



COMMENTARY

PIP₂ as the “coin of the realm” for neurovascular coupling

Scott Earley^{a,b,1} and David Kleinfeld^{c,d}

Cerebral small vessel diseases (SVDs) are a group of related pathologies that collectively account for over 25% of ischemic strokes and more than 40% of all dementias (1, 2). Although genetic forms have been identified, sporadic SVDs are the most common and become prevalent with increasing age. The causes of sporadic SVDs remain poorly understood, and no treatment options are currently available. SVDs can occur in any organ in the body. However, the brain's microvasculature is uniquely susceptible to dysfunction. In tissues such as skeletal muscle, metabolic demand is met in part by an organ-wide dilation of the vasculature that lowers the resistance to flow so that increased demand is satisfied by a surge of blood flow throughout the tissue. In contrast, the skull imposes an essentially fixed volume to prevent global increases in the amount of blood in the brain. Thus, nature has evolved mechanisms unique to the cerebral circulation to rapidly redirect blood flow to brain regions with higher metabolic activity at the cost of diminished flow elsewhere (3, 4). This process is termed functional hyperemia. It involves communication between active brain regions and the cerebral vasculature by loosely defined processes known as “neurovascular coupling” (5–7).

Neurovascular coupling is disrupted in cerebral SVDs (1, 2), and the diminished state of functional hyperemia contributes to vascular cognitive impairment and dementia. In PNAS, Dabertrand et al. (8) demonstrate the molecular basis for the loss of functional hyperemia for a particular SVD and, impressively, show how the dysfunction may be reversed. In particular, impaired functional hyperemia is rescued by exogenously supplying the minor phospholipid, phosphatidylinositol 4,5-bisphosphate (PIP₂), to a mouse model of cerebral autosomal dominant arteriopathy with subcortical infarcts and leukoencephalopathy (CADASIL) (9). This is the predominant genetic SVD and a model for more common sporadic forms of SVD. The findings by Dabertrand et al. (8)

may set the stage for the development of treatments for impaired neurovascular coupling and dementias associated with cerebral SVDs.

The vasculature of the brain is organized as a hierarchy (10). The pial arteries form a highly interconnected network that spans the surface of the cortex. Dynamic changes in the diameter of different branches allow the pia to shuttle blood to areas of acute metabolic need (11). This network sources penetrating arterioles that dive into the parenchyma and, in turn, supply a vast, interconnected network of capillaries that provide energetic substrates to all brain cells. Despite the great numbers of paths for blood cells to take as they journey from a penetrating arteriole to their eventual exit through a penetrating venule and then vein, the capillaries provide the greatest resistance to flow in the brain (12).

An emerging model of functional hyperemia in the brain focuses on the capillaries. While the density of the capillary network varies between different regions of the brain, the typical distance from a location in the neocortical parenchyma to the nearest capillary is quite small, about 13 μm (13). Drawing on this implicit, intimate relation between neurons and capillaries, Longden et al. (14) hypothesized that the brain uses the capillary network as a sensory web to detect elevated neuronal activity and subsequently signal upstream penetrating arterioles and pial arteries to dilate. The mechanism involves K⁺ ions and the inwardly rectifying K⁺ channel Kir2.1 (Fig. 1). Potassium ions are released during every neuronal action potential, and in principle, the local [K⁺] can approach 10 mM in the vicinity of capillaries (14, 15). This concentration is sufficient to activate Kir2.1, whose threshold for opening is raised by the increase in extracellular [K⁺]. This leads to the onset of a regenerative, hyperpolarizing pulse that propagates to adjacent endothelial cells via gap junctions, thereby stimulating further Kir2.1 channel activity to spread the signal. Upon reaching upstream arterioles, this hyperpolarizing signal is conveyed

^aDepartment of Pharmacology, University of Nevada, Reno, School of Medicine, Reno, NV 89557-0318; ^bCenter for Molecular and Cellular Signaling in the Cardiovascular System, University of Nevada, Reno, School of Medicine, Reno, NV 89557-0318; ^cDepartment of Physics, University of California San Diego, La Jolla, CA 92093; and ^dSection of Neurobiology, University of California San Diego, La Jolla, CA 92093

Author contributions: S.E. and D.K. wrote the paper.

The authors declare no competing interest.

Published under the PNAS license.

See companion article, “PIP₂ corrects cerebral blood flow deficits in small vessel disease by rescuing capillary Kir2.1 activity,” [10.1073/pnas.2025998118](https://doi.org/10.1073/pnas.2025998118).

¹To whom correspondence may be addressed. Email: searley@med.unr.edu.

Published May 5, 2021.

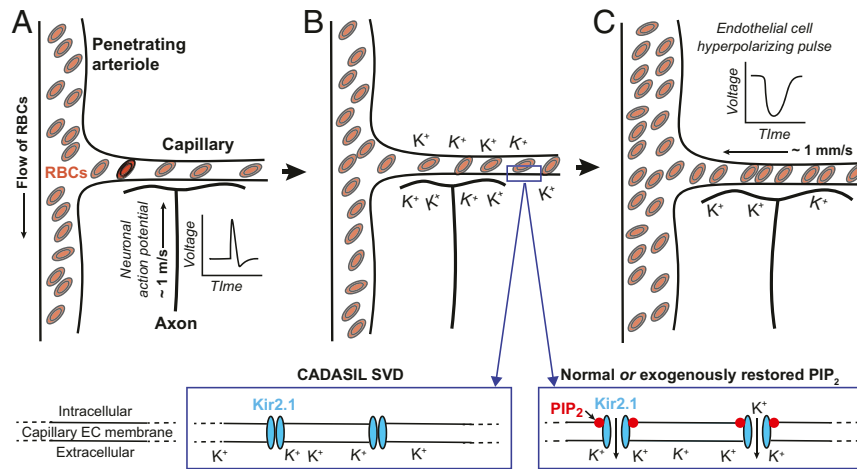


Fig. 1. The initial signaling events in functional hyperemia. (A and B) Neuronal action potentials induce hyperpolarizing pulses in capillary endothelial cells via buildup of extracellular $[K^+]$ to open Kir2.1 channels. Opening of these channels further requires binding of PIP₂. (C) Hyperpolarizing pulses in capillary endothelial cells (ECs), caused by K^+ flux through the opened Kir2.1 channels, are electrically conducted to upstream penetrating arterioles and induce dilation of the penetrating arterioles by relaxation of the associated smooth muscle. This leads to an elevated pressure head on the capillary network and an increase in red blood cell (RBC) flux. (Inset) Loss of PIP₂ in the CADASIL small vessel disease (SVD) model prevents the opening of Kir2.1 channels and blocks functional hyperemia, while normal or restored levels of PIP₂ support opening of Kir2.1 and a normal hemodynamic response.

through gap junctions to overlying smooth muscle cells, causing them to relax. The relaxation of arteriole smooth muscle and subsequent dilation of the penetrating and pial vessels leads to an increase in the pressure head on the capillary network and an increase in blood flow through the region with heightened activity. Finally, activation of the transient receptor potential V4 (TRPV4) cation channel and possibly other mechanisms lead to the recovery to the membrane potential in endothelial cells.

Exploration of the K^+ /Kir2.1-based model makes use of an innovative ex vivo cerebral microvascular preparation that comprises a cannulated, pressurized penetrating arteriole segment with an intact capillary tree (14). Direct stimulation of the tree with a bolus of K^+ leads to a rapid dilation of upstream arterioles in the parenchyma. This response is blocked by infusion with low concentrations of the known Kir2.1 channel blocker BaCl₂ and is absent in endothelial cell-specific Kir2.1-knockout mice. Stimulation of the vibrissae, a classic sensory pathway in neurovascular physiology, induces functional hyperemic responses in the vibrissa primary somatosensory (vS1) cortex. Functional hyperemia is blunted by infusion with BaCl₂ and impaired in endothelial cell-specific Kir2.1-knockout mice. The obligatory role of PIP₂ in the Kir2.1-based mechanism for the control of functional hyperemia was observed in follow-up studies (Fig. 1, Inset). In particular, Harraz et al. (16) showed that prolonged stimulation of G_q G-protein-coupled receptors, which signal through phospholipase C (PLC) in capillary endothelial cells, will cripple the K^+ /Kir2.1-based mechanism for the control of functional hyperemia. Interestingly, the underlying mechanism is the consumption of PIP₂ by the G_q signaling pathway.

Dabertrand et al. (8) demonstrate that the K^+ /Kir2.1-based neurovascular coupling mechanism is absent in CADASIL SVD mice due to twofold diminished activity of capillary endothelial cell Kir2.1 channels. This deficit leads to a significantly blunted vibrissa stimulation-induced functional hyperemic response in the vS1 cortex. Dabertrand et al. (8) go on to rescue the suppressed Kir2.1 currents in three ways. First, they show that the addition of PIP₂ to the intracellular recording solution used with isolated capillary endothelial cells from CADASIL SVD mice restores the Kir2.1 currents. Second, applying a synthetic dipalmitoyl form of PIP₂,

diC16-PIP₂, to the external solution that perfuses their preparation rescues the capillary-to-arteriole dilation in response to stimulation of a capillary tree with K^+ . Last, infusing mice with PIP₂ restores vibrissa stimulation-induced functional hyperemia in vivo in CADASIL SVD mice.

Investigations into the cause of reduced PIP₂ levels initially focused on processes that degrade PIP₂. In particular, conventional wisdom pointed to PLC-mediated hydrolysis of PIP₂ downstream of G_qPCR signaling. However, inhibition of PLC did not affect blunted Kir2.1 current activity, which ruled out the degradation pathway. Subsequent investigation addressed PIP₂ synthesis by lipid kinases, which are low ATP-affinity enzymes that require high ATP levels (17). Notably, ATP levels were depressed in brain capillaries from CADASIL SVD mice. This suggests that a decrease in ATP synthesis in brain capillary endothelial cells is the ultimate cause of diminished PIP₂ levels, which drives the cascade that impairs Kir2.1 channel activity and leads to the failure of neurovascular coupling in CADASIL SVD mice.

Collectively, the data of Dabertrand et al. (8) demonstrate that the molecular basis of faulty neurovascular coupling associated with CADASIL SVD is an exclusively capillary Kir2.1 channelopathy that is caused by PIP₂ depletion. These findings provide proof-of-concept for the therapeutic potential of PIP₂ replacement. More generally, they spell out the complete molecular sequence for a cerebral SVD. However, questions remain. Is the PIP₂ depletion-dependent impairment in microvascular function unique to the CADASIL SVD model, or does it contribute to other cerebral SVDs? A recent report demonstrating that PIP₂ treatment restores impaired functional hyperemia in the 5xFAD mouse model of Alzheimer's disease (18) provides intriguing evidence for a generalized PIP₂-centric model of cerebral microvascular dysfunction. As a potential clinical issue, how does exogenously supplied PIP₂ enter into cells? Flippases on the plasma membrane can import extracellular PIP₂, but the process requires ATP, which is compromised in the capillaries of CADASIL SVD mice. Ca²⁺-dependent scramblase activity, independent of ATP, could also transport PIP₂ to the inner leaflet of the plasma membrane. Understanding this transport process may be the key to unlocking the therapeutic potential of PIP₂ supplementation.

The K^+ /Kir2.1-based neurovascular coupling mechanism appears to drive the initial response, on the 1-s timescale, for increased nutrients to a region in the brain (Fig. 1). Other aspects of neurovascular coupling work on longer timescales (19, 20). A recently discovered complementary mechanism is capillary-to-arteriole signaling triggered by Ca^{2+} influx through the transient receptor potential ankyrin 1 (TRPA1) channels in capillary endothelial cells (20). The vasodilatory signal initiated by TRPA1, which is essential for maintaining functional hyperemia during long-duration somatosensory stimuli, propagates through a biphasic mechanism that involves slow intercellular Ca^{2+} waves as well as the Kir2.1-dependent electrical conduction mechanism identified by Longden et al. (14, 20). Thus, PIP_2

depletion likely impairs functional hyperemia in the brain that is orchestrated by different molecular sensors over multiple timescales. PIP_2 depletion may prove to be a universal feature of cerebral SVDs.

Acknowledgments

We thank Beth Friedman and Xiang Ji for comments on a draft of the Commentary. Our neurovascular research programs are supported by grants from the National Heart, Lung, and Blood Institute (R35HL155008, R01HL122770, and R01HL146054 to S.E.), the National Institute of General Medical Sciences (P20GM130459 to S.E.), the National Institute of Mental Health (R01MH111438 to D.K.), and the National Institute of Neurological Disorders and Stroke (RF1NS110044 and R61NS115132 to S.E.; R35NS097265 to D.K.).

- 1 L. Pantoni, Cerebral small vessel disease: From pathogenesis and clinical characteristics to therapeutic challenges. *Lancet Neurol.* **9**, 689–701 (2010).
- 2 F. Bosetti et al., “Small Blood Vessels: Big Health Problems” Workshop Participants, “Small blood vessels: Big health problems?”: Scientific recommendations of the National Institutes of Health Workshop. *J. Am. Heart Assoc.* **5**, e004389 (2016).
- 3 T. A. Woolsey et al., Neuronal units linked to microvascular modules in cerebral cortex: Response elements for imaging the brain. *Cereb. Cortex* **6**, 647–660 (1996).
- 4 D. Attwell, S. B. Laughlin, An energy budget for signaling in the grey matter of the brain. *J. Cereb. Blood Flow Metab.* **21**, 1133–1145 (2001).
- 5 H. Girouard, C. Iadecola, Neurovascular coupling in the normal brain and in hypertension, stroke, and Alzheimer disease. *J Appl Physiol (1985)* **100**, 328–335 (2006).
- 6 D. Attwell et al., Glial and neuronal control of brain blood flow. *Nature* **468**, 232–243 (2010).
- 7 D. Kleinfeld et al., A guide to delineate the logic of neurovascular signaling in the brain. *Front. Neuroenergetics* **3**, 1–9 (2011).
- 8 F. Dabertrand et al., PIP_2 corrects cerebral blood flow deficits in small vessel disease by rescuing capillary Kir2.1 activity. *Proc. Natl. Acad. Sci. U.S.A.* **118**, e2025998118 (2021).
- 9 A. Joutel et al., Cerebrovascular dysfunction and microcirculation rarefaction precede white matter lesions in a mouse genetic model of cerebral ischemic small vessel disease. *J. Clin. Invest.* **120**, 433–445 (2010).
- 10 A. Y. Shih et al., Robust and fragile aspects of cortical blood flow in relation to the underlying angioarchitecture. *Microcirculation* **22**, 204–218 (2015).
- 11 A. Devor et al., Stimulus-induced changes in blood flow and 2-deoxyglucose uptake dissociate in ipsilateral somatosensory cortex. *J. Neurosci.* **28**, 14347–14357 (2008).
- 12 I. G. Gould, P. Tsai, D. Kleinfeld, A. Linninger, The capillary bed offers the largest hemodynamic resistance to the cortical blood supply. *J. Cereb. Blood Flow Metab.* **37**, 52–68 (2017).
- 13 X. Ji et al., Brain microvasculature has a common topology with local differences in geometry that match metabolic load. *Neuron* **109**, 1168–1187.e13 (2021).
- 14 T. A. Longden et al., Capillary K^+ -sensing initiates retrograde hyperpolarization to increase local cerebral blood flow. *Nat. Neurosci.* **20**, 717–726 (2017).
- 15 R. Rasmussen et al., Cortex-wide changes in extracellular potassium ions parallel brain state transitions in awake behaving mice. *Cell Rep.* **28**, 1182–1194.e4 (2019).
- 16 O. F. Harraz, T. A. Longden, F. Dabertrand, D. Hill-Eubanks, M. T. Nelson, Endothelial GqPCR activity controls capillary electrical signaling and brain blood flow through PIP_2 depletion. *Proc. Natl. Acad. Sci. U.S.A.* **115**, E3569–E3577 (2018).
- 17 O. F. Harraz, D. Hill-Eubanks, M. T. Nelson, PIP_2 : A critical regulator of vascular ion channels hiding in plain sight. *Proc. Natl. Acad. Sci. U.S.A.* **117**, 20378–20389 (2020).
- 18 A. Mughal, O. F. Harraz, A. L. Gonzales, D. Hill-Eubanks, M. T. Nelson, PIP_2 improves cerebral blood flow in a mouse model of Alzheimer’s disease. *Function (Oxf.)* **2**, b010 (2021).
- 19 B. Cauli et al., Cortical GABA interneurons in neurovascular coupling: Relays for subcortical vasoactive pathways. *J. Neurosci.* **24**, 8940–8949 (2004).
- 20 P. Thakore et al., Brain endothelial cell TRPA1 channels initiate neurovascular coupling. *eLife* **10**, e63040 (2021).