Flow Resistance of Non-aggregating Blood Under Vibration

S. H. Shin* · Y. H. Ku**

1. Introduction

It has been known that blood flow resistance is an important parameter involved in various cardiovascular diseases. One of the determining factors of blood flow resistance is a degree of red blood cell (RBC) aggregation. However, the effect of RBC aggregation on flow resistance has been a controversial issue. Historically, Fahraeus was the first scientist who pointed out that RBC aggregation might be advantageous to the blood flow, mostly based on the observations made in capillary tubes. Johnson et al.[1] reported relationship between RBC aggregation and venous microcirculation: Flow resistance of RBC suspension in non-aggregating medium (6% Dextran 40) showed smaller values over a range of flow rates than that of normal blood. Furthermore, increasing red cell aggregability by adding Dextran 250 also attenuated the flow resistance in a low flow rate region, which was an unexpected result. These controversial results triggered researchers to investigate the physics of blood flow characteristics *in-vivo* as well as *in-vitro*.

Meanwhile, there has been considerable research concerning the flow behavior of non-Newtonian fluids subjected to a mechanical vibration or oscillation. It has been reported that mechanical vibration causes flow enhancement in shear-thinning fluids, whereas it causes flow retardation in shear-thickening fluids. It is worthy to note that the applied vibrations and oscillations had a longitudinal direction to the flow. Deshpande and Barigou[2] investigated the effects of vibration on flow characteristics by comparing experiments and numerical calculations. They explained the mechanism of flow rate enhancement by introducing flow resistance reduction due to extra shear induced by the oscillation. In other words, the superimposed shear at the wall due to both time-averaged flow and moving boundary condition caused the changes in the shear-thinning viscosity, which, in turn, affected either the flow rate or flow resistance. In addition, Shin and Lee[3] investigated the effect of traversal vibration on apparent viscosity of suspension: They reported that the suspension viscosity was significantly reduced with increasing either frequency or amplitude of vibration.

After reviewing previous research, a question arises whether the blood flow can be increased with traversal vibration. As indicated earlier, there were too many parameters involved in blood flow characteristics. As a first step, it would be better to decouple the effect of aggregation from the blood flow under vibration. To do this, it is necessary to use non-aggregating blood: vibrating on whole blood as pre-processing. In addition, the flow rate dependency of flow resistance should be investigated. Therefore, the objective of the present study is to investigate the effect of traversal vibration on the flow resistance of non-aggregating blood over a range of flow rates. To achieve this goal, we measured flow resistance of flowing suspension under transversal vibration.

2. Materials and Methods

Samples of venous blood were drawn from the antecubital vein and collected into EDTA containing Vacutainers (BD, Franklin Lakes, NJ). In order to demonstrate the validity of this pressure-scanning capillary viscometer, the viscosity data were compared with data obtained from a rotating viscometer viscometer (Physica model UDS-200, Parr Physica, Inc., Glen Allen, VA). In order to measure either viscosity or flow resistance of blood with vibration, one needs to repeat the measurement over a range of flow rates by varying driving pressure for fixed vibration parameters such as frequency and amplitude and then by varying the vibration frequency or amplitude for a fixed flow rate, which is a time consuming process. Recently, Shin *et al.*[4] introduced a new pressure-scanning capillary viscometer (PSCV). The PSCV enabled the measurement of non-Newtonian viscosity continuously over a range of shear rates at a time.

In addition, there was neither difficulty in applying vibration to the instrument nor accuracy decrease in accuracy due to the vibration. Using the PSCV with slight modification, it is possible to measure both the flow resistance and viscosity of blood over a range of flow rates with vibration. Thus, the present study used the modified PSCV.

3. Results and Discussion

Fig. 1 shows microscopic examination of RBCs in an adulterated blood with varying vibration frequency from 0 *Hz* to 100 *Hz* for 3 min. Blood without applying vibration ($f = 0$ *Hz*) shows aggregates of red blood cells. As frequency increases, the degree of red blood cell aggregates is significantly deceases. There was no significant RBC aggregation at $f = 100$ *Hz*.

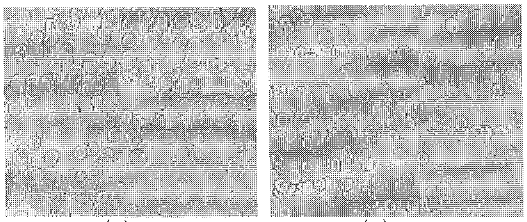
Figure 2 shows the flow resistance of an adulterated blood at 37°C measured with the PSCV before and after applying vibration (f = 70 *Hz*, t = 3 *min*). The viscosity data measured after applying vibration show

* Graduate, Kyungpook National University

** Kyungpook National University, School of Mechanical Eng

higher values than those before applying vibration in lower shear rates. Recalling that RBC aggregation was almost disappeared after vibration as shown in Fig. 1. The mechanism of viscosity change before and after applying vibration can be interpreted by introducing particle migration. It is commonly known that the bigger cells are, the more axial migration occurs. Thus, in tube flow, red blood cell aggregates tend to migrate toward the center of the tube. The plasma-rich zone next to the tube wall, although very thin, causes a decrease of blood viscosity.

Fig. 3 shows the effect of vibration on the flow resistance for wide rages of flow rate for disaggregated blood. Prior to measuring flow resistance, test blood samples were applied vibration ($f = 70\ Hz$, $t = 3\ min$) so that the RBCs in the sample blood were disaggregated. As shown in Fig. 3, as the vibration frequency increases, the flow resistance of the test blood gradually decreases linearly. The flow resistance was significantly reduced at a low shear rate range. At this point, it may be useful to recall that flow resistance reduction indicates flow rate enhancement. In other words, as vibration frequency increases, flow rate increases at a fixed driving pressure. The flow resistance reduction is caused solely by transversal vibration applied to the perpendicular direction to the flowing blood. This result did not occur for Newtonian fluids, but only for shear-thinning suspensions. Thus, one of the reasons for reducing flow resistance may be the increased shear associated with the transversal vibration as previous study suggested [7]. Furthermore,



(a) (b)

Fig. 1 Microscopic examination of RBCs of blood (X400). (a) before vibration (b)after vibration

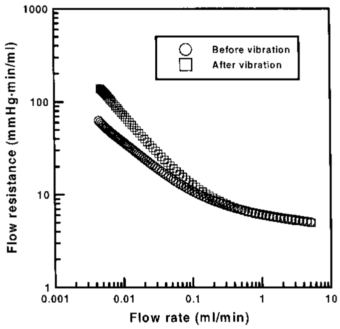


Fig.2 Comparison of flow resistance measured before and after vibration

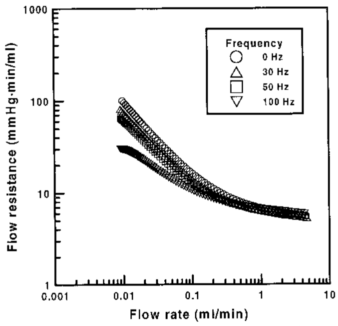


Fig.3 Flow resistance vs. flow rate for various vibration frequencies

this phenomenon of flow resistance reduction can be interpreted by introducing a concept of particle-free layer near wall. In other words, particles having higher inertia than liquid which were forced to move into central layer by vibrated wall could not follow the speed of the vibrated wall moving outward. In turn, particles are concentrated in the central region, which resulted in the particle-free layer near the wall.

4. Conclusion

The present study investigated the effect of transversal vibration on the flow resistance of an adulterated blood. Vibration frequency was found to be a main parameter causing flow resistance reduction in the blood flow. Flow resistance reduction due to vibration was greater at the lower flow rate than at the higher rate. The present study conclusively confirms that these phenomena should be interpreted by both the shear-induced and forced cell migrations associated with traversal vibration.

Acknowledgement

This research was supported by KRF research fund (KRF-2002-002-D00032).

Reference

(1) J.J. Bishop, A.S. Popel, M. Intaglietta, and P.C. Johnson, 2001 "Effects of erythrocyte aggregation and venous network geometry on red blood cell axial migration," Am. J. Physiol. Heart Circ. Physiol., 282:H939-H950

(2) N. S. Deshpande and M. Barig, Vibrational flow of non-Newtonian fluids, Chem. Eng. Sci. 56: 3845-3853, 2001.

(3) S. Shin and J.H. Lee, 2002, "Effect of vibration on the suspension viscosity", Int. Comm. Heat Mass Transfer, (in press).

(4) S. Shin and Y. H. Ku, 2002, "Blood Viscosity Measurement Using a Pressure-Scanning Capillary Viscometer," *KSME Int. J.*, 16 (in press)