Definition of an Experimental Blood Like Fluid for Laser Measurements in Cardiovascular Studies

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Abstract:
Nowadays it is necessary to perform experimental measurements to compare with numerical calculations. In this study we focus on different aqueous solutions which are tested to obtain in the same time a rheological blood like fluid and particular optical properties for laser measurements (particle image velocimetry (PIV) or laser Doppler velocimetry (LDV)). Using viscometric tests we show that the non Newtonian behavior of blood is reached by adding xanthan gum in aqueous glycerol and aqueous potassium thiocyanate solutions. Optical properties are directly achieved by modifying glycerol or thiocyanate potassium concentrations. Indeed we proove using refractometric measurements that the addition of xanthan gum does not affect the value of the refractive indexes. Finally, we can prepare an optical blood like fluid adapted to cardiovascular studies by adjusting the proportion of the different components.

Zusammenfassung:
Heutzutage ist es notwendig, experimentelle Messungen durchzuführen und sie mit numerischen Berechnungen zu vergleichen. In dieser Arbeit konzentrieren wir uns auf verschiedene wässrige Lösungen, die getestet werden, um eine gleichzeitig von den rheologischen Eigenschaften blutähnliche Flüssigkeit und insbesondere optische Eigenschaften für Lasermessungen zu erhalten (sog. „Particle Image Velocimetry (PIV)" oder „Laser-Doppler-Velocimetry (LDV)"). Mit Hilfe viskometrischer Messungen zeigen wir, dass das nicht-Newtonsche Verhalten von Blut durch die Zugabe von Xanthan-Gummi in wässrigem Glyzerin und wässrigen Kaliumthiozyanat-Lösungen erzielt wird. Die optischen Eigenschaften werden direkt durch die Modifikation von Glyzerin oder Kaliumthiozyanatlösungen eingestellt. In der Tat zeigen wir mit Hilfe refraktometrischer Messungen, dass die Zugabe von Xanthan-Gummi den Brechungsindex nicht verändert. Schließlich können wir eine Flüssigkeit für kardiovaskuläre Studien durch eine Anpassung der Anteile der einzelnen Komponenten herstellen, die bzgl. der optischen Eigenschaften dem Blut ähnelt.

Résumé:
L'étude des écoulements cardiovasculaires demande un degré important de réalisme anatomique, que ce soit pour l'étude de l'arbre vasculaire (coronaire simple, bifurcations, anévrisme ou sténose) ou pour la compréhension des phénomènes de transport dans les prothèses médicales (stent, valves cardiaques, filtres veineux). La complexité géométrique de ces systèmes passe le plus souvent par une modélisation numérique. Il est pourtant une nécessité de pouvoir comparer les mesures expérimentales aux simulations numériques dans l'optique d'une validation des résultats. Dans cette étude nous nous intéressons à différentes solutions aqueuses testées dans le but d'obtenir un fluide possédant à la fois les caractéristiques rhéologiques du sang et des propriétés optiques adaptées à des mesures laser (vélocimétrie par image de particules (PIV) ou vélocimétrie par effet Doppler laser (LDV)). A partir des essais viscosimétriques nous montrons que le caractère non-Newtonien du sang est obtenu en ajoutant de la gomme de xanthane dans des solutions aqueuses de glycérol et de thiocyanate de potassium. Les propriétés optiques sont, quant à elle, directement obtenue en jouant sur les concentrations de glycérol et de thiocyanate de potassium. En effet, nous montrons à partir des résultats de réfractométrie que l'ajout de gomme de xanthane ne modifie pas la valeur des indices de réfraction. Dans le cadre des études cardiovasculaires, nous pouvons finalement élaborer un fluide optique ayant les propriétés du sang en ajustant les proportions des différents composants.

Key words: blood viscosity, hemorheology, refractive index, PIV, xanthan gum, Shear thinning, Biomedical engineering

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obtain a refractive index strictly identical to that of the PMMA but an additional study needs to be realized in order to define the viscosimetric curves according to the temperature. In practice a precise regulation of the temperature (with ± 0.2°C according to Liu et al. [19]) for large volumes is ambitious because the use of a mechanical pump in the test ring conduces to temperature elevations by frictional drags and then requires to limit the acquisition periods and to envisage times of heating down.

In all events, some practical limitations exist with these experimental blood analog fluids in particular for the test ring definition and applications using pulsatile conditions. The glycerol and the xanthan gum are non-toxic current products contrary to the potassium thiocyanate which can cause adverse effects on the respiratory and the nervous systems. The test loop must be completely closed for safety use but a mixture containing glycerol requires similar conditions of use in accordance with its water absorbent behaviour. Potassium thiocyanate also reacts with ferric ion and a deep coloration could appear, the whole of the screws and bolts of the test ring must consequently be made of aluminium. The system pump of the test ring needs to be carefully selected. The large deformations induced by a gear pump can deteriorate or destroy the molecular network of the xanthan gum and therefore conduce to lower dynamic viscosity values [20].

The role of the deformations undergone before by the blood on its behavior is ignored in this study. The blood is a thixotropic fluid and shows both time and shear rate dependence. Application of a constant shear rate over time (t=2.5 s) alternate with short resting time (t = 1.5 s) for blood sample presents an overshoot at the first shearing due to an aggregation of the RBC in resting state but once this aggregation is destroyed the following shear rate overshoots decrease [8, 21]. The RBC can not reaggregate because Sharp et al. [1] precise that the characteristic red cell aggregation time is about 10 s. For a pulsatile flow, the cardiac period is ten times greater than the aggregation time. The RBCs have not enough time to fully reaggregate apart from the stagnation or the slow recirculating regions. The use of the experimental fluids defined in this study seems to be valid only in local areas of the flow, in particular near the walls where pathogenic flow disturbances can exist.

Blood suspension also exhibits viscoelastic behavior and has some ability to store and recover shear energy. The elastic RBCs are the primary structural element responsible for the blood viscoelasticity. RBC aggregation at low shear rate and RBC deformability at high shear rate are key factors in the viscoelasticity of blood [22]. The model used in this study thus reflects only imperfectly the physiological rheological behavior of blood. The glycerol and potassium thiocyanate solutions were not dynamically tested but the viscoelasticity of these solutions can only be assigned to the xanthan gum. A low concentration rate of xanthan gum (< 390 ppm) in aqueous glycerol generates low elastic characteristics [23]. According to Gijsen et al. [11], the relation between the elasticity component and shear rate for a potassium thiocyanate solution added with 250 ppm of xanthan gum presents some difference regarding a blood sample but the range of value is similar. These authors compare laser Doppler anemometry and CFD results for steady flows in 3D arterial bifurcation. The viscoelasticity of the experimental fluid were not included in the numerical model but the comparisons between the numerical and experimental velocity profiles reveal good agreements. The authors conclude that the viscoelasticity of the potassium thiocyanate solution has no influence on velocity for a carotid bifurcation flow. Dutta and Tarbell [24] studied the influence of viscoelasticity of blood for unsteady flow in large artery and they concluded that a purely shear thinning model is realistic enough. Sharp et al. [1] also demonstrated that viscous and viscoelastic flow differences (velocity profiles and wall shear stress) were small (2 - 3%) for unsteady circulation in femoral, aorta and coronary arteries. Consequently, an experimental elastic model of the blood suspension is obvious for vessel flow investigations but no data are available for ventricular flows.

5 CONCLUSION

Viscosimetrics and refractometrics measurements were realized for aqueous solutions of glycerol and potassium thiocyanate added with small xanthan gum quantities. Addition of 300 ppm of xanthan gum allows modifying the rheological properties of the solutions and is enough to obtain a macroscopic shear thinning behavior which can mimic the blood suspension at standard hematocrit rate. The light deviations for

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quantitative experiments based on laser measurements can be reduced by matching the refractive indexes between the experimental blood analog fluid and the cardiovascular model. The refractive index only depends on the concentration rate of the suspending fluid (no xanthan gum concentration dependence) and the viscous properties are more related to the xanthan gum amount than the suspending fluid constituents. Experimental fluids with refractive index adaptation and adequate shear thinning behavior can consequently be deduced from these results for cardiovascular model made of silicon or PMMA.

More investigations need to be realized in order to characterize the dynamic behavior of these experimental blood like fluids. The actual results are fully valid for steady state investigations although of the cardiovascular flows are pulsatile. But steady analyses are still frequent in biomedical literature and steady results are often comparable to an instantaneous snap of the pulsated flow in particular for blood flow circulation in vessels at moderate Womersley number.

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