Applications of ultrasonic spinning rheometry

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Ultrasonic spinning rheometry (USR), a novel rheometry based on ultrasonic velocity profiling and equation of motion of fluids, was applied to some of dysphasia diets as typical heterogeneous foods, which have no effective evaluation tools on their rheological properties. Effective viscosity curves obtained by USR with phase difference method characterize the rheological behavior of the foods. Time variations of viscosity curves obtained by USR on rice gruel with adding α-amylase represented time variation of the rheological property due to fluidization of the rice gruel by hydrolysis. To advance the measurement system for abbreviated examinations of foods, applicability of a novel, portable UVP equipment was evaluated.

Keywords: Velocity profiling, Rheometry, Viscosity curve, Heterogeneous materials

1. Introduction

Dysphasia – disorder on food swallowing – has become critical issue in medicine for elderly health care and rehabilitation from surgery. Major cause of the disorder is aging, and it has become a serious social problem in Japan at which society is aging. On the other hand, quality of life has been pointed out for well-being society as listed in "Sustainable development goals (SDGs)" and demands of the patients who want to eat delicious food should be considered next to safeness on eating. Figure 1 indicates the guideline for providing dysphasia diet to the patients, termed Dysphasia diet pyramid, established by Japan Society of Dysphasia Rehabilitation [1]. Difficulty to eat increases from top to bottom with considering viscosity, heterogeneity, and stability of food bolus. The reason of such quite qualitative representation is explained as absence of appropriate measurement tools applicable in food-providing site and capable for "heterogeneous" foods. Nishinari *et al*. [2] indicated importance on extensional viscosity of continuum (or adhesive) material of food bolus to evaluate the stability of bolus. But no quantitative evaluation of rheology of heterogeneous food bolus itself.

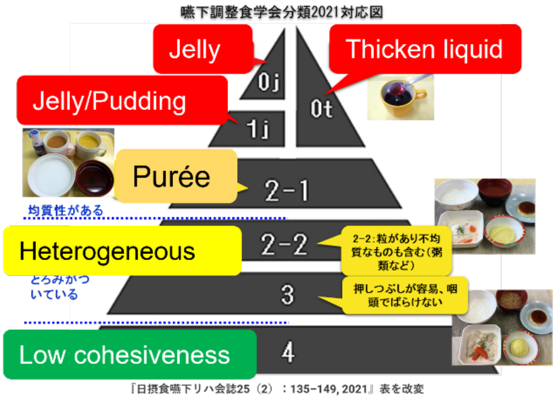

Figure 1: Dysphasia diet pyramid – guideline for providing dysphasia diet to patients established by Japan Society of Dysphasia Rehabilitation [1]

Standard torque-type rheometer cannot be a reliable tool satisfying the demand mentioned above, because of assumptions of ideal uniform shearing in a test fluid layer. To satisfy the condition, usual rheometers adopt a sufficiently thin test fluid layer, which are incompatible with heterogeneous materials. Velocity profiling assisted rheometry, combination between axial torque measurement to determine shear stress acting on the test fluids and velocity profile measurement to ensure actual shear rate in the fluid layer, circumvents these issues [3]. Our group has also established an idea of ultrasonic spinning rheometry (USR), which can evaluate rheological properties of heterogeneous fluid via inverse analysis on equation of motion with spatio-temporal velocity information measured in a test fluid periodically oscillated by a cylindrical vessel with sinusoidal azimuthal oscillations [4-6]. From its first application to bubble suspensions, many kinds of complex fluids have been examined by USR as listed in Table 1. With this wide applicability and recent invention of portable USR [7,8], USR can be recognized as a tool to solve the problem on the conventional torque-type rheometers.

In this study, we apply USR to typical dysphasia diets with different levels classified in Dysphasia diet pyramid to evaluate efficacy of USR for the purpose. Also, we adopt UB-Lab-P[9], a palm-size portable UVP as the new generation of UVP provided by Ubertone, as the velocity profiler of USR for future development of tabletop USR.

Table 1: List of examples of fluids examined by USR

Newtonian fluids:
Silicone oil (50 cSt – 1000 cSt) [5,10]
Glycerol solution
Polymer aqueous solutions:
Carboxymethylcellulose (CMC) [5, 8, 10, 11]
Xanthan gum [12]
Polyacrylamide (PAM) [10, 11]
Polyvinylpyrrolidone (PVP) [13]
Suspension (dispersion, slurry)

Bubbles (silicone oil, ~1 mm) [4,6]
Particles (silicone oil, 10 μm – 500 μm) [4, 14]
Water drops (silicone oil, ~ 100 μm) [15]
Clay (low concentration [5,10, 16], high concentration)
$BaSO_4$ (contrast agent)

Foods:
Tomato juice (present)
Potage
Total nutritional drink (present)
Tofu (bean curd) processed by blender
Curry [5]
LM pectin gel with fruit pulp [5, 17]
Cheese analogue (skimmed milk with rennet) [18]
Rice gruel (porridge) with alpha amylase (present)

2. Ultrasonic spinning rheometry (USR)

2.1 Measurement system configuration

A schematic diagram of the measurement configuration for USR is shown in Fig. 2(a). A cylindrical open vessel with radius, $R = 72.5$ mm, filled with a test fluid is oscillated sinusoidally with amplitude Θ and frequency f_0. With assumption of azimuthally one-directional flow with axial symmetry, UVP measurement along the line set with displacement Δy from the centerline of cylinder can capture time variations of radial profile of azimuthal velocity component $u_\theta(r, t)$ as shown in Fig. 2(b). Selection of Θ, f_0, Δy, and TDX is dependent on test fluids, especially their viscosity and scattering property. Further details of the setup are given in references [e.g. 4-6]. Here we mainly use UVP monitor model Duo (Met-Flow S.A.) as a reliable, stable UVP system for USR purpose. We also use a portable system – a UB-Lab-P from Ubertone (see Fig. 2(c)) – to perform USR measurements for future tabletop USR.

2.2 Phase difference method [4,5,19]

With assumptions mentioned in the previous section, fluid motion in the test cylinder obeys Cauchy's equation of motion,

$$\rho \frac{\partial u_\theta}{\partial t} = \frac{\partial \tau}{\partial r} + \frac{\tau}{r} \qquad (1)$$

with shear stress τ and density of fluid ρ. Relation between the fluid motion and the shear stress is described by constitutive equations,

$$f(\tau, \dot{\gamma}; \Pi_1, \Pi_2, \Pi_3, \cdots) = 0, \qquad \dot{\gamma} = \frac{\partial u_\theta}{\partial r} - \frac{u_\theta}{r} \qquad (2)$$

with some rheological parameters, Π_i. Here we adopt local effective Newtonian viscosity as the constitutive equation. The shear stress is proportional to the shear rate $\dot{\gamma}$ (Eq. 2) with local effective "kinematic" viscosity ν_{eff}. With the constitutive equation, Eq. 1 can be analytically solved using Bessel function of the first kind, J_1, and radial phase lag of the oscillatory motion of fluid $\alpha(r)$ and ν_{eff} are in the unique relation,

$$\alpha(r) = \tan^{-1} \frac{\Phi(R)\Psi(r) - \Phi(r)\Psi(R)}{\Phi(r)\Phi(R) + \Psi(r)\Psi(R)} \qquad (3)$$

$$\Phi(r) = \Re[J_1(\beta r)], \Psi(r) = \Im[J_1(\beta r)],$$
$$\beta = (-1 + i)k, k = \sqrt{\pi f_0 / \nu_{\text{eff}}}.$$

The effective viscosity is thus determined at each radial position by comparing $d\alpha/dr$ between the analytic solution and experimentally obtained phase profile. The radial phase profile is calculated from velocity data measured by UVP by sinusoidal function fitting with frequency f_0 instead of Fourier transform to avoid dispersion of information to different Fourier modes [19]. In addition to this, local shear rate is also calculated from the amplitude of fitting curve by radial derivative [19].

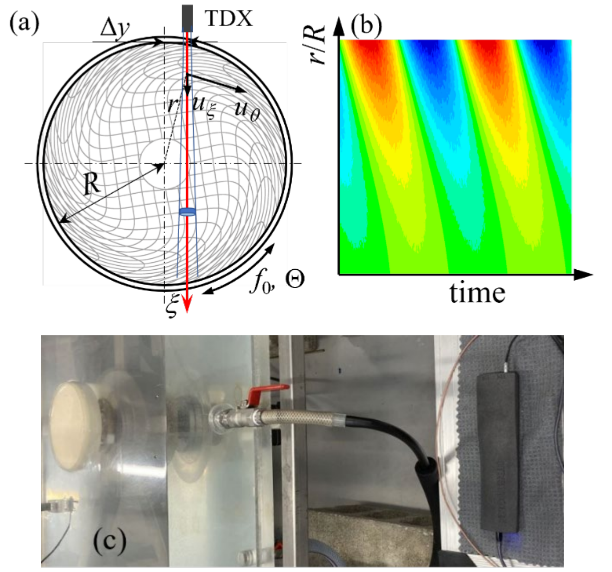

Figure 2: (a) Schematic diagram of measurement configuration for ultrasonic spinning rheometry and deformation of test fluid layer in the cylinder oscillation, (b) space-time velocity map of oscillating flow of a test fluid due to the cylinder oscillation, (c) a photograph of the test chamber, the test cylinder, and a UB-Lab P

3. Measurement results

We examine three different foods, total nutritional drink (Meibalance, Meiji Co.), tomato juice, and rice gruel, which is a typical hospital meal. These are classified by Dysphasia diet pyramid (Fig. 1) as 2-1, 2-2, and 3, respectively.

3.1 Total nutritional drink

The test fluid is milk-like, but contains larger percentage of carbohydrate, fat, and proteins. Fine emulsions may scatter incident ultrasonic wave for the UVP measurement and we expect difficulty of measurement for long range. Figure 3 shows kinematic viscosity curve obtained by USR, where the set conditions are $\Theta = 240°$, $f_0 = 0.2$ Hz, Δy ~17 mm. We adopted 2MHz and 4MHz TDXs to investigate influence of ultrasonic scattering by the test material and results are displayed by white and black plots in the figure.

As we expected, measurable range of UVP is limited in both cases of TDXs. As shown in the viscosity curve, range of the shear rate is quite narrow, especially for 4 MHz TDX. Ultrasonic wave in the case can penetrate the region nearby the cylinder wall, where the shear rate is largest. Viscosity curves obtained by the TDXs show very strong shear-thinning behavior. The curves overlap well and seem to be expressed by power law, $\nu_{\text{eff}} = K\dot{\gamma}^{n-1}/\rho$. Red line in the figure represents fitting curve determined by least square approximation on the data. The fitting provides K/ρ = 170 and n = 0.0. This small value of n suggests existence of yield stress and/or elastic effect.

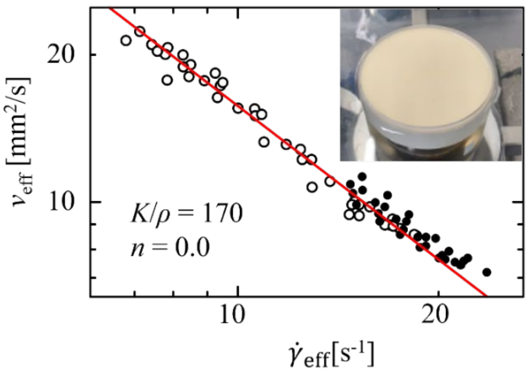

Figure 3: Effective kinematic viscosity map of total nutritional drink (inserted picture) determined by USR, where white and black plots represent the date measured with 2 MHz and 4 MHz TDXs, red line is the approximated fitting curve.

3.2 Tomato juice

Tomato juice contains relatively large ingredients in comparison with the nutritional drink. 4 MHz ultrasonic wave can penetrate inner region of the test fluid layer, because of lower number of ingredients. Setting parameters of the measurement are Θ = 113°, f_0 = 0.4 Hz, and Δy ~16 mm, respectively.

Viscosity curve obtained by USR is shown in Fig. 4. Because of the longer measurable range of UVP, wider range of shear rate is obtained. The curve also shows strong shear thinning property and seems to be expressed by power law. The fitting curve indicated by the red curve in the figure gives K/ρ = 1200 and n = -0.2. Such very small power law index n, $n < 0$, is not usual in polymer solutions exhibiting shear thinning property. This may be due to structure change of multiphase media.

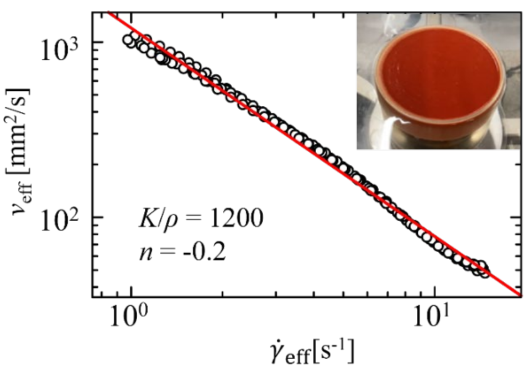

Figure 4: Effective kinematic viscosity map of tomato juice (inserted picture) determined by USR, where red line is the approximated fitting curve.

3.3 Dissolving rice gruel (porridge)

Rice gruel is categorized as the most difficult food for eating as dysphasia diet classified in Dysphasia diet pyramid (smaller than "3" in Fig. 1). Here we examined time variation of the viscosity curve of the rice gruel dissolved by hydrolysis as an analog experiment of eating process in oral cavity mixing with digestive enzyme. Instead of the real digestive enzyme, α-amylase was used. Because of the rapid reaction as shown in Fig. 5, where a bolus of rice gruel w/o or with α-amylase are put on a tilted plate, weak concentration of the amylase is added.

UVP measurement with 2 MHz TDX was performed under the conditions of Θ = 60°, f_0 = 1 Hz, Δy ~20 mm, and temperature T = 25°C, respectively. The measurement was started just after adding the amylase, as t = 0. Then, each 1000 profiles with 25 ms in the time resolution were analyzed to obtain "instantaneous" viscosity curves. Figure 6 shows some of the viscosity curves at different time, from t = 0 to 30 min. Immediately after adding the amylase, t = 2 min, the viscosity curve surely represents shear thinning behavior. This is due to fluidization of rice gruel by hydrolysis. But further development of hydrolysis decreases viscosity at lower shear rates and the viscosity curves are modified toward Newtonian fluids. Such time variation may be able to be characterized by K and n in power law. Ohie *et al*.[12] proposed K-n diagram, time variation of plot of (K, n) to evaluate food rheology. We will apply this data arrangement for the different foods in future.

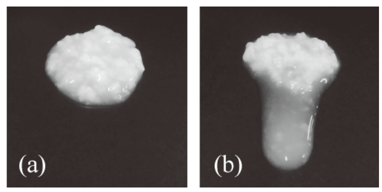

Figure 5: Pictures of a bolus of rice gruel (porridge) (a) w/o and (b) with α-amylase

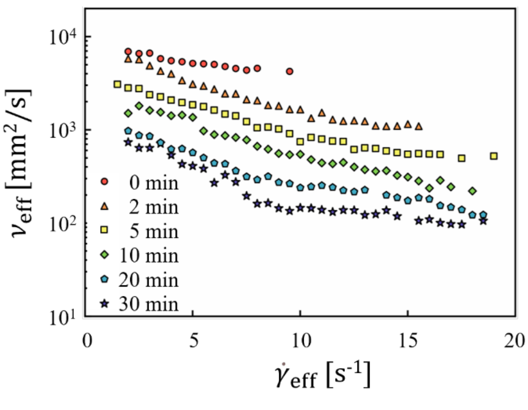

Figure 6: Time variations of effective kinematic viscosity curves of rice gruel after adding α-amylase

3.4 Hardware dependence

Finally, we investigate applicability of UB-Lab P as UVP equipment for portable USR. UB-Lab P was adopted to measure the oscillating fluid flows of the total nutritional drink as explained in section 3.1. Because of the limitation on measurement point in UB-Lab P, the measurement section is set only nearby the cylinder wall. The setting parameters of the oscillation are the same with those in section 3.1. The TDX was replaced by that with 3.6 MHz.

Viscosity curve obtained from the velocity data is shown in Fig. 7. The viscosities distribute from 6 to 20 mm^2/s and seem reasonable in comparison with Fig. 3. But the evaluated shear rate is quite small even with the same setting parameters. One of the reasons can be found in time variations of measured velocity, u_ξ shown in Fig. 8. Unlike the set sinusoidal motion, the variations express quasi rectangular profiles. Here in the figure, black and red curves represent velocity fluctuations at neighboring spatial points, and we can distinguish clear phase difference between them. Phase difference method utilizes phase difference information of velocity fluctuations without their amplitude information. This may be the reason why the viscosity values obtained are reasonable. This result suggests that further improvement of quality of instantaneous velocity information by UB-lab P will allow fast, reliable, handheld USR measurements for a broad range of fluids.

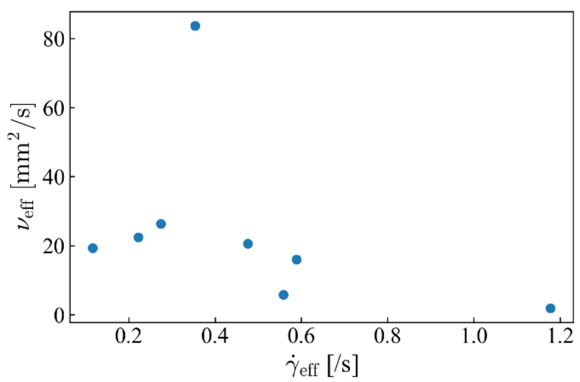

Figure 7: Effective kinematic viscosities of the total nutritional drink (see Fig. 3) estimated from velocity data measured by UB-Lab P

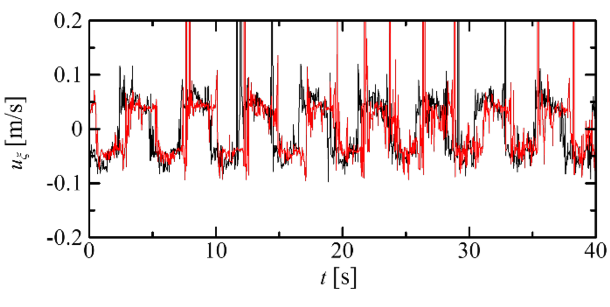

Figure 8: Time variations of local velocity of the total nutritional drink oscillated by the test cylinder, where red curve indicated the variation at a radial position little far that that for the black line

4. Summary

Applications of USR for three dysphasia diets with different classifications, total nutritional drink, tomato juice, and rice gruel, idicated that high applicability of USR for heterogeneous foods. Time variations of viscosity curves obtained by USR on rice gruel with adding α-amylase represented fluidization of the rice gruel by hydrolysis. We will advance this methodology toward more reliable, handhelf examination of safety of foods.

Acknowlegment

This work was supported by Japan Science and Technology Agency PRESTO (Grant No. JPMJPR2106), and creative research program in Hokkaido University, FY2022.

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