Genetic Ablation of CaV3.2 Channels Enhances the Arterial Myogenic Response by Modulating the RyR-BKCa Axis

Osama F. Harraz, Suzanne E. Brett, Anil Zechariah, Monica Romero, Jose L. Puglisi, Sean M. Wilson, Donald G. Welsh,

Objective—In resistance arteries, there is an emerging view that smooth muscle CaV3.2 channels restrain arterial constriction through a feedback response involving the large-conductance Ca2+-activated K+ channel (BKCa). Here, we used wild-type and CaV3.2 knockout (CaV3.2−/−) mice to definitively test whether CaV3.2 moderates myogenic tone in mesenteric arteries via the CaV3.2-ryanodine receptor-BKCa axis and whether this regulatory mechanism influences blood pressure regulation.

Approach and Results—Using pressurized vessel myography, CaV3.2−/− mesenteric arteries displayed enhanced myogenic constriction to pressure but similar K+-induced vasoconstriction compared with wild-type C57BL/6 arteries. Electrophysiological and myography experiments subsequently confirmed the inability of micromolar Ni2+, a CaV3.2 blocker, to either constrict arteries or suppress T-type currents in CaV3.2−/− smooth muscle cells. The frequency of BKCa−/− induced spontaneous transient outward K+ currents dropped in wild-type but not in knockout arterial smooth muscle cells upon the pharmacological suppression of CaV3.2 channel. Line scan analysis performed on en face arteries loaded with Fluo-4 revealed the presence of Ca2+ sparks in all arteries, with the subsequent application of Ni2+ only affecting wild-type arteries. Although CaV3.2 channel moderated myogenic constriction of resistance arteries, the blood pressure measurements of CaV3.2−/− and wild-type animals were similar.

Conclusions—Overall, our findings establish a negative feedback mechanism of the myogenic response in which CaV3.2 channel modulates downstream ryanodine receptor-BKCa to hyperpolarize and relax arteries. (Arterioscler Thromb Vasc Biol. 2015;35:00-00. DOI: 10.1161/ATVBAHA.115.305736.)

Key Words: arteries ■ calcium-activated potassium channels ■ calcium channels ■ calcium signaling ■ ryanodine receptors ■ T-type calcium channels ■ vascular smooth muscle ■ vasodilation

The cardiovascular system comprises a muscular pump and a distribution network of arteries, veins, and capillaries. Within this integrated system, resistance arteries control the magnitude and distribution of tissue perfusion and respond to vasoactive stimuli, including mechanical forces, neurotransmitters, and metabolites. Bayliss first described the inherent ability of resistance arteries to constrict to elevated pressure, and studies have shown that the so-called myogenic response is intimately tied to depolarization and the activation of smooth muscle L-type Ca2+ channels. It is often presumed that CaV1.2 is the only Ca2+ channel of functional significance because dihydropyridines, L-type blockers, prominently attenuate myogenic tone. This traditional perspective has begun to change with the identification of arterial T-type Ca2+ channels, including CaV3.1 and CaV3.2 subtypes. Recent findings suggest that the former (ie, CaV3.1) modestly facilitates myogenic constriction at hyperpolarized voltages, whereas the latter (ie, CaV3.2) facilitates a negative feedback response restraining arterial constriction.

Our recent observations have tied the paradoxical ability of rat cerebral arterial CaV3.2 channel to limit myogenic tone to the triggering of ryanodine receptors (RyR) on the sarcoplasmic reticulum. The RyR-mediated generation of Ca2+ sparks subsequently activates the large conductance Ca2+-activated K+ channels (BKCa), eliciting a hyperpolarization to counteract pressure-induced constriction. Furthermore, the CaV3.2 conductance in the human cerebral circulation seems to mediate a similar physiological role. Although the concept of a voltage-gated Ca2+ channel counterbalancing vasoconstriction is novel and intriguing, it is one delimited by 2 primary concerns. First, current work is heavily reliant on the presumed selectivity of Ni2+ to block CaV3.2 channels. Second, there is a lack of corroborative observations, outside the cerebral circulation, in vascular beds known to acutely and sustainably regulate systemic blood pressure.

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Here, we used wild-type and CaV3.2 knockout (CaV3.2−/−) mice to definitively test whether CaV3.2 channel moderates myogenic tone in mesenteric arteries via the CaV3.2-RyR-BKca axis and, more generally, whether this regulatory mechanism influences blood pressure regulation. Experiments ranged from cells to whole animals and encompassed the integrative use of myography, electrophysiology, Ca2+ imaging, and intravascular catheterization. Arteries displayed enhanced myogenic tone when CaV3.2 channels were genetically ablated or pharmacologically suppressed using Ni2+. Subsequent analyses indicated that Ni2+ inhibited BKca currents and Ca2+ sparks in wild-type but not CaV3.2−/− arteries. Although CaV3.2 channel moderated myogenic constriction, the blood pressure measurements of both animal types were similar. In conclusion, this study establishes a negative feedback response in which CaV3.2 channel modulates downstream activity of the RyR-BKca complex to hyperpolarize and relax resistance arteries.

Materials and Methods
Materials and Methods are available in the online-only Data Supplement.

Results
Genetic Ablation of CaV3.2 Enhances Arterial Myogenic Tone
Our earlier reports revealed the involvement of CaV3.2 channels in negative feedback control of rat cerebral arterial tone10 because such channel deletion should enhance myogenic tone. Figure 1A and 1B demonstrates that C57BL/6 mesenteric arteries constricted to elevations in intravascular pressure from 20 to 100 mm Hg in Ca2+ containing physiological saline solution (PSS). Maximum arterial diameters were obtained by replacing Ca2+ PSS with PSS with zero Ca2++2 mmol/L EGTA (n=12). B, Traces and averaged data of the myogenic response in CaV3.2−/− mesenteric arteries (n=8). C, Percentage myogenic tone was significantly higher in CaV3.2−/− (n=7) than in wild-type C57BL/6 (n=11) arteries (unpaired t test, *P ≤ 0.05). D, Vasoconstriction evoked by 60 mmol/L K+ was similar in C57BL/6 and CaV3.2−/− pressurized (15 mm Hg) arteries (n=11–17, unpaired t test; NS denotes not significant). E, Messenger RNA of key genes (CaV1.2, CaV3.1, BKca-α, and RyR2) were not different in C57BL/6 and CaV3.2−/− mesenteric arteries. Relative expression was calculated using 3 independent quantitative PCR reactions.

Nonstandard Abbreviations and Acronyms

<table>
<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tr>
<td>BKca</td>
<td>large-conductance Ca2+-activated K+ channel</td>
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<tr>
<td>CaV3.2−/−</td>
<td>CaV3.2-deficient (knockout) mice</td>
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<tr>
<td>RyR</td>
<td>ryanodine receptor</td>
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<td>STOC</td>
<td>spontaneous transient outward K+ current</td>
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Figure 1. CaV3.2−/− arteries display enhanced myogenic tone. A, Representative traces and summary data demonstrate that C57BL/6 mesenteric arteries constricted to elevations in intravascular pressure from 20 to 100 mm Hg in Ca2+ containing physiological saline solution (PSS). Maximum arterial diameters were obtained by replacing Ca2+ PSS with PSS with zero Ca2++2 mmol/L EGTA (n=12). B, Traces and averaged data of the myogenic response in CaV3.2−/− mesenteric arteries (n=8). C, Percentage myogenic tone was significantly higher in CaV3.2−/− (n=7) than in wild-type C57BL/6 (n=11) arteries (unpaired t test, *P ≤ 0.05). D, Vasoconstriction evoked by 60 mmol/L K+ was similar in C57BL/6 and CaV3.2−/− pressurized (15 mm Hg) arteries (n=11–17, unpaired t test; NS denotes not significant). E, Messenger RNA of key genes (CaV1.2, CaV3.1, BKca-α, and RyR2) were not different in C57BL/6 and CaV3.2−/− mesenteric arteries. Relative expression was calculated using 3 independent quantitative PCR reactions.
and Ca\(_{3.2}^{2+}\) arteries were myogenically active and constricted as intravascular pressure increased from 20 to 100 mm Hg. Ca\(^{2+}\)-free saline (0 mmol/L Ca\(^{2+}\)+2 mmol/L EGTA) reversed myogenic constriction and evoked passive arterial dilation. Expressing data as a percentage myogenic tone (Figure 1C) revealed the predicted enhancement in Ca\(_{3.2}^{-/-}\) arteries (at 60 mm Hg: Ca\(_{3.2}^{-/-}\), 28%±2; C57BL/6, 19%±3). Although myogenic tone was significantly different, 60 mmol/L K\(^+\)-induced vasoconstriction was similar in C57BL/6 (40%±2%) and Ca\(_{3.2}^{-/-}\) (43%±2%) pressurized arteries (Figure 1D). Note, the basal diameter of Ca\(_{3.2}^{-/-}\) arteries was smaller than that of C57BL/6, a finding consistent with variable myogenic tone. Interpretational cautious is, however, warranted because Ca\(_{3.2}^{-/-}\) mice display a lighter body mass than wild-type animals. Quantitative PCR showed that mRNA expression of Ca V1.2, Ca V3.1, BKCa-\(\alpha\), or RyR2 was comparable in wild-type and Ca\(_{3.2}^{-/-}\) arteries (Figure 1E).

Micromolar Ni\(^{2+}\) Selectively Blocks Ca\(_{3.2}^{2+}\) Currents

Mesenteric arterial smooth muscle cells from C57BL/6 mice express 3 subtypes of voltage-gated Ca\(^{2+}\) channels (Ca\(_{1.2}\), Ca\(_{3.1}\), and Ca\(_{3.2}\)) and thus, total inward current is representative of this ensemble of channels. To distinguish between the subcomponents, we used patch clamp electrophysiology in combination with defined pharmacology. First, nifedipine (200 nmol/L) was applied to block L-type Ca\(_{1.2}\) channels and reveal a current predominated by T-type conductances (Figure 2A). Subsequent application of 50 \(\mu\)mol/L Ni\(^{2+}\), which is presumed to be a selective Ca\(_{3.2}\) blocker, reduced the nifedipine-insensitive T-type currents in C57BL/6 but not in Ca\(_{3.2}^{-/-}\) smooth muscle cells (Figure 2B and 2C). The absence of an effect of Ni\(^{2+}\) in Ca\(_{3.2}^{-/-}\) myocytes is consistent with this pharmacological selectivity. Note that the broad-spectrum T-type blocker (NNC 55–0396, 1 \(\mu\)mol/L) subsequently abolished the residual current in both C57BL/6 and Ca\(_{3.2}^{2+}\) myocytes because of the suppression of remaining Ca\(_{3.1}\) current (Figure 2C). Importantly, voltage dependence profiles demonstrated that the T-type current is available for activation at physiological membrane potentials (Figure I in the online-only Data Supplement). As noted previously, Ca\(_{3.1}\) mRNA levels were similar among the 2 groups of animals, whereas Ca\(_{1.2}\) was modestly but insignificantly lower in Ca\(_{3.2}^{-/-}\) arteries (Figure 1E).

Ca\(_{3.2}\) Activity Regulates BK\(_{ca}\)-Mediated STOCs

Given the enhancement of myogenic constriction in Ca\(_{3.2}^{-/-}\) arteries, we next tested whether this T-type channel modifies myogenic reactivity through a negative feedback response that involves downstream BK\(_{ca}\). We used perforated patch clamp electrophysiology to monitor BK\(_{ca}\)-mediated spontaneous transient outward K\(^+\) currents (STOCs) in arterial smooth muscle cells from wild-type and knockout animals. In C57BL/6 cells held at the physiological voltage of −40 mV, Ni\(^{2+}\) significantly suppressed STOC frequency. In contrast, Ni\(^{2+}\) had no effect on STOCs when C57BL/6 cells were voltage-clamped at more depolarized potentials (−20 mV), a finding consistent with the voltage profile of Ca\(_{3.2}\) channel (Figure 3A). In Ca\(_{3.2}^{-/-}\) cells, Ni\(^{2+}\) had no effect at either −40
Figure 3. Ca\textsubscript{\textit{\textalpha}}\textsubscript{3.2} channel modulates BK\textsubscript{\textalpha} mediated spontaneous transient outward K\textsuperscript{+} currents (STOCs). A and B, Representative traces of STOCs recorded at −40 and −20 mV in wild-type C57BL/6 (A) or Ca\textsubscript{\textalpha}3.2\textsuperscript{−/−} (B) arterial smooth muscle cells. Application of 50 μmol/L Ni\textsuperscript{2+} suppressed STOC frequency only at −40 mV in C57BL/6 cells with no noticeable effect at other conditions. C, Averaged bar graphs illustrate the effect of Ni\textsuperscript{2+} on STOC frequency (Hz) and amplitude (pA) at −40 or −20 mV in C57BL6 or Ca\textsubscript{\textalpha}3.2\textsuperscript{−/−} arterial myocytes (n=8–11, *P≤0.05, paired t test).
or −20 mV (Figure 3B). All STOCs were fully abolished by the application of the BK<sub>Ca</sub> inhibitor paxilline (1 μmol/L; Figure II in the online-only Data Supplement). Message expression of the BK<sub>Ca</sub> pore-forming subunit (BK<sub>Ca</sub>-α) was similar in C57BL/6 and Ca<sub>V3.2</sub><sup>−/−</sup> arteries (Figure 1E). Further, Ni<sup>2+</sup> had no effect on STOC amplitude under different experimental conditions (Figure 3C). Note, basal STOCs tended to fire at lower frequencies in Ca<sub>V3.2</sub><sup>−/−</sup> myocytes compared with C57BL/6 counterparts. Statistical analysis was not performed across groups as cells that did not fire sufficient STOCs were eliminated a priori from experimentation.

**Ca<sub>V3.2</sub> Channel Controls Ca<sup>2+</sup> Spark Generation**

Given the ability of Ca<sub>V3.2</sub> channel to modulate BK<sub>Ca</sub> current (Figure 3) and the reported correlation between RyR-mediated spark generation and BK<sub>Ca</sub> activation,<sup>10,16</sup> we next explored the Ca<sub>V3.2</sub>-Ca<sup>2+</sup> spark relationship using Ca<sup>2+</sup> imaging and line scan analysis of mouse mesenteric arteries (Figure 4). In C57BL/6 arteries loaded with Fluo-4, Ca<sup>2+</sup> sparks were observed in 76% of the 454 line scans performed under control conditions. Depolarizing arteries (30 mmol/L K<sup>+</sup>) increased spark activity (95%), whereas the subsequent addition of Ni<sup>2+</sup> significantly reduced firing (52%; Figure 4A and 4B). In comparison, 30 mmol/L K<sup>+</sup> increased spark firing in Ca<sub>V3.2</sub><sup>−/−</sup> arteries from 58% to 94% (456 line scans) but Ni<sup>2+</sup> failed to attenuate sparks (98%; Figure 4A and 4B). In depolarized wild-type C57BL/6 arteries, Ca<sup>2+</sup> spark frequency was calculated to be 0.0347 and 0.0153 sparks/μm s in the absence and presence of Ni<sup>2+</sup>, respectively; spark frequency in knockout tissues was distinctively insensitive to the application of Ni<sup>2+</sup> (Figure 4C). The genetic absence of Ca<sub>V3.2</sub> channels was notably associated with lower percentage firing (Ca<sub>V3.2</sub><sup>−/−</sup>, 58%; C57BL/6, 76%) and lower basal Ca<sup>2+</sup> spark frequency when compared with wild-type arteries (Ca<sub>V3.2</sub><sup>−/−</sup>, 0.0065±0.0014; C57BL/6, 0.0169±0.0005 sparks/μm s). The amplitudes and spatiotemporal characteristics of Ca<sup>2+</sup> sparks displayed no significant changes before and after the application of Ni<sup>2+</sup> on C57BL/6 and Ca<sub>V3.2</sub><sup>−/−</sup> arteries (Figure 4D).

**Ca<sub>V3.2</sub> Activity Restrains Myogenic Constriction by Altering BK<sub>Ca</sub> Feedback**

The application of Ni<sup>2+</sup> (50 μmol/L) onto C57BL/6 arteries evoked vasoconstriction at intravascular pressure values between 20 and 60 mmHg, and this vasomotor effect diminished at higher pressures; Ca<sub>V3.2</sub><sup>−/−</sup> arteries lacked a similar response (Figure 5A). The percentage of myogenic tone in wild-type C57BL/6 arteries increased after the application of Ni<sup>2+</sup> (at 60 mmHg: control 20%±4% versus Ni<sup>2+</sup> 25%±1%), but was not altered in Ca<sub>V3.2</sub><sup>−/−</sup> arteries (control 30%±5% versus Ni<sup>2+</sup> 28%±8%; Figure 5B). Coinciding with vasomotor data, membrane potential measurements showed that Ni<sup>2+</sup> only depolarized C57BL/6 but not Ca<sub>V3.2</sub><sup>−/−</sup> pressurized arteries.
In C57BL/6 arteries, the BK Ca blocker (paxilline, 1 μmol/L) evoked vasoconstriction and enhanced myogenic tone similar to that of Ni2+ (Figure 5D), an observation consistent with a common signaling axis between CaV3.2 and BKCa channels. When Ni2+ and paxilline were sequentially added to the same wild-type artery, Ni2+ evoked vasoconstriction, whereas subsequent paxilline had no additional effect. Similar experiments using CaV3.2−/− arteries demonstrated a lack of vasomotor responses to Ni2+ but preserved responsiveness to paxilline (Figure 5E).

**Discussion**

This study used wild-type and Ca3.2 knockout mice to examine the purported contribution of Ca3.2 channels to a negative feedback response that counterbalances arterial tone development. Using mesenteric arteries, functional experiments illustrated that the genetic ablation or pharmacological suppression of CaV3.2 channel selectively enhanced myogenic constriction. Subsequent electrophysiological recordings revealed that Ca3.2 channel modulates downstream BKCa-mediated STOCs. Ca2+ imaging further demonstrated that Ca3.2−/− Mice Display Normal Blood Pressure Responses

Pharmacological and genetic approaches suggested that Ca3.2 channel counterbalances myogenic constriction (Figure 1 and 5) and could as such influence blood pressure regulation. To explore this possibility, we catheterized carotid arteries of C57BL/6 and CaV3.2−/− mice to monitor blood pressure under resting conditions and in response to a vasopressor challenge. As depicted (Figure 6A), basal mean arterial pressure was similar in wild-type and knockout mice (C57BL/6, 100±2 mm Hg; Ca3.2−/−, 103±5 mm Hg), a finding consistent with earlier reports in conscious animals.17,18 Given that Ca3.2 channels seem to be involved in a feedback mechanism, we next assessed whether this conductance can alter mean arterial pressure responsiveness to a vasopressor challenge. The intravenous administration of phenylephrine (α1-adrenoceptor agonist, 1–16 μg/kg body weight) evoked dose-dependent rises in mean arterial pressure, and these transient responses were similar among the 2 groups (Figure 6B). Analogous to in vivo experiments, phenylephrine (0.01–10 μmol/L)-induced vasoconstriction was similar in C57BL/6 and Ca3.2−/− mesenteric arteries (Figure 6C and 6D).
Ca\textsuperscript{2+} spark generation is an intermediary step in the Ca\textsubscript{V3.2}-BK\textsubscript{Ca} functional axis. Finally, although Ca\textsubscript{V3.2} moderated myogenic tone, this regulatory mechanism did not influence resting blood pressure or vasopressor-induced responses. In summary, findings from this study establish a model by which Ca\textsubscript{V3.2} channel restrains myogenic constriction by driving a process where Ca\textsuperscript{2+} influx triggers Ca\textsuperscript{2+} sparks and downstream activation of BK\textsubscript{Ca} currents (Figure III in the online-only Data Supplement).

Resistance arteries control tissue perfusion and respond to a range of vasoactive stimuli.\textsuperscript{1–5} The integral ability of resistance arteries to respond to perturbations in arterial pressure, known as the myogenic response,\textsuperscript{6} is intrinsic to vascular smooth muscle and plays an essential role in maintaining blood flow and capillary pressure to tissues, such as the brain and the heart.\textsuperscript{19} This response is mechanistically linked to a rise in cytosolic [Ca\textsuperscript{2+}] driven by a depolarization that activates L-type Ca\textsubscript{V1.2} channels. The traditional perspective that Ca\textsubscript{V1.2} is the only voltage-gated Ca\textsuperscript{2+} channel of functional significance\textsuperscript{3} has shifted with the identification of 2 T-type Ca\textsuperscript{2+} channels,\textsuperscript{7,8} the first being Ca\textsubscript{V3.1}, which modestly facilitates myogenic tone at hyperpolarized voltages.\textsuperscript{9} In contrast, Ca\textsubscript{V3.2} channels have been reported to drive a paradoxical feedback response that limits arterial constriction.\textsuperscript{10,12} The feedback response begins with Ca\textsuperscript{2+} influx through Ca\textsubscript{V3.2} channels triggering ryanodine receptors to initiate Ca\textsuperscript{2+} sparks. These discrete sarcoplasmic reticulum–driven events in turn activate BK\textsubscript{Ca} channels to hyperpolarize and dilate resistance arteries.\textsuperscript{10} Although an intriguing concept, data interpretation is singularly dependent on the presumed selectivity of Ni\textsuperscript{2+} as a pharmacological Ca\textsubscript{V3.2} blocker.\textsuperscript{11} Current knowledge is also restricted to the cerebral circulation, and experiments have not extended to other vascular beds essential to blood pressure regulation.

One means to better probe the functional properties of arterial Ca\textsubscript{V3.2} channel is to use an animal model in which the channel has been genetically ablated.\textsuperscript{12} In this regard, we performed pressure myography on arteries from Ca\textsubscript{V3.2} knockout (Ca\textsubscript{V3.2}\textsuperscript{−/−}) mice to study the vascular phenotype. Consistent with the view that Ca\textsubscript{V3.2} channel mediates feedback vasodilation, we observed enhanced myogenic constriction in mesenteric arteries from Ca\textsubscript{V3.2}\textsuperscript{−/−} mice. This finding was somewhat akin to the functional observations in coronary arteries\textsuperscript{12} and the enhancement of rat cerebral arterial myogenic tone noted in the presence of Ni\textsuperscript{2+}.\textsuperscript{10} Our present findings overcome concerns raised by past studies that off-target effects of Ni\textsuperscript{2+} could theoretically have accounted for the vasomotor responses.\textsuperscript{20–22} In particular, we were unable to elicit Ni\textsuperscript{2+}-sensitive current in Ca\textsubscript{V3.2}\textsuperscript{−/−} arterial myocytes, and Ni\textsuperscript{2+} also failed to constrict/depolarize arteries from knockout mice.

The unexpected ability of Ca\textsubscript{V3.2} channel to mediate a negative feedback response has been previously tied to downstream modulation of BK\textsubscript{Ca} channels through intermediary activation of ryanodine receptors.\textsuperscript{10} In arterial smooth muscle, BK\textsubscript{Ca} is ubiquitously expressed and known to moderate membrane depolarization and arterial constriction.\textsuperscript{23} To activate arterial BK\textsubscript{Ca}, vasoactive stimuli must induce depolarization and elicit a discrete micromolar rise in [Ca\textsuperscript{2+}]\textsubscript{i} in the subsarcolemma taking the form of a Ca\textsuperscript{2+} spark.\textsuperscript{24} Here, we present multiple lines of evidence implicating BK\textsubscript{Ca} as the final downstream effector of Ca\textsubscript{V3.2} channel. First, electrophysiology revealed that BK\textsubscript{Ca}–mediated STOCs were sensitive to Ni\textsuperscript{2+} in wild-type but not in Ca\textsubscript{V3.2}\textsuperscript{−/−} arterial myocytes. Second, pressure myography illustrated that adding Ni\textsuperscript{2+} or paxilline (BK\textsubscript{Ca} blocker) to Ca\textsubscript{V3.2} knockout arteries did not alter the myogenic response, suggesting that the resistance to Ni\textsuperscript{2+}–sensitive current is not due to the inability of Ni\textsuperscript{2+} to reach BK\textsubscript{Ca} channels.

![Figure 6. Ca\textsubscript{V3.2}−/− mice display normal resting blood pressure and responsiveness to phenylephrine. A. Resting mean arterial pressure of anesthetized C57BL/6 or Ca\textsubscript{V3.2}−/− mice (n=10 each). B. Changes in mean arterial pressure (ΔMAP, mm Hg) in response to intravenous phenylephrine (1–16 μg/kg body weight) in C57BL/6 and Ca\textsubscript{V3.2}−/− mice (n=10 each). C. Diameter responses of C57BL/6 and Ca\textsubscript{V3.2}−/− mesenteric arteries to increased pressure from 15 to 60 mm Hg followed by cumulative application of phenylephrine (PE; 0.01–10 μmol/L). Maximum diameters (D\textsubscript{max}) were finally achieved by perfusion of Ca\textsuperscript{2+}–free PSS. D. Phenylephrine concentration response curve shows no significant differences between wild-type C57BL/6 and Ca\textsubscript{V3.2}−/− arteries (n=8 each).](http://atvb.ahajournals.org/doi/fig/10.1161/HCJI.117.129668)
inhibitor) to the superfusate comparably augmented myogenic tone. Intriguingly, applying paxilline to wild-type arteries pretreated with Ni2+ had no additive effect, consistent with CaV3.2 and BKCa channels being linked through a common sequential pathway.

It has been long established that RyR activation is responsible for the initiation of BKCa-mediated STOCs in arterial smooth muscle,6,23,24 and this recognized relationship led us to examine the nature of Ca2+ spark generation in mouse mesenteric arteries. Indeed, inhibitors of RyR (eg, ryanodine) has been shown to suppress the generation of STOCs in vascular smooth muscle irrespective of their origin.24 Here and in consistency with CaV3.2 channel driving Ca2+ sparks and subsequently STOC generation, we used Ca2+ imaging and line scan analysis and observed that spark frequency decreased in wild-type arteries when CaV3.2 channels were inhibited with Ni2+. We also found that firing of Ca2+ sparks was unaffected by this divalent cation in CaV3.2−/− arteries and that basal Ca2+ spark frequency was lower than those of wild-type arteries. These findings align well with recent work from the cerebral circulation where a variety of functional, structural, electrophysiological, and computational observations draw a critical relationship between CaV3.2 and RyR and then BK Ca (Figure III in the online-only Data Supplement).10 Intriguingly, the preceding work is distinct from neuronal studies where T-type conductances have been suggested to directly activate Ca2+-activated K+ channels independent of RyR.11,25-28

With CaV3.2 channels playing an intimate role in limiting myogenic constriction, it is logical to argue that the loss of this conductance would alter peripheral resistance and systemic blood pressure regulation. We tested this supposition by catheterizing unanesthetized mice and assessing blood pressure at rest and in response to a vasopressor challenge. Resting blood pressure was similar among wild-type and knockout mice, a finding consistent with earlier reports which used different monitoring approaches (eg, catheterization, tail cuff) in conscious animals over longer time spans (days to weeks).17,18 Given the presumed role of CaV3.2 in feedback (rather than active vasodilation), we challenged blood pressure regulation using intravenous phenylephrine. This multidose challenge evoked comparable rises in blood pressure in arteries isolated from wild-type and CaV3.2−/− mice (Figure III in the online-only Data Supplement). This novel functional axis, posed CaV3.2/RyR/BKCa feedback mechanism to effectively suppress the generation of STOCs in arterial vessels irrespective of their origin.24 Here, this intriguing anomaly.

In conclusion, this study showed that arterial CaV3.2 channels retain a unique ability to counterbalance myogenic constriction. This negative feedback response entails a modulatory paradigm in which Ca2+ flux through CaV3.2 channel triggers Ca2+ spark generation and then activates BKCa channels to hyperpolarize and relax arteries (Figure III in the online-only Data Supplement). This novel functional axis, recently described in the human cerebral circulation,31 challenges the traditional view that voltage-gated Ca2+ channels solely facilitate arterial tone development.

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**Disclosures**

None.

**References**


Significance

Vascular smooth muscle cells express T-type Ca2+ channels along with L-type channels. Although the latter have been long implicated in arterial excitation–contraction coupling, studies have only recently begun to assess the role of T-type channels. Using an animal model in which Ca3.2, a T-type channel, was genetically deleted, we tested its role in arterial tone development. We demonstrate that resistance arteries from knockout animals paradoxically display enhanced responsiveness to arterial pressure. This enhancement was mechanistically attributed to the ability of Ca3.2 to modulate downstream K+ channels, which hyperpolarize and relax arteries. This novel data challenge the traditional view that voltage-gated Ca2+ channels are singularly involved in the genesis of arterial constriction.
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SUPPLEMENTAL MATERIALS

Genetic ablation of Ca\textsubscript{v}3.2 channels enhances the arterial myogenic response by modulating the RyR-BK\textsubscript{Ca} axis

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Running Title: Ca\textsubscript{v}3.2 counterbalances myogenic constriction

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DETAILED METHODS

Animal procedures

Animal procedures were approved by the Animal Care and Use Committee at the University of Calgary and Loma Linda University. Briefly, male or female C57BL/6J (wild-type) and Cav3.2 knockout (Cav3.2−/−) mice (2–4 months old, obtained from Jackson Laboratories) were asphyxiated in a CO2 chamber. The mesentery was carefully removed and placed in cold phosphate-buffered saline solution (pH 7.4) containing (in mM): 138 NaCl, 3 KCl, 10 Na2HPO4, 2 NaH2PO4, 5 glucose, 0.1 CaCl2 and 0.1 MgSO4. Third and fourth order mesenteric arteries were dissected out of surrounding tissues and cut into 2–3 mm segments.

Vessel myography and membrane potential (VM) measurement

Mesenteric arteries were mounted in an arteriograph and superfused with physiological saline solution (PSS; 37°C; pH 7.4; 21% O2, 5% CO2, balance N2) containing (in mM): 119 NaCl, 4.7 KCl, 20 NaHCO3, 1.1 KH2PO4, 1.2 MgSO4, 1.6 CaCl2 and 10 glucose. To limit the endothelial influence, air bubbles were passed through the lumen for 1–2 min. Arteries were equilibrated at 15 mmHg and contractile responsiveness assessed by briefly applying 60 mM KCl. Following equilibration, intravascular pressure was incrementally elevated from 20 to 100 mmHg and external diameter monitored. Maximal diameter was assessed in Ca2+-free PSS (zero Ca2+ + 2 mM EGTA). Percentage myogenic tone was calculated as follows: % Myogenic tone=100*(D0–D)/D0; where D is external diameter under control conditions (Ca2+ PSS) or treated conditions, and D0 is external diameter in Ca2+-free PSS. Smooth muscle membrane potential (VM) was ascertained as previously published1 by inserting a glass microelectrode backfilled with 1 M KCl (tip resistance ~120-150 MΩ) into the vessel wall while pressurized at 60 mmHg. Criteria for successful impalement included: 1) a sharp negative VM deflection upon insertion; 2) a stable VM for ≥1 min after entry; and 3) a sharp return to baseline upon electrode removal.

Quantitative polymerase chain reaction (qPCR)

Total RNA was isolated from mouse C57BL/6 or Cav3.2−/− mesenteric arteries using the RNeasy plus micro kit (Qiagen) following manufacturer’s recommendations. Reverse transcription was performed with 20 ng per sample of total RNA using the Quantitect reverse transcription kit (Qiagen). For the negative control groups, all components except the reverse transcriptase were included in the reaction mixtures. Real-Time PCR using intron-spanning primer sequences was performed using the Kapa SYBR Fast Universal qPCR Kit (Kapa Biosystems). Mouse beta-actin gene was utilized as the reference gene. Control reactions and those containing cDNA from arteries were performed with 1 ng of template per reaction. The running protocol extended to 45 cycles consisting of 95°C for 5 s, 55°C for 10 s and 72°C for 10 s using an Eppendorf Realplex 4 Mastercycler. PCR specificity was checked by dissociation curve analysis, and assay validation was confirmed by testing serial dilutions of pooled template cDNAs suggesting a linear dynamic range of 50-0.05 ng template and yielded percent efficiencies ranging from 85-95%. No template controls yielded no detectable fluorescence. Expression levels of the various genes of interest in arteries from Cav3.2−
relative to C57BL/6 mice were determined using the relative expression software tool (REST) version 2.0.13.2

Quantitative PCR primer sequences and validation parameters.

<table>
<thead>
<tr>
<th>Target</th>
<th>Primers</th>
<th>Amplicon</th>
<th>Efficiency (%)</th>
<th>Linear Dynamic Range (ng template (Cq values))</th>
<th>Cq values ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cav1.2</td>
<td>ATTCGACGTGAAGGCACTG GAGTTCAAGGACCACCTGGAG</td>
<td>90</td>
<td>95</td>
<td>50-0.05 (23.41-33.75)</td>
<td>33.22±0.43</td>
</tr>
<tr>
<td></td>
<td>TCCTGGTCATAACCTCAGC GAGGCTGTGGAAGACGATGT</td>
<td>98</td>
<td>85</td>
<td>50-0.005 (24.09-39.29)</td>
<td>38.98±0.21</td>
</tr>
<tr>
<td>Cav3.1</td>
<td>TCCTAGCATTGGTGCCCTCAGC GTAGAGGGAAGACGATGT</td>
<td>127</td>
<td>92</td>
<td>33-0.0033 (22.48-36.48)</td>
<td>34.56±0.06</td>
</tr>
<tr>
<td></td>
<td>TGGCTGATGATGAGGAGGAAACACGTTGAA</td>
<td>144</td>
<td>88</td>
<td>50-0.005 (21.78-36.15)</td>
<td>35.11±0.50</td>
</tr>
<tr>
<td>BKCaα</td>
<td>ACTGCGAAGCTGGTCCGTAACGGAC AGCCCTTGTGAAGCCACAG</td>
<td>100</td>
<td>88</td>
<td>50-0.0005 (20.61-39.35)</td>
<td>31.15±0.43</td>
</tr>
</tbody>
</table>

Isolation of arterial smooth muscle cells

As previously described3, arterial segments were placed in an isolation medium containing (in mM): 60 NaCl, 80 Na-glutamate, 5 KCl, 2 MgCl2, 10 glucose and 10 HEPES with 1 mg/ml bovine serum albumin (pH 7.4, 37 °C, 10 min). Vessels were then exposed to a two-step digestion process: 1) 13 min incubation in isolation medium containing 0.5 mg/ml papain and 1.5 mg/ml dithioerythritol; and 2) 10 minutes incubation in isolation medium containing 100 μM Ca2+, 0.7 mg/ml type F collagenase and 0.4 mg/ml type H collagenase. Following incubation, tissues were washed repeatedly with ice-cold isolation medium and triturated with a fire-polished pipette. Liberated cells were stored in ice-cold isolation medium for use within ~6 hr.

Electrophysiological recordings

Conventional patch-clamp electrophysiology was used to monitor whole-cell voltage-gated Ca2+ channel currents in isolated smooth muscle cells. 3 Recording electrodes (5-8 MΩ) were pulled from borosilicate glass microcapillary tubes using a micropipette puller, and backfilled with pipette solution (in mM): 135 CsCl, 5 Mg-ATP, 10 HEPES, and 10 EGTA (pH 7.2). Cells were voltage-clamped and equilibrated in bath solution (in mM): 110 NaCl, 1 CsCl, 10 BaCl2, 1.2 MgCl2, 10 glucose, and 10 HEPES (pH 7.4). A 1 M NaCl–agar salt bridge between the reference electrode and the bath solution was used to minimize offset potentials. To record whole-cell Ba2+ currents, isolated cells held at -60 mV were exposed to a pre-pulse (-90 mV, 200 ms) and then test pulses (-50 to 40 mV, 10 mV intervals, 300 ms).
Perforated patch-clamp electrophysiology was used to measure spontaneous transient outward K⁺ currents (STOCs) in freshly isolated smooth muscle cells. The bath solution contained (in mM): 134 NaCl, 4 KCl, 2 MgCl₂, 2 CaCl₂, 10 glucose, and 10 HEPES (pH 7.4). The pipette solution contained (in mM): 110 K aspartate, 30 KCl, 10 NaCl, 2 MgCl₂, 10 HEPES, and 0.05 EGTA (pH 7.2) with 200 µg/ml amphotericin B. Currents were recorded while cells were held at -40 or -20 mV. STOC analysis was performed using Clampfit 10.3; threshold for detection was set to be ~3 times the BK_{Ca} single channel conductance. Whole-cell currents were recorded using an Axopatch 200B patch-clamp amplifier, filtered at 1 kHz, digitized at 5 kHz, and were stored on a computer for offline analysis. Whole-cell capacitance averaged ~13 pF and all experiments were performed at room temperature.

**Ca²⁺ spark measurement**

Ca²⁺ sparks were recorded in mouse arterial myocytes loaded with the Ca²⁺ sensitive dye Fluo-4 AM and using a Zeiss LSM 710 NLO laser scanning confocal imaging workstation on an inverted microscope platform (Zeiss Axio Observer Z1). Fluo-4 AM was dissolved in DMSO and added from a 1 mM stock to the arterial suspension at a final concentration of 10 μM, along with 0.1% pluronic F127 for 1-1.5 hr at room temperature in the dark in balanced salt solution. Arterial segments were then washed (30 min) to allow dye esterification and then cut into linear strips. Arterial segments were pinned to Sylgard blocks and placed in an open bath imaging chamber mounted on the confocal imaging stage. Arteries were illuminated at 488 nm with a krypton argon laser, and emitted light was collected using a photomultiplier tube. Line scans were imaged at 529 fps with the emission signal recorded at 493-622 nm. The acquisition period for Ca²⁺ spark recordings was 18.9 s and the resultant pixel size ranged from 0.0148 to 0.0911 μm per pixel. To ensure that sparks within the cell were imaged, the pinhole was adjusted to provide an imaging depth of 2.5 μm, this is roughly equivalent to 50% the width of the cell based on morphological examination of live preparations. Analysis was performed to characterize the percentage of scans with Ca²⁺ sparks (% firing), Ca²⁺ spark frequency, amplitude and spatiotemporal characteristics using SparkLAB 4.2.1. Threshold for spark detection was 3.2 times the standard deviation of the background noise above mean background. Prior to analysis, background fluorescence was subtracted from each image assuming homogeneous background levels in each cell.

**Intravascular catheterization**

Male C57BL/6 or Cav3.2⁻/⁻ mice were anesthetized with intraperitoneal injection of ketamine (150 mg/kg) and xylazine (10 mg/kg). Anesthesia was extended by additional ketamine (10 mg/kg) as required. Anesthesia adequacy was verified by the abolition of the withdrawal and blink reflexes. A small neck incision was made and the left common carotid artery was ligated and catheterized using an arterial cannula. Similarly, a small incision was made to expose and catheterize the right jugular vein for intravenous drug administration. Changes in mean arterial pressure (ΔMAP) were monitored using a data acquisition system (ACQKnowledge). Mice were sacrificed at the end of the experiment using a high dose of anesthetic.
Statistical analysis

Data are expressed as means±S.E.M., and n indicates the number of cells, arteries or mice. Where appropriate, paired/unpaired t-tests or one way ANOVA were performed to compare the effects of a given condition/treatment on arterial diameter, or whole-cell current. *P values ≤ 0.05 were considered statistically significant. Averaged current-voltage relationships were fit to the following Peak Gaussian function: \( I(V) = I_{\text{max}} \cdot \exp\left[-0.5\left(\frac{V-V_{\text{max}}}{b}\right)^2\right] \); where \( I_{\text{max}} \) is peak current (I), \( V_{\text{max}} \) is \( V \) at \( I_{\text{max}} \), and \( b \) is the slope of the distribution.

Solutions and Chemicals

Drugs, enzymes and buffer reagents were purchased from Sigma-Aldrich, unless otherwise mentioned.

SUPPLEMENTAL REFERENCES


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Supplementary Figure I: Voltage-dependence of activation and steady-state inactivation of T-type current. In C57BL/6 mesenteric arterial smooth muscle cells, voltage dependence of activation and steady-state inactivation (availability) of T-type current was assessed. Barium (10 mM) was employed as the charge carrier and recordings were made in the presence of an L-type blocker (nifedipine, 200 nM). Upper insets depict protocols employed to assess availability (left) and activation (right). The red bar denotes physiological potentials that overlaps with the window current. Note that in physiological Ca$^{2+}$ curves are expected to shift rightward by ~10-20 mV and window currents are expected to remain overlapping with physiological potentials.
**Supplementary Figure II: Paxilline abolishes STOCs.** Spontaneous transient outward K⁺ currents were fully abolished in wild-type (C57BL/6) or knockout Cav3.2⁻⁻ smooth muscle cells by paxilline. This BKca inhibitor was equally effective at holding potentials -40 or -20 mV (n=10 cells each).
Supplementary Figure III: A diagram highlighting the proposed role of Cav3.2 channels in vascular smooth muscle. A stimulus, such as an increase in intravascular pressure, elicits membrane potential ($V_M$) depolarization of the smooth muscle cells. This electrical stimulus triggers the activation of the voltage-gated $Ca^{2+}$ channel, Cav3.2. Ensuing $Ca^{2+}$ influx through Cav3.2 pores activates RyR on the sarcoplasmic reticulum to release $Ca^{2+}$ sparks. The latter release events then activate $BK_Ca$ to generate hyperpolarizing $K^+$ currents. This hyperpolarizing stimulus feedbacks upon membrane depolarization (red) and $Ca^{2+}$ influx responsible for smooth muscle contraction.