Measurement of Flow Properties of Mammalian Blood with Different Hematocrit Values Using Falling Needle Rheometer

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ABSTRACT

The development of viscometry with high accuracy and quick operation, as well as the establishment of a data evaluation method by pathology are largely required. Especially, the flow properties of human blood are an important factor in the evaluation of blood disease on the medicine, but the method of viscometry and the data collection are not so easy. This study has been described on the viscosity measurement and their evaluations for mammalian blood (rabbit, pig and horse) including human blood. A compact-sized falling needle rheometer (FNR) and a flow analysis method using this device for blood have been developed, and the relationship between the apparent viscosity and physical properties (density, hematocrit value) of blood have also been evaluated. Measured flow properties of blood are evaluated as a flow curve showing the relationship between the shear stress and shear rate. Observed flow curves of mammalian bloods show three typical fluid regions, these are, the Non-newtonian fluid region for a low shear rate range, the transition region and the Newtonian fluid region for a high shear rate range. Flow properties of blood in the Casson fluid region and the apparent viscosity (μ) in the Newtonian fluid region are measured, and they are compared between mammals.

Keywords: Flow property, Viscosity, Mammalian blood, Rheometer and Flow curve.

1. Compact-Sized Falling Needle Rheometer

The flow model of a falling needle in a static fluid according to the above assumptions is given in Fig.1. This model shows that the falling needle falls at a terminal velocity (Ut) in the static fluid introduced into the cylindrical fluid vessel. The fluid vessel diameter is R, and k is the ratio of the needle diameter to fluid vessel diameter. The minute circular cylinder core is assumed as the fluid model for theoretical analysis. The inner diameter and outer diameter of this core are γ and γ +dr, and the total length is L. The shear stresses on the inside and outside surfaces of the minute circular cylinder core are τ and τ +dτ, respectively. The pressures at the top and bottom of the minute circular cylinder core are P_1 and P_2. When the falling needle falls at a terminal velocity in the static sample fluid, the momentums affected on four surfaces of the minute circular cylinder core are balanced with each other, and they are balanced while the needle is falling at the terminal velocity. Therefore, this force balance can be described by the following equation:

$$\mathrm{P}_1\left\{(r+dr)^2\pi - r^2\pi\right\} + 2\pi rL\tau = \mathrm{P}_2\left\{(r+dr)^2\pi - r^2\pi\right\} + 2\pi(r+dr)L(\tau+d\tau) \qquad (1)$$

When $\Delta P = P_1 - P_2$ is less than 0, Eq.1 is arranged as follows:

$$\frac{1}{r}\frac{\mathrm{d}(r\tau)}{\mathrm{d}r} = \frac{\Delta P}{L} \qquad (2)$$

Furthermore, while the needle falls at the terminal velocity in the sample fluid, the force balance of gravity, buoyancy, pressure and shear stress affected on the needle surfaces are given as

$$(\rho_{\mathrm{s}} - \rho_{\mathrm{f}})g\pi(kR)^2 L + \pi(kR)^2\Delta P = 2\pi kRL\tau_{(r=kR)} \qquad (3)$$

In this equation, ρ_f and ρ_s are the fluid and needle density, respectively. The left-hand side first term of Eq.3 is the force of gravity and buoyancy, and the second term is the force of the pressure difference. The right-hand side term is the shear stress. This balance can be simply described by

$$\left(\rho_{\mathrm{s}}-\rho_{\mathrm{f}}\right)g+\frac{\Delta P}{L}=\frac{2\tau_{(r=kR)}}{kR} \tag{4}$$

Figure 1 illustrates the velocity distribution of the sample fluid due to falling of the needle. The amount of fluid (Q) to transfer between the falling needle surface and the container wall due to falling of the needle can be calculated by

$$Q=2\pi\int_{kR}^{R}ur\,\mathrm{d}r=\pi(kR)^2U_{\mathrm{t}} \tag{5}$$

Figure 1 shows that the sample fluid around the falling needle is pulled downward with falling of the needle in the static sample fluid. On the other hand, the fluid near the container wall rises with the falling needle. The maximum velocity in the sample fluid is that on the needle surface. The maximum velocity is equal to that of the falling needle velocity. On the other hand, the velocity on the container wall becomes zero according to the above assumptions. Therefore, the boundary conditions of the velocity distribution can be described by

$$u_{(r=kR)}=-U_{\mathrm{t}} \tag{6a}$$

$$u_{(r=R)}=0 \tag{6b}$$

In order to obtain the relationship between the shear rate and shear stress for the sample fluid, the Eqs. 2, 4, 5, 6a, and 6b and a constitution equation of the sample fluid are used simultaneously for flow analysis [6].

The constitution equation for a Newtonian fluid based on the law of viscosity is given by

$$\tau=\mu\left(\frac{\mathrm{d}u}{\mathrm{d}r}\right)=\mu\gamma \tag{7}$$

where μ is the viscosity, τ is the shear stress, and γ is the shear state. The viscosity of the fluid sample can be calculated by the following equation from combining Eqs.2, 4, 5, 6a, 6b, and 7.

$$\mu=-\frac{\left(\rho_{\mathrm{s}}-\rho_{\mathrm{f}}\right)g(kR)^2\left\{\left(k^2+1\right)\ln k+1-k^2\right\}}{2\left(k^2+1\right)U_{\mathrm{t}}} \tag{8}$$

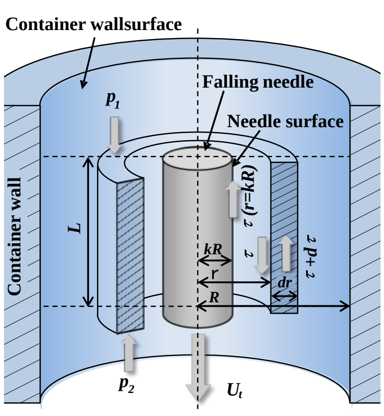

Fig.1 Flow model of the sample fluid in the fluid vessel of falling needle rheometer

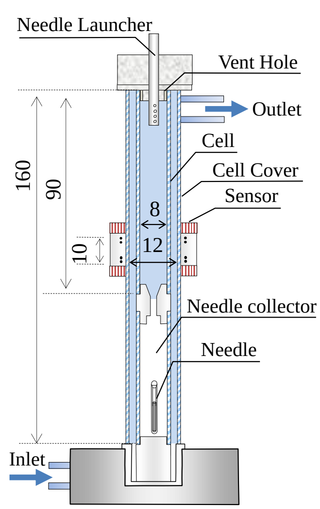

Fig.2 Schematic diagram of the compact-sized falling needle rheometer for measurement of blood viscosity

2. Experimental Method

A schematic diagram of the compact-sized falling needle rheometer for measurement of blood viscosity is shown in Fig.2. The experimental apparatus consists of vertical double cylindrical vessels (one is a fluid vessel and the other is an insulating vessel cover) made of acrylic material. The cap and bottom of the inner fluid vessel are made of Teflon. The inner fluid vessel for a blood sample is covered with the insulating vessel cover. The temperature of the inner fluid vessel is controlled at 310.15 K using a constant temperature water circulation system. The diameter of the inner fluid vessel is 8 mm, and the height of the vessel is 90 mm. The total volume of the inner fluid vessel is about 4cm^3. A needle collector for the collection of the falling needles is connected to the bottom of the inner fluid vessel via a needle-fluid separator made of Teflon. The needle-fluid separator is a slender cylindrical tube, and its diameter is 2.2 mm, which is similar to the needle diameter (2 mm). Densities of blood are measured by the portable density meter (DMA-35, Anton Paar Co., Ltd.) within an uncertainty of 10^{-4}g•cm^{-3}. The flow analysis is carried out using the observed passing time (terminal velocity) of the falling needles, needle densities, and blood density.

3. Results and Discussion

The observed flow curve for male human, male horse, rabbit and pig blood with anticoagulant is shown in Fig. 3. This flow curve shows a linear relationship between the shear stress and shear rate in a high shear stress range. However, non-Newtonian behavior (Casson behavior) was confirmed in a low shear stress range. The observed flow curve of fresh blood showed the three typical fluid regions, that is, the non-Newtonian fluid region for the low shear rate range, and the transition region and Newtonian fluid region for the high shear rate range.

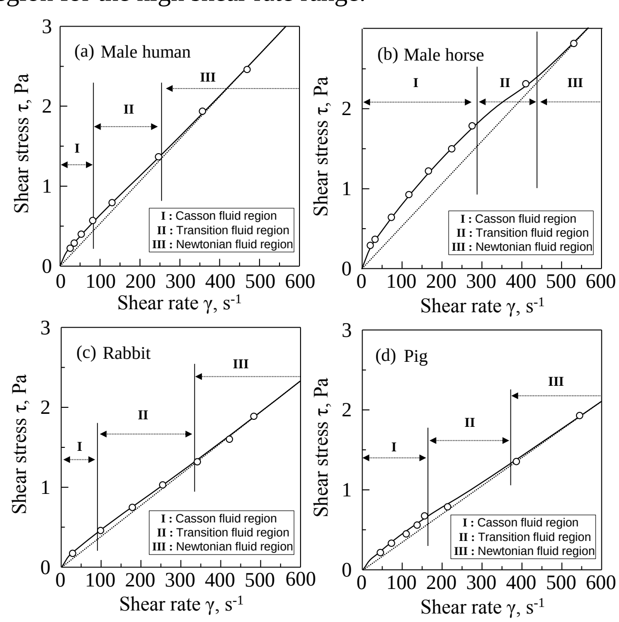

Fig.3-a Flow curve of fresh human blood for male with anticoagulant at 310.15K
Fig.3-b Flow curve of fresh horse blood for male with anticoagulant at 310.15K
Fig.3-c Flow curve of fresh rabbit blood with anticoagulant at 310.15K
Fig.3-d Flow curve of fresh pig blood with anticoagulant at 310.15K

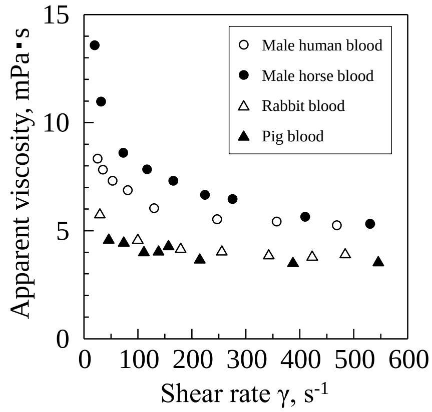

Fig.4 Relationship between apparent viscosity and shear rate for mammalian blood at 310.15K

Figure 4 showed the relationship between the apparent viscosity and shear rate for mammalian blood at 310.15 K. Apparent viscosity at low shear rate range shows higher value than that of high shear rate range. Apparent viscosity for each mammalian blood showed different behavior under the low shear rate range. The rheological parameters that were obtained are listed in Table 1. Apparent horse blood viscosity for the high shear rate range was similar range with human blood. The blood viscosities of pig and rabbit showed lower value than that of human and horse. Blood viscosity and hematocrit value were confirmed the different for each mammalian blood. It was found that the apparent viscosity for blood was closely connected with the hematocrit values. Figure 3 and Table 1 show that the curvature of flow curve at low shear rate range became large with increasing of the hematocrit value.

Table1 Comparison of apparent viscosity, hematocrit value and density of mammalian blood with anticoagulant at 310K

	Density [kg/m^3]	Ht* [%]	Apparent viscosity [mPa ·s] (Newtonian fluid region)
Male Human	1050.6	43.6	5.374
Male Horse	1053.3	44.0	5.336
Rabbit	1046.9	36.0	3.879
Pig	1037.9	28.0	3.551

* Hematocrit value is the volume percentage of red blood cells included in whole blood.

Table 2 shows the physical properties for healthy mammalian blood that are a mean red blood cell count, a mean corpuscular volume and a hematocrit value. It is thought that physical properties of the mammalian blood are so different, such as red blood cell volume and diameter, and have an effect on the apparent viscosity at low shear rate range.

Table2 The properties of normal mammalian blood

	Human	Horse	Rabbit	Pig
Red blood cell count (10^4/μL)	430-570 (male) 390-520 (female)	700-1.100	400-800	600-800
Mean corpuscular diameter (μm)	8	5.5	7	6
Mean corpuscular volume（fL）*	83-101	42-47	58-71	38-52
Hematocrit value（%）	40-50(male) 35-45(female)	35-45	28-45	25-40

* The mean corpuscular volume (MCV) is a measure of the average red blood cell volume that is reported as part of a standard complete blood count.

4. Conclusion

A compact-sized falling needle rheometer with quick operation has been developed for the viscometry of mammalian blood with anticoagulant. The measured flow properties of mammalian blood are evaluated as a flow curve, that is, the relationship between the shear stress (τ) and shear rate (γ). The comparison examination of the flow curves for each mammalian blood was carried out. The curvature of flow curves at low shear rate range closely connected with hematocrit value. It is thought that comparison of viscosity with other physical properties for human blood is indispensable in order to discuss about human blood rheology in the future. Value of the apparent viscosity showed horse > human > pig = rabbit. It became clear that the developed falling needle rheometer has high application for viscometry of mammalian blood.

Nomenclature

d	needle diameter, m
g	gravitational acceleration, m·s^{-2}
G	geometric needle constant, 1･m^{-2}
k	ratio of container to needle diameter
kR	needle radius, m
n	fluid index
L	total needle length, m
P_1, P_2	pressure of the upper and lower end of a minute circular cylinder, Pa
Q	flow rate of fluid pushed aside by the needle, m^3·s^{-1}
r	radius coordinate, m
R	container radius, m
u	velocity in the system length direction, m·s^{-1}
U_t	terminal velocity of a falling needle, m·s^{-1}
ρ_f , ρ_s	fluid density and needle density, kg·m^{-3}
γ	shear rate, s^{-1}
τ	shear stress, Pa
μ	Newtonian viscosity, Pa·s

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