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Development of a Compact-Sized Falling Needle Rheometer for Measurement of Flow Properties of Fresh Human Blood

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Abstract A compact-sized falling needle rheometer with rapid operation and automatic flow analysis has been developed for viscometry of fresh human blood without anticoagulant. The volume of a fresh blood sample only needs to be 3 mL, and the measuring time is within 2 min after taking a blood sample from the human body. Measured flow properties of human blood are evaluated as a flow curve, that is, the relationship between the shear stress (τ) and shear rate (γ). Observed flow curves of fresh human blood show three typical fluid regions, that is, the Casson fluid region for a low shear rate range of $0 < \gamma > 140\,\mathrm{s}^{-1}$, the transition region for a shear rate near $140\,\mathrm{s}^{-1} < \gamma < 160\,\mathrm{s}^{-1}$, and the Newtonian fluid region for a high shear rate range of $160\,\mathrm{s}^{-1} < \gamma > 400\,\mathrm{s}^{-1}$. Flow properties of human blood such as the yield stress (τ_y) in the Casson fluid region and the apparent viscosity (μ) in the Newtonian fluid region are measured, and they are compared between male and female blood. It is found that the range of human blood viscosity for males is (5.5 to 6.4) mPa · s, and for females is (4.5 to 5.3) mPa · s. The viscosities of male blood without anticoagulant show higher values than those of female blood. Human blood viscosities with anticoagulant show a lower value than that without anticoagulant. A linear relationship between the hematocrit value, that is, the volume percentage of red corpuscles in the

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human blood, and the apparent viscosity are observed for both male and female blood. This article is concerned with the flow analysis of fresh human blood viscosity without anticoagulant using a newly developed compact-sized falling needle rheometer.

Keywords Flow curve · Flow property · Human blood · Rheometer · Viscosity

List of Symbols

d	Needle diameter, m
f_e	Yield stress of a Casson fluid, Pa
g	Gravitational acceleration, $m \cdot s^{-2}$
G	Geometric needle constant, m^{-2}
K	Fluid consistency, $Pa \cdot s^{-n}$
k	Ratio of container to needle diameter
kR	Needle radius, m
L	Total needle length, m
n	Fluid index
P_1, P_2	Pressure of the upper and lower ends of a minute circular cylinder, Pa
ΔP	Pressure difference ($\Delta P = P_1 - P_2$), Pa
Q	Flow rate of fluid pushed aside by the needle, $m^3 \cdot s^{-1}$
r	Radius coordinate, m
R	Container radius, m
u	Velocity in the system length direction, $m \cdot s^{-1}$
U_t	Terminal velocity of a falling needle, $m \cdot s^{-1}$
γ	Shear rate, s^{-1}
μ	Newtonian viscosity, $Pa \cdot s$
π	Circular constant
ρ_f	Fluid density, $kg \cdot m^{-3}$
ρ_s	Needle density, $kg \cdot m^{-3}$
τ	Shear stress, Pa
τ_y	Yield stress, Pa

1 Introduction

Rheology of human blood is a specialized part of fluid mechanics and is closely concerned principally with non-Newtonian properties. The rheological properties of fresh human blood are not only one of the important factors in the pathological diagnosis of the human body, but also basic data essential for analytical study of the change of fluid mechanics of the human blood arising from deterioration of the health condition [1–4]. Furthermore, non-quantitative words such as smooth blood or thick blood are often used for viscosity evaluation of human blood. These expressions for blood condition cause a social problem when selling supplements. In this context, the development of viscometry with high accuracy and rapid operation, as well as the establishment of a data evaluation method by pathology are largely required. However, currently, there is little observed data of blood viscosity from measurements immediately after collection of a blood sample in comparison with the viscosity data of human blood with anticoagulant.

In research so far, it was found that the flow properties of human blood are available for preventive medicine for blood dyscrasia, clinical medicine, health care, functional foods, or the inspection of the effects of medicines. Also, it was reported that the viscosity of human blood influenced the concentration of fibrinogen in the plasma and the hematocrit value, and that the viscosity of human blood could offer important information for myocardial infarction and cerebral infarction, etc. However, the measurement of the viscosity just after blood collection from a human body is not so easy, and the accumulation of numerical data of the viscosity is not yet sufficient. Most of the measurements of human blood viscosity were carried out using human blood with anticoagulant, and at present there is little measurement of human blood without anticoagulant. Also, it is problematical that many different viscometers can be applied to these purposes, and a standard method has not yet been determined; hence, the values differ according to the type of device.

The difficulties of flow analysis of human blood come not only from an aggregation–dispersion phenomenon of red corpuscle cells, but also its transformation property, many interaction forces between corpuscle cells and blood plasma. Therefore, the establishment of exact viscometry for fresh human blood is desired for further discussion about the relationship between blood disease and its flow properties.

In this article, a compact-sized falling needle rheometer and a flow analysis method using this new device for fresh human blood without anticoagulant have been developed, and the relationship between the apparent viscosity and physical properties of fresh blood has also been evaluated.

The theory of the presented viscometer is mainly based on the Stokes type of equation, and this is a kind of a falling body viscometer [5–9]. The viscosity of human blood can be measured with a small blood sample of about 3 mL (total capacity is 4 mL) and with rapid operation within 2 min after taking a blood sample from the human body. The total scale of this compact-sized falling needle rheometer is downsized to about 1/30 the size of the previous apparatus [6]. A circular cylinder needle made of polypropylene is applied for the experiment, and its outer diameter and total length are 2 mm and 20 mm, respectively. This needle size is also minimized at 1/5 that of a previous needle [6]. The density of the falling needle is controlled by the mass of a sinker enclosed in the needle tube. Flow analysis of the sample fluid is carried out using the needle's terminal velocity and the density difference between that of human blood and of a falling needle [10,11].

As stated above, the compact-sized falling needle rheometer is applied to the viscosity measurement of fresh blood before its coagulation. This article is concerned with the development of a new rheometer for the measurement of flow properties of fresh human blood.

2 Compact-Sized Falling Needle Rheometer

A schematic diagram of the compact-sized falling needle rheometer for measurement of human blood viscosity is illustrated in Figs. 1 and 2. The experimental apparatus

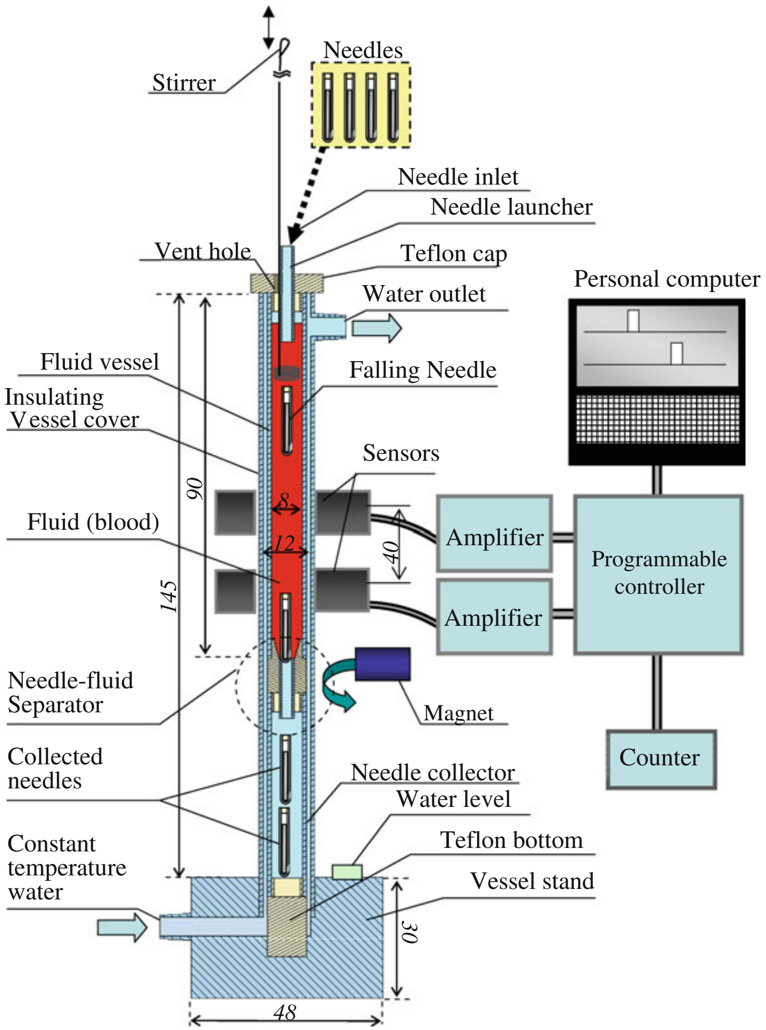


Fig. 1 Schematic diagram of the compact-sized falling needle rheometer for measurement of human blood viscosity

consists of vertical double cylindrical vessels (one is a fluid vessel and the other is an insulating vessel cover) made of acrylic material (Fig. 2a, b). The cap and bottom of the inner fluid vessel are made of Teflon. The inner fluid vessel for a human blood sample is covered with an insulating vessel cover. The temperature of the inner fluid vessel is controlled at 310 K using a constant temperature water bath within an uncertainty of 0.05 K. Constant temperature water is circulated in the space between the inner fluid vessel and the insulating vessel cover. The diameter of the inner fluid vessel is 8.0 mm, and the height of the vessel is 90 mm. The total volume of the inner fluid vessel is about 4 cm^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

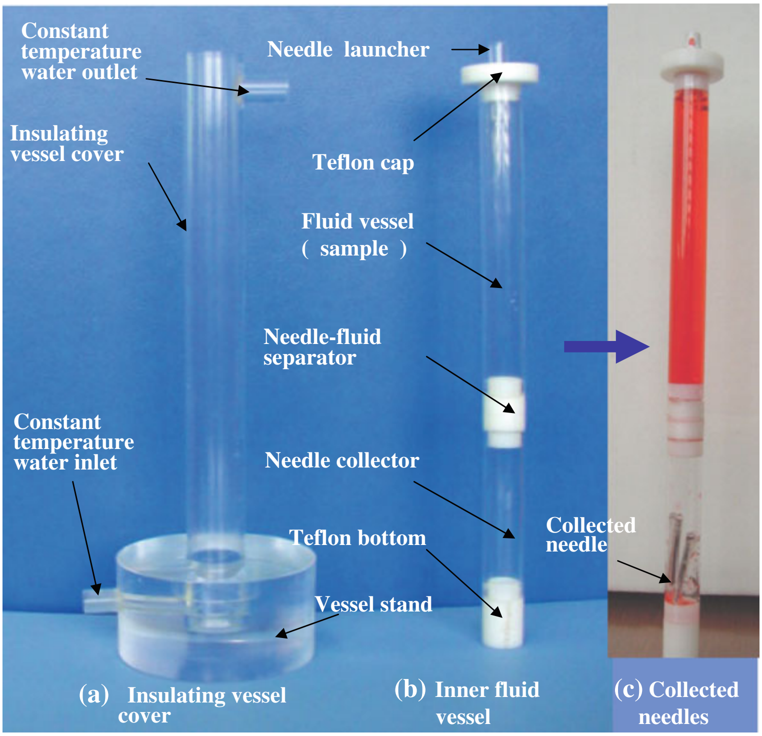


Fig. 2 Photograph of (a) the insulating vessel cover, (b) cylindrical fluid vessel, and (c) collected needles in the compact-sized falling needle rheometer

needle-fluid separator is a slender cylindrical tube, and its diameter is 2.2 mm, which is similar to the needle diameter (2 mm) shown as the dotted circle line in Fig. 1.

When a sample fluid (human blood) is introduced into the fluid vessel, the sample fluid does not leak into the space of the needle collector because the pressure in the needle collector is controlled at atmospheric pressure. After the operation of the first needle dropping, this needle stopped at the bottom of the fluid vessel shown in Fig. 1 and is rapidly manually moved into the space in the needle collector by the guidance of a small magnet from outside the vessels. This movement of the falling needle from the bottom of the fluid vessel to the needle collector is important and indispensable for rapid measurement of fresh human blood within 2 min. Figure 2c shows a photograph of a falling needle separated into the needle collector according to the above-mentioned method. It was found in the preparatory experiment that the leakage of sample fluid into the needle collector from the fluid vessel is very little.

As each of the parts of the experimental apparatus such as the fluid vessel, the needle collector, the insulating vessel cover, and a vessel stand shown in Fig. 2a, b can be taken apart easily, the collection of falling needles after the experiment can be very rapid and easy. This experimental apparatus is considerably compact for measurement of the viscosity of human blood compared with previous apparatuses.

A photograph and details of the falling needle used in this experiment are given in Fig. 3. The falling needle is a slender hollow cylindrical tube made of polypropylene.

Fig. 3 Details of the falling slender cylindrical needle used in this rheometry. (a) Cross section of needle. (b) Photo of needle

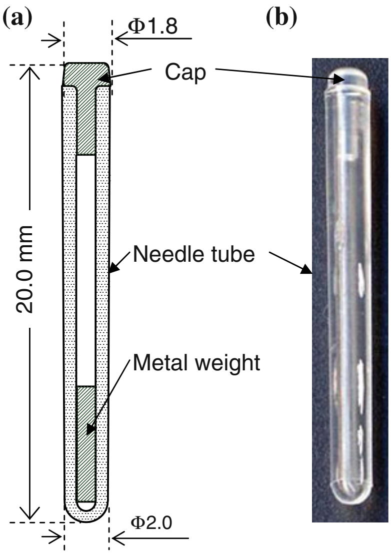


Table 1 Densities of falling needles used in human blood viscometry

Needle no.	Density (10^3 kg · m^{-3})
1	1.090
2	1.118
3	1.212
4	1.278
5	1.360
6	1.400
7	1.438
8	1.563

The diameter of the needle is 2 mm, and its total length is 20 mm. The shape of both sides of each needle is hemispherical. Eight falling needles with different densities listed in Table 1 are used in this experiment. The density of each falling needle is controlled by the mass of a sinker (iron) enclosed inside the needle tube. This sinker is fixed at the bottom of the needle tube so that the center of gravity is at a lower position. The density is calculated by the volume and mass of each needle, and its uncertainty is estimated to be within $\pm 0.5 \times 10^{-3}$ g · cm^{-3}. Table 1 lists the measured needle densities used in the experiment; they are determined in consideration of the blood density (1.0 to 1.1) g · cm^{-3}. In order to guide the falling needle to the center of the sample fluid, a needle inlet and a needle launcher are equipped at the top of the fluid vessel. The needle launcher is a slender cylindrical tube as shown in Fig. 1. A pair of magnetic sensors is also installed at the middle part of the fluid vessel as shown in Fig. 1. The distance between the magnetic sensors is 40 mm vertically. The passing time of each falling needle between magnetic sensors is automatically measured by a programmable controller manufactured by Keyence Co., Ltd. This magnetic sensor unit can be applied not only to clear liquids, but also to opaque liquids. The programmable controller is connected to the personal computer via an amplification unit. It is possible to evaluate the falling velocity of each needle, and flow analysis such as a flow curve, apparent viscosity, and yield stress of the sample fluid can be obtained automatically.

3 Experimental Method

Just after taking a blood sample from a human vein, the fresh human blood is introduced into the fluid vessel shown in Fig. 1 and the top of the fluid vessel is covered with the Teflon cap in which the needle launcher is installed. This fluid vessel is equipped in the insulating vessel cover with two magnetic sensors. The vertical distance between the two magnetic sensors is 40 mm, and the fluid vessel is placed vertically on the vessel stand using a water level. Constant temperature water is circulated through the space between the fluid vessel and insulating vessel cover. The temperature of the fluid sample is kept at 310 K within an uncertainty of 0.05 K. Eight needles with different densities are dropped down vertically in the sample fluid. The flow analysis is carried out using the observed passing times of the falling needles, needle densities, and blood density. Eight falling needles with different densities are used for measurement of the viscosity. Densities of human blood are measured by the portable density/specific gravity meter (Kyoto Electronic Manufacturing Co., Ltd.) within an uncertainty of $10^{-4}\ \mathrm{g \cdot cm^{-3}}$. The calibration of the presented falling needle viscometer is carried out using a standard liquid for calibrating a viscometer (JS2.5, JS5, JS10) manufactured by Nippon Grease Co., Ltd. EDTA-2Na manufactured by Wako Pure Chemicals Co., Ltd., is used as an anticoagulant for human blood.

4 Fluid Flow Analysis Using Compact-Sized Falling Needle Rheometer

Figure 4a, b shows the model for flow analysis and velocity distribution in the compact-sized falling needle rheometer. This model is based on the flow analysis around the falling circular cylinder (falling needle) in the static fluid introduced into the cylindrical vessel. In order to apply this model to the motion of a falling needle and the mass transfer, the following four conditions are assumed [12]:

(1) Fluid is an incompressible liquid
(2) Slip between the falling needle surface and container wall is negligible
(3) Flow in the cylindrical vessel is laminar
(4) The falling needle free-falls in the center of the vessel with a terminal velocity

These assumptions and the constitutive equation of a fluid are used for flow analysis. This flow model can be applied for many types of constitutive equations shown in Fig. 5. In this study, the constitutive equations of Newtonian and Casson fluids are applied for human blood. The flow model of a falling needle in a static fluid according to the above assumptions is given in Fig. 4a. This model shows that the falling needle falls at a terminal velocity (U_t) in the static fluid introduced into the cylindrical fluid

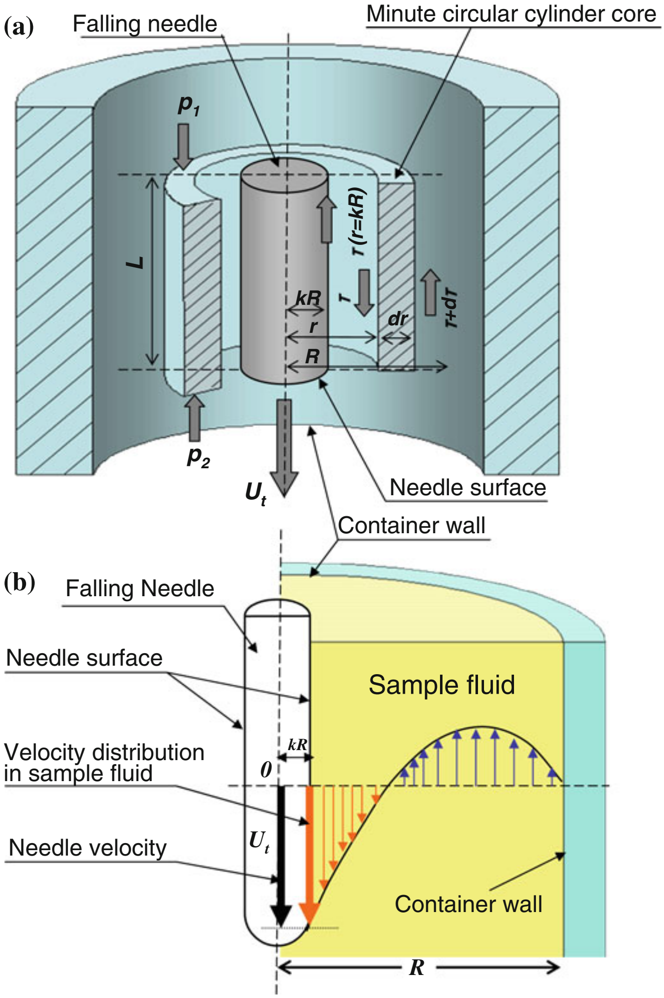


Fig. 4 (a) Flow model and (b) velocity distributions of sample fluid in the fluid vessel of falling needle rheometer

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 shown in Fig. 4 is assumed to be the fluid model for theoretical analysis. The inner and outer diameters of this core are r and $r + \mathrm{d}r$, and the total length is L. The shear stresses on the inside and outside surfaces of the minute circular cylinder core are τ and $\tau + \mathrm{d}\tau$, respectively. The pressures at the top and bottom of the minute circular cylinder core are P_1 and P_2, respectively. When the falling needle falls at a terminal velocity in the static sample fluid, the momenta affected on four surfaces of the minute circular cylinder core shown in Fig. 4a 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:

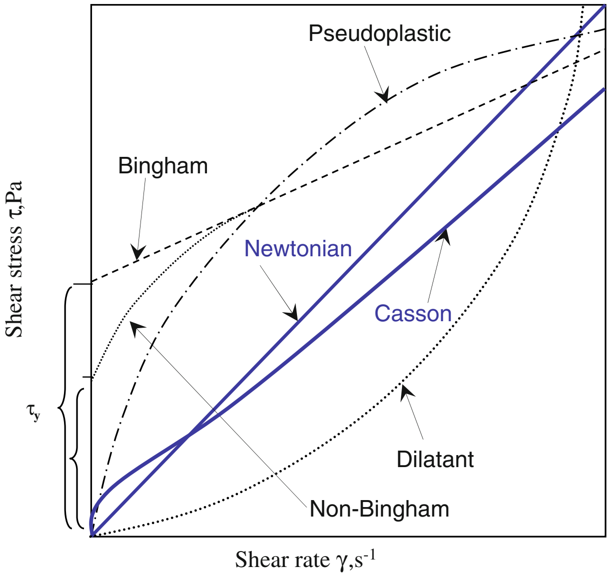


Fig. 5 Typical *flow curves* for Newtonian and non-Newtonian fluids; *solid lines* are used for flow analysis of blood

$$P_1 \left\{(r+\mathrm{d}r)^2\pi - r^2\pi\right\} + 2\pi r L\tau = P_2 \left\{(r+\mathrm{d}r)^2\pi - r^2\pi\right\} + 2\pi\,(r+\mathrm{d}r)\,L\,(\tau+\mathrm{d}\tau) \tag{1}$$

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

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

Furthermore, when 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

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

where 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

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

Figure 4b 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

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

Figure 4b 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, Eqs. 2, 4–6b, and a constitutive equation of the sample fluid are used simultaneously for flow analysis [6].

The constitutive 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, 4–7:

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

As R and k in Eq. 8 are fixed values according to the size of the fluid vessel and falling needle, they are expressed by the following equation using the geometric constant G:

$$G = -\frac{2\left(k^2+1\right)}{(kR)^2\left\{\left(k^2+1\right)\ln k + 1 - k^2\right\}} \tag{9}$$

Therefore, the viscosity of a fluid can be simply described by

$$\mu = \frac{(\rho_\mathrm{s} - \rho_\mathrm{f})g}{GU_\mathrm{t}} \tag{10}$$

The shear rate of the sample fluid on the falling needle surface can be obtained from Eqs. 7 and 9 as

$$\gamma_{(r=kR)} = \frac{\mathrm{d}u}{\mathrm{d}r} = \frac{(k^2-1)U_\mathrm{t}}{kR\left\{\left(k^2+1\right)\ln k + 1 - k^2\right\}} \tag{11}$$

The shear rate distribution for the radius direction can also be calculated by this equation. The shear stress of the sample fluid on the falling needle surface can also be described by the following equation by substituting Eqs. 8 and 11 for Eq. 7:

$$\tau_{(r=kR)} = \frac{(\rho_\mathrm{s}-\rho_\mathrm{f})g\left(1-k^2\right)kR}{2\left(k^2+1\right)} \tag{12}$$

Equations 11 and 12 become fundamental relations for flow analysis of the sample fluid. In this experiment, eight needles with different densities are used for the flow analysis. A flow curve of the sample fluid is obtained from the relationship between the shear stress and shear rate for eight needles [6].

5 Determination of Parameters in Casson's Constitutive Equation

In the case of human blood, eight needles are also applied for flow analysis. In previous research, it has been reported that the flow curve of human blood shows Casson fluid behavior as shown in Fig. 5 [1,3]. Therefore, the correlation equation between the shear rate and shear stress is not a linear relationship; Casson's constitutive equation is needed for flow analysis. A typical Casson's constitutive equation is given by

$$\sqrt{\gamma} = \frac{1}{\sqrt{\eta_\mathrm{c}}}\left(\sqrt{\tau} - \sqrt{f_\mathrm{c}}\right) \tag{13}$$

where $\sqrt{f_\mathrm{c}}$ is the yield stress of Casson's equation and $\sqrt{\eta_\mathrm{c}}$ is the viscosity. In the case of flow analysis of a Casson fluid (blood), a Casson plot is useful for determination of each parameter. A Casson plot treatment is carried out using the relationship between $\sqrt{\tau}$ and $\sqrt{\gamma}$ on the diagram. The apparent viscosity (μ) is obtained from the slope of this linear relationship, and the yield stress (τ_y) is determined from the y-intercept on the Casson plots.

6 Results and Discussion

6.1 Accuracy of the Compact-Sized Falling Needle Rheometer

The accuracy and the reproducibility of the presented rheometer are ascertained by viscosity measurements of a standard liquid for calibration of viscometers manufactured by Nippon Grease Co., Ltd. The standard liquids (JS2.5, JS5, and JS10) were chosen after careful consideration of the blood viscosity range (3.0 to 7.0) mPa · s. Good uncertainty within 0.8 % and reproducibility within ±1.0 % are confirmed by comparison with reference data, and this experimental apparatus is improved from previous work (previous uncertainty was 1.25 %) [6]. It is thought that this improvement of accuracy was caused by the manufacturing method of falling needles, that is, the presented needle is manufactured using a model made of metal with high accuracy.

6.2 Flow Analysis of Fresh Human Blood

Flow analysis of fresh human blood for two females and two males was carried out using a compact-sized falling needle rheometer. Each result was evaluated as a flow curve, Casson plot, an apparent viscosity, yield stress, and hematocrit values. These rheological properties were compared between female and male blood.

In the experiment, fresh human blood of 20 mL volume was taken from human veins, about 3 mL of whole blood was rapidly introduced into the fluid vessel without anticoagulant. The temperature of the fresh human blood was kept at 310 K using a constant temperature water bath. The anticoagulant (EDTA-2Na) was added to the other blood (17 mL), and that blood was kept at 278 K and sent to a medical center for measurement of the hematocrit value. During the experiment, the fresh blood sample was agitated by a stirrer as shown in Fig. 1 with a constant interval for avoiding the precipitation of corpuscle cells in the fluid vessel.

At first, the first needle was introduced into the needle launcher shown in Fig. 1, and the passing time of the needle between two magnetic sensors was measured by a programmable controller. After this operation, the falling needle stopped at the bottom of the fluid vessel and was rapidly moved into the space in the needle collector by the guidance of a small magnet from outside the vessel through manual operation. Next, the second needle was also introduced into the needle launcher as soon as possible. When the final needle (eighth needle) was introduced into the needle launcher and the passing time was measured, the rheometric operation was finished. Densities of fresh human blood were measured by a portable density/gravity meter manufactured by Kyoto Electric Co., Ltd., within an uncertainty of 10^{-4} g $\cdot$ cm^{-3} as soon as possible. Human blood densities for females and males are listed in Table 2.

The experimental treatment of fresh human blood without anticoagulant was carried out within 120 s except for the time needed for taking the blood (about 60 s), that is, the total time needed for this operation for each person was finished within 3 min.

The observed flow curve for male blood without anticoagulant is shown in Fig. 6. This flow curve shows a linear relationship between the shear stress and shear rate in a high shear stress range (150 to 400) s^{-1}. However, non-Newtonian behavior (Casson behavior) was confirmed in a low shear stress range (0 to 150) s^{-1}.

Table 2 Densities of fresh human blood measured by electronic densimeter within 3 min after collecting blood at 310 K

Density of flesh human blood (10^3 kg $\cdot$ m^{-3})

Male (1)	Male (2)	Female (1)	Female (2)
1.0531	1.0549	1.0511	1.0381

Fig. 6 Flow curve of fresh human blood for male without anticoagulant at 310 K

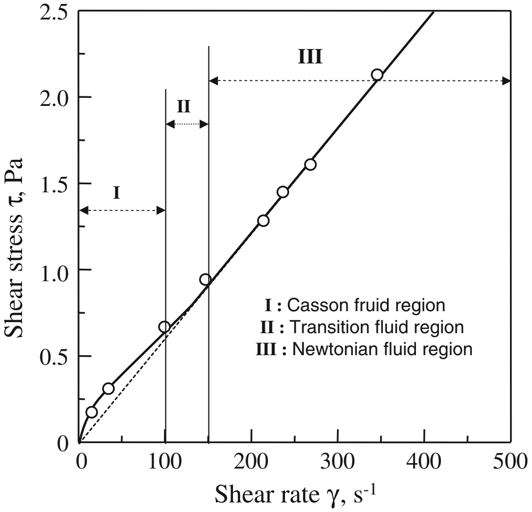
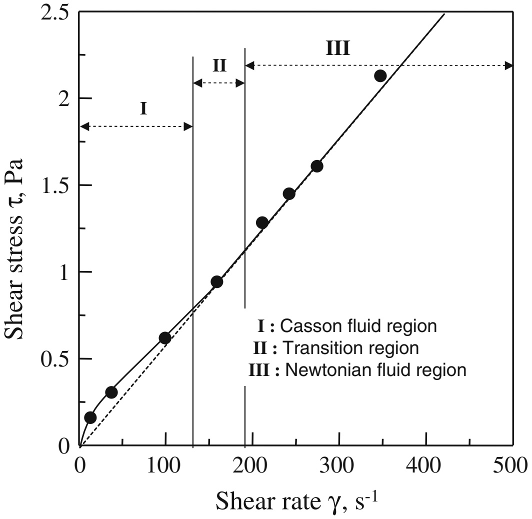


Fig. 7 Flow curve of fresh human blood for male with anticoagulant at 310 K



The observed flow curve of fresh human blood showed the three typical fluid regions, that is, the Casson fluid region for the low shear rate range, and the transition region, and Newtonian fluid region for the high shear rate range. Figure 7 shows the flow curve of male human blood with anticoagulant, and a similar tendency with Fig. 6 as the Casson fluid was obtained. Figures 8 and 9 show Casson plots of male blood with and without anticoagulant, respectively. Two parallel linear relationships with similar slopes were obtained. It was found that fresh human blood could be expressed as a Casson fluid on this diagram. Parameters were determined using Eq. 13, and they are listed in the upper part of Table 3.

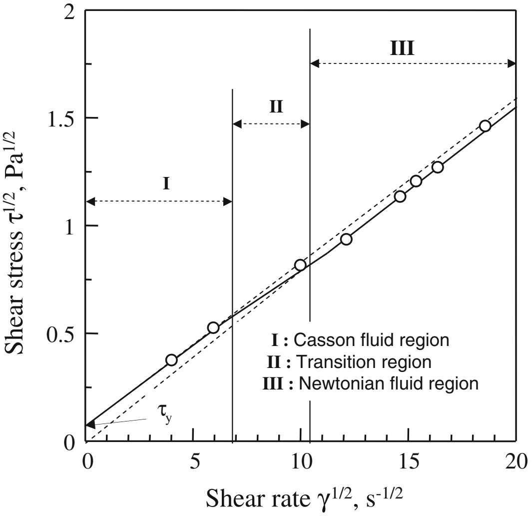


Fig. 8 Casson plots of fresh human blood for male without anticoagulant at 310 K

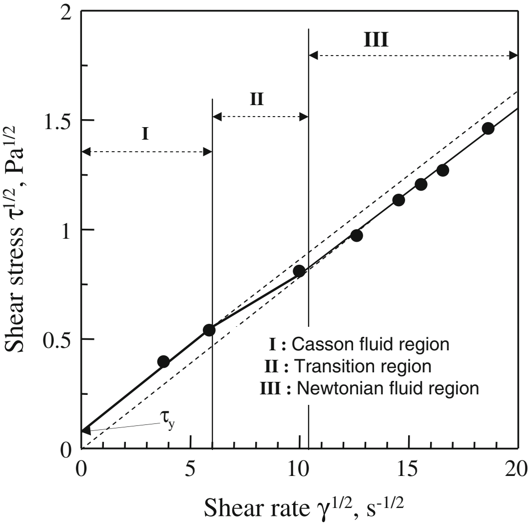


Fig. 9 Casson plots of fresh human blood for male with anticoagulant at 310 K

Table 3 Average viscosity, hematocrit value, and yield stress of fresh human blood at 310 K

Sex	Ht[a] (%)	Fresh blood (mPa · s)	Fresh blood + anticoagulant (mPa · s)	Yield stress[b] (Pa)
Male (1)	42.8	6.02	5.96	0.093
Male (2)	44.0	6.41	5.50	0.095
Female (1)	38.1	5.33	4.96	0.044
Female (2)	35.5	4.79	4.55	0.050

[a] Hematocrit value
[b] Yield stress was determined from *y*-intercept of Casson plots

Fig. 10 Flow curve of fresh human blood for female without anticoagulant at 310 K

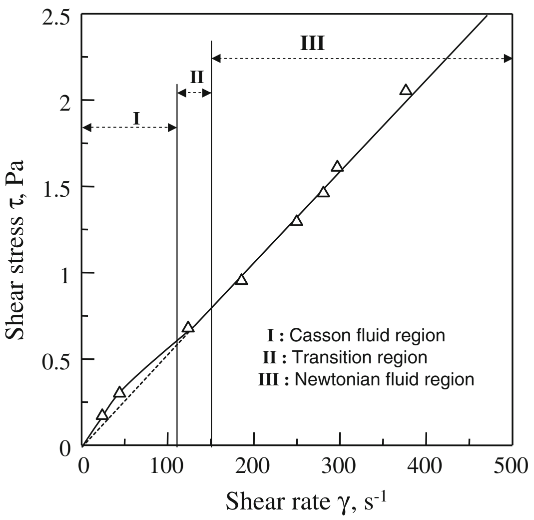
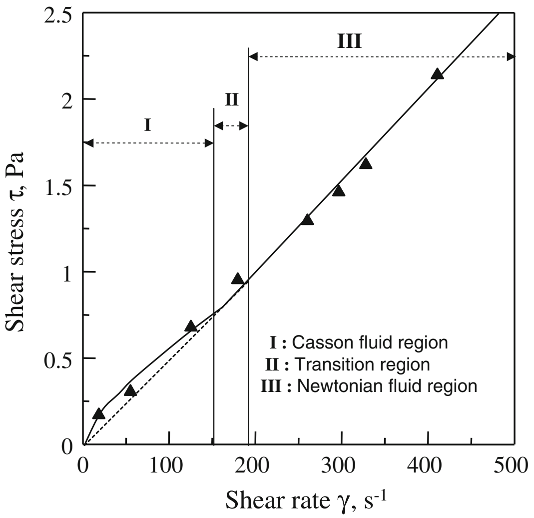


Fig. 11 Flow curve of fresh human blood for female with anticoagulant at 310 K



The observed flow curve for female blood without anticoagulant is shown in Fig. 10. This flow curve also shows a linear relationship between the shear stress and shear rate in the high shear stress range (130 to 400) s^{-1}. However, non-Newtonian behavior (Casson behavior) was confirmed in the low shear stress range (0 to 130) s^{-1}. It was also found that fresh human blood of females had the typical behavior of a Casson fluid. Figure 11 shows the flow curve of female human blood with anticoagulant. A similar tendency for Fig. 10 was obtained. Figures 12 and 13 show Casson plots of female blood with and without anticoagulant, respectively.

Fig. 12 Casson plots of fresh human blood for female without anticoagulant at 310 K

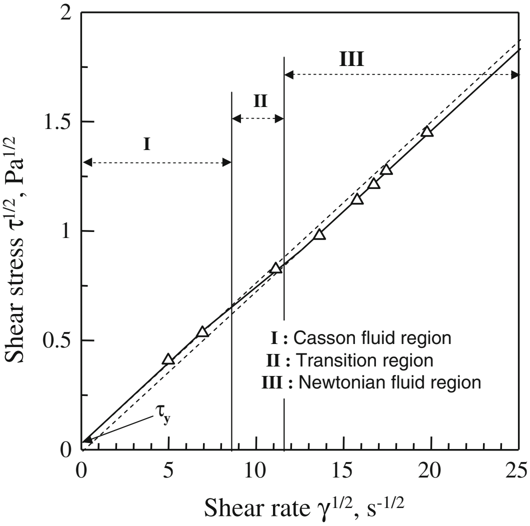
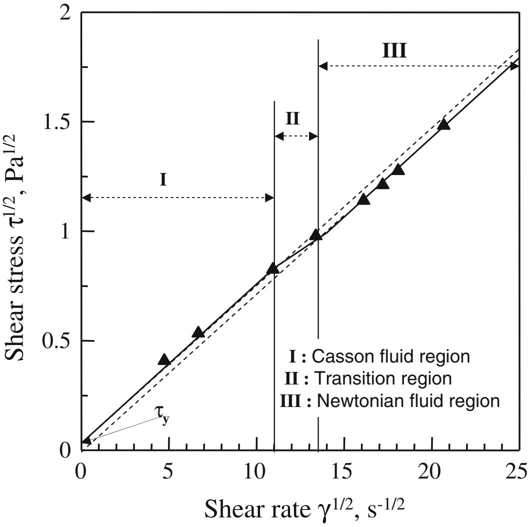


Fig. 13 Casson plots of fresh human blood for female with anticoagulant at 310 K



Parameters were determined using Eq. 13, and they are also listed in the lower part of Table 3. Figure 14 shows the relationship between the apparent viscosity and shear rate for fresh human blood with or without anticoagulant at 310 K, and the rheological parameters that were obtained are listed in Table 3.

Figure 14 and Table 3 show a comparison between the flow properties of male and female blood. In the case of the apparent viscosity without anticoagulant, the viscosity of male blood was higher than that of female blood. A similar tendency for human blood with anticoagulant was observed. Furthermore, the viscosity of blood with anticoagulant for both showed a lower value than that without anticoagulant. The

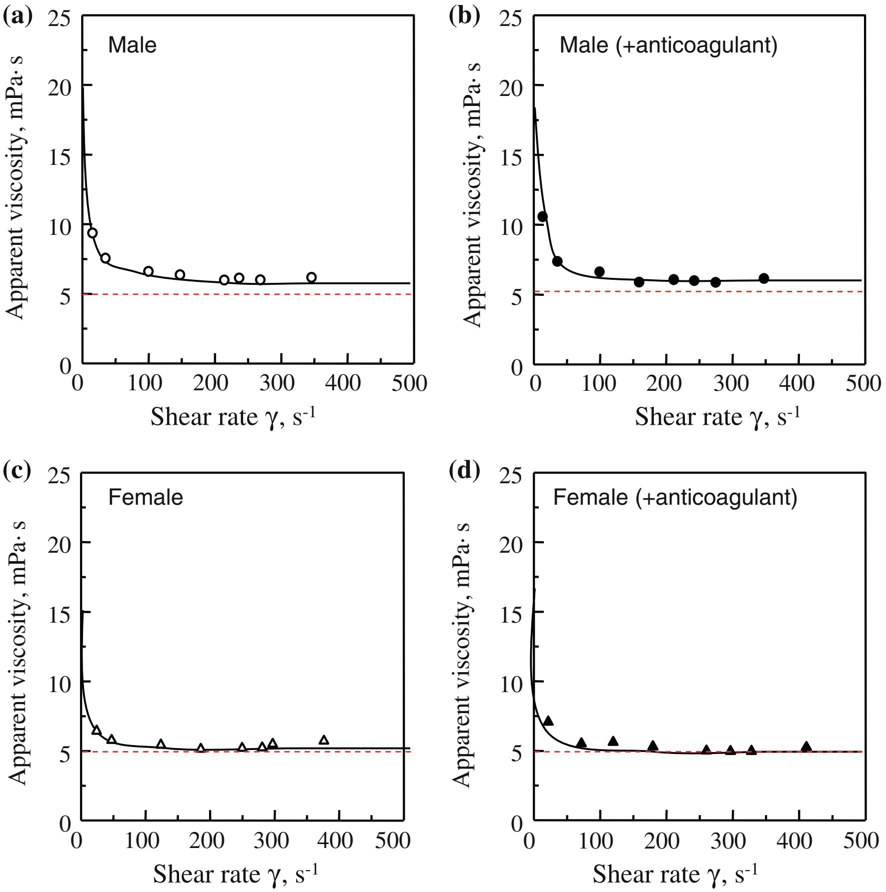


Fig. 14 Relationship between apparent viscosity and shear rate for fresh human bloods with or without anticoagulant at 310 K

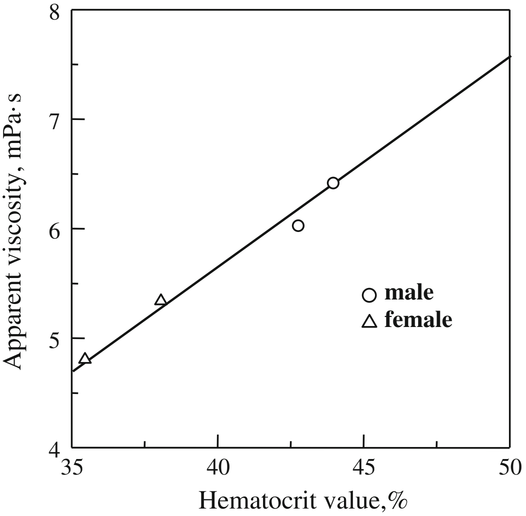
yield stress of fresh human blood for males was a little higher than that for females. However, since the value of the yield stress was so small for the apparent viscosity, it was a little difficult to discuss the behavior of the yield stress. More experimental data in the range of low shear rates are needed for this purpose.

Figure 15 shows the relationship between the apparent viscosity for human blood and hematocrit values that are the percentage of red cells included in whole blood. A linear relationship with the hematocrit values was obtained. It was found that the viscosity for human blood for both females and males is closely connected with the hematocrit values.

7 Conclusion

A compact-sized falling needle rheometer with rapid operation and automatic flow analysis has been developed for the viscometry of fresh human blood without

Fig. 15 Relationship between average viscosity and hematocrit values of fresh human blood without coagulating agent at 310 K



anticoagulant. The volume of a fresh blood sample only needs to be 3 mL and the measuring time is within 3 min after taking a blood sample from the human body. The measured flow properties of human blood are evaluated as a flow curve, that is, the relationship between the shear stress (τ) and shear rate (γ). Observed flow curves of fresh human blood show the three typical fluid regions, that is, the Casson fluid region for the low shear rate range, and the transition region and Newtonian fluid region for the high shear rate range. Flow properties of human blood such as the yield stress (τ_y) in the Casson fluid region and the apparent viscosity (μ) in the Newtonian fluid region are measured, and they are compared between male and female blood. It is found that the human blood viscosity of males (6.0 to 6.4) mPa · s shows a higher value than that of females (4.8 to 5.3) mPa · s. Human blood viscosities with anticoagulant show lower values than those without anticoagulant. A linear relationship between the hematocrit value, which is the volume percentage of red corpuscles in the human blood, and the apparent viscosity is observed for male and female blood. It is found that the compact-sized falling needle rheometer presented in this study is very useful for rheometry studies of fresh human blood without anticoagulant.

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