1. INTRODUCTION

In medical facilities, thickening agents are used to avoid the risk of aspiration\(^1\)\(^-\)\(^5\). However, it is problematic that clinical staff is often unsure how to adjust the liquid consistency for each individual dysphagic patient. We need to determine a common index of consistency when we use thickening agents.\(^6\)\(^-\)\(^10\)

In Japan, the value of viscosity for patients with difficulties in masticating and swallowing had been measured using a B-type viscometer at a rotor rotation rate of 12 rpm and 20 °C as decided by the Ministry of Health, Labor and Welfare. This rotor rotation rate, calculated as an approximate shear rate of 2-3 s\(^{-1}\)\(^11\), is a much lower shear rate than that stated for liquid flows through the pharynx.\(^12\)\(^,\)\(^13\) Recently the Japanese Society of Dysphagia Rehabilitation proposed a new criterion for thickened solutions for elderly patients with swallowing difficulties measured by using a cone-and-plate viscometer at a shear rate of 50 s\(^{-1}\). The rate of 50 s\(^{-1}\) had been adopted as the criterion on the grounds that Wood\(^14\) found that a power function described the relationship between shear stress measured at 50 s\(^{-1}\) and the oral perception of viscosity, so that a shear rate of 50 s\(^{-1}\) was related to the oral perception of viscosity. Other studies of oral shear rates of thickened liquid samples\(^15\)\(^-\)\(^18\) have been reported, showing that the correlation between the shear rate of oral perception and the shear rate of objective viscosity is a matter of opinion.

In a previous study, we reported a measurement for evaluating the physical properties of thickened solutions and liquid food to examine the correlation with non-oral sensory properties (by tilting the containers, stirring the contents with a spoon, or dripping the thickened solution from a spoon) to establish an index (model foods) of thickened solutions such as honey-like solutions.\(^19\) However, this suggested that the food was not appropriate for the index. The reason was most thickened solutions contain thickening agents that are non-Newtonian; thus, their apparent viscosity varies with shear rate, while other liquid foods, like honey and syrup, are Newtonian. Therefore, flow properties and non-oral sensory properties, e.g., dripping from a spoon, indicated difference between Newtonian and non-Newtonian flow.

Recently many kinds of commercial thickening agents have been developed using major ingredients of xanthan gum, guar-gum, modified starch, etc. Thickened solutions with these ingredients are non-Newtonian; thus, their apparent viscosity varies with shear rate, and they show different dependence on the shear rate of the solution due to the added thickening

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**Key Words:** Thickening agents / Viscosity / Oral sensory evaluation / Non-oral sensory evaluation / Shear rate
agents.

To date, many studies have been published on the influence of shear rate dependence of thickened solutions on the sensory properties and deglutition movement.\textsuperscript{20-22} However, there have been no reports describing the effects of shear rate dependence on oral and non-oral sensory properties of thickened solutions.

The aim of the present study was to examine the effects of viscosity on the oral and non-oral perception of non-Newtonian solutions with different shear rate dependence but the same viscosity indicated at a shear rate point. We had expected to assess the ease of swallowing thickened solutions by non-oral perception to prepare the standing consistency of solutions each time. Therefore, we measured the flow viscosity by steady-state flow method with a cone-and-plate viscometer and the dynamic viscoelasticity. These properties were analyzed, and correlations between the physical viscosity and oral and non-oral perceived viscosity were determined.

2. MATERIALS AND METHODS

2.1 Materials

The major ingredients of three kinds of commercial thickening agents that impart different shear thinning behaviors are given in Table I: commercial thickening agent A, which contains guar gum as the main thickening ingredient; commercial thickening agent B, using modified starch as the main ingredient; and commercial thickening agent C using xanthan gum as the main ingredient.

2.2 Preparation (Concentration) of Sample

The commercial thickening agents were dissolved in distilled water at 20 °C and stirred for 1 min with a rod at a speed of about 120 cycles/min and left for 60 min. The concentration of thickening agents described in Table I was decided as follows. The sample with a 1.00 % (w/v) solution of guar gum thickening agent was used in this study as a reference for the viscosity of the other samples and was indicated as G. Thus thin solutions with added thickening agents were regarded as more easily swallowed.\textsuperscript{18,23} We prepared samples of S1 and S50 using modified starch thickening agents, X1 and X50 using a xanthan gum thickening agents. The samples of S1 and X1 were prepared with viscosity at the rate of 1 s\textsuperscript{-1} of fall within those of sample G. The samples of S50 and X50 were prepared with viscosity at the rate of 50 s\textsuperscript{-1} of fall within those of sample G. The viscosity of the samples was measured with the cone-and-plate viscometer.

2.3 Physical Measurements

2.3.1 Viscosity measurement with a cone-and-plate viscometer

The steady shear viscosity of sample solutions was measured using a cone-and-plate viscometer (R type: Tohki Sangyo Co., Ltd., Tokyo, Japan) with either of two cones (one with a 24-mm radius and a 1° 34’ cone angle, and the other with a 14-mm radius and a 3° cone angle) at 20 °C. The shear stress was measured under a shear rate that changed stepwise in a range of 0.01 - 48.0 s\textsuperscript{-1}. There were 5 measured points each 120 s.

Shear rate dependences of viscosity measured with the cone-and-plate viscometers. The measured solutions had yield stress, i.e. distinguished into plastic flow. So the Herschel-Bulkley equation $P - P_y = k \cdot \gamma^n$, where $P$ is shear stress (Pa·s) and $P_y$ is the yield stress(Pa) was extrapolated to the shear stress-shear rate relation to determined the value of the viscosity at shear rate of 1 s\textsuperscript{-1}, the viscosity at shear rate of 50 s\textsuperscript{-1}, the flow behavior index $n$ and the yield stress.

2.3.2 Dynamic viscoelasticity of measurement

The data showing a frequency sweep was obtained by maintaining a strain amplitude of 0.1 % throughout the test. Dynamic viscoelasticity was measured at 20 °C with an ARES 100FRT-N1 over the frequency range $\omega = 0.1$ to 100 rad/s. On the assumption the position of the tongue and the plate within the oral cavity , authors used parallel-plate geometry with a diameter of 50 mm and sample height of 2.0 mm. Storage modulus , loss modulus, and dynamic viscosity ($G', G''$ and $\eta'$ respectively) were recorded referencing Takahashi et al.\textsuperscript{22}

2.4 Sensory Evaluation

The samples were divided into 2 groups, and each group was assigned a different set of 3 samples. Group 1: samples of G, S1, and X1 were shown to be the same viscosity level with the rate of 1 s\textsuperscript{-1}. Group 2: samples of G, S50, and X50 were shown to be the same viscosity level at the rate of 50 s\textsuperscript{-1}.

<table>
<thead>
<tr>
<th>Thickeners</th>
<th>Major ingredients</th>
<th>Symbol</th>
<th>Conc (w/v)</th>
<th>Apparent viscosity($\times 10^3$Pa·s)</th>
<th>Shear rate of 1 s$^{-1}$</th>
<th>Shear rate of 50s$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Guar gum</td>
<td>G</td>
<td>1.00</td>
<td>9.93±0.29</td>
<td>1.64±0.24</td>
<td></td>
</tr>
<tr>
<td>B</td>
<td>Modified starch</td>
<td>S1</td>
<td>3.75</td>
<td>9.84±0.31</td>
<td>0.95±0.02</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>S50</td>
<td>2.45</td>
<td>22.1±0.26</td>
<td>1.61±0.21</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>Xanthan gum</td>
<td>X1</td>
<td>0.60</td>
<td>9.66±0.30</td>
<td>0.75±0.01</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>X50</td>
<td>1.10</td>
<td>37.2±5.19</td>
<td>1.55±0.04</td>
<td></td>
</tr>
</tbody>
</table>

Viscosity values measured by cone-and-plate viscometer are expressed as mean ± standard deviation, $n$=8
The sensory evaluation method was carried out in 2 parts: oral and non-oral evaluation. The oral evaluation was based on stickiness, cohesiveness in the mouth, swallowing, and remaining in the mouth. A mouthful of each sample (5 g) was measured with a spoon and swallowed.

The non-oral sensory evaluation used 3 different evaluation procedures following F. Shama et al. and Houska et al. which included 1) tilting the container gently, 2) stirring the contents with teaspoon, 3 times, and 3) dripping the thickened solution from a spoon. Samples were contained in a plastic cup (approximately 50 ml) at room temperature (20 ± 2 ºC).

The experimental principle was Scheffe’s Method of Paired Comparison. Subjects were presented with 2 samples simultaneously, and they scored one sample in 7 steps (−3 to +3) in comparison with the other one. Panelists for the evaluation were total of 72 female university students aged 21 to 29.

3. RESULTS AND DISCUSSION

3.1 Physical Measurements

3.1.1 Steady shear viscosity

Figure 1 shows the flow properties and shear rate dependence on the viscosity of the solutions measured with the cone-plate viscometer. Samples G, X1 and S1 showed the crossover at rate of 1 s⁻¹ and showed the same viscosity level around 0.966-0.993 Pa·s. Samples G, X50, and S50 showed a crossover at a rate of 50 s⁻¹ and showed the same viscosity around 0.155-0.164 Pa·s. Table I shows the mean ±standard deviation of the viscosity of the sample at 1 s⁻¹ and 50 s⁻¹. The viscosity level at 50 s⁻¹ of all samples was 0.075 to 0.164 Pa·s which was at the same viscosity level as salad oil.

Shear rate dependences of viscosity measured was indicated (Fig. 1). Herschel-Bulkley rheological model could be adapted to the the samples. In the exponent, n is equal to 1.00 for Newtonian fluids and is less than 1.00 for non-Newtonian fluids that become thinner at higher shear rates. The value of n obtained for the solutions used in this study are listed in Table II. The value for sample G was highest and was closer to Newtonian behavior than samples containing xanthan gum (X1 and X50) and modified starch (S1 and S50). For the different thickening ingredients, X1 had more Newtonian tendency than X50, but there was no difference between samples S1 and S50 in the value of n, so the effect of concentration of thickening agents was different according to main ingredients.

The yield stress Py, obtained for the solutions are listed in Table III. The value for samples G, X1 and S1 were smaller compared with those of the X50 and S50. There was no difference among thin solutions (G, X1 and S1). The solution added xanthan gum has a week gel structure and relatively higher yield stress. This result (Table III) suggested that

<table>
<thead>
<tr>
<th>Sample solution</th>
<th>n</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0.54 ± 0.10</td>
<td>a</td>
</tr>
<tr>
<td>S1</td>
<td>0.37 ± 0.10</td>
<td>ab</td>
</tr>
<tr>
<td>X1</td>
<td>0.35 ± 0.01</td>
<td>ab</td>
</tr>
<tr>
<td>S50</td>
<td>0.36 ± 0.15</td>
<td>ab</td>
</tr>
<tr>
<td>X50</td>
<td>0.19 ± 0.01</td>
<td>b</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± standard deviation (n=8). Significant differences among values in the same row are indicated by different letters (p<0.01).

<table>
<thead>
<tr>
<th>Sample solution</th>
<th>Py (Pa)</th>
<th>Significance</th>
</tr>
</thead>
<tbody>
<tr>
<td>G</td>
<td>0.71 ± 0.06</td>
<td>a</td>
</tr>
<tr>
<td>S1</td>
<td>0.65 ± 0.12</td>
<td>a</td>
</tr>
<tr>
<td>X1</td>
<td>0.99 ± 0.03</td>
<td>a</td>
</tr>
<tr>
<td>S50</td>
<td>2.06 ± 1.18</td>
<td>b</td>
</tr>
<tr>
<td>X50</td>
<td>3.91 ± 0.19</td>
<td>c</td>
</tr>
</tbody>
</table>

Values are expressed as mean ± standard deviation (n=8). Significant differences among values in the same row are indicated by different letters (p<0.01).
yield stress of xanthan gum solution had no difference to the
guar gum and modified starch at thin solutions had indicated
more easily swallowed concentration (0.5-1.5 % (w/w)) of
thickening agents.23)

3.1.2 Dynamic viscoelasticity

Figure 2 shows the frequency dependence of $G'$, $G''$ and $\eta'$
for the solution.

The storage modulus $G'$ of sample G is larger than the loss
modulus $G''$ at low frequencies, whereas $G''$ is larger than the
storage modulus $G'$ at high frequencies. Both of $G'$ and $G''$
increased steeply with increasing frequency, and the dynamic
viscosity $\eta'$ was almost independent of frequency. This
indicated typical viscoelastic behavior such as elastic behavior
in the high-frequency region and a liquid-like behavior in the
low frequency region. This solution behavior of G was typical
"random coil" polymer solutions.20 In differences of behavior
to sample G, the samples X1 and X50 was a typical weak
viscoelastic gel which storage modulus $G'$ was greater than
its loss modulus $G''$ over the measured frequency range. Both
of $G'$ and $G''$ showed little variation with frequency, and $\eta'$
decreases steeply with increasing the frequency.

Samples S1 and S50 showed intermediate rheological
behavior between the properties of samples G and X. At low
frequencies of oscillation, $G'$ was slightly higher than $G''$,
but with increasing frequency, the values of the two moduli
converged. This was accompanied a decrease in $\eta'$ with
increasing frequency.

From the perspective of major ingredients, it can be seen
that the solutions with modified starch had the highest $G'$
among the three of difference ingredients samples having the
same viscosity level at rate of 50 s$^{-1}$ and 1 s$^{-1}$, respectively. In
contrast, the value of $G'$ for sample X1 dropped from the line
near 100 rad/s. It was likely that test condition of torque was
not appropriate because the sample of X1 had significantly
lower viscosity.

3.2 Sensory Evaluation

3.2.1 Oral sensory evaluation

Figure 3-(1) shows the results for Group1: samples G, S1
and X1 showed the same viscosity level at a shear rate of
1 s$^{-1}$. In the sensory evaluation of stickiness, the sample X1
was judged less sticky than the samples S1 and G ($p < 0.01$).
There was no difference between samples S1 and G. For
cohesiveness in the mouth, there was a significant difference
in the 3 samples, decreasing in the order of samples X1,
S1 and G ($p < 0.01$). Prior research on this topic18,22, has
demonstrated a correlation between dynamic viscosity and
the sensation of oral stickiness (evaluation of sensation while

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Fig. 2. Frequency dependence of dynamic viscoelasticities.
Results are shown for filled square, $G'$ (Pa) indicate storage modulus; open square, $G''$ (Pa) indicate loss modulus; filled circle, $\eta'$ (Pa s) indicate
dynamic viscosity. Sample symbols are the same as in Table I.
swallowing). In referring to these studies, we can see that these results that sample X1 had the lowest value which was consistent with the results for $\eta'$ at 100 rad/s by dynamic viscosity.

For swallowing, there was no significant difference among the samples. These samples were relatively thin solutions in instrumental measurements of viscosity, so that all of the samples were easy to swallow. For remaining in the mouth, sample X1 was judged thinner than sample S1 ($p < 0.01$). Sample G was not different from samples S1 and X1. It was suggested that the sample remaining in the mouth was affected by stickiness and cohesiveness in mouth.

Figure 3-(2) shows the results for Group2: samples G, S50 and X50 showed the same viscosity at the shear rate of 50 s^{-1}. For all sensory evaluation items, there was no significant difference among the samples, i.e., the subjects reported the same sensation during swallowing for each of the different sample. These results support well a previous study that indicated the shear rate of at the moment of swallowing was 50 s^{-1}.\(^{14}\) The other studies of oral shear rate have been suggested, Shame and Sherman’s\(^{15}\) proposed that thicker solutions were distinguished by differences in the perception of shear stresses developed at a constant shear rate at 10 s^{-1}. Housk et al.\(^{16}\) reported that subjects may take multiple viscosity measurements at a range of shear rates and that the resultant perception of a solutions viscosity may represent some form of average viscosity reading. Yamagata et al.\(^{18}\) concluded that thicker solutions are perceived from shear stress developed at a constant shear rate at approximately 100 s^{-1} rather than 2-3 s^{-1}. In the present study, researchers found that even viscosity at a shear rate of 1 s^{-1}, subjects reported the differences in the sensation during swallowing (thickness), but no differences for solution even viscosity at a shear rate of 50 s^{-1}. In addition, there were no changes in the order used for the solutions viscosities at shear rates from 50 s^{-1} to 100 s^{-1}, accordingly, our reported results were identical to those published by Yamagata et al. However, the results for Group 1 indicated there were no significant differences between solutions G and S1 showed that discriminating by the sensory evaluation at the time of swallowing (thickness) would be difficult with respect to differences in shear rate dependence of the solution.

### 3.2.2 Non-oral sensory evaluation

The data in Fig. 4 show the non-oral sensory evaluation of the viscosities by tilting the container, stirring with spoon, and dripping from the spoon. Fig. 4-(1) showed the results of Group 1: samples G, S1 and X1 had the same viscosity at the shear rate of 1 s^{-1}. Fig. 4-(2) showed the results of Group 2: samples G, S50 and X50 had the same viscosity at the shear rate of 50 s^{-1}.

**Tilting the container gently:** For Group 1, the flowing speed of the solutions by gently tilting the container was faster in the order of samples X1, S1 and G. There was a significant difference between samples X1 and G ($p < 0.01$). For Group 2, the order was samples G, S50 and X50. The sample G was judged faster than samples S50 and X50 ($p < 0.01$). There was no difference between the samples S50 and X50.

**Stirring with a spoon:** For the resistance by stirring with a spoon, the evaluated result was the same ranking as for tilting the container. There was no uniform consensus in evaluations.

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**Fig. 3. Distance scale for oral sensory evaluation of the samples as follows.**

1. (1) Group1: the samples indicated same level viscosity at 1 s^{-1}.
2. (2) Group2: the samples indicated same level viscosity at 50 s^{-1}.

Sample symbols are the same as in Table I.

\*; significant difference at $p < 0.05$ and **; significant difference at $p < 0.01$. $n = 12$
of the three testing solutions given at both Groups 1 and 2. As such, we were able to verify that there was a relationship between viscosity levels measured through sensation evaluation based on non-oral evaluation such as stirring motion, and viscometer with respect to not only Newtonian solutions but also non-Newtonian solutions. In referring to researches\(^{(16,24)}\), we compare the viscosity levels obtained by the viscometer, it was found that the non-oral sensory evaluation items of “tilting the container gently” and “stirring with spoon” corresponded to the average viscosity at the shear rate of 1–40 s\(^{-1}\) (Fig. 1). We were also able to demonstrate a correlation between subjective sensory evaluations and solution viscosity within a fixed shear rate range in different solutions with shear rate dependences.

Dripping from spoon: For the elongation of a drop dripping from the spoon, in Group 1, the sample G was judged to be longer than samples S1 and X1 \((p < 0.01)\). There was no difference between samples S1 and X1. The same result applies in Group 2, in which the sample G was judged longer than samples S50 and X50 \((p < 0.01)\). There was no difference between samples S50 and X50. With respect to the instrumental characteristics, the flow behavior index \((n)\), and not viscosity, was consistent with this result. Figure 5 indicated the relation between \(n\) and the value of the elongation of a drop dripping from the spoon. These findings imply that, the higher the \(n\), the longer a dripping. \(N\) was peculiar to not only concentration but the main ingredient of the thickening agents, so we assumed that surface tension and dynamic viscoelasticity influenced the elongation of a drop by dripping from spoon. It was suggested that the sensory evaluation item of dripping from spoon was not appropriate for the index of viscosity of thicker solutions.

4. CONCLUSION

Conditional on means of measurement of viscosity, for instance, ease of swallowing, tilting the container and stirring the contents with teaspoon, viscosity of solution was different, with the changing shear rate. We prepared the samples thickened with thickening agents indicated same viscosity level at the shear rate of 1 s\(^{-1}\) or 50 s\(^{-1}\) to examine the relationship between non-oral sensory evaluations, oral sensory evaluations, and physical properties. The following results were obtained.

1) As result of dynamic viscosity, clear differences emerged even when indicating same viscosity at a shear rate point, due to the effect of differences main ingredients.

2) Oral sensation (such as ease of swallowing) for viscosities was correlated with shear rates above 50 s\(^{-1}\).

3) For “solution resistance during stirring” and “ease of flow during tilting the container,” we reflected the viscosity levels with respect to a shear rate of 1–40 s\(^{-1}\), and for “dripping from the spoon” it was shown that dependence \(n\) exhibited an effect rather than solution apparent viscosity.

Measurement of apparent viscosity at lower shear rate was related to non-oral sensory evaluation items of “tilting the container gently” and “stirring with spoon”, while the viscosity at higher shear rate was related to oral sensory evaluation “ease of swallowing”. This approach, which can be used with solutions being different shear rate dependence. To prepare consistent thickened solutions with commercial thickening agents, it was desirable to measure by a viscometer at the appropriate shear rate. It was too difficult to measure by a viscometer of in actual. The results of the study revealed that means to measure viscosity by dripping from the spoon

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**Fig. 4.** Distance scale for non-oral sensory evaluation of the samples as follows.

(1) Group 1: the samples indicated same viscosity at 1 s\(^{-1}\).

(2) Group 2: the samples indicated same viscosity at 50 s\(^{-1}\).

Sample symbols are the same as in Table I.

*; significant difference at \(p < 0.05\) and **; significant difference at \(p < 0.01\). \(n = 12\).

**Fig. 5.** Relationship between flow behavior index \((n)\) and the value of the elongation of a drop dripping.

Sample symbols are the same as in Table I.
was not good means because of dependence on the main ingredient used as thickening substance and shear rate dependence, whereas by tilting the container and stirring with spoon was useful means to know rough viscosity.

REFERENCES

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