Transcriptional Upregulation of $\alpha_2\delta$-1 Elevates Arterial Smooth Muscle Cell Voltage-Dependent Ca$^{2+}$ Channel Surface Expression and Cerebrovascular Constriction in Genetic Hypertension


See Editorial Commentary, pp 894–895

Abstract—A hallmark of hypertension is an increase in arterial myocyte voltage-dependent Ca$^{2+}$ (Ca$_{\text{v1.2}}$) currents that induces pathological vasoconstriction. Ca$_{\text{v1.2}}$ channels are heteromeric complexes composed of a pore-forming Ca$_{\text{v1.2}\alpha_1}$ with auxiliary $\alpha$,$\delta$ and $\beta$ subunits. Molecular mechanisms that elevate Ca$_{\text{v1.2}}$ currents during hypertension and the potential contribution of Ca$_{\text{v1.2}}$ auxiliary subunits are unclear. Here, we investigated the pathological significance of $\alpha$,$\delta$ subunits in vasoconstriction associated with hypertension. Age-dependent development of hypertension in spontaneously hypertensive rats was associated with an unequal elevation in $\alpha$,$\delta$-1 and Ca$_{\text{v1.2}\alpha_1}$ mRNA and protein in cerebral artery myocytes, with $\alpha_2\delta$-1 increasing more than Ca$_{\text{v1.2}\alpha_1}$. Other $\alpha$,$\delta$ isoforms did not emerge in hypertension. Myocytes and arteries of hypertensive spontaneously hypertensive rats displayed higher surface-localized $\alpha$,$\delta$-1 and Ca$_{\text{v1.2}\alpha_1}$ proteins, surface $\alpha$,$\delta$-1:Ca$_{\text{v1.2}\alpha_1}$ ratio, Ca$_{\text{v1.2}}$ current density and noninactivating current, and pressure- and depolarization-induced vasoconstriction than those of Wistar-Kyoto controls. Pregabalin, an $\alpha$,$\delta$-1 ligand, did not alter $\alpha$,$\delta$-1 or Ca$_{\text{v1.2}\alpha_1}$ total protein but normalized $\alpha$,$\delta$-1 and Ca$_{\text{v1.2}\alpha_1}$ surface expression, surface $\alpha$,$\delta$-1:Ca$_{\text{v1.2}\alpha_1}$, Ca$_{\text{v1.2}}$ current density and inactivation, and vasoconstriction in myocytes and arteries of hypertensive rats to control levels. Genetic hypertension is associated with an elevation in $\alpha$,$\delta$-1 expression that promotes surface trafficking of Ca$_{\text{v1.2}}$ channels in cerebral artery myocytes. This leads to an increase in Ca$_{\text{v1.2}}$ current-density and a reduction in current inactivation that induces vasoconstriction. Data also suggest that $\alpha$,$\delta$-1 targeting is a novel strategy that may be used to reverse pathological Ca$_{\text{v1.2}}$ channel trafficking to induce cerebrovascular dilation in hypertension. (Hypertension. 2012;60:1006-1015.)

Key Words: calcium channels  ■ genetic hypertension  ■ vasodilation  ■ vasoconstriction

Hypertension is associated with an elevation in arterial contractility that increases systemic blood pressure and restricts organ blood flow, leading to end-organ damage. Hypertension is also a major predictor for a variety of cerebral diseases, including stroke, Alzheimer disease, and dementia. One characteristic pathological alteration that occurs in hypertension is an elevation in vascular smooth muscle cell (myocyte) voltage-dependent Ca$^{2+}$ influx. Voltage-dependent L-type Ca$^{2+}$ (Ca$_{\text{v1.2}}$) channels are the primary Ca$^{2+}$ entry pathway in arterial myocytes and are essential for contractility regulation by a wide variety of stimuli, including intravascular pressure, membrane potential, and vasoconstrictors. A hypertension-associated elevation in Ca$_{\text{v1.2}}$ currents leads to an increase in intracellular Ca$^{2+}$ concentration and vasoconstriction. However, molecular mechanisms that elevate arterial myocyte Ca$_{\text{v1.2}}$ currents in hypertension, leading to vasoconstriction, are unclear.

Ca$_{\text{v1.2}}$ channels are heteromeric complexes composed of a pore-forming $\alpha_1$ with auxiliary $\alpha$,$\delta$ and $\beta$ subunits. Four $\alpha$,$\delta$ (1–4) subunit isoforms have been identified that are each encoded by different genes. $\alpha$,$\delta$ subunits undergo posttranslational cleavage into a highly glycosylated extracellular $\alpha$, and a smaller $\delta$ subunit, which are subsequently coupled by a disulfide bond to form a single functional protein. $\alpha_2\delta$ subunits are membrane bound by the bilayer-spanning $\delta$ subunit. Recently, $\alpha_2\delta$-1 was identified as being critical for functional trafficking of Ca$_{\text{v1.2}\alpha_1}$ subunits to the plasma membrane (surface) in arterial myocytes. To date, no studies have investigated pathological or disease-associated molecular changes in Ca$_{\text{v1.2}}$ auxiliary subunits, including $\alpha_2\delta$ subunits, in myocytes of resistance-sized...
arteries. In addition, it is unclear whether the subunit composition of arterial myocyte surface CaV1.2 channels is altered in disease. Given that arterial myocyte CaV1.2 currents are elevated during hypertension, leading to vasoconstriction, we determined the subunit composition of CaV1.2 channels and investigated the involvement of α,δ subunits in this pathological alteration.5–11 Elucidating molecular mechanisms governing α,δ subunit regulation of CaV1.2 channels in hypertension could lead to the development of novel approaches to treat cardiovascular diseases.

Here, we used a genetic model of hypertension, the spontaneously hypertensive rat (SHR), to investigate the pathological significance of arterial myocyte α,δ subunits in hypertension. We showed that, during hypertension, an elevation in α,δ-1 expression increases plasma membrane CaV1.2 currents in arterial myocytes, leading to vasoconstriction. We also identified α,δ-1 as a novel therapeutic target to induce cerebrovascular dilation in hypertension.

Methods

Cell Isolation and Tissue Preparation

All of the animal protocols used were reviewed and approved by the animal care and use committee at the University of Tennessee Health Science Center. Male 6- or 12-week-old SHR and Wistar-Kyoto (WKY) rats were euthanized by IP injection of sodium pentobarbital (150 mg/kg of body weight, Vortech Pharmaceuticals, Dearborn, MI). Middle cerebral, posterior cerebral, and cerebellar arteries (≈100–200 μm diameter) were studied. Myocytes were enzymatically dissociated from dissected cerebral arteries, as described previously.4

Blood Pressure Measurements

Diastolic and systolic blood pressures were measured in conscious rats using a tail-cuff sphygmomanometer (Kent Scientific, Torrington, CT).

RT-PCR

RT-PCR was performed on myocytes individually collected under a microscope using an enlarged patch-clamp pipette to prevent contamination from other arterial wall cell types, as described previously.5

Quantitative Real-Time PCR

Total RNA was isolated from cerebral arteries using TRIzol (Invitrogen, Grand Island, NY). cDNA was transcribed using Affinity Script multiple temperature reverse transcriptase (Stratagene, Clara, CA). Gene specific primers and probes were designed using the Universal Probe Library. Sequences of primers and probes used and PCR reaction efficiencies are given in Table S1 (available in the online-only Data Supplement).

Protein Analysis and Biochemistry

Proteins were separated on SDS-PAGE gels and analyzed by Western blotting. Blots were cut at the 75-kDa marker to allow simultaneous probing of the upper section for α,δ-1 and lower section for α,δ-1. Protein band intensities were determined using Quantity One (BioRad, Hercules, CA) software. For quantification, protein band intensities were first normalized to actin and then to appropriate control samples.

Artery Surface Biotinylation

To determine the distribution of α,δ-1 and CaV1.2α,1 subunit proteins between surface and intracellular compartments, artery surface biotinylation was used, as described previously.16

Patch-Clamp Electrophysiology

Whole cell CaV1.2 currents were recorded in isolated myocytes using the whole cell patch clamp configuration, as described previously.16

Pressurized Artery Myography

Endothelium-denuded artery diameter was measured over a range of intravascular pressures (20–100 mmHg) in the presence and absence of nimodipine (1 μmol/L) using edge-detection myography, as described previously.12 Diameter responses to elevating extracellular K+ from 6 to between 20 and 60 mmol/L at 10 mmHg in the presence of pinacidil (10 μmol/L), a KATP channel opener, were also recorded. Arteries treated with pregabalin for 24 hours were also maintained in pregabalin throughout these experiments to inhibit CaV1.2 subunit membrane reinsertion.

Statistical Analysis

Summary data are presented as mean±SEM. Significance was determined using paired or unpaired t tests with Welch correction or ANOVA followed by Student-Newman-Keuls for multiple groups. P<0.05 was considered significant. Power analysis was carried out where P value was >0.05 to verify that sample size was sufficient to give a value of >0.8.

An expanded Methods section is available in the online-only Data Supplement.

Results

Age-Dependent Development of Genetic Hypertension Is Associated With an Elevation in Arterial Myocyte α,δ-1 and CaV1.2α,1 Subunit Expression

The pathological involvement of arterial myocyte CaV1.2 subunits was studied using a rat genetic model of hypertension. At 6 weeks of age, WKY and SHR diastolic, systolic, and mean arterial blood pressures were similar (Figure S1, available in the online-only Data Supplement). In contrast, at 12 weeks of age, diastolic, systolic, and mean arterial pressures were ≈63, 65, and 72 mmHg higher in SHRs than WKY rats, respectively (Figure S1).

Four different α,δ isoforms have been described, with α,δ-1 the only isoform expressed in normotensive Sprague-Dawley (SD) rat cerebral artery myocytes.14,15 We tested the hypothesis that hypertension is associated with a shift in α,δ isoform expression in myocytes of resistance-size arteries. RT-PCR detected only α,δ-1 in pure cerebral artery myocytes from 12-week-old WKY rats and hypertensive SHRs (Figure 1A). In contrast, the same primers amplified transcripts for all of the α,δ isoforms in WKY and SHR whole brain (Figure 1A).

Quantitative PCR was performed to compare α,δ-1 and CaV1.2α,1 message levels in 6- and 12-week-old WKY and SHR cerebral arteries. Eight different reference genes were screened to identify those with similar mRNA levels in cerebral arteries of WKY rats and SHRs (Table S1, available in the online-only Data Supplement). Rps5 mRNA levels were similar in WKY and SHR arteries and, thus, Rps5 was used as the reference gene for these experiments (Table S2). Quantitative PCR indicated that mean α,δ-1 and CaV1.2α,1 mRNA levels were similar in 6-week-old WKY and SHR arteries (Figure 1B). In contrast, α,δ-1 and CaV1.2α,1 mRNAs were ≈2.1- and 1.5-fold higher, respectively, in 12-week-old SHR compared with WKY arteries (Figure 1B).
Age-dependent development of hypertension was also associated with a larger increase in $\alpha_\delta$-1 than $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ mRNA (Figure 1B). These data indicate that hypertension is associated with an elevation in $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ protein but not with the appearance of other $\alpha_\delta$ isoforms in arterial myocytes.

Next, we investigated whether age-dependent development of genetic hypertension is associated with upregulation of $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins in cerebral arteries. $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ protein levels were similar in 6-week-old WKY and SHR arteries (Figure 1C and 1D). Aging between 6 and 12 weeks did not alter $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ protein in WKY rat arteries but increased these proteins $\approx$2.1- and 1.4-fold in SHR arteries (Figure S2). At 12 weeks of age, $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins were $\approx$2.5- and 1.7-fold higher in SHR compared with age-matched WKY arteries (Figure 1C and 1D). In agreement with message levels, age-dependent development of hypertension also increased $\alpha_\delta$-1 more than $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ protein (Figures 1C, 1D, and S2).

In summary, these data indicate that genetic hypertension is associated with transcriptional upregulation of both $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ in cerebral artery myocytes. $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins are elevated more than their respective mRNAs (Figures 1B through 1D and S2), suggesting that hypertension-associated changes in posttranslational events also contribute to increased $\text{Ca}_{\text{a}}$ $\text{a}_1,2$ channel subunit expression during hypertension. Furthermore, during hypertension there is a larger increase in mRNA and protein for $\alpha_\delta$-1 than for $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$.

**Hypertension Is Associated With an Elevation in Surface $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ Proteins in Arteries**

$\alpha_\delta$-1 induces membrane trafficking of $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ subunits in SD rat arterial myocytes. Therefore, we tested the hypothesis that an increase in $\alpha_\delta$-1 contributes to elevated surface $\text{Ca}_{\text{a}}$ $\text{a}_1,2$ expression in hypertension. Surface (plasma membrane) and intracellular $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins were measured in age-matched WKY and hypertensive SHR cerebral arteries using biotinylation. Surface-localized $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins were $\approx$2.6- and 2-fold higher, respectively, in SHR compared with WKY rat arteries (Figure 2A and 2B). A larger percentage of total $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ was located at the plasma membrane in SHR compared with WKY arteries (Figure 2A and 2C). In WKY arteries, more of the total amount of $\alpha_\delta$-1 ($\approx$85%) than $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ ($\approx$77%) was located at the surface. In contrast, in SHR arteries, the percentages of total $\alpha_\delta$-1 ($\approx$93%) and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ ($\approx$92%) located at the surface were similar (Figure 2A and 2C). These data indicate that, during hypertension, an elevation in $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$, total protein translates to an increase in surface expression of these subunits in arterial myocytes. Furthermore, hypertension is associated with an alteration in the distribution of $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ proteins between intracellular and surface compartments.

**Pregabalin Reduces Surface Trafficking of $\text{Ca}_{\text{a}}$ $\text{a}_1,2$ Channel Subunits More Effectively in Hypertensive Than Normotensive Rat Arteries**

Pregabalin, an $\alpha_\delta$-1/2 ligand, reduces surface trafficking of $\text{Ca}_{\text{a}}$ $\text{a}_1,2$, 2.1, and 2.2 channels in neurons and arterial myocytes. Next, we studied pregabalin regulation of $\alpha_\delta$-1 and $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ subunit surface expression and subunit cellular distribution in WKY and SHR cerebral arteries. For these experiments, arteries were incubated for 24 hours with or without pregabalin. Pregabalin (24 hours) did not alter total protein of $\alpha_\delta$-1 (% control: WKY, 115±9; SHR, 118±20) or $\text{Ca}_{\text{a}}$ $\text{a}_1,2\alpha_1$ (% control: WKY, 116±10; SHR, 109±14;...
Hypertension was associated with a larger increase in surface $\alpha_\delta$-1 than $\text{Ca}_{1,2\alpha_1}$ protein in arteries (Figure 2A and 2B). We calculated the band intensity ratio of surface $\alpha_\delta$-1: $\text{Ca}_{1,2\alpha_1}$ and regulation by pregabalin. Although this methodology cannot determine subunit stoichiometry, total protein loaded in each lane is identical, allowing for comparison of this ratio in SHR and WKY arteries from the same blot. The mean surface $\alpha_\delta$-1: $\text{Ca}_{1,2\alpha_1}$ band intensity ratio was 1.38 in SHR arteries and 1.06 in WKY arteries, or 1.3-fold higher in SHRs (Figure 3E). Pregabalin reduced the surface $\alpha_\delta$-1: $\text{Ca}_{1,2\alpha_1}$ band intensity ratio to $\approx$0.91 in SHR arteries but did not change the ratio in WKY rat arteries (Figure 3E).

Collectively, these data indicate that pregabalin blocks surface expression of $\alpha_\delta$-1 and $\text{Ca}_{1,2\alpha_1}$ subunits more...
Figure 4. Pregabalin reverses elevated voltage-dependent Ca\textsuperscript{2+} (Ca\textsubscript{V1.2}) currents in hypertensive rat arterial smooth muscle cells. A, Representative Ca\textsubscript{V1.2} current density recordings from control and pregabalin-treated Wistar-Kyoto (WKY) and spontaneously hypertensive rat (SHR) arterial smooth muscle cells (10 mmol/L of Ba\textsuperscript{2+} as charge carrier). B, Mean current density-voltage relationships of WKY (n=17), pregabalin-treated WKY (n=13), SHR (n=16), and pregabalin-treated SHR (n=18) cells. C, Scatter plot with linear fit for peak Ca\textsubscript{V1.2} current vs cell capacitance in WKY (n=17), pregabalin-treated WKY (n=13), SHR (n=16), and pregabalin-treated SHR (n=18) cells. WKY: slope=-4.20, r\textsuperscript{2}=0.97, P<7.0\times10^{-4}. WKY+pregabalin: slope=-1.79, r\textsuperscript{2}=0.90, P=7.5\times10^{-4}. SHR: slope=-5.41, r\textsuperscript{2}=0.77, P=3.5\times10^{-4}. SHR+pregabalin: slope=-2.25, r\textsuperscript{2}=0.72, P=1.1\times10^{-4}. D, Voltage-dependent Ca\textsubscript{V1.2} current activation in WKY (n=13), pregabalin-treated WKY (n=9), SHR (n=12), and pregabalin-treated SHR (n=6) cells. E, Voltage-dependent current inactivation of WKY (n=17), pregabalin-treated WKY (n=13), SHR (n=16), and pregabalin-treated SHR (n=18) cells. *Significance from WKY at indicated potentials (P<0.05). F, Graph illustrating the time course of Ca\textsubscript{V1.2} currents (at +20 mV) and inhibition by acute pregabalin (100 µmol/L); WKY (control n=8, 0.8 pA/pF in WKY cells, or 2.3-fold higher (Figure 4C). Pregabalin reduced slopes by 58% and 25% in SHR and WKY cells, respectively (Figure 4C). Slopes were similar for untreated WKY cells and pregabalin-treated SHR cells (Figure 4C; P>0.05). Mean cell capacitance for WKY (16.3±0.8 pF) and SHR (17.1±1.3 pF) cells were similar and were not altered by pregabalin (WKY, 18.8±1 pF; SHR, 15.8±0.8 pF; P>0.05 when comparing all), indicating that current density and slope increased because of changes in Ca\textsubscript{V1.2} channels (Figure 4B and 4C).

**α,δ-1 Targeting Reverses Hypertension-Associated Modifications in Ca\textsubscript{V1.2} Current Density and Inactivation in Arterial Myocytes**

To investigate the functional impact of elevated α,δ-1 expression and effects of α,δ-1 targeting, Ca\textsubscript{V1.2} currents were measured in age-matched WKY and hypertensive SHR cerebral artery myocytes. Mean peak Ca\textsubscript{V1.2} current density (Ba\textsuperscript{2+} as charge carrier) was 5.3 pA/pF in hypertensive SHR cells compared with 2.4 pA/pF in WKY cells or 2.2-fold larger (Figure 4A and 4B and Table). Pregabalin (24 hours) reduced peak Ca\textsubscript{V1.2} current density in SHR cells to 2.2 pA/pF, or by 59%, and to 1.6 pA/pF in WKY cells, or by 32% (Figure 4A and 4B and Table). Pregabalin reduced peak Ca\textsubscript{V1.2} current density in SHR myocytes to the current density of untreated WKY cells (Figure 4A and 4B and Table). The relationship between cell capacitance and peak Ca\textsubscript{V1.2} current was investigated (Figure 4C). When data were fit with a linear function, the slope was −5.41 for SHR cells and −2.40 for WKY cells, or 2.3-fold higher (Figure 4C). Pregabalin reduced slopes by 58% and 25% in SHR and WKY cells, respectively (Figure 4C). Slopes were similar for untreated WKY cells and pregabalin-treated SHR cells (Figure 4C; P>0.05). Mean cell capacitance for WKY (16.3±0.8 pF) and SHR (17.1±1.3 pF) cells were similar and were not altered by pregabalin (WKY, 18.8±1 pF; SHR, 15.8±0.8 pF; P>0.05 when comparing all), indicating that current density and slope increased because of changes in Ca\textsubscript{V1.2} channels (Figure 4B and 4C).

The voltage-dependence of half-maximal Ca\textsubscript{V1.2} current activation and slope were similar in untreated control and pregabalin-treated WKY and SHR arterial myocytes (Figure 4D and Table). The voltage dependence of half-maximal inactivation and slope were also similar in untreated control and pregabalin-treated WKY and SHR cells (Figure 4E and Table). In contrast, untreated SHR cells displayed a non-activating Ca\textsubscript{V1.2} current that was 2-fold larger than in WKY cells (Figure 4A and 4E). Pregabalin (24 hours) reduced the
noninactivating current in SHR cells such that it was similar to WKY cells (Figure 4A and 4E). CaV1.2 current inactivation rates (τ) were similar in control and pregabalin-treated WKY and SHR cells (Figure S4).

In addition to acting as an inhibitor of αδ-1-induced CaV1.2 channel trafficking, pregabalin is a weak CaV1.2 channel pore blocker that does not directly alter CaV1.2 current voltage dependence in normotensive SD rat arterial myocytes.16 To determine whether the reduction in CaV1.2 current amplitude in pregabalin-treated WKY and SHR myocytes was because of CaV1.2 pore block, we measured CaV1.2 current regulation in untreated cells by acute bath application of pregabalin. Acute pregabalin reduced CaV1.2 currents in WKY cells by ≈12% (Figure 4F). In contrast, pregabalin reduced CaV1.2 currents in SHR myocytes by ≈23%, or ≈1.9-fold more than in WKY cells (Figure 4F). Acute pregabalin-induced CaV1.2 current inhibition was significantly smaller than that induced by 24-hour pregabalin treatment in both WKY (≈32% inhibition) and SHR (≈59% inhibition) cells (Figure 4B, 4C, and 4F). When combined with the biochemical data illustrated in Figure 3, these data indicate that acute and chronic pregabalin inhibit CaV1.2 currents through distinct mechanisms in arterial myocytes.

Collectively, data indicate that genetic hypertension is associated with an elevation in αδ-1 expression that stimulates surface expression of CaV1.2α1 subunits, leading to a CaV1.2 current elevation and an increase in noninactivating current. αδ-1 targeting reduces the hypertension-associated αδ-1-induced elevation in CaV1.2α1 surface expression, leading to a reduction in CaV1.2 current density. αδ-1 targeting also restores CaV1.2 current inactivation.

### αδ-1 Targeting Reverses Elevated Pressure- and Depolarization-Induced Vasoconstriction in Hypertension

The functional significance of hypertension-associated alterations in αδ-1 signaling was studied by measuring arterial contractility. Diameter regulation by intravascular pressure (20–100 mmHg) was measured in WKY and SHR cerebral arteries that had been incubated for 24 hours with or without pregabalin. SHR arteries developed more myogenic tone than WKY arteries over the entire pressure range (Figure 5A, B).

#### Table. Properties of Arterial Myocyte CaV1.2 Currents

<table>
<thead>
<tr>
<th>Variable</th>
<th>WKY</th>
<th>WKY+Pregabalin</th>
<th>SHR</th>
<th>SHR+Pregabalin</th>
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<tr>
<td>IV relationship</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Peak current density (pA/pF)</td>
<td>2.40±0.15 (17)</td>
<td>1.65±0.13 (13)*</td>
<td>5.33±0.38 (16)*,#</td>
<td>2.23±0.14 (16)</td>
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<tr>
<td>Peak voltage (mV)</td>
<td>10.25±0.74 (17)</td>
<td>12.31±1.45 (13)</td>
<td>11.09±1.03 (16)</td>
<td>11.26±0.89 (18)</td>
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<tr>
<td>Voltage-dependent activation</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Voi half-maximal (mV)</td>
<td>9.24±1.88 (12)</td>
<td>10.70±3.72 (9)</td>
<td>11.62±1.80 (12)</td>
<td>11.18±3.29 (5)</td>
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<tr>
<td>Slope</td>
<td>13.09±1.55 (12)</td>
<td>14.56±1.66 (9)</td>
<td>12.74±2.84 (12)</td>
<td>10.51±1.09 (5)</td>
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<tr>
<td>Voltage-dependent inactivation</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Voi half-maximal (mV)</td>
<td>−14.23±1.57 (8)</td>
<td>−17.20±1.28 (13)</td>
<td>−11.33±1.90 (16)</td>
<td>−14.71±1.15 (11)</td>
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<tr>
<td>Slope</td>
<td>6.44±0.76 (8)</td>
<td>8.58±1.16 (13)</td>
<td>7.86±0.70 (16)</td>
<td>8.09±0.69 (11)</td>
</tr>
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</table>

Numbers in parentheses indicate experimental No. WKY indicates Wistar-Kyoto rat; SHR, spontaneously hypertensive rat; V1/2act half-maximal CaV1.2 current activation.

*P<0.05 vs WKY.

#P<0.05 vs SHR+pregabalin.

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**Figure 5.** Pregabalin reverses elevated pressure-induced vasoconstriction in hypertension. A. Representative traces illustrating steady-state myogenic tone in response to increasing intravascular pressure in a Wistar-Kyoto (WKY) and spontaneously hypertensive rat (SHR) artery. Horizontal black bars indicate an increase in bath K+ from 6 to 60 mmol/L. B. Pregabalin (24 hours, 100 µmol/L) reduced pressure (20–100 mmHg)-induced myogenic tone (filled symbols) more so in arteries from hypertensive rats than in controls. Myogenic tone was abolished by nimodipine (1 µmol/L, empty symbols). Mean data (n: WKY, 6–10; WKY + pregabalin, 6–9; SHR, 6–10; SHR+pregabalin, 6–7). *P<0.05 vs untreated WKY; #P<0.05 for SHR+pregabalin vs untreated SHR.
Pregabalin reduced myogenic tone in WKY and SHR arteries, decreased tone more in SHR than in WKY arteries (eg, % reduction in myogenic tone at 60 mm Hg: SHR, ≈41%; WKY, ≈28%), and reduced tone in SHR arteries to levels in untreated WKY arteries (Figure 5). Nimodipine (1 µmol/L), a voltage-dependent Ca$^{2+}$ channel blocker, fully dilated control and pregabalin-treated WKY and SHR arteries at all pressures (20–100 mm Hg) studied, indicating that myogenic tone occurred because of Ca$_{\alpha_{1.2}}$ channel activation (Figure 5B). Passive arterial diameters were similar for WKY (249±11 µm) and hypertensive SHR (242±9 µm) cerebral arteries (values given at 60 mm Hg; n=10 for each; P<0.05).

Elevating extracellular K$^{+}$ induces depolarization, activation of voltage-gated Ca$^{2+}$ channels, Ca$^{2+}$ influx, and vasoconstriction. As an alternative approach to investigate the functional impact of α$_{\delta}$-1 targeting, we studied K$^{+}$-induced vasoconstriction in WKY and SHR arteries. Increasing extracellular K$^{+}$ from 6 to 20, 40, or 60 mmol/L induced graded vasoconstriction that was larger in SHR than in WKY cerebral arteries (Figure 6). Pregabalin reduced K$^{+}$-induced vasoconstriction more in SHR than in WKY arteries (Figure 6). For example, pregabalin reduced the mean 60-mmol/L K$^{+}$-induced constriction by ≈54% in SHR and ≈37% in WKY rats (Figure 6B). These data indicate that α$_{\delta}$-1 targeting reduces pressure- and depolarization-induced vasoconstriction more effectively in hypertensive SHR arteries than in control WKY rat arteries.

**Discussion**

To date, no studies have investigated involvement of Ca$_{\alpha_{1.2}}$ channel auxiliary subunits in the pathological elevation of arterial myocyte Ca$_{\alpha_{1.2}}$ currents and vasoconstriction in hypertension. Here, we demonstrated for the first time that genetic hypertension is associated with transcriptional and posttranslational upregulation of α$_{\delta}$-1 subunits in myocytes of resistance-size arteries. The additional α$_{\delta}$-1 subunits increase surface trafficking of Ca$_{\alpha_{1.2\delta_{1}}}$ subunits, which are also elevated in hypertension. The consequent increase in surface α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ proteins elevates Ca$_{\alpha_{1.2}}$ current density and generates a nonactivating current, leading to vasoconstriction. We also demonstrated that α$_{\delta}$-1 targeting normalizes myocyte α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ surface expression, re-establishes Ca$_{\alpha_{1.2}}$ current density and inactivation, and reduces hypertensive rat artery contractility to levels in controls. These data indicate that α$_{\delta}$-1 elevates Ca$_{\alpha_{1.2}}$ currents and Ca$_{\alpha_{1.2}}$-dependent vasoconstriction during hypertension and demonstrate that α$_{\delta}$-1 targeting is a viable therapeutic strategy to reverse these pathological alterations and induce cerebrovascular dilation.

Our data indicate that the development of genetic hypertension is associated with a transcriptional and posttranslational increase in α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ in arterial myocytes. In contrast, other α$_{\delta}$ isoforms did not emerge during hypertension, an alteration that could have contributed to pathological Ca$_{\alpha_{1.2}}$ current modifications. Previous studies have described that Ca$_{\alpha_{1.2\delta_{1}}}$ mRNA and protein are higher in mesenteric arteries and aorta of hypertensive SHRs than WKY rat controls. In contrast, angiotensin II– and hypoxia-induced hypertension did not alter Ca$_{\alpha_{1.2\delta_{1}}}$ mRNA but elevated Ca$_{\alpha_{1.2\delta_{1}}}$ protein in cultured mesenteric arteries and neonatal piglet pulmonary arteries. These findings lead to the proposal that hypertension may not be associated with an increase in Ca$_{\alpha_{1.2\delta_{1}}}$ message but posttranslational upregulation of Ca$_{\alpha_{1.2\delta_{1}}}$ protein. Here, we used both age-dependent development of hypertension in SHRs and comparison with WKY rat controls to investigate relative changes in α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ mRNA and protein. Our data indicate that the increase in α$_{\delta}$-1 (≈2.1-fold) and Ca$_{\alpha_{1.2\delta_{1}}}$ (≈1.5-fold) mRNA cannot fully account for the elevation in α$_{\delta}$-1 (≈2.5-fold) and Ca$_{\alpha_{1.2\delta_{1}}}$ (≈1.7-fold) proteins during hypertension. These data indicate that both transcriptional and posttranslational mechanisms elevate α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ proteins in cerebral artery myocytes during hypertension.

Using a novel application of biotinylation, we recently determined the surface to intracellular distribution of arterial α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ proteins in normotensive rats. Essentially all (>95%) α$_{\delta}$-1 and Ca$_{\alpha_{1.2\delta_{1}}}$ proteins locate to the surface in cerebral artery myocytes of normotensive SD rats. Here, a smaller percentage of total α$_{\delta}$-1 (≈85%) and Ca$_{\alpha_{1.2\delta_{1}}}$ proteins locate to the surface in cerebral artery myocytes of hypertensive rats.
Ca\textsubscript{\(\alpha1\2\alpha1\)} (\(\approx77\%\)) was located in the plasma membrane in WKY rat arteries. Explanations for slight differences in \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) distribution between SD and WKY rats include the different rat strains and animal age (7 weeks in Reference 16 versus 12 weeks here). To determine the cellular distribution of \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) subunit proteins in SHR and WKY cerebral arteries, we compared the percentage of total protein expressed at the surface and the surface/intracellular protein ratio in both SHR and WKY cerebral arteries. Both of these analysis methods indicate that a higher proportion of \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) is located at the plasma membrane in hypertensive rat arteries compared with controls. The net result of both the transcription and translational increase in \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) protein and higher relative surface expression elevates plasma membrane levels of these proteins. Our data also indicate that there is a fractional shift in surface \(\alpha\delta-1\):\text{Ca}_{\alpha1\2\alpha1}\) during hypertension, a change that occurs because of a larger elevation in surface \(\alpha\delta-1\) than in \(\text{Ca}_{\alpha1\2\alpha1}\). These results provide evidence that an elevation in \(\alpha\delta-1\):\text{Ca}_{\alpha1\2\alpha1}\) subunit ratio can modify native \(\text{Ca}_{\alpha1\2\alpha1}\) current properties and that there may not be rigid \(\alpha\delta-1\):\text{Ca}_{\alpha1\2\alpha1}\) subunit stoichiometry in arterial myocytes. Also possible is that, in normotension, a proportion of arterial myocyte \(\text{Ca}_{\alpha1\2\alpha1}\) channel complexes may not contain \(\alpha\delta-1\) subunits. During hypertension, the higher elevation in surface \(\alpha\delta-1\) than in \(\text{Ca}_{\alpha1\2\alpha1}\) may increase the proportion of channels that contain \(\alpha\delta-1\). Future studies should be designed to further investigate native \(\text{Ca}_{\alpha1\2\alpha1}\) channel stoichiometry in arterial myocytes and changes that occur in cardiovascular disease. Collectively, these results indicate that \(\alpha\delta-1\) increases surface expression and functionality of \(\text{Ca}_{\alpha1\2\alpha1}\) subunits in arterial myocytes during hypertension.

Pregabalin is a gabapentinoid drug used to treat neuropathic pain, fibromyalgia, and epileptic seizures.\textsuperscript{25,26} Of all 4 \(\alpha\delta\) isoforms, only \(\alpha\delta-1\) and -2 contain complete metal ion adhesion site and RRR motifs, which are required for gabapentanoid drug binding.\textsuperscript{14,20} Gabapentin reduced \(\alpha\delta-1\) subunit recycling from Rab-11–positive recycling endosomes.\textsuperscript{17} Pregabalin also reduced surface expression of both \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) proteins in cerebral artery myocytes of normotensive SD rats.\textsuperscript{16} Here, pregabalin did not alter total \(\alpha\delta-1\) or \(\text{Ca}_{\alpha1\2\alpha1}\) protein. Rather, pregabalin reduced surface \(\alpha\delta-1\) and \(\text{Ca}_{\alpha1\2\alpha1}\) more in hypertensive arteries than in control rat arteries, essentially normalizing surface levels of these proteins compared with those in WKY rats. Pregabalin also reduced the \(\alpha\delta-1\):\text{Ca}_{\alpha1\2\alpha1}\) subunit ratio in hypertensive rat arteries compared with that in WKY controls. Given that pregabalin normalized elevated \(\text{Ca}_{\alpha1\2\alpha1}\) current density and the proportion of noninactivating current to those in WKY cells, our data indicate that upregulated \(\alpha\delta-1\) functionality contributes to the increase in \(\text{Ca}_{\alpha1\2\alpha1}\) currents in arterial myocytes in hypertension.

Voltage-dependent Ca\textsuperscript{2+} currents are elevated in myocytes from vasculature, including renal, cerebral, and mesenteric arteries, when studying a variety of different hypertension models, such as SHR, angiotensin II–induced, aortic banding, stroke-prone SHR, hypoxia-induced pulmonary hypertension, and Osborne-Mendel rats on a high fat diet.\textsuperscript{2,3,7,9,21,23,24,26–30} \(\text{Ca}_{\alpha1\2\alpha1}\) current density measured here is consistent with that reported previously in cerebral artery myocytes when using WKY and SHR models.\textsuperscript{2,30} Our data indicate that \(\text{Ca}_{\alpha1\2\alpha1}\) current density was \(\approx2.2\)-fold larger in hypertensive than in control rat arterial myocytes. In contrast, half-maximal \(\text{Ca}_{\alpha1\2\alpha1}\) current activation and voltage dependence of half-maximal inactivation were similar in WKY and SHR cells, consistent with previous reports.\textsuperscript{2,9,28,30} A nonactivating \(\text{Ca}_{\alpha1\2\alpha1}\) current in myocytes of hypertensive rats was double that in controls, a modification that would significantly increase Ca\textsuperscript{2+} influx at steady-state membrane potentials, thereby stimulating vasoconstriction. Pregabalin (24 hours) reduced elevated \(\text{Ca}_{\alpha1\2\alpha1}\) current density and nonactivating current to levels in controls, suggesting that these pathological modifications occurred because of an increase in \(\alpha\delta-1\) surface expression. Our data are consistent with pregabalin acting as both a weak \(\text{Ca}_{\alpha1\2\alpha1}\) channel pore blocker and an effective chronic inhibitor of \(\alpha\delta-1\) surface expression in hypertensive rat arterial myocytes. In our previous study, acute pregabalin reduced \(\text{Ca}_{\alpha1\2\alpha1}\) currents by \(\approx33\%\) in SD rat cerebral artery myocytes.\textsuperscript{16} Here, the same acute pregabalin concentration reduced \(\text{Ca}_{\alpha1\2\alpha1}\) currents by \(\approx12\%\) in WKY rat myocytes. Our previous study used 7-week–old SD rats, whereas here acute pregabalin effects were measured in 12-week–old WKY rat myocytes. Our data indicate that \(\text{Ca}_{\alpha1\2\alpha1}\) channel properties in 12-week–old WKY myocytes are not identical to those in 7-week–old SD rat myocytes, including the percentage of \(\text{Ca}_{\alpha1\2\alpha1}\) protein that is located at the surface. Data here indicate that acute pregabalin is a more effective inhibitor of \(\text{Ca}_{\alpha1\2\alpha1}\) currents in SHR compared with WKY myocytes. This may be because of the higher number of surface \(\alpha\delta-1\) subunits and the higher \(\alpha\delta-1\):\text{Ca}_{\alpha1\2\alpha1}\) ratio in SHR myocytes. Acute gabapentin also inhibited voltage-dependent Ca\textsuperscript{2+} currents in pyramidal neocortical cells but did not alter currents generated by recombinant Ca\textsubscript{2\(1\)} channels or endogenous Ca\textsubscript{2\(1\)} channels in dorsal root ganglia neurons.\textsuperscript{31,32} In a model of neuropathic pain in which \(\alpha\delta-1\) is upregulated, chronic pregabalin inhibited \(\alpha\delta-1\) trafficking to presynaptic terminals, thereby inhibiting Ca\textsuperscript{2+} channel function.\textsuperscript{19} Our data indicate that chronic pregabalin inhibits \(\alpha\delta-1\)–induced trafficking of \(\text{Ca}_{\alpha1\2\alpha1}\) channel subunits, thereby reducing \(\text{Ca}_{\alpha1\2\alpha1}\) currents in arterial myocytes during hypertension.

Intravascular pressure and depolarization both stimulated a larger vasoconstriction in arteries of hypertensive rats than in controls. Consistent with our findings, pressure-induced Ca\textsuperscript{2+} influx and associated vasoconstriction were larger in arteries from animal models with both genetic and induced hypertension.\textsuperscript{2,21,23,24} We show that nimodipine abolished myogenic tone at all pressures, indicating that \(\text{Ca}_{\alpha1\2\alpha1}\) channel activity was essential to generate tone in hypertensive and control rat arteries. Chronic pregabalin (24 hours) was a more effective vasodilator of hypertensive than control rat arteries, effectively reversing the pathological vasoconstriction. Pregabalin is also a weak \(\text{Ca}_{\alpha1\2\alpha1}\) channel pore blocker, which induces a small vasodilation.\textsuperscript{16} Thus, pregabalin-induced \(\text{Ca}_{\alpha1\2\alpha1}\) pore block may also have contributed to vasodilation in both WKY and SHR arteries. Although unlikely, pregabalin could have caused vasodilation through additional mechanisms, including through inducing membrane hyperpolarization. Our data are inconsistent with this possibility, because pregabalin similarly reduced surface \(\text{Ca}_{\alpha1\2\alpha1}\) subunits, \(\text{Ca}_{\alpha1\2\alpha1}\) currents, myogenic tone, and K\textsuperscript{+}-induced constriction, and inhibitions of
pressure- and depolarization-induced vasoconstriction were equivalent. Thus, data demonstrate that pregabalin dilates hypertensive rat arteries primarily by reducing surface expression of Ca$_{1.2}$ subunits in myocytes.

Hypertension is associated with increased risk for cerebral diseases, including stroke, Alzheimer disease, and dementia. Cerebral blood flow is reduced in hypertensive humans and 12-week-old SHR$_s$ when compared with normotensive controls.$^{33,34}$ Voltage-dependent Ca$^{2+}$ channel blockers have been used for >2 decades to treat hypertension.$^{35}$ However, Ca$^{2+}$ channel blockers inhibit Ca$_{1.2}$ channels in multiple cell types in vivo and induce multiple adverse effects, including sweating, edema, and nausea.$^{35,36}$ Therefore, the development of alternative approaches to target Ca$_{1.2}$ channels in arterial myocytes could provide significant benefits over current inhibitors. Here we used pregabalin as an in vitro tool to test the concept that α$_{δ}$ targeting induces vasodilation in cerebral arteries of hypertensive animals. Data here provide a foundation for future studies aimed at developing novel approaches to target α$_{δ}$-1 in arterial myocytes. All of the data in our study were obtained by studying cerebral arteries that regulate brain regional blood flow but do not control systemic blood pressure. Clinical pregabalin does not appear to modify systemic blood pressure in normotensive humans at doses used to treat neuropathic pain, fibromyalgia, and epileptic seizures.26 There are several explanations for this observation. First, there are a large number of distinct mechanisms that control cerebral and systemic artery contractility. To date, no studies have examined the molecular identity or physiological functions of α$_{δ}$ subunits in systemic artery myocytes that regulate diastolic and systolic blood pressures. α$_{δ}$-1 may not be the principal α$_{δ}$ isoform or α$_{δ}$ subunits may not regulate Ca$_{1.2}$ channel activity in systemic artery myocytes. Pregabalin is an α$_{δ}$-1/2 ligand. If α$_{δ}$-1 or α$_{δ}$-2 is not expressed or does not regulate Ca$_{1.2}$ channels in systemic artery myocytes, pregabalin should not induce systemic vasodilation or alter blood pressure. Second, clinical doses of pregabalin that are used to treat neuropathic pain, fibromyalgia, and epileptic seizures may be insufficient to induce vasodilation in vivo. Gabapentin, a lower affinity pregabalin analog, enters cells through system-L neutral amino acid transporters.32 Arterial myocytes may not uptake pregabalin as effectively as neurons. In vivo, intracellular myocyte pregabalin concentrations may be less than those obtained in vitro that alter Ca$_{1.2}$ function. Third, many in vivo mechanisms, including those mediated by baro-receptors or the renin-angiotensin system, may compensate for pregabalin-induced systemic vasodilation, leading to no net change in blood pressure. Fourth, our data indicate that pregabalin is more effective at inhibiting Ca$_{1.2}$α$_{1}$ subunit trafficking in cerebral artery myocytes of hypertensive compared with normotensive rats. In vivo, pregabalin may be a more effective vasodilator in hypertensive subjects and have a smaller effect in normotensive subjects in which clinical systemic blood pressure measurements have been obtained. Our study provides the first evidence that arterial myocyte α$_{δ}$-1 functionality is upregulated in hypertension and that α$_{δ}$-1 targeting is a novel approach for reducing pathological vasoconstriction in hypertension. Data also indicate that α$_{δ}$-1 targeting can modify cerebral artery contractility, setting the stage for future studies to use a variety of other α$_{δ}$-1 targeting strategies, including RNA interference and genetic models, to investigate physiological and pathological involvement of α$_{δ}$ subunits in arteries of other vascular beds and in vivo.

In summary, we identify for the first time that a hypertension-associated increase in α$_{δ}$-1 elevates Ca$_{1.2}$α$_{1}$ surface expression in arterial myocytes leading to pressure- and depolarization-induced vasoconstriction. Our data also indicate that α$_{δ}$-1 targeting is a novel approach to reverse elevated Ca$_{1.2}$ channel surface expression in arterial myocytes and vasoconstriction in hypertension.

**Perspectives**

A hallmark of hypertension is an increase in voltage-dependent Ca$_{1.2}$ currents in arterial myocytes that induces vasoconstriction.$^{1,3}$ Molecular mechanisms that elevate arterial myocyte Ca$_{1.2}$ currents in hypertension and the significance of auxiliary subunits in this pathological alteration are unclear. We show that the development of genetic hypertension is associated with a transcriptional and posttranslational upregulation of α$_{δ}$-1 subunits in cerebral artery myocytes. This increase in α$_{δ}$-1 subunits elevates Ca$_{1.2}$ channel surface expression, Ca$_{1.2}$ current density, and vasoconstriction. α$_{δ}$-1 targeting using pregabalin, an α$_{δ}$-1 ligand, reduced α$_{δ}$-1 and Ca$_{1.2}$ surface expression and Ca$_{1.2}$ current density in myocytes. Pregabalin also dilated cerebral arteries of hypertensive rats. Our study provides the first evidence that α$_{δ}$-1 subunits are upregulated in cerebral artery myocytes during hypertension and contribute to the pathological elevation in myocyte Ca$_{1.2}$ currents and vasoconstriction. We also identified α$_{δ}$-1 as a potential novel therapeutic target for inducing cerebrovascular dilation in hypertension.

**Acknowledgment**

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**Disclosures**

None.

**References**


Novelty and Significance

**What Is New?**

- We demonstrate for the first time that genetic hypertension is associated with a transcriptional and posttranslational upregulation of α,δ-1 subunits in myocytes of resistance-sized cerebral arteries that increase Ca\textsubscript{1,2} subunit surface trafficking, thereby elevating Ca\textsubscript{1,2} current density and arterial contractility.

- Pharmacological targeting of α,δ-1 inhibits the pathological increase in Ca\textsubscript{1,2} current density and cerebral artery contractility during hypertension. This study identifies α,δ-1 as a novel therapeutic target for inducing cerebrovascular vasodilation in hypertension.

**What Is Relevant?**

- Upregulation of α,δ-1 subunits is essential for the elevation in Ca\textsubscript{1,2} current density and cerebrovascular tone in genetic hypertension.

- Pharmacological targeting of α,δ-1 can reverse the pathological elevation in surface Ca\textsubscript{1,2} channels, Ca\textsubscript{1,2} current density, and vasoconstriction in cerebral artery myocytes.

**Summary**

Upregulation of α,δ-1 subunits during genetic hypertension increases Ca\textsubscript{1,2} channel surface expression and Ca\textsubscript{1,2} current density, leading to vasoconstriction. α,δ-1 targeting reverses this pathological increase in Ca\textsubscript{1,2} channel surface expression, Ca\textsubscript{1,2} current density, and contractility in cerebral arteries.
Transcriptional Upregulation of \( \alpha_2\delta-1 \) Elevates Arterial Smooth Muscle Cell Voltage-Dependent Ca\(^{2+} \) Channel Surface Expression and Cerebrovascular Constriction in Genetic Hypertension

John P. Bannister, Simon Bulley, Damodaran Narayanan, Candice Thomas-Gatewood, Patrik Luzny, Judith Pachuau and Jonathan H. Jaggar

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TRANSCRIPTIOINAL UPREGULATION OF \( \alpha_2\delta-1 \) ELEVATES ARTERIAL SMOOTH MUSCLE CELL CA\( \text{v}1.2 \) CHANNEL SURFACE EXPRESSION AND CEREBROVASCULAR CONSTRICITION IN GENETIC HYPERTENSION

by

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Short Title: \( \alpha_2\delta \)-induced vasoconstriction in hypertension

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Supplemental Methods

Cell isolation and tissue preparation
All animal protocols used were reviewed and approved by the Animal Care and Use Committee at the University of Tennessee Health Science Center. Male 6 or 12 week old SHR and Wistar Kyoto (WKY) rats were euthanized by intraperitoneal injection of sodium pentobarbital (150 mg/Kg body weight). The brain was removed and placed in oxygenated (21 % O2/5 % CO2) physiological saline solution (PSS) containing (in mmol/L): KCl 6, NaCl 112, NaHCO3 24, MgSO4 1.2, KH2PO4 1.2, CaCl2 1.8, and glucose 10. Middle cerebral, posterior cerebral and cerebellar arteries (~100-200 µm diameter) were dissected from the brain.

Blood pressure measurements
Diastolic, systolic, and mean arterial blood pressures were measured in 6 and 12 week old WKY and SHR rats using a CODA 2 tail cuff system (Kent Scientific, Torrington, Conn). Rats were acclimatized to the chamber and tail cuff on a heated platform (37°C) for 3 days prior to acquisition of blood pressure data. On the day of data acquisition, rats were again acclimatized for 30 min before blood pressure measurements were acquired. For each rat, 10-15 acclimatization cycles were run and data taken as the mean of 5-9 measurements.

RT-PCR
Total RNA was isolated from brain and cerebral arteries using Trizol (Invitrogen) and from isolated smooth muscle cells using the Absolutely RNA nanoprep kit (Strategene). RT-PCR was performed using α2δ isoform-specific primers, as previously described.1 Standard PCR reactions consisting of a 2 min heat shock (94˚C) and 40 cycles of denaturation (94˚C for 30 s), annealing (55˚C for 30 s) and extension (72˚C for 1 min), were used for all reactions.

Quantitative real time PCR
Quantitative Taqman PCR reactions were performed using an LC480 light cycler (Roche Applied Science). Reaction conditions were an initial denaturation step at 95˚C for 5 min followed by 40 cycles of 95˚C for 10 s, 60˚C for 30 s and 72˚C for 10 s. Negative control without cDNA was run for each reaction. Standard curves using four 10-fold dilutions of cDNA were run for all probe and primer pairs to determine PCR efficiency. α2δ-1 or CaV1.2α1 mRNA expression was calculated from the difference between fluorescence (Ct) values (ΔCt) of α2δ-1 or CaV1.2α1 and Rps5. ΔΔCt was calculated from the difference between the ΔCt values for SHR and WKY. α2δ-1 or CaV1.2α1 mRNA levels in SHR compared to WKY were calculated using the formula 100 x 2(-ΔΔCt).2 All PCR reactions including standard curves were performed in triplicate. Gene specific primers and probes were designed using the Universal Probe Library (UPL). The overall efficiency of each primer pair and probe for PCR reactions was calculated. Primer sequences, probes, gene accession numbers, amplicon length, and real-time PCR reaction efficiencies are provided in Table S1.

The following reference genes were screened: beta (β) actin, hypoxanthine-guanine phosphoribosyltransferase (HGPRT), TATA box binding protein (TBP), ribosomal RNA 18s (18S rRNA), ribosomal subunit protein 16 (Rps16), platelet/endothelial cell adhesion molecule 1 (Pecam1), cyclophilin B and Rps5. Rps5 was identified as the most suitable reference gene for this study after comparing both the fold change in mRNA levels in SHR compared to WKY and the coefficient of variation (expressed as %) in Ct values of WKY and SHR samples (Table S2). For each reference gene, coefficient of variation of the Ct values in all (SHR and WKY) samples was calculated using the following equation:

Coefficient of variation = (Standard Deviation/Mean) x 100
Protein analysis and biochemistry
Arteries were homogenized in 1x Laemmli buffer supplemented with 2 % β-mercaptoethanol. Cellular debris was removed by centrifugation. The method of Henkel et al. was used to determine protein concentration. Proteins were separated on 7.5 % SDS-PAGE gels and analyzed by Western blotting. Blots were cut at the 75 kDa marker to allow simultaneous probing of higher molecular mass (>75 kDa) proteins for αδ-1 and lower mass proteins (<75 kDa) for actin. The higher molecular mass blot was stripped and re-probed for CaV1.2α1. Antibodies used were anti-αδ-1 (Aviva Systems Biology), anti-CaV1.2α1 (Neuromab) and anti-actin (Millipore). Bands on Western blots were visualized using HRP conjugated secondary antibodies and a West Pico Chemiluminescence kit (Pierce), using a Kodak Image F-Pro system. Protein band intensities were determined using Quantity One (BioRad) software. For quantification, protein band intensities were first normalized to actin and then to appropriate control samples.

Artery surface biotinylation
Intact, cleaned arteries were incubated for 1 h in a mixture of EZ-Link Sulfo-NHS-LC-LC-Biotin and EZ-Link Maleimide-PEG2-Biotin reagents (Pierce, 1 mg/ml each) in phosphate-buffered saline (PBS, Invitrogen). Unbound biotin was removed by quenching with PBS supplemented with 100 mmol/L glycine and washing with PBS. For determination of protein concentration, arteries were homogenized in RIPA buffer (Sigma) and cellular debris removed by centrifugation. Protein concentration was determined using the method of Henkel et al. Equal amounts of biotinylated arterial lysate for each sample were then used for Avidin (Monomeric Avidin, Pierce) pulldown of biotinylated proteins. Following pulldown, the supernatant comprised the intracellular proteins and biotinylated surface proteins remained bound to Avidin. Following removal of the supernatant (intracellular fraction), biotinylated surface proteins were eluted from Avidin beads by boiling in 1x Laemmli buffer supplemented with 2 % β-mercaptoethanol. The entire supernatant comprising the intracellular and the entire eluate comprising the surface protein fraction from the pulldown, were separated on SDS-PAGE gels and analyzed by Western blotting. Band intensities were determined using Quantity One software (BioRad). Total protein was calculated as the sum of surface and intracellular band intensities. To determine the proportion of a protein located at the plasma membrane, surface band intensity was divided by total. Alternatively, the surface:intracellular ratio of a protein was calculated by dividing surface band intensity by intracellular band intensity. Pregabalin-induced changes in protein cellular distribution were calculated by normalizing to control protein distribution. The ratio of surface αδ-1 to CaV1.2α1 was calculated by dividing surface αδ-1 by surface CaV1.2α1 band intensity from the same blots.

Patch-clamp electrophysiology
CaV1.2 currents were recorded in isolated smooth muscle cells using the whole cell patch-clamp configuration at room temperature using an Axopatch 200B amplifier (Axon Instruments). Borosilicate glass electrodes (4-5 MΩ) were filled with pipette solution containing (in mmol/L): CsMeSO4 135, CsCl 5, EGTA 5, MgATP 4, Na2GTP 0.25, HEPES 10 and glucose 10 (pH 7.2 adjusted using CsOH). Extracellular bath solution contained (in mmol/L): BaCl2 10, NMDG 130, MgCl2 1, HEPES 10 and glucose 10 (pH 7.4 adjusted using L-Aspartic acid). Cell capacitance was measured by applying a 5 mV test pulse and correcting transients with series resistance compensation. Pregabalin (100 µmol/L) was present in the bath solution during recordings for chronically-treated cells, and applied acutely to the bath otherwise.

To measure whole-cell CaV1.2 currents and steady-state inactivation, 1 s conditioning pulses to between -80 and +60 mV were applied in 10 mV increments prior to a 200 ms test pulse to 0 mV. Current-voltage (IV) relationships were generated from the peak current obtained during the 1 s conditioning pulses. The rate of current inactivation was calculated from the current decay during each 1 s conditioning pulse. Steady state inactivation was determined from the current generated during the 200
ms test pulse to 0 mV. To measure steady state activation, tail currents were elicited by repolarization to -80 mV from 20 ms test pulses from -60 to +60 mV in 10 mV increments. To measure the time course and magnitude of acute pregabalin (100 µmol/L) inhibition, CaV1.2 currents were elicited by repetitive 300 ms steps to 10 mV from -80 mV every 30 s. Whole cell currents were filtered at 1 or 5 kHz and digitized at 5 or 20 kHz for the inactivation and activation protocols, respectively. P/-4 protocols were used to subtract leak and capacitive transients.

Scatter plot data points were fit with a linear function: \( y = mx \), where \( m \) is the slope, \( r \) is the strength of the linear relationship between the \( x \) and \( y \) variables, and \( p \) is the probability of the correlation co-efficient, with \( P < 0.05 \) significant. Steady state inactivation and activation curves were fit with a single power Boltzmann function: \( I/I_{\text{MAX}} = R_{\text{in}} + (R_{\text{MAX}} - R_{\text{in}})/(1 + \exp((V - V_{1/2})/k)) \), where \( I/I_{\text{MAX}} \) is the normalized peak current, \( V \) is the conditioning pre-pulse voltage, \( V_{1/2} \) is the voltage for half-inactivation or half-activation, \( k \) is the slope factor, \( R_{\text{in}} \) is the proportion of non-inactivating current and \( R_{\text{MAX}} \) is the maximal current amplitude. Inactivation kinetics data were fit with a single exponential function: \( I_t = (A \times e^{-t/\tau}) + I_0 \), where \( I_t \) is the inward current at time \( t \), \( A \) the amplitude and \( I_0 \) the residual current.

Pressurized artery myography
The endothelium was denuded by introduction of an air bubble into the artery lumen for ~1 min followed by PSS. Cerebral artery segments were cannulated at each end in a perfusion chamber (Living Systems Instrumentation) that was maintained at 37ºC and continuously perfused with PSS. Intravascular pressure was monitored using a pressure transducer and altered using an attached reservoir. Wall diameter was measured using a charge-coupled device camera and the edge detection function of IonWizard (Ionoptix), at 1 Hz. Arteries treated with pregabalin for 24 h were maintained in pregabalin throughout these experiments to inhibit CaV1.2 subunit membrane re-insertion. Myogenic tone (%) was calculated as: 100 \( x (1 - D_{\text{active}}/D_{\text{passive}}) \), where \( D_{\text{active}} \) is active arterial diameter and \( D_{\text{passive}} \) is the passive arterial diameter determined by applying Ca\(^{2+}\)-free PSS supplemented with 5 mM EGTA.

Chemicals
Pregabalin was a gift from Pfizer Inc (Groton, Conn) or was purchased from Sigma Aldrich (Milwaukee, WI).
References


Table S1

Gene specific oligonucleotide sequences for primers, probes, amplicon length, and reaction efficiencies of quantitative PCR experiments.

<table>
<thead>
<tr>
<th>Gene</th>
<th>Primer sequence</th>
<th>UPL probe #</th>
<th>Amplicon length (nt)</th>
<th>Amplification efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cav1.2α1</td>
<td>Forward: 5'-GAGAGCTTTCCGTGTCCTC-3', Reverse: 5'-GTTCAGGACCACCTGGAGAC-3'</td>
<td>109</td>
<td>70</td>
<td>1.991</td>
</tr>
<tr>
<td>α2δ-1</td>
<td>Forward: 5'-CATACTCCAGATTGGCTGGGTG-3', Reverse: 5'-AGTAGCTGCTGGAGAATAGACCA-3'</td>
<td>74</td>
<td>60</td>
<td>1.997</td>
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<tr>
<td>18S rRNA</td>
<td>Forward: 5'-AATCAGTTATGGTTCTTTGTGG-3', Reverse: 5'-GCTCTAGAATTACCACAGTTATCCAA-3'</td>
<td>55</td>
<td>65</td>
<td>1.94</td>
</tr>
<tr>
<td>β-actin</td>
<td>Forward: 5'-CCCGCGAGTACAACCTTCTC-3', Reverse: 5'-CGTCATCCATGGCGAACT-3'</td>
<td>17</td>
<td>72</td>
<td>2.01</td>
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<tr>
<td>TBP</td>
<td>Forward: 5'-CCCTATCACTCCTGACCCA-3', Reverse: 5'-GGTCAGTTTACAGCCAAGATTC-3'</td>
<td>110</td>
<td>98</td>
<td>1.883</td>
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<tr>
<td>HGPRT</td>
<td>Forward: 5'-TCAACGGGGGACATAAAAGT-3', Reverse: 5'-AGTGCAATTATATCCAAACCCAAT-3'</td>
<td>22</td>
<td>93</td>
<td>2.087</td>
</tr>
<tr>
<td>Pecam1</td>
<td>Forward: 5'-CTCAGTGCGTGCTAGAAGT-3', Reverse: 5'-AGGCTGAGTAGAGCAGCAT-3'</td>
<td>21</td>
<td>61</td>
<td>2.038</td>
</tr>
<tr>
<td>Rps16</td>
<td>Forward: 5'-CATGAGCCTTGACACATC-3', Reverse: 5'-GATGAGCCCATTTCCTCGT-3'</td>
<td>5</td>
<td>76</td>
<td>2.028</td>
</tr>
<tr>
<td>Rps5</td>
<td>Forward: 5'-GACTGAGAAGCCCGGTGGT-3', Reverse: 5'-CTTGATGCTCCGGGCTTCT-3'</td>
<td>5</td>
<td>83</td>
<td>1.949</td>
</tr>
<tr>
<td>Cyclophilin B</td>
<td>Forward: 5'-ACGTGGTTTTTCGGCAAAGT-3', Reverse: 5'-CTTGGGTCTCCACCTCC-3'</td>
<td>97</td>
<td>62</td>
<td>2.105</td>
</tr>
</tbody>
</table>
### Table S2
Comparison of mRNA levels for eight potential reference genes in 12 week old WKY and SHR cerebral arteries. Experimental number is given in parentheses.

<table>
<thead>
<tr>
<th>Reference Gene</th>
<th>Fold difference in mRNA levels (SHR/WKY)</th>
<th>Coefficient of variation in Ct values (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>18S rRNA</td>
<td>8.51 ± 0.37 (3)</td>
<td>6.02</td>
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<tr>
<td>β-actin</td>
<td>3.77 ± 0.27 (3)</td>
<td>3.35</td>
</tr>
<tr>
<td>TBP</td>
<td>4.70 ± 3.2 (3)</td>
<td>4.15</td>
</tr>
<tr>
<td>HGPRT</td>
<td>2.96 ± 0.26 (3)</td>
<td>2.61</td>
</tr>
<tr>
<td>Pecam1</td>
<td>2.27 ± 0.19 (3)</td>
<td>2.24</td>
</tr>
<tr>
<td>Rps16</td>
<td>4.39 ± 0.07 (3)</td>
<td>4.41</td>
</tr>
<tr>
<td>Rps5</td>
<td>1.14 ± 0.10 (3)</td>
<td>0.37</td>
</tr>
<tr>
<td>Cyclophilin B</td>
<td>1.88 ± 0.22 (3)</td>
<td>1.88</td>
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</tbody>
</table>
Figure S1. Diastolic, systolic, and mean arterial blood pressures are elevated more so in 12 week hypertensive SHR than age-matched WKY rats. A-C, Bar graphs showing mean diastolic pressures (A), mean systolic pressures (B), and mean arterial pressures (C) obtained from 6 week WKY, 6 week SHR, 12 week WKY and 12 week SHR rats by tail cuff. N numbers were as follows: 6 week WKY (n=10), 6 week SHR (n=6), 12 week WKY (n=10), 12 week SHR (n=11). * indicates P<0.05 when compared to 6 week WKY, # indicates P<0.05 when compared to 6 week SHR and § indicates P<0.05 when compared to 12 week WKY.
Figure S2. αδ-1 and Ca\textsubscript{v}1.2α\textsubscript{i} subunit protein are elevated during development of hypertension. Mean data illustrating that αδ-1 and Ca\textsubscript{v}1.2α\textsubscript{i} subunit protein increase with age in SHR but not in WKY cerebral arteries. * indicates P<0.05 when compared with WKY. # indicates P<0.05 when compared with Ca\textsubscript{v}1.2α\textsubscript{i} in SHR (n=8 for each protein at each age).
Figure S3. A longer time exposure of the intracellular lanes of the blot in Figure 3B illustrating that pregabalin increased intracellular α,δ-1 and Ca\(_{1.2}\alpha_1\) in WKY and SHR cerebral arteries.
Figure S4. Pregabalin (100 μmol/L) does not alter the rate of Ca\textsubscript{1.2} current inactivation in WKY or SHR cells. Graph showing that the rate of current inactivation (τ) was similar in untreated WKY (n=17), pregabalin-treated WKY (n=13), untreated SHR (n=16) and pregabalin-treated SHR (n=18) cells.