We are IntechOpen, the world’s leading publisher of Open Access books
Built by scientists, for scientists

3,900
Open access books available

116,000
International authors and editors

120M
Downloads

154
Countries delivered to

TOP 1%
Our authors are among the most cited scientists

12.2%
Contributors from top 500 universities

WEB OF SCIENCE™
Selection of our books indexed in the Book Citation Index in Web of Science™ Core Collection (BKCI)

Interested in publishing with us?
Contact book.department@intechopen.com

Numbers displayed above are based on latest data collected.
For more information visit www.intechopen.com
Chapter 3

The Endothelium: The Vascular Information Exchange

Ran Wei, Stephanie E. Lunn, Stephen L. Gust, Paul M. Kerr and Frances Plane

Additional information is available at the end of the chapter

http://dx.doi.org/10.5772/intechopen.79897

Abstract

Maintenance of adequate blood flow to tissues and organs requires that endothelial cells dynamically respond in a stimulus-specific manner to elicit appropriate changes in smooth muscle contractility and thus, arterial diameter. Endothelial cells can be stimulated directly by increases in blood flow and by humoral factors acting on surface receptors, as well as through flux of second messengers from smooth muscle cells activated by release of neurotransmitters from perivascular nerves. The ability of endothelial cells to generate stimulus-specific responses to these diverse inputs is facilitated by organization of ion channels and signaling proteins into microdomains that permit finely-tuned, spatially-restricted Ca\(^{2+}\) events to differentially activate key effectors such as nitric oxide (NO) synthase and Ca\(^{2+}\)-activated K\(^+\) (K\(_{Ca}\)) channels. NO is a diffusible mediator which acts locally to cause vasodilation. Opening of K\(_{Ca}\) channels causes hyperpolarization of the endothelial membrane potential which spreads to surrounding smooth muscle cells to also cause local vasodilation. However, once initiated, hyperpolarization also spreads longitudinally through the endothelium to effect coordinated changes in blood flow within multiple arterial segments. Thus, the signaling pathways activated by a particular stimulus determine whether its effects on arterial diameter are localized or can impact blood flow at the level of the vascular bed.

Keywords: endothelium, calcium, nitric oxide, microdomain, potassium channels

1. Introduction

Appropriate local control of blood flow through resistance arteries is critical to the functioning of tissues and organs, and to regulation of blood pressure. Lying at the interface between the blood and smooth muscle cells of the vessel wall, the endothelium plays a vital role in this dynamic process by transducing diverse chemical and mechanical stimuli into
coordinated changes in arterial diameter. Endothelial cells respond to vasodilatory stimuli by releasing diffusible mediators such as nitric oxide (NO) and prostacyclin (PGL₂) and by initiating membrane hyperpolarization that spreads to surrounding smooth muscle cells via myoendothelial gap junctions (MEGJs) to inhibit contractility, a mechanism termed endothelium-dependent hyperpolarization (EDH) [1–3]. NO and PGL₂ are local mediators that diffuse to surrounding smooth muscle cells to cause relaxation. Once initiated, EDH spreads to surrounding smooth muscle cells to affect relaxation but conduction of hyperpolarization longitudinally through the endothelial layer means that EDH also contributes to coordination of changes in blood flow in multiple arterial segments within a vascular bed [4]. Thus, the ability of a stimulus to engage diffusible mediators versus EDH determines whether its effects on arterial diameter and thus blood flow, are restricted to the local area or can impact blood flow at the level of the vascular bed.

Increases in endothelial intracellular Ca²⁺ concentration ([Ca²⁺]ᵢ) drive these vasodilator pathways; NO is synthesized from L-arginine by the Ca²⁺-calmodulin-dependent enzyme NO synthase (NOS) [3], PGL₂ is generated by the actions of cyclooxygenase on arachidonic acid released by the actions of Ca²⁺-dependent phospholipase A₂ on membrane phospholipids [5, 6], and opening of Ca²⁺-activated K⁺ (KᵥCa) channels causes hyperpolarization [3, 7]. Global changes in endothelial [Ca²⁺]ᵢ have been widely studied [8, 9], but development of new technologies such as high-speed, high-resolution confocal Ca²⁺ imaging and generation of transgenic mice expressing genetically encoded Ca²⁺ indicators has allowed resolution of a wide range of transient Ca²⁺ events within endothelial cells of intact arteries to provide a growing body of support for the concept of stimulus-specific engagement of effectors underpinned by spatially and temporally discrete Ca²⁺ signaling patterns that occur independently of changes in bulk endothelial [Ca²⁺] [10–13].

Pulsars [10] and wavelets [11] are spontaneous, short-lived, (<0.03 s duration) spatially fixed Ca²⁺ events originating from distinct clusters of inositol 1,4,5-trisphosphate (InsP₃) receptors on the membrane of endoplasmic reticulum (ER). First identified in mouse mesenteric artery and hamster skeletal muscle arteriolar endothelial cells, these events predominantly occur close to endothelial projections that abut or form MEGJs with smooth muscle cells [10, 11] and exert a basal vasodilator influence through activation of intermediate conductance (IKᵥCa) Ca²⁺-activated K⁺ channels. Their dependence on InsP₃ provides a mechanism by which pulsars are linked to and regulated by G protein-coupled receptor (GPCR) signaling. Elevation of InsP₃ by endothelium-dependent vasodilators [10] or by flux of InsP₃ from smooth muscle cells following stimulation of α₁-adrenoceptors [11] increases pulsar size and/or frequency through recruitment of new sites and a reduction in the interval between pulsars at a given site. In porcine coronary arteries, InsP₃-dependent Ca²⁺ events similar to pulsars propagate into longer lasting Ca²⁺ waves (>8 s duration) facilitated by the longitudinal arrangement of ER/InsP₃ receptors to promote directional Ca²⁺-induced Ca²⁺ release along the endothelial cell axis and are associated with activation of both NOS and KᵥCa channels [12].

Sparklets are generated by spatially restricted Ca²⁺ influx through members of the transient receptor potential (TRP) ion channel family [14, 15]. Sparklets were first identified in mouse mesenteric arteries under experimental conditions in which InsP₃-mediated pulsars were
eliminated [14]. Exposure of the endothelium to TRPV4 agonists and/or acetylcholine increased the activity of these discrete Ca\(^{2+}\) signals which were linked to activation of both IK\(_{Ca}\) and small conductance (SK\(_{Ca}\)) Ca\(^{2+}\)-activated K\(^+\) channels, effects which were absent in arteries from mice lacking TRPV4 [14]. In rat cremaster arterioles, clustering of TRPV4-mediated sparklets in endothelial projections was linked exclusively to activation of IK\(_{Ca}\) channels [16] and in mouse small pulmonary arteries, shear stress-stimulated TRPV4 activity was linked to NO production [17]. Larger endothelial sparklets mediated by simultaneous opening of two TRPA1 and leading to activation of IK\(_{Ca}\) channels were shown to underlie dilation to reactive oxygen species in rat cerebral arteries [18]. We will now discuss how grouping of Ca\(^{2+}\) signaling and effector proteins into microdomains allows dynamic, stimulus-specific Ca\(^{2+}\) events which determine the recruitment of effectors thus the degree to which blood flow is impacted.

2. Stimulus-specific endothelial Ca\(^{2+}\) signaling

2.1. Shear stress

In vivo, endothelial sensing of laminar shear stress, the tangential frictional force exerted by blood flowing across the cell surface, plays a dominant role in acute modulation of vascular tone and therefore, tissue perfusion [19–21]. In the majority of resistance arteries, increases in blood flow stimulate endothelium-dependent relaxation of surrounding smooth muscle cells and increase arterial diameter, a response termed flow-mediated dilatation. Flow also influences gene expression and structural remodeling with areas of disturbed flow and reduced shear stress is associated with development of atherosclerotic plaques [22]. Measurement of acute responses to increases in shear stress is the most widely used clinical index of endothelial function and vascular health with attenuation of flow-induced dilation associated with increased risk of cardiovascular diseases [23, 24]. Indeed, reductions in shear stress are a likely mechanism by which endothelial function is altered with inactivity, an effect which can be overcome by exercise interventions [25, 26].

In animals and humans, acute shear stress-induced vasodilation can be mediated by both NO and EDH [27–31]. Although endothelial cells express both SK\(_{Ca}\) and IK\(_{Ca}\) channels, data from isolated arteries indicate that it is SK\(_{Ca}\) channels that play a predominate role in mediating the EDH component of this response. Deletion of SK\(_{Ca}\) but not IK\(_{Ca}\) channels impaired both NO and EDH-mediated dilation to shear stress stimulation in mouse isolated carotid arteries [32]. In rat isolated perfused mesenteric beds, shear stress-induced modulation of sympathetic vasoconstriction was prevented by both the NOS inhibitor L-N\(^{G}\)-nitroarginine methyl ester (L-NAME) and apamin, a selective blocker of SK\(_{Ca}\) channels, but not by the IK\(_{Ca}\) channel inhibitor TRAM-34 [33]. Similarly, shear stress-evoked dilation of mouse isolated coronary arteries was inhibited by apamin [34] and L-NAME [35].

Mechanotransduction, the conversion of increases in shear stress into changes in arterial diameter, is reliant upon rises in endothelial [Ca\(^{2+}\)], mediated by Ca\(^{2+}\) entry. In vitro studies have identified multiple candidates as potential endothelial mechanosensors including
integrins [36], tyrosine kinase receptors [37], intercellular junction proteins [38], and P2X4 receptors which are cation channels activated by adenosine triphosphate (ATP) [39]. Work with transgenic mice has implicated GPR68, a proton-sensing rhodopsin-like GPCR [40], inwardly rectifying K$^{+}$ channels [41] and PIEZO1, a Ca$^{2+}$-permeable, non-selective cation channel [42, 43]. However, recently, it is the role of TRPV4 in endothelial responses to increases in shear stress that has received particular attention. This Ca$^{2+}$-permeable channel can be directly activated by shear stress [34, 44] via membrane deformation or through a lever-like action involving cytoskeletal linkages to molecules embedded in the glycocalyx [45, 46], the layer of proteoglycans and glycoproteins that covers the luminal surface of the endothelium, or indirectly through upstream production of arachidonic acid metabolites [47]. Genetic deletion of TRPV4 results in blunted flow-mediated dilation of mouse carotid and mesenteric arteries [31, 47, 48] and pharmacological inhibition of these channels blocked flow-evoked increases in endothelial [Ca$^{2+}$]i in isolated mouse mesenteric, human coronary, and rat carotid and gracilis arteries [31, 49–51]. In bovine coronary endothelial cells block of TRPV4 inhibited both shear stress-evoked increases in [Ca$^{2+}$], and activation of SKCa channels [34], indicating that there may be a direct link between TRPV4-mediated Ca$^{2+}$ influx and SKCa channel activity. This idea is supported by the demonstration that in rat pulmonary arteries, vasodilation to the TRPV4 agonist GSK1016790A was mediated by activation of SKCa channels [52]. In the same vessels, and in mouse small pulmonary arteries, shear stress-stimulated TRPV4 activity was also linked to NO production [17] suggesting a further link between TRPV4 and NOS.

Building on these findings, several lines of evidence now support the notion that acute increases in shear stress cause Ca$^{2+}$ influx through TRPV4 channels to selectively activate both SKCa channels and NOS, and that this pathway is enabled by organization of TRPV4, NOS, SKCa channels and the caveola scaffold protein caveolin-1 into microdomains within caveolae, flask-shaped structures on the endothelial cell surface rich in signaling proteins [34, 53, 54]. SKCa channels are localized to the luminal membrane of endothelial cells in rat mesenteric arteries [55] and SKCa channel protein was co-immunoprecipitated with caveolin-1 from endothelial cells of the same arteries and from porcine coronary arteries [56]. It is well established that endothelial NOS is localized to caveolae where it is negatively regulated through its interaction with caveolin-1 [57]. Increases in [Ca$^{2+}$], promote recruitment of Ca$^{2+}$-calmodulin to displace caveolin-1 from NOS thereby activating it [53]. In bovine coronary and human microvascular endothelial cells, SKCa channels were co-localized with caveolin-1, NOS and TRPV4 channels within microdomains at the luminal endothelial cell surface [34, 57, 58]. Furthermore, in mesenteric arteries from mice lacking caveolin-1, endothelial TRPV4 channel activity was impaired indicating that a direct interaction between TRPV4 and caveolin-1 may be functionally important for Ca$^{2+}$ entry in response to shear stress [57]. Caveolin-1 has been shown to initiate downstream signaling in response to increases in shear stress [59] leading to the suggestion that caveolae act as mechanosensors to elicit a cascade of events that promote vasodilation. In line with this proposal, shear stress-induced dilation is defective and endothelial SKCa current reduced in coronary and carotid arteries of mice lacking caveolin-1, an effect rescued by re-introduction of endothelial specific caveolin-1 [58, 60].

Together these findings, gathered using a range of approaches and from a number of different arteries, support an elegant model in which shear stress-evoked Ca$^{2+}$ influx through TRPV4 channels on the luminal surface of endothelial cells leads to spatially-restricted Ca$^{2+}$ sparklets
within a signaling microdomain to selectively activate SKCa channels and NOS to elicit vasodilation (Figure 1). However, a number of questions remain to be addressed. Shear stress increases PGI2 production in bovine coronary and human umbilical vein endothelial cells [34, 61] and rabbit isolated femoral arteries [62], and hydrogen peroxide (H2O2) contributes to flow-mediated dilation in coronary arterioles from patients with heart disease [63] but the functional role of these factors in acute flow-mediated vasodilation has not fully been explored. A significant component of flow-induced dilation remained in isolated mesenteric arteries of mice lacking TRPV4 [31] which could indicate that, as suggested in earlier reports, Ca2+-independent processes may also contribute to this response [64] or the involvement of another route for Ca2+ influx. The possibility that flow-induced increases in endothelial cell [Ca2+]i are stimulated by localized release endothelium-derived paracrine mediators such as ATP, substance P or acetylcholine, first proposed over 30 years ago [65, 66], has recently received renewed support with the demonstration that endothelial organic cation transporters release acetylcholine in response to increases in shear stress in rat isolated carotid arteries [67]. The same study suggests that InsP3-mediated Ca2+ release from ER stores and Ca2+ entry through TRPC but not TRPV4 contributes to flow-induced endothelial Ca2+ signaling in these vessels. This finding highlights the fact that further work is required to elucidate the differential signaling networks underlying endothelial responses to acute increases in shear stress in different arteries.

2.2. Agonists at endothelial GPCRs

Many endogenous and exogenous chemicals bind to GPCRs leading to stimulation of EDH and production of NO, PGI2 and other diffusible mediators such as epoxyeicosatrienoic acids and H2O2 to cause vasodilation [1, 2, 68]. Measurements of bulk endothelial [Ca2+]i, established

Figure 1. Model of localized endothelial Ca2+ signaling evoked by increases in shear stress. Shear stress-evoked Ca2+ influx through TRPV4 channels on the luminal surface of endothelial cells leads to spatially-restricted Ca2+ sparklets within a signaling microdomain to selectively activate SKCa channels and endothelial NOS (eNOS).
the role of InsP$_3$-mediated Ca$^{2+}$ release and subsequently store-operated Ca$^{2+}$ entry (SOCE) in this process [9]. The mechanism underlying endothelial SOCE has been controversial but recent evidence supports a model in which Ca$^{2+}$ store depletion allows spatial reorganization of Ca$^{2+}$ sensor protein stromal interaction molecules (STIMs) so that they can aggregate into clusters that physically interact with Ca$^{2+}$-selective Orai channels at the ER-plasma membrane junction [69–72]. TRPC and TRPV4 can also interact with STIMs [73] and studies of knock-out mice have provided evidence for a role for TRPC4 in acetylcholine-evoked SOCE in aortae [74] and for TRPV4 in SOCE in mesentery [75] and carotid arteries [76]. A receptor-operated Ca$^{2+}$ entry mechanism can also be mediated by DAG-induced activation of TRPC and TRPV channels. For example, in human umbilical vein endothelial cells, bradykinin stimulated both translocation of DAG-sensitive TRPC6 to the cell membrane and Ca$^{2+}$ influx [77, 78]. Expression of mRNA for another ER Ca$^{2+}$ release channel, the ryanodine receptor (RyR), has been detected in endothelial cells of human mesenteric arteries [79], and RyRs have been suggested to mediate Ca$^{2+}$ oscillations in cultured bovine aortic and human umbilical vein endothelial cells [80] but to date, ryanodine has been shown to have no effect on endothelial Ca$^{2+}$ signaling or vasodilation [12, 81]. There is significant variation in the reported contribution of EDH, NO and other mediators to agonist-evoked dilation, both in terms of differences between agonists and arteries. Thus, for the purposes of this chapter we will limit our discussion to three agents commonly used to stimulate endothelium-dependent vasodilation in experimental studies, acetylcholine, ATP and substance P.

The first evidence that differential endothelial Ca$^{2+}$ signaling underlies agonist-evoked EDH and NO came from a study of rat isolated middle cerebral arteries in which EDH-dependent vasodilation to purinergic agonists required a larger increase in [Ca$^{2+}$]$_i$ than for NO [82]. Measurements of global [Ca$^{2+}$]$_i$ indicated that different sources of Ca$^{2+}$ contributed to agonist-stimulated production of NO and EDH; NO production is associated with SOCE [83] whereas EDH is linked to both InsP$_3$-mediated Ca$^{2+}$ release and SOCE [84]. Similarly, both agonist evoked SOCE and NO production are suppressed in isolated aortae from mice lacking STIM1, the primary endothelial STIM [85]. Building on these findings, data accrued over the past 15 years from functional, histological, Ca$^{2+}$ imaging and immunohistochemical studies of intact arteries and endothelial-smooth muscle co-cultures support agonist-evoked EDH and NO release being mediated by distinct Ca$^{2+}$ signaling within specialized domains.

2.2.1. EDH

EDH is mediated by opening of both IK$_{Ca}$ and SK$_{Ca}$ channels but their relative contribution to agonist-evoked vasodilation, based on the effects of selective pharmacological inhibitors, displays significant variation between agonists and arteries. Simultaneous block of both IK$_{Ca}$ and SK$_{Ca}$ channels is required to inhibit acetylcholine-evoked EDH in mesenteric arteries from rats and mice, and guinea-pig coronary arteries [86–88] whereas in rat cerebral and human mesenteric arteries the same response is largely reliant on IK$_{Ca}$ channels [89, 90].

IK$_{Ca}$ and SK$_{Ca}$ channels display a differential spatial distribution within endothelial cells and their contribution to agonist-evoked EDH appears to be mediated by different signaling pathways. In mesenteric arteries from rats, mice and humans, IK$_{Ca}$ channels are localized within
regions associated with MEGJs in which ER membrane, InsP$_3$ receptors, gap junction connexins, TRPC3 and TRPV4 have also been identified [10, 11, 14, 55, 90–93]. In mouse and rat mesenteric arteries, acetylcholine increased the frequency and number of InsP$_3$-dependent Ca$^{2+}$ pulsars in this region which were linked to activation of IK$_{Ca}$ channels to evoke EDH [10, 93] (Figure 2). TRPC3 may support this process by providing Ca$^{2+}$ entry for refilling of InsP$_3$-sensitive ER stores, and/or direct activation of both SK$_{Ca}$ and IK$_{Ca}$ channels [91, 94]. However, in other reports acetylcholine exclusively stimulates TRPV4 in the vicinity of MEGJs to generate Ca$^{2+}$ sparklets and which in turn activate IK$_{Ca}$ channels in mouse mesenteric arteries [14, 95]. This occurs via a mechanism dependent on the anchoring protein AKAP, and is consistent with deletion of TRPV4 resulting in blunting of acetylcholine-evoked increases in endothelial [Ca$^{2+}$], and loss of EDH in mouse mesenteric arteries [75, 76]. TRPV3 [96] and TRPA1 [97] are also expressed in endothelial cells and activators of these channels can certainly initiate increases in Ca$^{2+}$ signaling and EDH in cerebral arteries, but a role for these channels in agonist-stimulated EDH has yet to be demonstrated.

In contrast to IK$_{Ca}$ channels, SK$_{Ca}$ channels are associated with caveolae and are diffusely distributed across the cell membrane with a higher level expression at endothelial-endothelial cell borders [12, 55, 90, 93]. Also, unlike IK$_{Ca}$ channels, evidence is lacking for a direct link between agonist-evoked, InsP$_3$-mediated Ca$^{2+}$ events and SK$_{Ca}$ channel activity. Instead, it

![Figure 2](http://dx.doi.org/10.5772/intechopen.79897)
appears that Ca\textsuperscript{2+} influx through TRP channels is the primary source of Ca\textsuperscript{2+} for agonist stimulation of endothelial SK\textsubscript{Ca} channels [94, 98]. In mouse cerebral artery, ATP caused rapid trafficking of TRPC3 to the plasma membrane to provide Ca\textsuperscript{2+} influx to selectively activate SK\textsubscript{Ca} channels to cause EDH [98] (Figure 2). As described earlier, TRPV4 are also associated with caveolae and are a source of Ca\textsuperscript{2+} for SK\textsubscript{Ca} channel activation in response to increases in shear stress but whether this relationship accounts for engagement of SK\textsubscript{Ca} channels by agonists has not been explored.

2.2.2. NO

In contrast to EDH, the role of localized Ca\textsuperscript{2+} signaling in agonist-evoked NO release has received little attention. NOS, TRPV4 and TRPC3 are located in caveolae microdomains, and deletion of either channel blunts acetylcholine-evoked NO release and NO-mediated relaxation in mouse mesenteric and carotid arteries [75, 99] suggesting they may provide a source of Ca\textsuperscript{2+} for agonist-driven NOS activation. Heteromultimers of TRPV4-TRPC1 channels mediate vasorelaxation of rabbit mesenteric arteries in response to stimulation of the Ca\textsuperscript{2+}-sensing receptor through NO production [100] but the underlying Ca\textsuperscript{2+} dynamics were not assessed.

A recent study has shown that TRPV4-mediated sparklets underlie ATP driven activation of endothelial NOS in mouse small pulmonary arteries. The resulting NO initiates vasodilation and also guanylyl cyclase-protein kinase G signaling in the endothelium that limits TRPV4 channel cooperativity and serves as a negative feedback signal to regulate TRPV4 channel function [17]. This description of ATP-evoked, spatially distinct TRPV4 sparklets and localized TRPV4-NOS signaling support a novel paradigm that NOS can be activated by spatially restricted Ca\textsuperscript{2+} signals, and identifies TRPV4 channels as a key regulator of NOS activity in the pulmonary microcirculation.

In contrast, in porcine isolated coronary arteries, substance P increased the occurrence of discrete InsP\textsubscript{2}c-dependent endothelial Ca\textsuperscript{2+} events in a concentration-dependent manner; low concentrations primarily increased the number of Ca\textsuperscript{2+} events and at higher concentrations the number of Ca\textsuperscript{2+} events saturated while the magnitude of individual events increased [12]. This pattern correlated with a greater role for NO in vasorelaxation at lower concentrations suggesting subtle Ca\textsuperscript{2+} signal expansion at low stimulation levels may preferentially target NOS. A key finding of this study was that idiosyncratic Ca\textsuperscript{2+} signal expansion corresponded with coronary artery vasorelaxation whereas global changes in [Ca\textsuperscript{2+}]\textsubscript{i} did not highlighting that frequency modulation of discrete Ca\textsuperscript{2+} signals is the primary driver of this functional response and that measurement of changes in bulk [Ca\textsuperscript{2+}] do not adequately describe the Ca\textsuperscript{2+} signaling pathways that underlie endothelium-dependent vasodilation.

2.2.3. Membrane potential and Ca\textsuperscript{2+} microdomain signaling

Production of NO and stimulation of EDH have long been regarded as separate mechanisms for agonist-evoked vasodilation but several lines of evidence indicate that there may be a facilitatory relationship between endothelial SK\textsubscript{Ca} and IK\textsubscript{Ca} channel activity and NO. SK\textsubscript{Ca} channel activity has been linked to NO-mediated vasodilation to agonists with deletion of these channels causing impaired NO-mediated dilation to acetylcholine in mouse carotid arteries and increased expression enhancing NO-mediated dilation of cremaster arterioles.
In rat mesenteric arteries, block of SK\textsubscript{Ca} and IK\textsubscript{Ca} channels reduces agonist-evoked, NO-mediated vasorelaxation and NO release [101]. Conversely, activators of endothelial K\textsubscript{Ca} channels can enhance NO release from cultured endothelial cells, enhance ATP-induced increases in cytosolic Ca\textsuperscript{2+} concentration and NO synthesis in rat cremaster arterioles, and elicit NO-mediated relaxation in mesenteric arteries [102–104].

Lacking voltage-operated Ca\textsuperscript{2+} channels, endothelial Ca\textsuperscript{2+} influx is mediated by TRP channels and so membrane hyperpolarization may be required to maintain an appropriate electrochemical driving force for agonist-induced Ca\textsuperscript{2+} influx and also to prevent channel inactivation and/or reduction in unitary conductance [105, 106]. Membrane depolarization does inhibit both agonist-induced increases in [Ca\textsuperscript{2+}], and NO release in cultured endothelial cells [107, 108], and in rat isolated basilar arteries, endothelial depolarization was associated with a reduction in NO-mediated relaxation to acetylcholine [109]. Nonetheless, the ability of hyperpolarization to regulate Ca\textsuperscript{2+} entry by increasing the electrical driving force is controversial. The large concentration gradient (~20,000-fold for extracellular versus intracellular) [110] and driving force for Ca\textsuperscript{2+} entry raising the question of whether a small amplitude hyperpolarization will be insufficient to modulate Ca\textsuperscript{2+} entry. In rat mesenteric and cerebral arteries, that certainly appeared to be the case as changes in global endothelial [Ca\textsuperscript{2+}], were independent of changes membrane potential [89, 111]. However, more recent work with endothelial cell tubes isolated from resistance arteries has provided renewed support for hyperpolarization enhancing acetylcholine-evoked Ca\textsuperscript{2+} influx through TRPV4 [112] and indicate that pharmacological activation of SK\textsubscript{Ca} and IK\textsubscript{Ca} channel may not only enhance Ca\textsuperscript{2+} entry to further amplify K\textsubscript{Ca} channel activity, but also boost NO production [113]. In mouse mesenteric arteries, acetylcholine-evoked TRPV4-dependent Ca\textsuperscript{2+} signaling was inhibited in arteries from mice lacking IK\textsubscript{Ca} channels indicating that in these arteries, endothelial stimulation drives sufficient IK\textsubscript{Ca}-dependent Ca\textsuperscript{2+} entry through TRPV4 to enhance dynamics [13]. IK\textsubscript{Ca} channel activity modestly augmented Ca\textsuperscript{2+} event amplitude but the most notable impact was in recruiting new Ca\textsuperscript{2+} firing sites as well as increasing firing frequencies at pre-existing sites. In the same study, increasing or decreasing SK\textsubscript{Ca} expression had little additional effect on the occurrence of Ca\textsuperscript{2+} events but did promote increased amplitudes and durations indicating that SK\textsubscript{Ca} channels may play a role in positive feedback Ca\textsuperscript{2+} regulation by shaping the size and time course of individual events. In porcine coronary arteries stimulation of NOS by InsP\textsubscript{3}-dependent, large amplitude-low frequency Ca\textsuperscript{2+} waves [12], exactly the types of events which were lost in mesenteric arteries from mice with an endothelial specific knockout of SK\textsubscript{Ca} channels [114], suggests that SK\textsubscript{Ca} channels are required for their development. As mentioned above, deletion of SK\textsubscript{Ca} channels impaired NO-mediated dilation to acetylcholine [32] and together, these findings support the notion that their role in protraction of Ca\textsuperscript{2+} events may be important in stimulation NOS.

2.3. Myoendothelial feedback

The sympathetic nervous system regulates total peripheral resistance and is a key modulator of resistance artery diameter through release of noradrenaline and co-transmitters such as ATP and neuropeptide Y [115]. Noradrenaline causes vasoconstriction through activating \alpha\textsubscript{1}-adrenoceptors on vascular smooth muscle cells, a process which is limited by engagement of
endothelial mechanisms through myoendothelial feedback. The current model of myoendothelial feedback involves flux of InsP$_3$ from smooth muscle to endothelial cells to elicit localized increases in Ca$^{2+}$, activation of IK$_{Ca}$ channels and possibly NOS, to limit smooth muscle contractility [11, 91, 116]. This model is supported by ultrastructural and histochemical studies showing that in rat mesenteric and basilar, and hamster retractor feed arteries, MEGJ connexins and IK$_{Ca}$ channels are in close spatial association with ER and InsP$_3$ receptors within endothelial projections that extend through the internal elastic lamina to make contact with smooth muscle cells [11, 55, 91, 94]. In hamster retractor feed arteries, myoendothelial feedback is fully accounted for by EDH. The $\alpha_1$-adrenoceptor agonist phenylephrine induced localized, InsP$_3$-mediated Ca$^{2+}$ signaling events within endothelial projections and block of endothelial IK$_{Ca}$ channels enhanced smooth muscle depolarization and vasoconstriction [11]. In rat basilar arteries in which NO makes a major contribution to myoendothelial feedback, smooth muscle depolarization to 5-HT was accompanied by IK$_{Ca}$ channel-mediated endothelial hyperpolarization. Inhibition of IK$_{Ca}$ channels, gap junctional communication, TRPC3 or NOS potentiated smooth muscle depolarization to 5-HT in a non-additive manner indicating that rather being distinct pathways, NO and endothelial IK$_{Ca}$ channel activity are part of an integrated mechanism for the regulation of agonist-induced vasoconstriction [91]. In the latter study, Ca$^{2+}$ signaling was not investigated and the link between IK$_{Ca}$ channel activity and NO production was not defined. However, NOS has now been localized close to MEGJs [117] and in co-cultures stimulation of smooth muscle cells with phenylephrine leads to MEGJ specific NOS phosphorylation within endothelial cells to increase NO [118]. Also, in mouse mesenteric vessels, phenylephrine stimulated endothelial TRPV4 sparklets in an InsP$_3$-dependent manner, to engage SK$_{Ca}$ and IK$_{Ca}$ channels as well as, to a lesser extent, NOS [17]. Thus, given the ability of IK$_{Ca}$ channels to modulate endothelial Ca$^{2+}$ dynamics [12, 113, 114], it may be proposed that activation of IK$_{Ca}$ channels at MEGJs following stimulation of smooth muscle cells by GPCR agonists, may amplify dynamic Ca$^{2+}$ signals to enhance NO production.

3. Local versus conducted responses

The majority of studies described in this chapter have been conducted on isolated resistance arteries which in in vivo would be part of branching network of resistance vessels supplied by feed arteries in which effective control of blood flow requires coordinated behaviour amongst arterial segments [119]. As described above, diffusible mediators such as NO act locally to increase arterial diameter. In contrast, K$_{Ca}$ channel-mediated hyperpolarization leads to both local dilation and conduction of the response through the endothelium for distances of several millimeters. This conduction allows for coordination of changes in arterial diameter in multiple vessel segments and so optimizes blood flow [4, 119, 120]. That is not to say that diffusible mediators do not play a role in global blood flow regulation within vascular beds. A recent study of the vascular bed of the mouse gluteus maximus muscle revealed that NO and EDH provide complementary endothelial pathways for ascending vasodilatation to optimize oxygen delivery to the muscle. EDH of downstream arterioles conducts along the endothelium into proximal feed arteries to cause dilation, and NO is released in response to luminal shear stress which increases secondary to downstream dilatation [120].
4. Conclusion

It has become apparent over the past 15 years that endothelial Ca\(^{2+}\) signaling patterns underlie the engagement of effectors such as NOS and/or K\(_{Ca}\) channels. The physiological significance of these stimulus-specific signaling pathways is not just that they determine the mediator of vasodilation, but also the scope of the impact of each stimulus on blood flow. Stimuli which predominantly elicit release of diffusible mediators will elicit local vasodilation whereas those that initiate EDH have the potential to dilate multiple arterial segments and so affect tissue perfusion. Further work is required to determine if the patterns of Ca\(^{2+}\) signaling described here have widespread applicability, and how they are impacted by age, sex and cardiovascular risk factors. Investigation of how changes in the components of signaling microdomains contribute to the etiology of endothelial dysfunction in conditions such as diabetes and hypertension may lead to the identification of new therapeutic targets.

Acknowledgements

Work in the author’s lab is supported by a grant-in-aid from the Heart and Stroke Foundation of Alberta, Nunavut and the North West Territories to F.P. (G13003076). P.M.K. received a RASCAF award from MacEwan University. Stipend support for graduate students was provided by the University of Alberta (QEII scholarships to S.E.L. and S.L.G., Walter H Johns Graduate Fellowship to S.E.L., 75th Anniversary award to R.W., Faculty of Medicine Recruitment Scholarship to S.L.G.), CIHR (Banting and Best Canada Graduate Scholarship, Masters Award to S.E.L.) and AIHS (Doctoral Studentship to S.E.L.).

Conflict of interest

The authors have declared no conflict of interest.

Author details

Ran Wei\(^1\), Stephanie E. Lunn\(^1\), Stephen L. Gust\(^1\), Paul M. Kerr\(^3\) and Frances Plane\(^{1,2*}\)

*Address all correspondence to: fplane@ualberta.ca

1 Department of Pharmacology, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada

2 Cardiovascular Research Centre, Faculty of Medicine and Dentistry, University of Alberta, Edmonton, Alberta, Canada

3 Faculty of Nursing, Robbins Health Learning Centre, MacEwan University, Edmonton, Alberta, Canada
References


58  Calcium and Signal Transduction

coronary arterioles: Role of Ca\textsuperscript{2+} entry and mitochondrial ROS signaling. The American Journal of Physiology. 2012;302(3):H634-H642


[83] Dedkova EN, Blatter LA. Nitric oxide inhibits capacitative Ca^{2+} entry and enhances endoplasmic reticulum Ca^{2+} uptake in bovine vascular endothelial cells. The Journal of Physiology. 2002;539(Pt 1):77-91


[95] Sonkusare SK, Dalsgaard T, Bonev AD, Hill-Eubanks DC, Kotlikoff MI, Scott JD, Santana LF, Nelson MT. AKAP150-dependent cooperative TRPV4 channel gating is central to endothelium-dependent vasodilation and is disrupted in hypertension. Science Signaling. 2014;7(333):ra66


Lückhoff A, Busse R. Calcium influx into endothelial cells and formation of endothelium-derived relaxing factor is controlled by the membrane potential. Pflügers Archiv. 1990; 416(3):305-311


