A Comparison of the Microcirculation in Rat Spinotrapezius Muscle and Muscle Fascia

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Résumé

Des propriétés de la microcirculation dans le muscle de spinotrapezius de rat et la fasce de muscle sont obtenues à partir des simulations numériques. On observe des différences importantes dans les modèles d' embranchement aussi bien que des distributions de longueur, de diamètre, et de taux cisaillement.

Abstract

The microcirculation in rat spinotrapezius muscle and muscle fascia is investigated using a computational approach. The simulations are based on a realistic microvascular network structure obtained from microscope observations and consider both blood rheology and vessel elasticity. An improved model for the apparent viscosity of blood is developed to take the shear thinning nature of blood into account. Capillary bundles of muscle tissue are composed of vessels that mainly follow the direction of muscle fibers. In muscle fascia, however, the capillary vessels form a mesh like network without a preferred direction. This structural difference leads to significant differences in the microcirculation. In the muscle fascia, vessel length, velocity, and shear rate follow a lognormal distribution. In muscle, however, the data does not support a lognormal distribution. For both networks, the hematocrit follows an approximately normal distribution.

Mots clefs: microcirculation, rat spinotrapezius muscle, fascia, apparent viscosity, simulation

1 Introduction

In this study, a comprehensive model for the apparent viscosity of blood is developed and applied to simulations of capillary bundles in rat spinotrapezius muscle and muscle fascia. A good understanding of the microcirculation may help to improve early detection and treatment of diseases that first manifest themselves in the microcirculation (e.g. diabetes or hypertension [7]). In order to simulate the microcirculation, knowledge about the microcirculatory network topology, properties of vessel elasticity, and rheology of blood is required.

The microcirculation in rat spinotrapezius muscle has been studied extensively in the past. Feeder vessels supply blood to a mesh or arcading arterial vessels [3]. Transverse arterials then supply the blood to bundles of capillary vessels [8]. Finally, collecting venules transport the blood to a mesh of arcading venule vessels [2]. The arcading arterial and venule vessels are almost superposed, while transverse arterials and collecting venules formed a staggered arrangement. Most capillary vessels in the muscle are unidirectional and follow the muscle fibers.

The microcirculation in rat spinotrapezius muscle fascia has received somewhat less attention [10]. The fascia, a connective tissue, has a similar structure of arcade arterials, transverse arterials, capillaries, collecting venules, and arcade venules. However, the capillary vessels do not show a preferred direction in the muscle fascia, but form a mesh-like structure.

This study compares features of the microcirculation of muscle and muscle fascia in order to investigate the impact of the different structure of the capillary networks. In the following, the simulation approach is introduced, results are presented and briefly discussed, and a summary of the work is provided.

2 Simulation Approach

In order to simulate the microcirculation in rat spinotrapezius muscle and muscle fascia, information about the vessel network, vessel elasticity, and blood rheology is required [4]. The simulation approach followed

here assumes a Hagen-Poisseuille balance in each microvessel. A sparse matrix solver is used to compute the pressure at each node in the network from vessel length, diameter, apparent viscosity, and specified pressures at the network inlet and outlet. In order to consider the non-linear effects introduced by vessel elasticity and blood rheology an iterative approach is taken. A converged solution is typically found after less than ten iterations.

2.1 Capillary Bundles of Rat Spinotrapezius Muscle and Muscle Fascia

Microscope images of tissue samples of rat spinotrapezius muscle and muscle fascia are used to provide information about vessel length, diameter, and connectivity in a capillary bundle. The capillary bundle of muscle consists of 389 vessels interconnected at 260 nodes. The capillary bundle of muscle fascia consists of 286 vessels interconnected at 190 nodes. Examples for capillary networks of rat spinotrapezius muscle can be found in [8] and examples for capillary networks of fascia can be found in [10].

2.2 Blood Vessel Elasticity

Both passive and active vessel responses to transmural pressure are considered. Blood vessels are distensible and their diameters increase with increasing transmural pressure [9]. In addition, arterioles contain vascular smooth muscle and actively contract in response to higher pressure [1].

2.3 Blood Rheology

This section describes the development of an improved comprehensive model for the apparent viscosity of blood. Blood is a complex non-Newtonian fluid and its apparent viscosity is determined by vessel diameter, hematocrit (red blood cell concentration), and shear. The vessel diameter and hematocrit dependence of the apparent viscosity of blood is captured by a model developed by Pries, Secomb, Gaehtgens, and Gross [6] (in the following referred to as the Pries model). This model determines the apparent viscosity of blood μ_{app} from the plasma viscosity μ_{plasma} and a factor η_{Pries} to describe diameter and hematocrit dependence:

$$\mu_{app} = \mu_{plasma}\, \eta_{Pries} \tag{1}$$

where,

$$\eta_{Pries}=1+(e^{Hd\,\alpha} - 1)/(e^{0.45\,\alpha} - 1)(110e^{-1.424\,D}+3-3.45e^{-0.035\,D}) \tag{2}$$

and,

$$\alpha = 4/(1 + e^{-0.593(D - 6.74)}) \tag{3}$$

Here H_d is the discharge hematocrit. The tube hematocrit H_t is related to the discharge hematocrit through the following relationship:

$$H_t = H_d(H_d + (1 - H_d)\,(1 + 1.7e^{-0.415\,D} - 0.6e^{-0.011D})) \tag{4}$$

The model uses the following expression for velocity of blood:

$$v = (0.4*D-1.9)*1000 \tag{5}$$

The Pries model does not consider the shear thinning of blood. Very little past experimental work has been performed to quantitatively investigate the shear thinning of blood in blood vessels. The most comprehensive data on the shear rate dependence of apparent viscosity of blood has been provided by Lipowsky, Usami, and Chien from in vivo measurements in the mesentery of the cat [5]. The authors provide the dependence of apparent viscosity of blood as a function of shear rate at a variety of hematocrit values. The authors define the shear rate as follows:

$$\gamma = (8*v)/D \tag{6}$$

In order to develop an improved comprehensive model for the apparent viscosity of blood, the following approach was taken (in the following referred to as the shear model):

$$\mu_{app} = \mu_{plasma}\, \eta_{Pries}\, \eta_{shear} \tag{7}$$

Here η_{shear} is a shear factor describing the shear thinning effect of blood. A simple power-law is used to express the shear factor as follows:

$$\eta_{shear} = A_0 + A_1\, \gamma^{A2} \tag{8}$$

The coefficients A_0, A_1, and A_2 and their dependence on the hematocrit are then determined from the experimental data:

$$A_0 = 1 - 0.29688\ H_t^2 \quad (9)$$

$$A_1 = 19.7182\ H_t \quad (10)$$

$$A_2 = -0.68131 \quad (11)$$

The shear model is an extension of the Pries model to include the shear thinning of blood. The results of the model have been validated by comparison to the shear dependence of the apparent viscosity of blood observed in viscometer measurements.

In the simulations, the hematocrit is found from consideration of the phase-separation effect found at each branching node. The fraction of red blood cell flow is higher for larger daughter vessels, leading to a decreased hematocrit in the smaller daughter vessel [6].

3 Results

In this section, results from simulations of the microcirculation in rat spinotrapezius muscle and muscle fascia are presented and discussed. Figure 1 shows the pressure-flow relationship for (a) muscle fascia and (b) muscle. The arterial pressure is varied from 40 to 140mmHg and the venual pressure remains constant at 20mmHg. Four different cases are compared. The first case (circles) considers no vessel elasticity or blood rheology. The vessel diameters and blood (plasma) viscosity remain constant. Due to the Hagen-Poisseuille equation and the linearity of the problem, a linear relationship between pressure and flowrate is obtained. The second case (squares) considers vessel elasticity, but the blood (plasma) viscosity remains constant. Due to vessel distensibility, a larger flowrate is found for small arterial pressure compared to the first case. The active contraction of arterioles causes a decrease of the flowrate for larger values of arterial pressure. The third case (diamonds) considers vessel elasticity and uses the Pries model to determine the apparent viscosity of blood. The inclusion of the Fahraeus-Lindqvist effect increases the viscosity and leads to a decrease of the flowrate compared to the second case. The fourth case (triangles) considers vessel elasticity and uses the newly-developed shear model to determine the apparent viscosity of blood. While the shear factor decreases apparent viscosity in vessels with high shear, there are many vessels with relatively low shear rates, resulting in an increase of the apparent viscosity. The overall effect on the pressure-flow relationship is small compared to the third case. The flowrates in the muscle simulations are smaller than the flowrates in the muscle fascia simulations for the same arterial pressure. This is due to the muscle's larger size and thereby increased resistance to flow.

In the following, results from two simulations are presented and discussed. Results for the microcirculation in muscle fascia and muscle are compared for simulations with vessel elasticity, the shear model, and 100mmHg arterial pressure. Figure 2 shows the distributions of vessel length in (a) muscle fascia and (b) muscle together with a lognormal fit. While the vessel length distribution of muscle fascia follows the lognormal distribution, the distribution of muscle does not. The muscle has many vessels with a length of around 100microns. These vessels are mainly capillary vessels that are aligned with muscle fibers. Figure 3 shows the distribution of vessel diameters. The muscle fascia shows a range of diameter values due to an extensive collecting venule vessel system characterized by loops. The muscle, however, has only simple tree-like transverse arterial and collecting venule systems. The vast majority of vessels are capillaries and the diameter distribution in narrow. This observation is reflected in the pressure distributions shown in figure 4.

The hematocrit distribution is shown in figure 5. For both the muscle fascia and muscle the hematocrit histogram follows an approximately normal distribution. The hematocrit supplied to the networks is 0.35 and a large number of vessels reflect this value. The mean of the distributions is somewhat lower for the muscle due to the presence of many capillary vessels with small diameters. The velocity distribution observed in the microvessels is shown in figure 6. For the muscle fascia, the velocity histogram follows a lognormal distribution. For the muscle, the distribution deviates from lognormal, mainly due to the contribution of a much larger number of capillaries aligned with the muscle fibers. The alignment causes a substantial pressure difference over the vessels, resulting in larger velocities. The distribution of shear rates shown in figure 7 reflects this observation.

Figure 8 shows the distribution of apparent viscosity in (a) muscle fascia and (b) muscle. The peak of the distribution is somewhat lower for muscle (1.7cP) than for muscle fascia (1.8cP) due to increased shear rates.

Muscle fascia shows a wider range of apparent viscosity values. Large venule vessels with large diameter, low flowrates, and low shear rates result in large apparent viscosity values.

All vessels in the capillary bundles are given order numbers to distinguish where they are located between the capillaries and the arcading networks. These numbers are assigned based on vessel size and connectivity patterns in the network. These patterns are formed by the joining of two like vessels. The order numbers are larger for parent vessels and subsequently less for each daughter vessel. This allows for the calculation of branching ratios or average number of daughter vessels per single parent vessel. It was found that in the arteriole side of the muscle fascia the branching ratios exhibited a regular behavior with an average branching ratio of 1.8. The venule side of the network demonstrated more irregularity in the ratios which was caused by the looping patterns of large venule vessels. This made the ratios deviate from approximately 1 to 5. The branching patterns in the muscle tissue were more evenly distributed on both the arteriole and venule sides with an average branching ratio of 3.

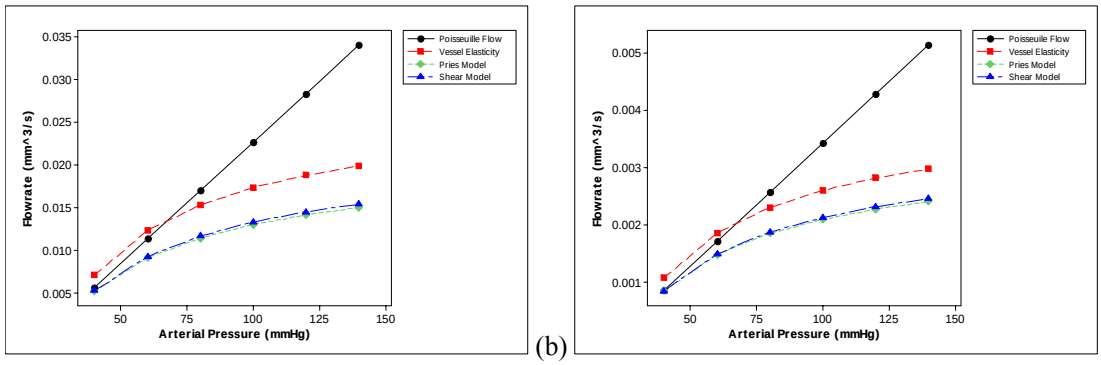

FIG. 1 – Pressure-flow relationship in (a) muscle fascia and (b) muscle.

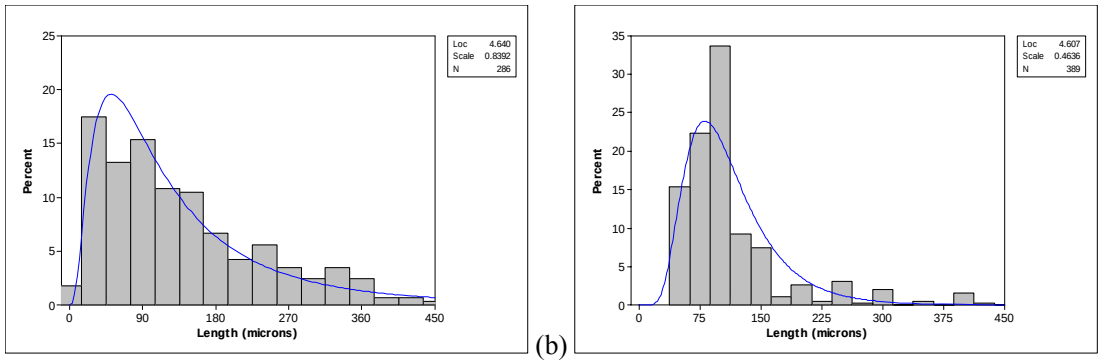

FIG. 2 – Vessel length distribution in (a) muscle fascia and (b) muscle.

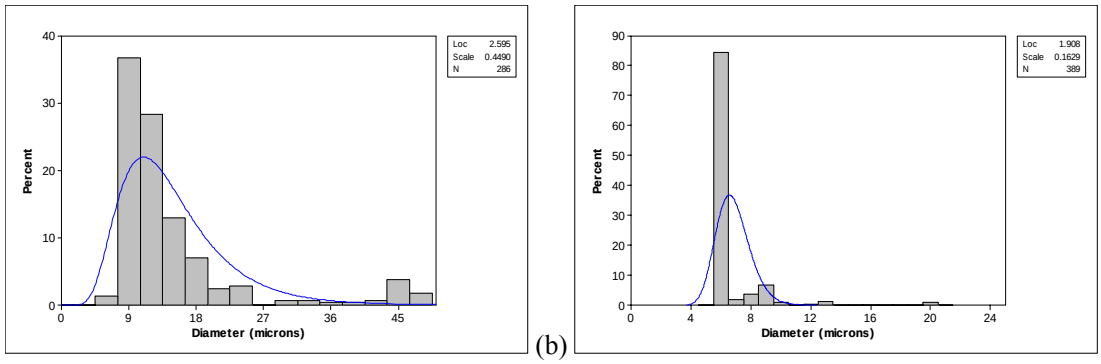

FIG. 3 – Vessel diameter distribution in (a) muscle fascia and (b) muscle.

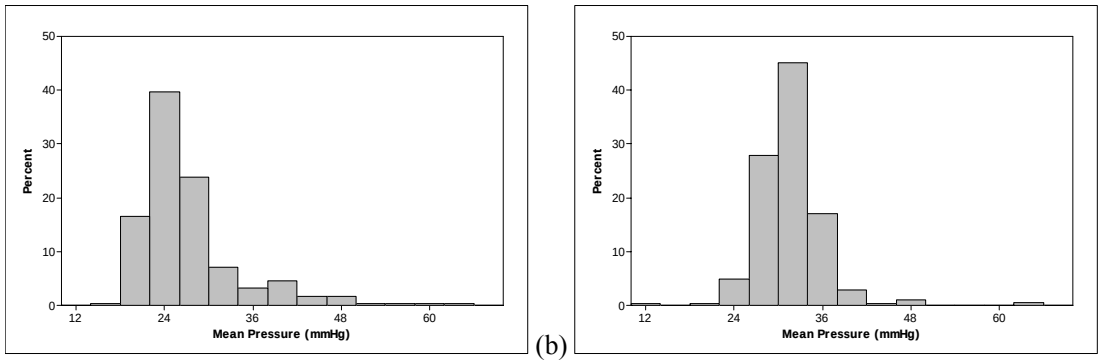

FIG. 4 – Mean vessel pressure distribution in (a) muscle fascia and (b) muscle.

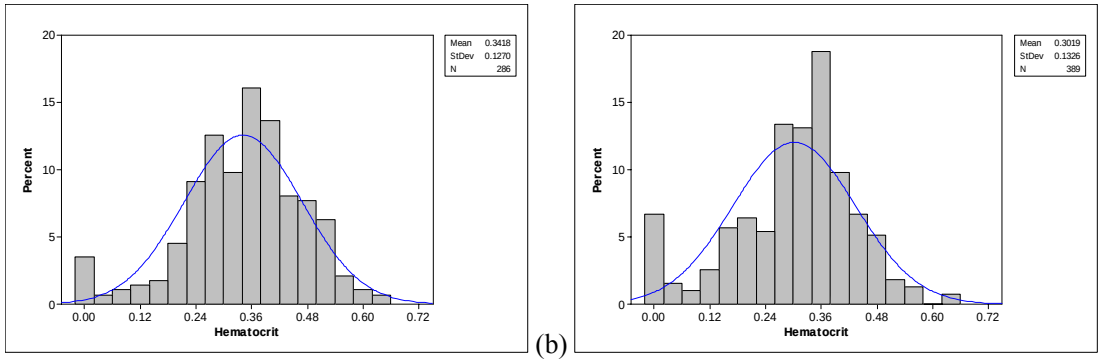

FIG. 5 – Hematocrit distribution in (a) muscle fascia and (b) muscle.

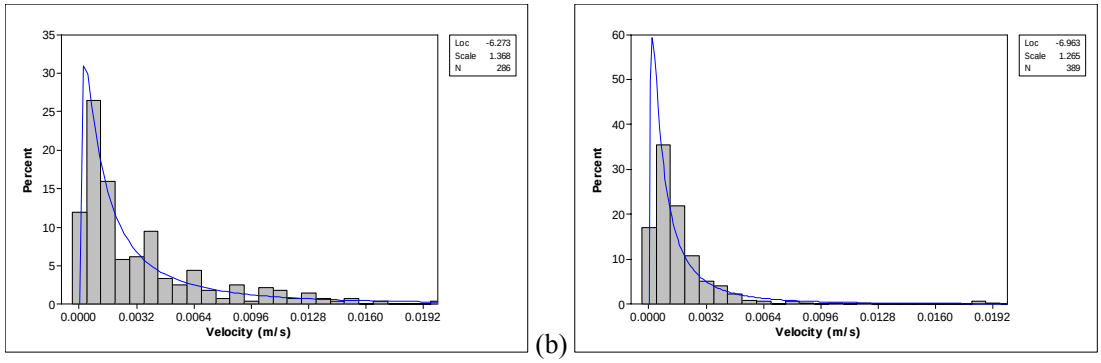

FIG. 6– Velocity distribution in (a) muscle fascia and (b) muscle.

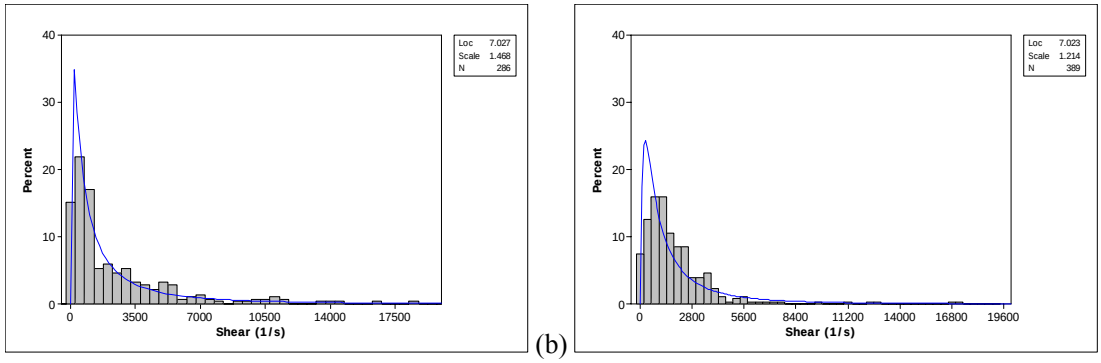

FIG. 7– Shear rate distribution in (a) muscle fascia and (b) muscle.

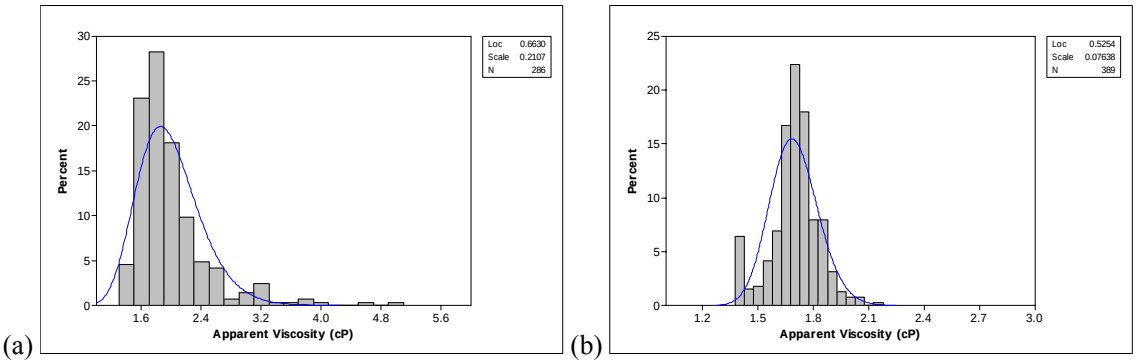

FIG. 8 – Apparent viscosity distribution in (a) muscle fascia and (b) muscle.

4 Summary

Properties of the microcirculation in rat spinotrapezius muscle and muscle fascia have been obtained from simulations and are compared. The simulations use realistic vessel networks obtained from microscope observations, vessel elasticity, and blood rheology. An improved comprehensive model for the apparent viscosity of blood was developed in order to include the shear-thinning properties of blood. The structural differences between muscle and muscle fascia have an important impact on the distributions of vessel length, velocity, and shear rate. Lognormal distributions are obtained for the muscle fascia, but deviations from lognormal are observed for the muscle. The branching patterns also show significant differences between the two network types.

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