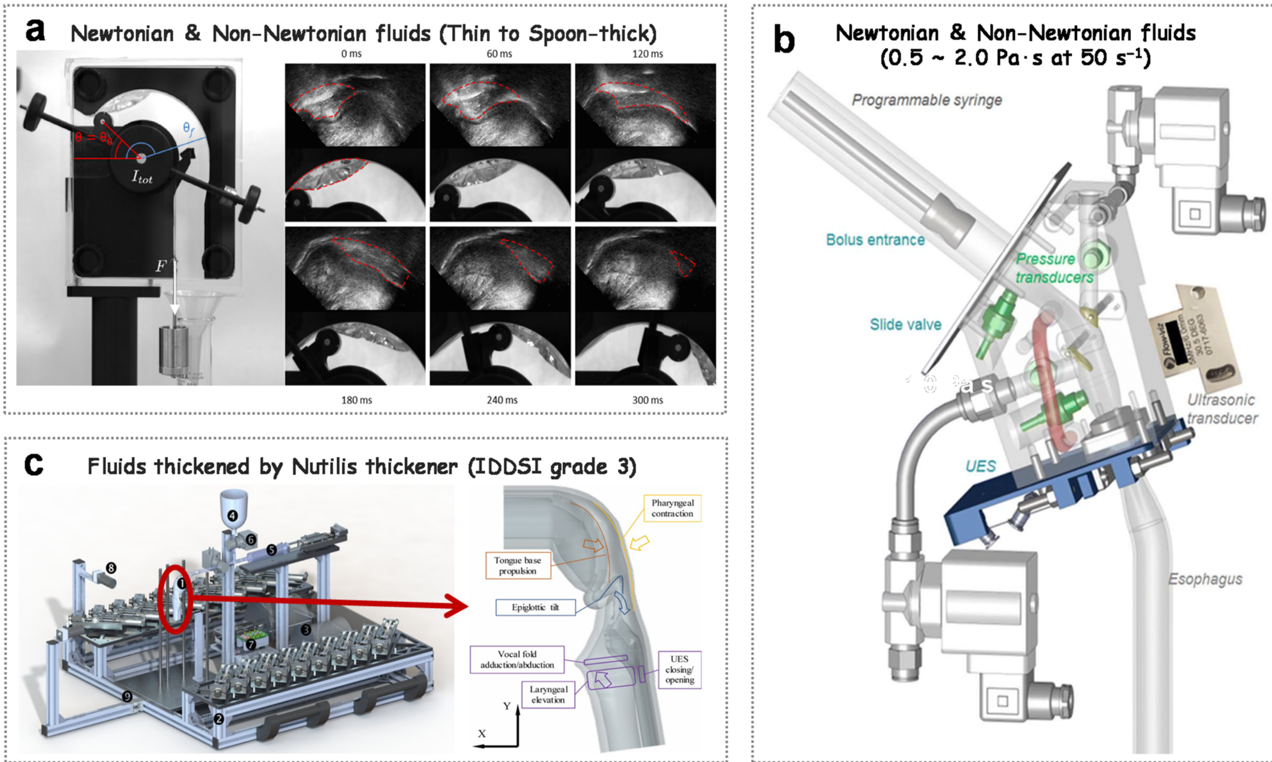


Figure 6. *In-vitro* simulation equipment: (a) the cambridge throat; (b) sketch of the gothenburg pharynx model; (c) Overview and side view of the Swall-E swallowing robot.
(a) is adapted from Ref. (Mowlavi et al. 2016) with permission from Elsevier, Copyright 2016. (b) is adapted from Ref. (Qazi et al. 2019), and (c) is adapted from Ref. (Fujiso et al. 2018).

Thickener (containing modified starch, MD, XG, and modified cellulose). Results indicated that the rapeseed oil fluid showed a parabolic curve in terms of shear rate, while the velocity profile of the Fresubin Clear fluid exhibited a plug flow curve due to the presence of surfactants. However, when it came to pressure measurement, rapeseed oil showed no difference from Fresubin Clear fluid (Stading et al. 2019). Furthermore, for honey-like (1 Pa·s) and pudding-like (2 Pa·s) fluids thickened with Nutricia Nordic AB (Stockholm, Sweden), the thicker fluids exhibited slower flow rates, lower shear rates and higher pharyngeal pressures than the thinner fluids.

In addition, Fujiso et al. (2018) developed a robotic simulator called Swall-E (Figure 6c) to replicate the pharyngeal phase of human swallowing. This innovative model was used to assess a fluid (IDDSI grade 3) thickened with a Nutilis thickener containing MD, XG, and GG. During simulation, high-speed camera observations captured the velocity and motion of the fluid within the model, and the residue of the fluid bolus was recorded. The accuracy of the model was validated by comparing its results with VFSS images (Fujiso et al. 2018).

4.3. In-silico evaluation methods for fluid swallowing behaviors

In-silico simulation methods have been established for the noninvasive and visual assessment of the swallowing performance of thickened fluids, including those with polysaccharide–dextrin formulations (Table 4). These simulations involve modeling the swallowing process of thickened fluids using mesh-based methods, such as Euler, Lagrangian, and arbitrary Lagrangian-Euler (ALE), and organ representations are created using CT and VF images, along with other methods like finite element model (FEM) and finite volume model (FVM) (Sonomura et al. 2011; Ho et al. 2017; Michiwaki et al. 2020). To perform these simulations, physical and flow parameters (e.g., viscosity, density, and bolus volume) of thickened fluids are utilized as input parameters. In essence, *in-silico* models can depict the relationship between the input flow parameters of various thickened fluids and their resulting swallowing characteristics.

Mizunuma et al. (2009, Mizunuma, Sonomura, and Shimokasa 2020) and Sonomura et al. (2011) employed the Euler mesh method to simulate water and non-Newtonian fluids with varying viscosities in assessing oropharyngeal swallowing dynamics (Figure 7a). Their simulations involved modeling the movement of different fluid volumes within a healthy model and two dysphagia models characterized by epiglottis dysfunctions. Their findings indicated that higher viscosity led to reduced fluid flow velocity, and the aspiration pattern was influenced by bolus size. In cases of dysphagia marked by premature termination of the swallowing process, excessively viscous fluids moved slowly, and residual fluid entered the trachea after epiglottis closure, resulting in aspiration (Sonomura et al. 2011; Mizunuma et al. 2009; Mizunuma, Sonomura, and Shimokasa 2020).

Table 4. *In-silico* methods assessing fluid swallowing behaviors.

Equipment	Reference System	Simulation situation	Parameters	Verification method	Remark	References
Oral 2D model	Arbitrary Lagrangian-Eulerian (ALE) & finite element model (FEM)	Oral	• Simulated movement of pills;	Newtonian fluids (1000 cP and 10 cP)	• High-viscosity pills better prevent liquid from spilling out of the mouth	(Nicosia 2007)
Oral swallowing mathematical model	Mathematical model	Oral	• Estimated shear rate for viscosity and boundary slip pair	• Numeral calculations; • Newtonian fluids (1, 100, and 1000 cP);	• Bolus viscosity influences shear rate	(Nicosia 2013)
Elastic pharyngeal model	Euler & FEM	Oropharyngeal model of health and swallowing disorders;	• Speed and trajectory of the pill;	• Jelly, water, and Non-Newtonian fluids; • VFSS verification	• Increasing viscosity reduces bolus velocity; • Aspiration depends on bolus volume and swallowing motion;	(Mizunuma et al. 2009; Sonomura et al. 2011)
Semi-implicit motion particle method	Moving particles semi-implicit (MPS)	Healthy and dysphagia throat model	• Fluid velocity; • Shear rate; • Viscosity and trajectory;	• Iodine contrast media; • Non-Newtonian liquid containing contrast media;	• Inhaled particles flow faster than non-inhaled particles;	(Kamiya et al. 2013; Kikuchi et al. 2015; Kikuchi et al. 2017; Michiwaki et al. 2020; Osada et al. 2014)
Smoothed particle hydrodynamics	Smoothed particle hydrodynamics (SPH)	Healthy throat model	• Apparent viscosity vs. shear rate; • Oral transit time and residue content; • Image;	• Water (1 cP); • Nectar-like fluids (with 2.5% w/w *Top Balance III*) and honey-like fluids (5% w/w);	• Fluid simulation closer to *in-vivo* swallowing without slippage;	(Ho et al. 2017)

Furthermore, mesh-based methods like ALE were employed to simulate and monitor the changes in the fluid boundary (Hirt, Amsden, and Cook 1974). Nicosia (2007) utilized the ALE mesh method to simulate thickened fluids with varying viscosities (1000 and 10 cP). The data revealed that high-viscosity fluids could be better retained in the oral cavity compared to low-viscosity fluids. However, it is important to note that the meshes methods can exhibit significant distortion when the fluid exceeds its boundaries, which is undesirable for accurately assessing the swallowing behaviors of thickened fluids (Nicosia 2007).

To address this challenge, mesh-free methods have been proposed, such as smoothed particle hydrodynamics (SPH) and the moving particles semi-implicit (MPS) method. These approaches offer advantages in simulating two-phase flows, fluid splashes, and intricate 3D geometries (Kamiya et al. 2013). Ho et al. (2017) applied the SPH method to simulate throat fluid flow in the presence of saliva lubrication, using both thin and nectar- and honey-like fluids for testing (Figure 7b). The results indicated that fluid flow closely resembled reality when lubrication was absent, although residual levels were significantly higher than actual values.

While SPH is suitable for simulating compressible fluids, the MPS method is employed for simulating incompressible fluids. Michiwaki et al. (2020) introduced the Hamiltonian moving particles semi-implicit (HMPS) method, derived from MPS, to simulate Newtonian and non-Newtonian liquids. They utilized this approach to construct a 3D swallowing simulator known as “Swallow Vision” (Figure 7c). With this model, it becomes possible to realistically simulate various swallowing characteristics, such as flow velocity, aspiration probability, shear rate, and residual amount, for fluids thickened with polysaccharide–dextrin. The viscosity of non-Newtonian fluids was defined using a power-law function, and input parameters like density, viscosity, surface tension, and contact angle could be readily adjusted based on fluid properties and formula calculations. Importantly, the Swallow Vision simulation of polysaccharide-thickened fluids aligns with the VFSS images (Kikuchi et al. 2015; Kikuchi et al. 2017; Michiwaki et al. 2020).

Hence, considering fluid flow behaviors, both *in-vitro* and *in-silico* models demonstrate significant promise in evaluating and designing thickened fluid foods tailored to the desired characteristics of individuals with dysphagia. Present models facilitate numerical analyses of the swallowing process of developed fluids, which can be cross-referenced with actual VFSS and CT images. However, it is important to acknowledge that swallowing is a multifaceted process, and current models somewhat simplify the incorporation of fluid flow attributes and organ movements. In the future, for a more accurate assessment of the swallowing performance of thickened fluid matrices, it will be crucial to integrate more comprehensive features like yield stress, extensional viscosity, and the presence of saliva into the development of various *in-vitro* and *in-silico* methods.

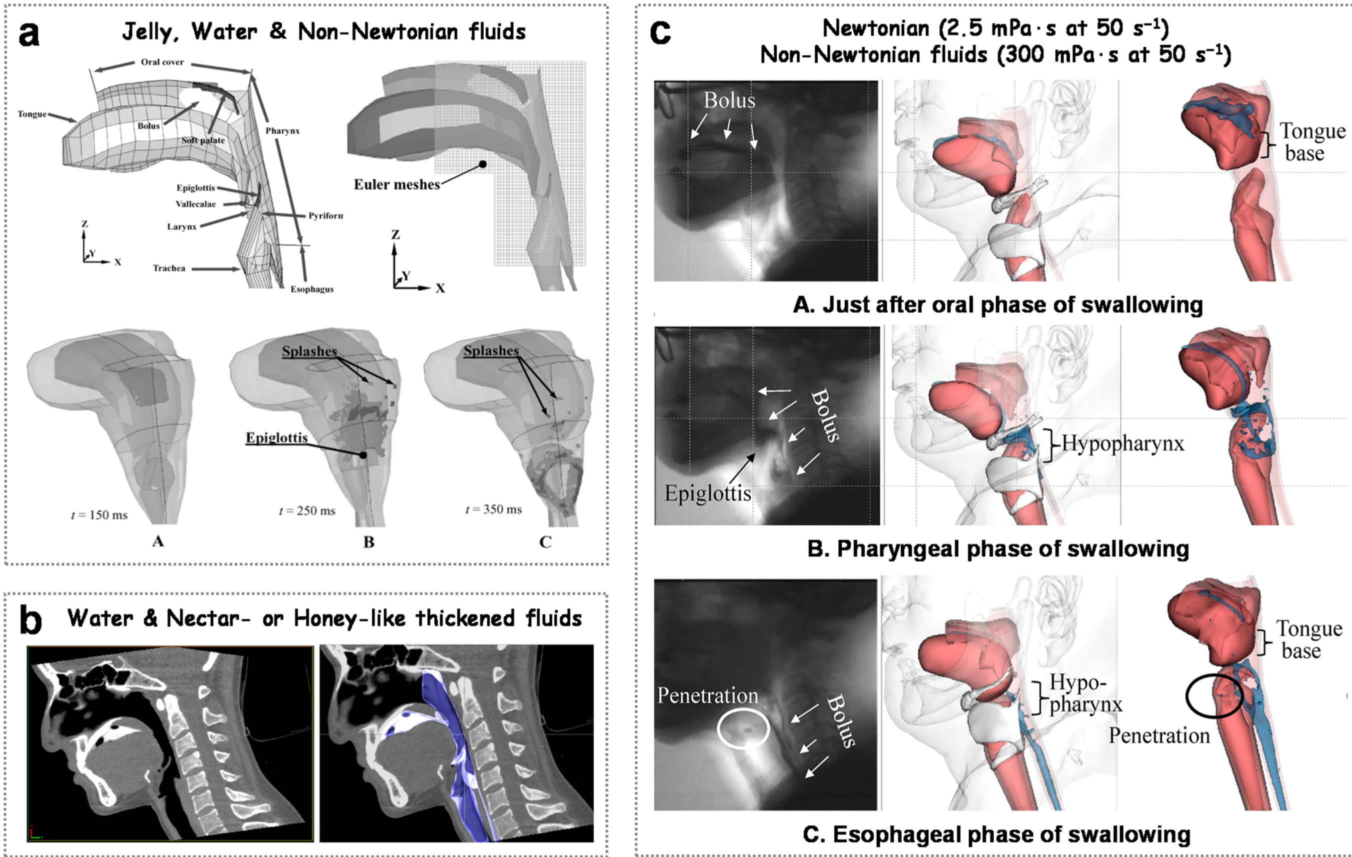


Figure 7. *In-silico* simulation equipment: (a) finite element model (FEM) of fluid simulation with euler meshes; (b) smoothed particle hydrodynamics (SPH) with a dynamic mesh as the fluid boundary condition. The bolus is grey and streaky, and the air is dark; (c) Hamiltonian moving particle semi-implicit (HMPS) method. The simulation of swallowed non-Newtonian fluids in patients with mild dysphagia appeared to be penetrating and corresponded well to the VFSS images.
(a) is adapted from Ref. (Sonomura et al. 2011) with permission from John Wiley & Sons, Copyright 2011. (b) is reprinted from Ref. (Ho et al. 2017) with permission from Elsevier, Copyright 2017. (c) is adapted from Ref. (Michiwaki et al. 2020) with permission from Elsevier, Copyright 2020.

5. Conclusions and outlook

Polysaccharide–dextrin-thickened fluids play a vital role in meeting the nutrition needs of individuals with dysphagia. In the pursuit of tailored dysphagia diets, extensive efforts have been dedicated to comprehending the flow characteristics of these thickened fluids and subsequently devising methods to assess their swallowing behavior. Previous research has illuminated the impact of dextrin inclusion on chain entanglement and hydrogen bonding within polysaccharide-thickened fluids, resulting in alterations to key flow characteristics, including viscosity (both shear and extensional), modulus, cohesiveness, adhesiveness, yield stress, thixotropic properties, and coefficient of friction. These flow characteristics are intimately linked to the swallowing performance of thickened fluids. For instance, elevating the viscosity of a polysaccharide–dextrin-thickened fluid can decelerate its flow during swallowing, affording ample time for epiglottis closure, thereby reducing the risks of choking and aspiration. Lowering the coefficient of friction makes it easier to swallow and provide a refreshing sensation. Taking into account and incorporating flow characteristics, a range of methods has emerged for assessing the swallowing attributes of polysaccharide-thickened fluids. While *in-vivo* approaches (e.g., VFSS, swallowing acoustics, sEMG, CT, and animal models) have been documented, considerable emphasis has been placed on the development of *in-vitro* models (e.g., the Cambridge Throat and the Gothenburg Throat) and *in-silico* modeling techniques (e.g., HMPS, Lagrangian, and ALE). In comparison to *in-vivo* methods, *in-vitro* and *in-silico* modeling offer ethical advantages, enhance data reproducibility, and prove more cost-effective. These models empower us to scrutinize various swallowing characteristics (e.g., flow velocity, choking, aspiration risk, and residual amount) of thickened fluids.

Nonetheless, existing *in-vitro* and *in-silico* modeling approaches tend to oversimplify fluid dynamics, often focusing on only partial flow parameters like shear viscosity. For future model development, it becomes imperative to incorporate more comprehensive flow characteristics (e.g., extensional rheological characteristics) of polysaccharide–dextrin-thickened fluids, as these are pivotal for an accurate assessment of thickened fluid swallowing behaviors. Furthermore, our understanding of the intricate interplay among polysaccharide–dextrin interactions, flow characteristics, and the swallowing performance of related thickened fluids remains incomplete. This knowledge is of utmost importance in the evaluation and design of dysphagia-friendly foods that meet safety, nutritional and sensory requirements.

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Author contributions

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Nomenclature

AFM	atomic force microscopy
ALE	arbitrary Lagrangian and Eulerian
BBE	ball-back extrusion
BLD	branched limit dextrin
CD	cyclodextrin
CMC	carboxymethylcellulose
CMCD	carboxymethylated curdlan
CT	computed tomography
DE	dextrose equivalent
FEM	finite element model
FVM	finite volume model
G'	storage modulus
G''	loss modulus
GA	gum Arabic
GG	Guar gum
HMPS	Hamiltonian moving particles semi-implicit
IDD	indigestible dextrin
IDDSI	international Dysphagia diet standardization initiative
JDD	the Japanese Diet for Dysphagia
JSDR	the Japanese Society for Dysphagia Rehabilitation
K	consistency coefficient
KC	κ-Carrageenan
KGM	Konjac glucomannan
LAOS	large amplitude oscillatory shear
LBG	Locust bean gum
LES	lower esophageal sphincter
LST	line-spread test
LVR	linear viscoelastic region
MD	maltodextrin
MC	methylcellulose
MPS	moving particles semi-implicit
n	flow index
N_1	first normal stress difference
NDD	the National Dysphagia Diet
PDMS	polydimethylsiloxane
PT	Purathick
QCM-D	quartz crystal microbalance with dissipation monitoring
QT	QuikThik
SAOS	small-amplitude oscillatory shear
SAXS	small-angle X-ray scattering
sEMG	surface electromyography
SP	supercol
SPH	smoothed particle hydrodynamics
THU	Nestlé ThickenUp
TIC	thick-it clear advantage
TMFs	texture-modified foods
TUC	Nestlé ThickenUp Clear
UES	upper esophageal sphincter
VFSS	Videofluoroscopy swallowing study
XG	Xanthan gum
τ_0	yield stress
σ	stress
$\tan\delta$	loss factor
G'_M	minimum strain elastic modulus,
G'_L	maximum strain elastic modulus
η'_M	instantaneous viscosity at minimum shear rate
η'_L	instantaneous viscosity at maximum shear rate,

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