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A computational model of whole kidney oxygen regulation incorporating arterial to venous oxygen shunting

Background: Our understanding of renal tissue oxygenation is complicated by the ability of oxygen to diffuse directly from arteries to veins in the cortex; referred to here as arterial-to-venous (AV) oxygen shunting. Furthermore, changes in the delivery of oxygen in renal arterial blood, and in the consumption of oxygen by kidney tissue, affect the PO2 gradients driving AV oxygen shunting. To understand how AV oxygen shunting influences kidney oxygenation, we constructed a computational model of oxygen transport in the renal cortex. Methods: The model is based on a quantitative analysis of the three dimensional morphology of the rat renal circulation (1). It consists of a multiscale hierarchy of eleven counter-current vascular modules, representing the various branch levels of the cortical vasculature. At each level equations describing the reactive-advection-diffusion of oxygen are solved. Factors critical in renal oxygen transport incorporated into the model include: the parallel geometry of arteries and veins and their size, variation in blood velocity in each vessel, oxygen consumption and transport, and non-linear binding of oxygen to hemoglobin. Because quantitative information regarding the barriers to AV oxygen diffusion in the kidney is not available, the model was calibrated against published measurements of outer cortical microvascular PO2 and renal venous PO2 (2). As the outer cortex is the most well oxygenated part of the kidney, this approach provides a conservative estimate of the magnitude of AV oxygen shunting. Results: The model predicts that AV oxygen shunting is quantitatively similar to total renal oxygen consumption under basal physiological conditions. It is predicted that oxygen shunting increases as renal oxygen consumption increases or arterial PO2 increases, or when renal blood flow or hematocrit are reduced. Assuming the barriers for AV oxygen diffusion are quantitatively similar throughout the cortical circulation, the model predicts that AV oxygen shunting occurs mostly in distal vascular elements. Regardless, in severe ischemia or anemia, or when kidney oxygen consumption increases, AV oxygen shunting in proximal vascular elements may reduce the oxygen content of blood destined for the medullary circulation. Conclusions: Cortical AV oxygen shunting limits oxygen delivery to cortical tissue and stabilizes tissue PO2 when arterial PO2 changes, but renders both the cortex and medulla susceptible to hypoxia when oxygen delivery falls or consumption increases. The model also predicts how much kidney oxygen consumption must change, in the face of altered renal blood flow, to maintain cortical tissue PO2 at a stable level.

References

[1] Nordsletten DA et al. Structural morphology of renal vasculature. Am J Physiol Heart Circ Physiol 291: H296-309, 2006.

[2] Welch WJ et al. Nephron pO2 and renal oxygen usage in the hypertensive rat kidney. Kidney Int 59: 230-237, 2001.