RHEOLOGY OF FLUID FOODS FOR DYSPHAGIC PATIENTS

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SYNOPSIS
Steady-state flow properties, thixotropy, dynamic response, and creep recovery behavior of six fluid foods and two barium sulfate suspensions at two consistencies (e.g., nectar-like, honey-like) were investigated using a controlled-stress dynamic rheometer. All samples exhibited a shear-thinning behavior that was well described by the Cross model. The shear stress-shear rate relationships were well described by the Herschel-Bulkley model. Barium sulfate suspensions of honey consistency exhibited higher viscosity, higher yield stress, and higher elastic modulus than their fluid food counterparts. In contrast, barium sulfate suspensions with nectar consistency showed lower viscosity, lower yield stress, and lower elastic modulus than their liquid food counterparts. Frequency spectra of the nectar-like samples were similar to that of a macromolecular solution with both G’ and G” increasing with increased frequency, whereas those of the honey-like samples were typical of gel-like behavior with a little dependency of G’ and G” over frequency. Stress sweep experiments showed that the viscoelastic linear region of fluid foods and barium sulfate suspensions extended up to either 1 or 10 Pa.

Cichero et al. [5] also pointed out that there is need for objective assessment of rheological properties of videofluoroscopy fluids used in evaluation of dysphagia. Videofluoroscopy is a commonly used technique for diagnosis of dysphagia. The patient is given a radio-opaque barium sulphate suspension and his or her ability to swallow is monitored using videofluoroscopy. Videofluoroscopy would provide an indication of a patient swallowing ability at mealtime. However, this requires the assumption that the fluids used at mealtimes have the same rheological properties as their videofluoroscopy counterparts, which is not often the case. A thin barium solution that is more nectar-like than a true thin fluid may indicate that the patient can safely swallow thin fluids, while in fact he/she may aspirate true thin fluid [5]. Clinicians often rely on indications of the manufacturers of food thickeners to prepare dietary fluids with desired consistency (e.g., nectar consistency, honey consistency) or use pre-thickened ready-to-serve fluid foods. As Glassburn et al. [3] showed, in a recent study involving twenty-three professionals working on dysphagia evaluation, all clinicians were not consistent in their attempt to thicken liquid. The results of this study indicated the need for a standard protocol to ensure consistent viscosities across dysphagia evaluation and treatment.

In order to ensure a safe management of dysphagia, understanding the material properties of fluid foods given to dysphagic patients is important. Our objective was to fully characterize and compare the rheological properties of suspensions used for diagnosis and treatment of dysphagia.

2. MATERIALS AND METHODS

2.1. Materials
Six pre-thickened fluid foods (Novartis Nutrition, Minneapolis, MN, USA) and two barium sulfate suspensions (E-Z-EM, Inc., Westbury, NY, USA) were used in the current study. Manufacturers had labeled their fluid foods and barium sulfate suspensions as having either a “nectar consistency” or a “honey consistency” according to their standards.

2.2. Rheological Measurements
All rheological measurements were carried out at 25 °C using a controlled-stress, controlled-strain, and controlled-rate dynamic rheometer (Bohlin CVOR, Bohlin Rheologi Inc., Cranbury, NJ) equipped with a cone-and-plate geometry (40 mm, 4°).
2.2.1. Steady-state flow study

Steady-state flow properties were measured by subjecting samples to an increasing shear rate ramp in the range 0.001 to 1000 s⁻¹.

2.2.2. Thixotropy

Samples were subjected to an increasing and decreasing shear rate ramp in the range of 0.001 to 1000 s⁻¹ and their viscosity and shear stress measured.

2.2.3. Frequency sweep measurements

Samples were subjected to a frequency sweep (0.001 to 10 Hz) at a constant strain amplitude (0.5%) and their viscoelastic parameters (G', G'', and η*) measured.

2.2.4. Stress sweep measurements

Samples were subjected to a stress sweep (0.01 to 100 Pa) at 1 Hz and their viscoelastic parameters (G', G'') measured.

2.2.5. Creep Recovery test

Samples were subjected to a constant stress value in the range of 0.05 to 20 Pa during a short period (100 s) and their creep compliance (Jc) was measured over time. Stress was then suppressed and recovery compliance (Jr) of samples was measured over the same period.

3. RESULTS AND DISCUSSION

3.1. Steady-state flow properties

Figure 1: viscosity – shear rate of samples with nectar consistency.

Figure 1 shows the flow curves in terms of viscosity – shear rate relationships for three pre-thickened foods (2% milk, apple and cranberry juices) and one barium sulfate suspension labeled as nectar consistency (NC). For all samples, a strong shear-thinning or pseudoplastic behavior is found with presence of a Newtonian plateau at low shear rate values. Over the range of shear rates investigated, viscosity values of the three food samples seem to be very close whereas those of the barium sulfate suspension are slightly lower.

Viscosity vs. shear rate relationships for three pre-thickened liquids (water, orange and cranberry juices) and one barium sulfate suspension labeled as having a honey consistency (HC) are shown in Figure 2. For all samples, a strong shear-thinning behavior was found with presence of a Newtonian plateau at low shear rates values. Over the range of shear rates studied, the barium sulfate suspension has the highest viscosity values whereas pre-thickened fluid foods appeared to have almost identical viscosity values.

The viscosity vs. shear rate dependence was well approximated using the Cross Model. Results for samples with honey consistency are summarized in Table 1.

Table 1: Regression coefficients based on the Cross-model for samples with Honey Consistency (HC).

<table>
<thead>
<tr>
<th>Sample</th>
<th>η₀ (cP)</th>
<th>η∞ (cP)</th>
<th>k</th>
<th>n</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>422,400</td>
<td>217</td>
<td>34</td>
<td>0.85</td>
<td>0.95</td>
</tr>
<tr>
<td>Cranberry juice</td>
<td>220,000</td>
<td>150</td>
<td>19</td>
<td>0.85</td>
<td>0.94</td>
</tr>
<tr>
<td>orange juice</td>
<td>365,000</td>
<td>125</td>
<td>30</td>
<td>0.88</td>
<td>0.95</td>
</tr>
<tr>
<td>Barium sulfate</td>
<td>1,781,000</td>
<td>309</td>
<td>26</td>
<td>0.96</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Figure 2: viscosity – shear rate of samples with honey consistency.

Table 2: Regression coefficients based on the Herschel-Bulkley model for samples with Honey Consistency (HC).

<table>
<thead>
<tr>
<th>Sample</th>
<th>σ₀ (Pa)</th>
<th>K</th>
<th>n</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>water</td>
<td>6.2</td>
<td>1.2</td>
<td>0.77</td>
<td>0.99</td>
</tr>
<tr>
<td>Cranberry juice</td>
<td>5.1</td>
<td>1.4</td>
<td>0.69</td>
<td>0.99</td>
</tr>
<tr>
<td>orange juice</td>
<td>6.1</td>
<td>0.9</td>
<td>0.74</td>
<td>0.99</td>
</tr>
<tr>
<td>Barium sulfate</td>
<td>25.9</td>
<td>12</td>
<td>0.48</td>
<td>0.98</td>
</tr>
</tbody>
</table>
Flow curves in terms of shear stress vs. shear rate relationships were also examined for different samples. The shear stress vs. shear rate dependence is well approximated using the Herschel-Bulkely model. Results for HC samples are presented in Table 2.

### 3.2. Thixotropy

The shear stress vs. shear rate relationships for two liquid foods (milk, orange juice) with "nectar" and "honey" consistencies and their barium sulfate counterparts, are presented in Figure 3. Between 400 and 800 s\(^{-1}\), a small but noticeable hysteresis loop is observed. However, below or above this range the stress values recorded during gradual increase and decrease of shear rate superimposed well. At a given shear rate, the stress values of barium sulfate suspension with "honey" consistency are the highest whereas, those of barium sulfate sample with "nectar" consistency are the lowest. The stress values of "nectar" consistency milk sample are higher than those of its barium sulfate counterpart but lower than those of the "honey" consistency orange juice.

**Figure 3: Yield stress and thixotropic response of samples.**

### 3.3. Dynamic rheological properties

Frequency spectra of two liquid foods (milk, orange juice) and two barium sulfate suspensions with "nectar" or "honey" consistency are shown in Figure 4. Samples with "nectar" consistency show a \(G'\) - frequency dependence similar to that of concentrated macromolecular solutions with \(G'\) increasing as frequency increased. In contrast, samples with "honey" consistency exhibit a gel-like behavior with \(G'\) almost independent of frequency. For each given frequency, the barium sulfate suspension with "honey" consistency has the highest \(G'\) whereas that with "nectar" consistency has the lowest storage modulus. \(G'\) values of "nectar" consistency milk sample are higher than those of its barium sulfate counterpart but lower than those of the "honey" consistency orange juice.

**Figure 4: Mechanical spectra of samples.**

Stress sweep results for the four samples are presented in Figure 5. The two thickened liquid foods (milk, orange juice) show identical linear region, which extends to about 10 Pa. The barium sulfate sample with "honey" consistency has also almost the same linear region. In contrast, the barium sulfate sample with "nectar" consistency exhibits a narrower linear region. It extends up to only 1 Pa.

**Figure 5: Stress sweep of samples.**
3.4. Creep Recovery

Examples of creep recovery data recorded for milk samples with nectar consistency are shown in Figure 6 and Figure 7. Figure 6 presents the time-dependent response for the creep and recovery phases for three different values of applied stress (0.5 Pa, 1 Pa, 2 Pa). The “nectar” milk sample shows an elastic recovery in addition to its viscous response. The response of the compliance J to the instantaneous removal of stress can be reduced to three steps. Initially, J undergoes a step reduction as a pure elastic response. This is followed by an exponential decrease related to a viscoelastic response. Finally, J values approach an asymptotic value corresponding to the non-recovered deformation of the viscous flow. In contrast, Figure 7 shows that the recovery compliance of the same sample remains constant when stress applied was 5 or 10 Pa. This indicates a pure viscous behavior.

Figure 6: Creep recovery response of thickened milk with a nectar consistency at three different values of applied stress.

Figure 7: Creep recovery response of thickened milk with a nectar consistency at two different values of applied stress.

5. CONCLUSIONS

The rheological behavior of six fluid foods and two barium sulfate suspensions used for the treatment and evaluation of dysphagia were measured at room temperature using a controlled-stress dynamic rheometer. All samples exhibited a shear-thinning behavior that was well described using the Cross model. The shear stress vs. shear rate relationships were well described by the Herschel-Bulkley model. Barium sulfate suspensions with honey consistency exhibited higher viscosity, higher yield stress, and higher elastic modulus than their fluid food counterparts. In contrast, barium sulfate suspensions with nectar consistency showed lower viscosity, lower yield stress, and lower elastic modulus than their liquid food counterparts. The latter results suggest that the ready-to-serve fluids that currently exist in the market exhibit rheological properties significantly different from those of barium sulfate suspensions used for diagnosis of dysphagia, and thus there is a need to develop fluid foods with rheological properties that match exactly those of videofluoroscopy diagnostic fluids.

6. ACKNOWLEDGEMENTS

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6. REFERENCES