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Determination of whole blood and plasma viscosity by means of flow curve analysis

Peter Ruef[1,2], Jutta Gehm[3], Lothar Gehm[3], Claudia Felbinger[1], Johannes Pöschl[1] and Navina Kuss[1]

[1] *Department of Pediatrics, Clinic of Neonatology, University of Heidelberg, Germany*
[2] *Clinic of Pediatrics, SLK-Kliniken Heilbronn GmbH, Germany*
[3] *Expert office of rheology, Bad Homburg, Germany*

Abstract. The LS300 viscometer permits automated measurements of viscosity at several shear rates of non-Newtonian fluids. We determined whole blood and plasma viscosity, aggregation, red blood cell deformability, and hematocrit of 66 healthy adults. The effects of the anticoagulants EDTA, heparin and citrate, and of centrifugation on blood viscosity ($n = 12$) and red blood cell geometry ($n = 5$) were investigated. With regard to the whole blood viscosity of adults, the best agreement was obtained by Casson's calculation compared to the methods of Ostwald, Bingham and Newton. The approximated flow curve of plasma showed only marginal differences between the method of Newton and Ostwald, whereas the latter gave the best quality of approximation. Centrifugation and the anticoagulants had a significant impact on whole blood viscosity and yield shear stress, whereas erythrocyte geometry remained unaffected. By linear regression of hematocrit with viscosity and yield shear stress, its impact on blood viscosity could be calculated in a hematocrit range of 0.32–0.50. Determination of whole blood viscosity should be performed in a standardized manner at several shear rates and without centrifugation of the blood samples.

Key words: Casson — Ostwald — Anticoagulants — Flow curve — Yield shear stress — Viscosity

Introduction

Increased blood viscosity is a biological parameter which may be causally related to all significant cardiovascular risks: hypertension, high LDL cholesterol, low HDL, type-II diabetes, metabolic syndrome, obesity, smoking, age, and the male gender (Sloop 1996; Cowan et al. 2005). Cardiovascular events and risk factors are the most common causes of mortality and morbidity in our society. Therefore, knowledge of the flow properties of blood, a non-Newtonian fluid, at different shear forces is of great interest (Bajd et al. 2012).

Whole blood viscosity describes the interaction of the components on the basis of their flow resistance. It is specifically dependent on vessel diameter, hematocrit (hct), plasma viscosity, the shape and deformability of red blood cells (RBC), leukocyte count, RBC aggregation, the interaction of blood cells with plasma, and shear forces acting on blood cells (Begg et al. 1966; Chien et al. 1967; Reinhart et al. 1992).

Due to the new software of the LS300 viscometer, the shear forces of a fluid can be measured at freely selected shear rates. The flow curve thus obtained permits calculation of the viscosity of a non-Newtonian fluid like whole blood (Antonova et al. 2008, 2012) and not only the blood viscosity at a specific predefined shear force, an often used method. This permits calculation of shear forces at any desired shear rate, and the creation of a viscosity profile (Holsworth et al. 2013).

In addition to whole blood viscosity of healthy adults, individual factors that affect viscosity were determined: aggregation index (aggregometer), plasma viscosity (LS300, capillary tube viscosimeter), hct (microcentrifuge), shape of RBCs (RBC geometry using the micropipette technique), and RBC deformability (Rheodyn). Besides, the impact of anticoagulants (EDTA, heparin, citrate) and centrifugation (such as hct setting) on blood samples was determined. As

Correspondence to: Peter Ruef, Department of Pediatrics, Clinic of Neonatology, University of Heidelberg, Im Neuenheimer Feld 430, D-69120 Heidelberg, Germany
E-mail: peter.ruef@t-online.de

hct exerts a major impact on blood viscosity (Begg at al. 1966; Antonova 2012), it would be useful to develop an algorithm that takes the impact of hct (i.e. the proband`s current hct level) into account without having to specifically set this parameter. Parameters which might show some interdependence or correlation were tested by linear regression. All measurements were performed at 37°C.

Materials and Methods

Blood samples were taken from 66 healthy non-smoking adults (33 men and 33 women, age 33 ± 8 years) by slow and smooth aspiration after puncture of a cubital vein. Standard test tubes (10 ml) coated with ethylenediaminetetraacetic acid (EDTA) (1.5 mg/ml) were filled with the blood. In all samples, whole blood viscosity of original hct and at a set hct value of 0.4 as well as plasma viscosity was determined. The effects of the anticoagulants EDTA, lithium heparin (50 IU/ml) and sodium citrate (0.11 M) on viscosity (n = 12 men) and red blood cell geometry (n = 5 men) were also determined. Blood from healthy male probands was directly spread on the test tubes (10 ml) one by one coated with the three different anticoagulants. To set hct, the blood samples were gently and temperature controlled (21°C) centrifuged at 2000 × g for 10 minutes (Haereus Labofuge 400, Haereus Holding GmbH, Hanau, Germany). Plasma and the buffy coat were then pipetted carefully as usual. The desired hct value of 0.4 was set by adding autologous plasma. Hct was assessed in all samples using the microhematocrit method, by performing centrifugation of a small sample (60 µl) for 10 minutes at 15000 × g (Biofuge A, Heraeus Sepatech GmbH, Germany) (Anwar et al. 1994). The effect of setting the hct by this procedure to 0.4 to blood samples with a mean original hct of 0.4 (n = 50) was compared. All preparations for the measurements were performed at the ambient temperature of 21°C. Measurement of viscosity, aggregation and red blood cell deformability was performed at 37°C. For this purpose the aggregometer and Rheodyn SSD were placed in an incubator set to 37°C (Inkubator 7510, Drägerwerk, Lübeck, Germany). All measurements were performed within three hours after blood sampling (Baskurt et al. 2009). The study was performed in accordance with the Declaration of Helsinki, and had been approved by the ethics committee of the University of Heidelberg.

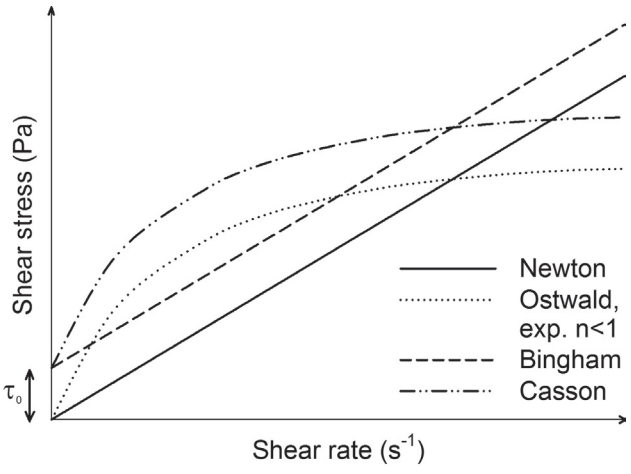

Figure 1. Examples of schematic drawings of flow curves by the models of Newton, Ostwald, Bingham and Casson. τ_0, yield shear stress; n, exponent by Ostwald.

Measuring principle of LS300

LS300 (proRheo GmbH, Althengstedt, Germany) is a rotational rheometer based on the Couette principle which is the same as the LS30 previously described (Aarts et al. 1984). The software of LS300 regulates the rotation count of the measuring cup. The number of measuring points at several shear rates and time may be selected as desired. The thermostat of LS300 works with cryoregulation; its accuracy is ±0.1°C. The new technology of LS300 permits determination of shear forces at multiple shear rates during a single measuring run, over a wide range of shear rates from 0.018 to 125 s^{-1}. By graphic presentation of shear rate versus shear stress one obtains data points which, when connected to each other, yield a flow curve (Fig. 1). When the curve does not pass the zero point but intersects the y-axis (shear stress τ, Fig. 1), one obtains yield shear stress τ_0.

Measurement of whole blood and plasma viscosity (LS300)

The samples (0.9 ml) were investigated by geometric distribution of ten measuring points in a shear velocity range from 0.5 s^{-1} to 50 s^{-1} (0.5, 0.76, 1.16, 1.76, 2.67, 4.06, 6.16, 9.37, 14.24, 21.64, 32.90, 50 s^{-1}) within a time of 120 s. In a first step, the flow curves (Fig. 1) may be described according to the rheological models of Newton, Ostwald, Bingham or Casson:

Newton: $$\tau = \eta_N \cdot \dot{\gamma} \quad (1)$$

Ostwald: $$\tau = \eta_{Ost} \cdot \dot{\gamma}^n \quad (2)$$

Bingham: $$\tau = \tau_0 + \eta_{BH} \cdot \dot{\gamma} \quad (3)$$

Casson: $$\sqrt{\tau} = \sqrt{\tau_0} + \sqrt{\eta_{Ca} \cdot \dot{\gamma}}$$

$$\tau = \tau_0 + 2\sqrt{\tau_0 \cdot \eta_{Ca} \cdot \dot{\gamma}} + \eta_{Ca} \cdot \dot{\gamma} \quad (4)$$

where: η_N, viscosity by Newton; η_{Ost}, viscosity by Ostwald; n, exponent by Ostwald; η_{BH}, viscosity by Bingham; τ_0, yield

shear stress by Bingham; η_{Ca}, viscosity by Casson; τ_0, yield shear stress by Casson, $\dot{\gamma}$, shear rate.

The agreement between the determined curve and the measuring points is calculated by the LS300 software. Ostwald's model includes mention of the exponent in addition to viscosity. Bingham's and Casson's model includes mention of yield shear stress (point of intersection of the flow curve and the y-axis). Ten blood and plasma samples were investigated to determine the influence of RBC sedimentation rate (Matrai et al. 1984a) of whole blood during the measuring cycle (120 s) and the development of a surface film at the air-fluid interface of plasma (Matrai et al. 1984b) on the viscosity and shear force. The viscosity and shear force at a medium shear rate of 9.37 s^{-1} of whole blood and of plasma during the above mentioned measuring cycle after 79 s and directly after filling the measuring chamber was compared. No significant differences were observed (Mann Whitney Rank Sum Test, whole blood viscosity $p = 0.77$ and shear force $p = 0.77$; plasma viscosity $p = 0.18$ and shear force $p = 0.20$). RBC sedimentation rate and the development of a surface film at the air-fluid interface of plasma seemed not to play a role in our experimental setting with the LS300. In a small number of samples ($n = 3$) RBC were suspended (hct 0.41) in phosphate buffer saline (PBS: Na_2HPO_4 3.53 g/l; KH_2PO_4 0.702 g/l; NaCl 7.0725 g/l, pH 7.4, 295 mOsm/kg) and aggregation and viscosity was determined.

Measurement of plasma viscosity (capillary tube viscosimeter)

Plasma viscosity was additionally determined with the capillary tube viscosimeter and compared to LS300 (KSPV-4, Rheomed GmbH, Aachen, Germany) (Jung et al. 1985).

Aggregation index

The aggregation index was determined with the Myrenne aggregometer MA1 (Myrenne GmbH, Roetgen, Germany). Twenty microliters of a sample of whole blood was pipetted into the shear opening and sheared at 600 s^{-1} for 10 s, assuming that all pre-existing aggregates are disaggregated by this process. Rotation is stopped for 10 s and aggregation is measured by the passage of light (M0). The aggregation index thus obtained is proportional to the area under the light transmission curve, which reflects the degree of aggregation attained at the end of the 10 s period (Schmid-Schönbein et al. 1983).

RBC deformability

RBC deformability was investigated in accordance with previous studies (Schmid-Schönbein et al. 1996), using the Rheodyn SSD shear stress diffractometer (Myrenne Gmbh, Roetgen, Germany). It is based on the elongation of RBC. Various shear forces (0.3, 0.6, 1.2, 3.0, 6.0, 12.0, 30.0, 60.0 Pa) were used and the elongation index is given in percentage. The whole blood sample was diluted with dextran. The viscosity of dextran (Dextran Lsg. FP 60, Art.-Nr. 8072921, 100 ml, Burg-Apotheke, Königstein, Germany) as a shear medium was tested with LS300. It was 24 mPa·s at room temperature, and 11 mPa·s at the measuring temperature of 37°C.

RBC geometry

RBC geometry was determined by the use of a micropipette system. Micropipettes with an internal diameter of 2.1 µm were used for this purpose. The suction force was set to a negative pressure of −15 mm H_2O. The micropipette system and the measuring principle have been described in a previous report (Ruef et al. 1999). The cellular volume, surface area, surface area index, and swelling index of RBCs could be determined by this procedure. The effects of anticoagulants and centrifugation (for adjustment of the hct) on the geometric properties of RBCs were determined.

Statistical analysis

Statistical analysis was performed to determine differences between the individual standard rheological models, and the effects of anticoagulants and centrifugation on viscosity. Means and standard deviations (SD) were determined for all data. Wilcoxon's signed rank test was used to compare two groups. To investigate differences between more than two groups, the null hypothesis was discarded and variance analysis was performed by one-way ANOVA for normally distributed data (Shapiro-Wilk), and the Kruskal-Wallis one-way analysis of variance on ranks for non-normally distributed data. Multiple mean value comparisons were performed by the Student-Newman-Keuls method (Glantz 2005).

Results

Comparison of the viscosity of whole blood by Casson's and Ostwald's model (based on the selected models of Casson, Bingham, Ostwald and Newton) showed the significant and best quality of Casson's flow curve (Table 1). Calculations according to Newton and Bingham revealed greater deviations; the data are not given here. By determination of viscosity at the original hct value of 0.41 ± 0.034 (3.79 ± 0.5 mPa·s), Casson's yield shear stress (4.93 ± 2.02 mPa) (Table 1) and the resulting flow curve, one is able to calculate the required shear force and the corresponding viscosity (Fig. 2) for every shear rate.

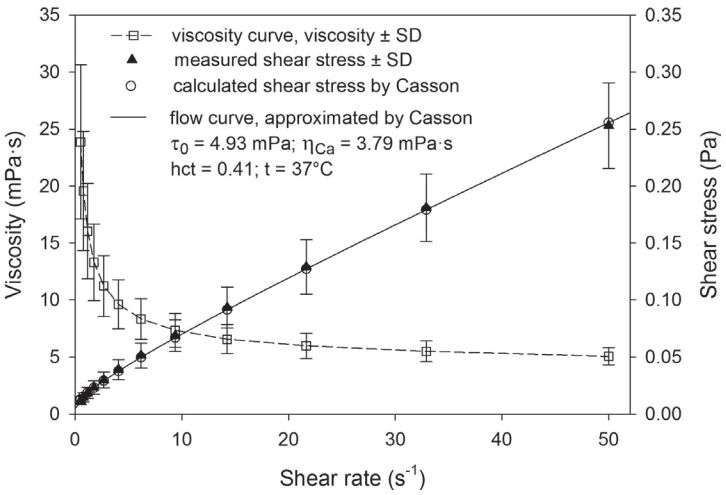

Figure 2. Flow curve (shear stress versus shear rate), approximated by Casson and viscosity curve (viscosity versus shear rate) of 66 healthy adults. Data are given as means ± SD. The open circles represent the shear stress, calculated by Casson.

The flow curve of plasma of healthy adults was nearly similar when approximated by either the method of Ostwald or Newton (Fig. 3). The exponent (n) determined by the method of Ostwald was nearly 1 and emphasized this result (Table 1). The best quality of approximation ($p < 0.001$) was achieved by the model of Ostwald (Table 1). Determination of plasma viscosity by the KSPV-4 and the LS300 revealed no significant differences of plasma viscosity (by Newton) but with a smaller standard deviation with determinations by the LS300 (Table 1).

Centrifugation for setting hct, as well as the various anticoagulants (EDTA, heparin and citrate) markedly influenced the viscosity of whole blood. Particularly centrifugation reduced the viscosity of blood (a non-Newtonian fluid) to a significant extent (Fig. 4, Table 2). The use of heparin as

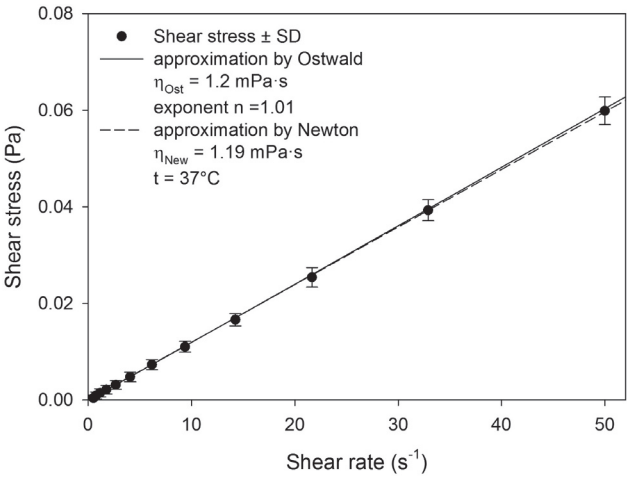

Figure 3. Flow curves of plasma approximated by the methods of Ostwald and Newton. Data are means ± SD ($n = 66$).

Table 1. Quality of methods to determine whole blood and plasma viscosity

Healthy adults ($n = 66$, hct = 0.41)	
Whole blood	
η_{Ca} (mPa·s)	3.79 ± 0.50
τ_0 (mPa)	4.93 ± 2.02
Quality (%)	99.71 ± 0.13*
η_{Ost} (mPa·s)	16.50 ± 4.11
n	0.67 ± 0.035
Quality (%)	99.21 ± 0.13
Plasma	
η_{Ost} (mPa·s)	1.20 ± 0.58
n	1.01 ± 0.12
Quality (%)	99.43 ± 0.42#
η_N (mPa·s)	1.19 ± 0.068
Quality (%)	98.53 ± 1.99
η_{KSPV4} (mPa·s)	1.18 ± 0.075
Healthy adults ($n = 3$, hct = 0.41)	
RBC in PBS, aggregation = 0.0	
η_{Ca} (mPa·s)	2.27 ± 0.18
τ_0 (mPa)	0.026 ± 0.0072
Quality (%)	99.23 ± 0.18
η_{Ost} (mPa·s)	2.52 ± 0.12
n	0.98 ±0.017
Quality (%)	99.46 ± 0.25

Values are mean ± SD; * $p \leq 0.001$ for comparison of the quality of determination of whole blood viscosity by Casson's method with that of Ostwald; # $p \leq 0.001$ for comparison of the quality of determination of plasma viscosity by Ostwald's method with that of Newton's. hct, hematocrit; η_{Ca}, viscosity by Casson; τ_0, yield shear stress by Casson; η_{Ost}, viscosity by Ostwald; n, exponent by Ostwald; , viscosity by Newton; η_{KSPV4}, viscosity determined with the capillary tube viscosimeter KSPV-4.

Table 2. Influence of centrifugation on blood viscosity (η_{Ca}) and yield shear stress (τ_0) by Casson

	η_{Ca} (mPa·s)	τ_0 (mPa)
Original hct 0.4 ± 0.032	3.67 ± 0.51	4.44 ± 1.97
Hct corrected by calculation to 0.4	3.67 ± 0.38	4.44 ± 1.86
Hct adjusted to 0.4	3.04 ± 0.30*	2.39 ± 1.47*

Values are mean ± SD. * $p < 0.05$ for comparison of the blood specimen with the original hct value and when the blood specimen were corrected to an hct value of 0.4 by linear regression ($n = 50$). hct, hematocrit.

anticoagulant was associated with the highest yield shear stress, followed by EDTA, whereas citrate showed the lowest yield shear stress and lowest viscosity according to Casson (Fig. 5). EDTA and heparin did not differ with regard to whole blood viscosity according to Casson. The anticoagulants and centrifugation had no significant impact on RBC geometry (Table 3).

Correlating the hct with Casson`s viscosity (r = 0.87; $p < 0.001$) and the hct with Casson's yield shear stress ($r = 0.89$; $p < 0.001$), the impact of hct (Fig. 6) could be considered by linear regression. Thus, viscosity and yield shear stress according to Casson could be corrected within a range of 0.32–0.50 to an arbitrarily set hct value of 0.4 (Table 2), without the need of centrifugation to influence blood for setting hct and thus falsifying viscosity or yield shear stress data. When this procedure was applied to all blood samples ($n = 50$, hct = 0.4 ± 0.024, max = 0.44, min = 0.34) it revealed similar means of yield shear stress by Casson and viscosity by Casson but with a smaller standard deviation (Table 2).

No correlation between aggregation (Table 4) and either yield shear stress by Casson ($r = 0.10$, $p = 0.41$) or viscosity by Casson ($r = 0.13$; $p = 0.28$) (Table 1) could be evaluated by linear regression. When RBCs were suspended in PBS, no aggregation could be determined and approximation of the flow curve by Casson revealed a yield shear stress (τ_0) close to zero, more than two orders smaller than for whole blood (Table 1). The best quality of approximation was found by the model of Ostwald (Table 1) for RBCs suspended in PBS.

A negative correlation (linear regression) was determined between viscosity by Casson of whole blood and RBC elongation (%) at shear forces of 60 Pa ($r = 0.64$, $p < 0.001$), 30 Pa ($r = 0.64$; $p < 0.001$), 12 Pa ($r = 0.62$, $p < 0.001$), 6 Pa ($r = 0.59$, $p < 0.001$) and 3 Pa ($r = 0.51$, $p < 0.001$). No correlations were found between viscosity by Casson and elongation at lower shear forces (less than 3 Pa, $r < 0.2$, $p > 0.05$), plasma viscosity by Ostwald ($r = 0.18$, $p = 0.14$) or Newton ($r = 0.07$, $p = 0.56$) and whole blood viscosity by Casson.

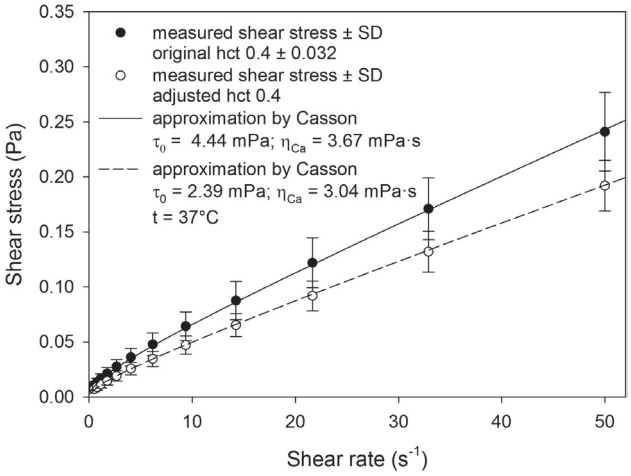

Figure 4. Influence of centrifugation for adjusting hct to shear stress. $n = 50$ healthy adults. $p \leq 0.001$ for comparison of shear stress at all given shear rates of blood samples without centrifugation with a mean hct of 0.4 ± 0.032 and the same blood samples after centrifugation necessary for adjusting hct at 0.4. hct, hematocrit.

Discussion

Whole blood viscosity (Forconi et al. 2009; Salazar et al. 2011) and plasma viscosity (Kiesewetter et al. 1986; Koenig et al. 1992; Sweeetnam et al. 1996; Lowe et al. 2000) play an important role in various cardiovascular diseases (Coull et al. 1991; Shi et al. 1996; Herrick 2005; Velcheva et al. 2011) as well as a key role in hyperviscosity syndrome (Stone et al. 2012) caused, for instance, by monoclonal gammopathy (Waldenström's disease) (Gertz 2012), multiple myeloma

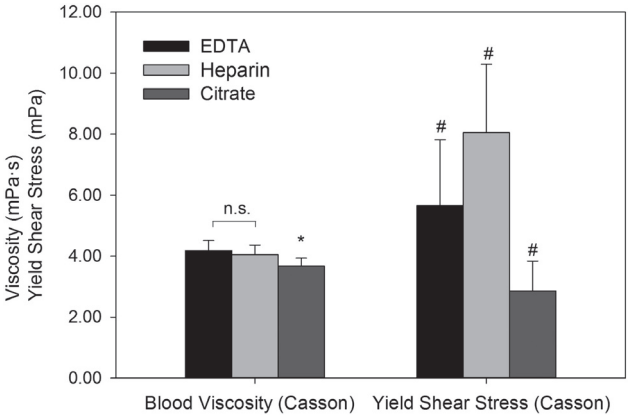

Figure 5. Influence of three anticoagulants on blood viscosity and yield shear stress by Casson. $n = 12$ healthy males; hct = 0.43 ± 0.016; * $p < 0.05$ when compared to EDTA and heparin; # $p < 0.05$ when compared to each group. hct, hematocrit.

Table 3. Influence of anticoagulants and centrifugation on the geometrical properties of erythrocytes

	without anticoagulant	EDTA	Heparin	Citrate	EDTA and centrifugation
Cellular volume (μm^3)	91.7 ± 6.7	94.3 ± 9.9	92.6 ± 8.9	89.9 ± 6.5	92.6 ± 8.2
Surface area (μm^2)	125.2 ± 5.7	127.5 ± 8.3	125.6 ± 6.6	122.7 ± 4.6	125.3 ± 7.2
Surface area index	1.27 ± 0.02	1.27 ± 0.02	1.27 ± 0.02	1.26 ± 0.01	1.27 ± 0.01
Swelling index	1.44 ± 0.03	1.43 ± 0.04	1.43 ± 0.02	1.42 ± 0.02	1.43 ± 0.02

Data are mean ± SD.

(Park et al. 2005), polycythemia (Ickenstein et al. 1999), leukemia with blast crises (Dearth et al. 1978) and polycythemia in the newborn infant (Mimouni et al. 2011).

With the LS300 the viscosity of fluids is determined by software assistance and by creating a flow curve. In a first step it is optimized and calculated according to the models of Newton, Ostwald, Bingham or Casson, and depicted numerically and in graphic form. The software contained in LS300 permits evaluation of the accuracy of the correlated flow curve of measured shear forces. Thus, one is able to determine whether the flow curve of a fluid should be determined according to Newton, Bingham, Ostwald or Casson. Other models such as those of Quemada or Ree-Eyring (Nefytou 2004; Marcinkowska-Gapinska et al. 2007) may provide even more accurate agreements, depending on the quality of the approximation of the flow curve. Mathematically, these models yield greater agreement because of the larger number of free parameters. However, the disadvantage of these models is that one needs to define several parameters, which are required for more precise agreement. In Casson's method this includes yield shear stress (in addition to the curve), which describes the behavior of a pseudoplastic fluid such as whole blood and which is influenced by the aggregation behavior of erythrocytes (Kowal 1998; Antonova et al. 2008). Casson`s approximation of whole blood viscosity of healthy adults showed a high quality of agreement in the present study. To apply the Casson´s model over the whole range of shear rate affords special attention to the $\dot{\gamma}$ range. In the range below 10 s^{-1}, we had to condense the measuring points. Otherwise the yield shear stress may be overestimated by the mathematical model. We could not find a significant correlation of aggregation versus yield shear stress by Casson (τ_0) or viscosity by Casson (η_{Ca}) in whole blood of healthy adults. However, in three blood samples, in which RBCs were resuspended in PBS, aggregation was not observable, the yield stress by Casson (τ_0) was in a very low range of 0.02–0.034 mPa (more than two orders smaller than found in whole blood) and the best quality of approximation was found by the model of Ostwald. In hypertensive patients, yield shear stress was found to be a parameter which showed the most significant changes compared to controls (Shi et al. 1996). A mathematical model with multiple parameters may bare the chance in future studies to identify one of these parameters as an indicator for pathologies in diseases.

RBC elongation and viscosity by Casson of whole blood showed interdependence at shear forces from 3 to 60 Pa. Especially at shear rates above 10 s^{-1} orientation and elon-

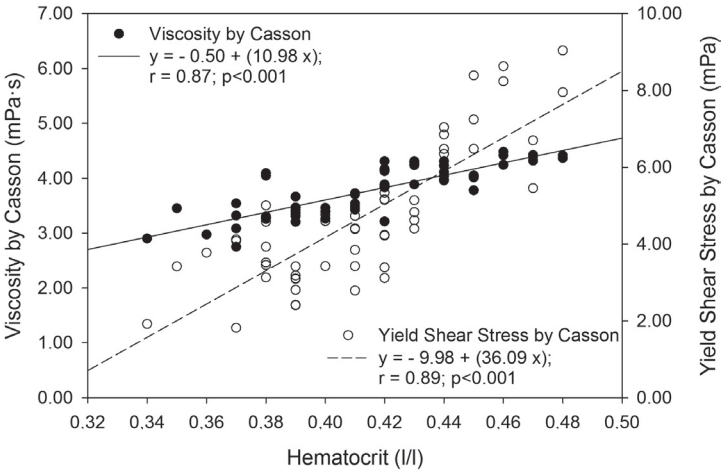

Figure 6. Linear regressions of whole blood viscosity by Casson *versus* hematocrit and yield shear stress by Casson *versus* hematocrit. n = 66 healthy adults.

Table 4. Blood parameters influencing whole blood viscosity in healthy adults

Hct		0.41 ± 0.034
Aggregation, original hct 0.41		14.63 ± 3.5
Aggregation, hct adjusted to 0.40		16.51 ± 4.4
	Shear force (Pa)	Elongation (%)
RBC deformability (Rheodyn SSD)	0.3	2.49 ± 0.73
	0.6	1.14 ± 0.72
	1.2	0.65 ± 0.95
	3.0	7.95 ± 3.35
	6.0	17.36 ± 4.45
	12.0	26.66 ± 4.76
	30.0	35.19 ± 5.17
	60.0	38.98 ± 5.63

Data are mean ± SD (n = 66). hct, hematocrit; RBC, red blood cells.

gation of RBC influences the resulting shear stress (Baskurt and Meiselman 2003).

Hct exerts a significant impact on whole blood viscosity (Gregersen et al. 1965). High hct values exert an especially strong effect on viscosity, which then increases exponentially (Begg et al. 1966; Antonova 2012). As the centrifugation and various anticoagulants influence whole blood viscosity, one should standardize the measurement of viscosity. Centrifugation of erythrocytes should be avoided. Even with other non-Newtonian fluids, stirring or centrifugation alters viscosity: cream turns stiff while honey becomes more fluid (Gehm 1998). By using the described algorithm, the impact of hct on whole blood viscosity is taken into account within the range of 0.32–0.50. EDTA was found to be the recommended anticoagulant when blood is drawn by venipuncture for in vitro hemorheological studies (Reinhart et al. 1990; Baskurt et al. 2009; Nemeth et al. 2009). Heparin (Bartoli et al. 1986), citrate (Rosenblum 1968) and oxalate (Mayer and Kiss 1965) influenced hemorheological parameters to a greater extent than EDTA and hence EDTA is preferred. EDTA was the anticoagulant of choice for determination of whole blood viscosity in the present study, too.

The flow curves of plasma approximated by Ostwald and by Newton were nearly similar, the exponent (n) was only marginally above 1. Nevertheless, a significantly better quality was noted for Ostwald's approximation of the flow curve of plasma compared to the Newtonian approximation. An additional parameter taken into account when determining the viscosity of plasma according to Ostwald compared to Newton is the exponent (n), which reflects the course of the flow curve: increasing (>1) – shear-thickening; decreasing (<1) – shear-thinning. The exponent (n) may be a relevant clue in pathologies with altered plasma viscosities with either shear – thickening or shear-thinning properties. A direct interdependence of plasma viscosity versus whole blood viscosity by Casson (η_{Ca}) or yield shear stress by Casson (τ_0) by linear regression in healthy adults was not confirmable.

Determination of whole blood viscosity may be helpful for regulating perfusion in macro- and microcirculation especially during bypass surgery. When the patient's body is cooled from 37 to 22°C with the heart-lung machine, microcirculation is crucially influenced by the rise in blood viscosity, the change in whole blood viscosity due to the inflammatory reactions, and the reduction of temperature (Matschke et al. 2012; Holsworth et al. 2013). With the new LS300, one is able to determine the viscosity of whole blood according to Casson by cryoregulation, by creating a flow curve, calculating yield shear stress, and obtaining a viscosity curve derived from it. This is also important for the determination of wall shear stress such as that of vessels or stents (Liepsch 2002; Box et al. 2005, Cavazzuti et al. 2011, Mejia et al. 2011).

We conclude that the new LS300 device and its controls permit calculation of the viscosity of a fluid by means of flow curve analysis. The determination of whole blood viscosity should be standardized (EDTA) and should not be influenced by centrifugation. By using the described algorithm, the impact of hct on whole blood viscosity is taken into account within the range of 0.32–0.50. The highest agreement for the whole blood of healthy adults was obtained by Casson's method, whereas the highest agreement for plasma was obtained by Ostwald's method. The flow curves of plasma approximated by Ostwald and Newton differed only marginally. Thus, one is able to calculate shear forces at predefined shear rates. By calculating whole blood viscosity and the corresponding yield shear stress from flow curves, shear forces in vessels or stents can be determined at predefined shear rates.

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