THE INFLUENCE OF FLOW REDISTRIBUTION ON WORKING RAT MUSCLE OXYGENATION

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Abstract: We applied a theoretical model of muscle tissue O$_2$ transport to investigate the effects of flow redistribution on rat soleus muscle oxygenation. The situation chosen was the anaerobic threshold where redistribution of flow is expected to have the largest impact. In the basic situation all capillaries received an equal proportion of the total flow through the tissue, resulting in 4.7% anoxic tissue and a mean tissue PO$_2$ = 3.62 kPa. Both a redistribution of flow where 1) capillaries in blocks of tissue receiving 50% of the basic flow alternated with tissue blocks with capillaries receiving 150% of the basic flow (6.8% anoxic tissue; mean tissue PO$_2$ = 3.32 kPa) and 2) matching flow to O$_2$ consumption (3.3% anoxic tissue; mean tissue PO$_2$ = 3.60 kPa) had little effect. When overall flow was decreased by 20%, the anoxic tissue increased to 7.6% and the mean tissue PO$_2$ decreased to 3.22 kPa. The conclusion from these model calculations is, that flow redistribution has little impact on skeletal muscle oxygenation, which is in line with earlier findings for rat heart.

1. INTRODUCTION

Tissue oxygenation is the result of a balance between O$_2$ supply, by the capillary blood, and O$_2$ consumption, in the tissue cells. In between, there is an important role for O$_2$ diffusion. For a muscle with a varying O$_2$ consumption depending on the work it performs, the question arises how blood flow and O$_2$ consumption are related and, in particular, if flow can be matched to consumption to maintain adequate oxygenation. To maintain an adequate oxygenation, the muscle has two mechanisms available; capillary recruitment and increasing blood flow. During maximal recruitment all, that is 100%, of the capillaries are open and available for O$_2$ exchange with the surrounding tissue. It is unlikely, however, that each individual capillary receives an equal proportion of the total supply.
blood flow through the muscle, since capillaries are distributed inhomogeneously in the tissue. Indeed, the flow distribution over capillaries may vary with varying (working) conditions. Yet, in an earlier investigation on rat heart\textsuperscript{1}, we found that flow redistribution has little influence on tissue oxygenation. It should be noted that this does not automatically apply to skeletal muscle, as skeletal muscle differs from heart in a number of ways, in particular in the much wider range of working states including lactate production at maximum work.

Heterogeneity of capillary spacing is the most important factor in muscle tissue oxygenation\textsuperscript{2}. Consequently, reliable data of capillary localisation must be available. Average tissue values of capillary density and heterogeneity of capillary spacing allow to select a representative tissue portion where calculations can be based on. Here we use data of rat soleus muscles that were obtained in a previous study\textsuperscript{3}.

2. MATERIALS AND METHODS

The muscle tissue considered here is rat soleus skeletal muscle. Since muscle working state can be very different, from rest to maximum work, we had to select a state where the relation between flow and consumption will be the most relevant. At rest, only few capillaries will be open. At maximum work, the muscle produces a significant amount of lactate from anaerobic energy production strongly suggesting inadequate \( \text{O}_2 \) supply at least locally. Thus, the anaerobic threshold, at the verge of lactate production, seemed the most relevant state for our investigation. According to textbooks on work physiology, we assumed this threshold to be at \( \frac{2}{3} \) of the maximum oxygen consumption and \( \frac{3}{5} \) of the maximum flow.

2.1. Mathematical model

The mathematical treatment is based on oxygen diffusion from a number of point-source capillaries into a surrounding plane, coordinate \( \vec{r} \)\textsuperscript{4}:

\[
\text{PO}_2 + \text{P}_F \text{S}_\text{Mbo}_2 = \frac{Q}{4\pi \rho} \left[ \Phi(\vec{r}) - \sum_{i=1}^{N} \frac{A_i}{\pi} \ln \left( \frac{\vec{r} - \vec{r}_i}{r_{ci}^2} \right) \right]
\]

where \( \text{PO}_2 \) is oxygen partial pressure, \( \text{P}_F \) is facilitation pressure\textsuperscript{5} of the tissue myoglobin, Mb, with saturation \( \text{S}_\text{Mbo}_2 \). \( Q \) and \( \rho \) are the tissue's oxygen consumption and oxygen permeability respectively, \( N \) is the number of capillaries, and \( A_i, \vec{r}_i \) and \( r_{ci} \) are supply area, location and radius of the \( i \)-th capillary respectively. The term \( \Phi(\vec{r}) \) accounts for the distribution of oxygen consumption and can be calculated, according to the cited paper; here, the solution for a homogeneous rectangle was taken \( r_4 \). The \( N \) supply areas can be calculated from the \( N \) capillary rim pressures \( P_{ri} \) which in turn were calculated from the capillary \( \text{O}_2 \) pressures \( P_{ci} \) by the method of the Extraction Pressure EP\textsuperscript{6,7}:

\[
P_{ri} = P_{ci} - \frac{A_i}{A} \text{EP}
\]