Protein Kinase C Downregulation Enhanced Extracellular Ca\(^{2+}\)-Induced Relaxation of Isolated Mesenteric Arteries from Aged Dahl Salt-Sensitive Rats

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ABSTRACT

The Ca\(^{2+}\)-sensing receptor (CaSR) detects small changes in extracellular calcium (Ca\(^{2+}\)) concentration ([Ca\(^{2+}\)]\(_e\)) and transduces the signal into modulation of various signaling pathways. Ca\(^{2+}\)-induced relaxation of isolated phenylephrine-contracted mesenteric arteries is mediated by the CaSR of the perivascular nerve. Elucidation of the regulatory mechanisms involved in vascular CaSR signaling may provide insights into the physiologic functions of the receptor and identify targets for the development of new treatments for cardiovascular pathologies such as hypertension. Protein kinase Ca\(_a\) (PKCa) is a critical regulator of multiple signaling pathways and can phosphorylate the CaSR leading to receptor desensitization. In this study, we used automated wire myography to investigate the effects of PKCa mutation and small-interfering RNA downregulation of PKCa on CaSR-mediated relaxation of phenylephrine-contracted mesenteric arteries from aged Dahl salt-sensitive (SS) rats on a low-salt diet. The data showed minimal relaxation responses of arteries to Ca\(^{2+}\) in wild-type (SS) and CaSR mutant (SS-Casrem1Mcwi) rats. Mutation of the CaSR gene had no significant effect on relaxation. PKCa expression was similar in wild-type and mutant rats, and small-interfering RNA downregulation of PKCa and/or inhibition of PKC with the Ca\(^{2+}\)-sensitive Gö 6976 resulted in a >80% increase in relaxation. Significant differences in EC\(_{50}\) values were observed between treated and untreated controls (P < 0.05 analysis of variance). The results indicate that PKCa plays an important role in the regulation of CaSR-mediated relaxation of mesenteric arteries, and its downregulation or pharmacological inhibition may lead to an increased Ca\(^{2+}\) sensitivity of the receptor and reversal of age-related changes in vascular tone.

SIGNIFICANCE STATEMENT

G protein-coupled CaSR signaling leads to the regulation of vascular tone and may, therefore, play a vital role in blood pressure regulation. The receptor has several PKC phosphorylation sites in the C-terminal intracellular tail that mediate desensitization. We have previously shown that activation of the CaSR in neuronal cells leads to PKC phosphorylation, indicating that protein kinase C is an important regulator of CaSR function. Therefore, PKC in the CaSR signaling pathway in mesenteric arteries is a potential target for the development of new therapeutic approaches to treat hypertension and age-related vascular dysfunction. The present studies show that small-interfering RNA downregulation of PKCa and pharmacological inhibition of PKC enhanced CaSR-mediated relaxation of phenylephrine-contracted mesenteric arteries from aged Dahl salt-sensitive rats.

INTRODUCTION

An important component of many physiologic functions, such as contraction of skeletal and smooth muscle cells, neuronal transmission, hormone secretion, and regulation of gene control, is the precise control of intracellular Ca\(^{2+}\). Availability of Ca\(^{2+}\) and availability in organs that participate in cardiovascular control is a crucial factor in the maintenance and regulation of blood pressure (Hatton and McCarron, 1994; McCarron and Reusser, 1999). Small changes in extracellular Ca\(^{2+}\) concentration ([Ca\(^{2+}\)]\(_e\)) induce changes in parathyroid hormone secretion through activation of the Ca\(^{2+}\)-sensing receptor (CaSR) in parathyroid glands to cause subsequent calcium absorption or elimination (Hannan et al., 2016). The CaSR has also been shown to regulate Ca\(^{2+}\) levels independently of parathyroid hormone activity (Kos et al., 2003; Kantham et al., 2009). The CaSR plays an important role in blood vessel tone and blood pressure control as it is involved in mediating...
Ca\(^{2+}\)-induced vascular reactivity (Scheppelmann et al., 2016). Previous studies from our laboratory indicated that a mechanism by which CaSR may regulate blood pressure involves Ca\(^{2+}\)-induced activation of perivascular sensory nerve CaSR signaling in the mesenteric artery network that leads to activation of the endocannabinoid system and subsequent vascular relaxation (Bukosi, 2001; Bukosi et al., 2001; Awumey et al., 2008). This transduction of changes in [Ca\(^{2+}\)]\(_e\) into changes in cell signaling makes the CaSR a promising target for therapeutic drug design. Elucidation of the regulatory mechanisms of CaSR-mediated signal transduction may not only provide insights into the physiology of the receptor but may also help identify its critical downstream signaling proteins as potential drug targets for treating diseases associated with poor blood pressure regulation.

The CaSR, unlike other G protein-coupled receptors (GPCRs), has a large N-terminal extracellular domain, with glycosylation sites, that binds Ca\(^{2+}\) with low affinity (Pin et al., 2005); a seven-transmembrane, hydrophobic domain that binds allosteric modulators; as well as a C-terminal intracellular tail containing multiple phosphorylation sites (Ruat et al., 1995; Ferry et al., 2000). The CaSR couples to several G\(_a\) subunits leading to mediation of G\(_{\beta\gamma}\) signaling (Neves et al., 2002) and regulation of numerous second messengers such as inositol-1,4,5-trisphosphate, Ca\(^{2+}\), cAMP, and phosphatidic acid (Ward, 2004). We have previously shown that activation of the CaSR leads to G\(_{\alpha}\) coupling and generation of inositol 1,4,5-trisphosphate and diacylglycerol that is metabolized to arachidonic acid and subsequent generation of epoxyeicosatrienoic acids (EETs) and glycated epoxideicosatrienoic acids (GEETs) that cause vascular relaxation (Awumey et al., 2008).

Agonist-induced activation of CaSR is typically followed by initiation of signaling cascades that result in rapid signal reduction, leading to functional desensitization of the receptor. Receptor phosphorylation by GPCR kinases (GRKs) and/or second messenger-dependent protein kinases such as protein kinase C (PKC) is an early step in functional desensitization (Conigrave and Ward, 2013). GRKs can also mediate signal attenuation by direct binding to the activated form of G\(_{\alpha}\) proteins, independently of receptor phosphorylation (Penela et al., 2003), and binding of \(\beta\)-arrestins to uncouple from G proteins (Hannan et al., 2018; Luttrell et al., 2018). An association of the receptor-\(\beta\)-arrestin complex with clathrin also initiates receptor internalization that contributes to functional desensitization (Lefkowitz and Sheny, 2005). We have previously reported that activation of PKCa and phosphorylation plays an important role in suppressing CaSR-mediated Ca\(^{2+}\) mobilization and in reduced receptor activity (Sesay et al., 2015). Furthermore, PKCa may indirectly mediate CaSR functional desensitization by modulating the activity of GRK2 (Krasel et al., 2001). In the current study, we investigated the role of PKCa in Ca\(^{2+}\)-induced activation of the CaSR and relaxation of mesenteric arteries from Dahl salt-sensitive hypertensive rats. Experiments were conducted with isolated arteries from aged wild-type salt-sensitive (SS) and mutant SS-Casr\(^{em1Mcwi}\) (with only one functional Casr allele) rats that were maintained on a low-salt (0.1% NaCl) diet.

## Materials and Methods

### Materials

Dulbecco’s modified Eagle’s medium (DMEM; cat. no. 11960-044), heat inactivated fetal bovine serum (cat. no. 1614-071), penicillin/streptomycin (cat. no. 15070-063), Opti-MEM I reduced serum medium (cat. no. 31985-062), and Halt Protease and Phosphatase Inhibitor Cocktail (cat. no. 78440-100). Casr was obtained from Invitrogen (Carlsbad, CA). Go 6976 (cat. no. 365253) was obtained from EMD biosciences (La Jolla, CA). PKCo small-interfering RNA (siRNA; cat. no. sc-108089), siRNA transfection reagent (cat. no. sc-29528), siRNA transfection medium (cat. no. sc-36868) as well as mouse monoclonal PKCo (H-7) antibody specific for an epitope mapping between amino acids 645–672 at the C-terminus of PKCo of human origin (cat. no. sc-8393), mouse monoclonal CaSR (6D4) antibody raised against amino acids 15–29 of CaSR of rat origin (cat. no. sc-47741), mouse monoclonal GAPDH (6C5) antibody raised against GAPDH purified from muscle of rabbit origin (cat. no. sc-22333), and antiGAPDH BP-HRP (cat. no. sc-516102), a purified recombinant mouse IgG\(_k\) light-chain binding protein conjugated to horseradish peroxidase were from Santa Cruz Biotechnology (Santa Cruz, CA).

### Animals

The animal studies have been carried out in accordance with the Guide for the Care and Use of Laboratory Animals as adopted and promulgated by the U.S. National Institutes of Health and were approved by the Institutional Animal Care and Use Committee of North Carolina Central University. Dahl SS wild-type and mutants (SS-Casr\(^{em1Mcwi}\)) rats were maintained in the Animal Research Center at the Julius L. Chambers Biomedical/Biotechnology Research Institute at constant temperature and humidity and provided with 0.1% NaCl (cat. no. TD.7034) rodent chow (Envigo Tekland Diets, Madison, WI) and water ad libitum. Animals used were approximately 8 months old and of weight, 450–500 g (Fig. 1).

### Generation of Mutant SS-Casr\(^{em1Mcwi}\) Rats

The SS-Casr\(^{em1Mcwi}\) mutant rat was generated from SS/JrHadMcwi parental strain (ID 61499) in collaboration with the Gene Editing Rat Resource Center at the Medical College of Wisconsin (Milwaukee, WI) in Round 2 of a competitive process in March 2014. The mutant rats were produced by injecting a clustered regulatory interspaced short palindromic repeat (CRISPR) targeting the Casr (RGD Gene ID: 92277) sequence, GTACTTCCGCTGGAACGTGGG, into SS/JrHadMcwi rat embryos. The mutation region (RGSC 5.0/rrns; chromosome 11: 70,329,456-70,329,457) is a 1-bp insertion resulting in a frameshift in exon 4 of the Casr. The target site and the insertion of a T is shown below:

GTACTTCCCCTGGAGACATGGG Casr CRISPR target (PAM in italics).

GTACTTCCCCTGGAACGTGGG Casr-m1 1-bp insertion mutation in exon 4 results in predicted frame-shift.

Founder animals were genotyped by the Cel-1 assay and confirmed by Sanger sequencing. The founders were backcrossed to the parental strain, and subsequent litters were identified by fluorescent genotyping. We received heterozygous pairs for breeding on April 4, 2015 and obtained offspring that were used to establish a colony for our studies.

### Protein Extraction and Western Blot Analysis

Total proteins were extracted from mesenteric arteries isolated from SS and SS-Casr\(^{em1Mcwi}\) mutant rats, under isoflurane anesthesia, and analyzed for expression of PKCo and CaSR proteins by Western blotting. After trimming fat from the arteries, tissues were homogenized in RIPA lysis buffer (Sigma-Aldrich) supplemented with protease (Sigma-Aldrich) and phosphatase inhibitor cocktail (Sigma-Aldrich) and incubated on ice. After centrifugation of the homogenates, the supernatants were collected and protein concentrations were determined by the Bradford method (Bio-Rad Laboratories, Inc.). The proteins were resolved using 10% SDS-PAGE gels and transferred to nitrocellulose membranes. Membranes were blocked with 5% non-fat milk in Tris-buffered saline–Tween (TBST) and incubated with primary antibodies. The membranes were washed and incubated with secondary antibodies conjugated to horseradish peroxidase. The bands were detected using an enhanced chemiluminescence detection kit (Pierce). The primary antibodies used were anti-PKC\(_{\alpha}\) (H-7) antibody specific for an epitope mapping between amino acids 645–672 at the C-terminus of PKCo of human origin (cat. no. sc-8393), mouse monoclonal CaSR (6D4) antibody raised against amino acids 15–29 of CaSR of rat origin (cat. no. sc-47741), mouse monoclonal GAPDH (6C5) antibody raised against GAPDH purified from muscle of rabbit origin (cat. no. sc-22333), and antiGAPDH BP-HRP (cat. no. sc-516102), a purified recombinant mouse IgG\(_k\) light-chain binding protein conjugated to horseradish peroxidase were from Santa Cruz Biotechnology (Santa Cruz, CA).

### Founder Animals

Four founder animals were genotyped by the Cel-1 assay and confirmed by Sanger sequencing. The founders were backcrossed to the parental strain, and subsequent litters were identified by fluorescent genotyping. We received heterozygous pairs for breeding on April 4, 2015 and obtained offspring that were used to establish a colony for our studies.
protein extraction. Tissues were homogenized in ice-cold Tris buffer (10 mM Tris, pH 7.5, 0.25 M sucrose and 3 mM MgCl₂) with freshly added Halt Protease and Phosphatase Inhibitor Cocktail. Homogenates were centrifuged at 800 g for 10 minutes, and the supernatant fractions separated using SDS-PAGE. Separated proteins were transferred onto polyvinylidene fluoride membranes, blocked with nonfat milk (Biorad, Hercules, CA), and then blotted with antibodies followed by incubation with m-IgG BP-HRP (1:5000 dilution) and visualization by enhanced chemiluminescence (ECL). Densitometry analysis of protein bands was done using Licor Image Studio software.

Vessel Isolation. Mesenteric arteries were dissected from rats under deep anesthesia with isoflurane and sacrificed by open-chest cardiac puncture as previously described (Awumey et al., 2008; Bridges et al., 2011). The small intestine and all the associated vessels were removed in block and placed in cold physiologic salt solution (PSS; millimolars: 115 NaCl, 4.7 KCl, 1.4 MgSO₄, 7H₂O, 5 NaHCO₃, 1.1 Na₂HPO₄, 1.2 KH₂PO₄, 1.0 CaCl₂, 20 HEPES, and 5 glucose; pH 7.4). Branches I and II mesenteric arteries were then cut into 2-mm segments for wire myography. Isolated vessels were then cut into 2-mm segments for wire myography.

siRNA Downregulation of PKCα in Mesenteric Arteries. To induce PKCα knockdown, isolated mesenteric arteries were incubated with PKCα siRNA for 24 hours. A solution containing 130 nM PKCα siRNA was mixed with transfection reagent in transfection medium and incubated at room temperature for 30 minutes to allow complex formation. Mesenteric arteries were then incubated at 37°C in 5% CO₂ for 6 hours, after which media was replaced with fresh DMEM containing 10% fetal bovine serum and antibiotics, and the incubation continued 24 hours before use in protein extraction or assay of reactivity to Ca²⁺ by wire myography.

Wire Myography. Isometric force generation in mesenteric artery segments was determined as previously described (Awumey et al., 2008; Bridges et al., 2011). Stainless steel wires (40-μm in diameter) were inserted through the lumens of 2-mm long artery segments and mounted in a small-vessel Mulvany-Halpern 510A Auto Dual Wire Myograph (DMT-USA, Marietta, GA). Segments were maintained in PSS containing 1 mM CaCl₂ and 100 μM ascorbic acid and gassed with a mixture of 95% air and 5% CO₂. After a 30-minute equilibration at 37°C, vessels were normalized by stepwise stretching using pre-established normalization protocols. The parameters used for normalization were as follows: target transmural pressure, 13.3 kPa (100 mm Hg); time, 60 seconds; IC1/IC100 = 0.9 (IC100 = internal circumference of normalized vessel); eyepiece calibration, 2°Δ (mm/division). The normalization procedure defines the lumen diameter (d₅₀) that the artery would have in vivo when relaxed and under a transmural pressure of 100 mm Hg (Halpern et al., 1978; Angus and Wright, 2000). The mounted vessels were then challenged with 5 μM phenylephrine (PE) until reproducible contractions were observed. Active force development of ≥10 mN was viewed as ideal for the experiment to proceed. Relaxation was assessed by addition of cumulative concentrations of Ca²⁺ to precontracted vessels. When an inhibitor was used, vessels were preincubated with the PKC inhibitor Gö 6976 for 5 minutes prior to addition of PE and was present throughout the relaxation assays.

Statistical Analysis. [Ca²⁺]ᵢ-response curves and bar graphs were analyzed using Sigma Plot 14 software (SYSTAT, Port Richmond, CA). EC₅₀ values were determined by fitting data to sigmoid curves in the program. Comparisons between groups were determined by one-way analysis of variance (ANOVA) with a difference of P < 0.05 considered significant. Power of performed test with α = 0.050:1.000.

Results

Genotyping of Mutant SS-Casrem1Mcwi Rats. Male and female SS-Casrem1Mcwi rats, from our colony, were randomly bred on a 0.3% NaCl diet (TD.95027; Tekland), and DNA extracts from tail samples of offspring were genotyped using a Custom TaqMan SNP Genotyping Assay, on a fee-for-service basis by the Molecular Genetics Core of the Duke Molecular Physiology Institute (Durham, NC). The probe sequences and the reporter dyes (in brackets) used are as follows:

**Reporter Sequence 1** - CCACCCAAGTTCCAG (VIC dye).
**Reporter Sequence 2** - CCACCCAGTTCCAG (FAM dye).

Most of the offspring from the breeding were wild-type SS (D/D) and heterozygous SS-Casrem1Mcwi (I/D) animals, confirming a single-allele mutation in the Casr (Supplemental Fig. 1). Thus, the breeding protocol we established has allowed us to maintain a colony of heterozygous breeder pairs in sufficient numbers to generate wild-type and age-matched heterozygous mutants in adequate numbers continuously for our studies. Figure 1 shows the ages and weights of SS wild-type and SS-Casrem1Mcwi heterozygous animals used in the present
studies. The ages of the animals used were about 8 to 9 months but the weights were similar.

Effects of CaSR and PKCα Downregulation on Protein Expression. To confirm knockdown of CaSR and PKCα expression, proteins extracted from isolated mesenteric arteries (control and those incubated with PKCα siRNA) were analyzed by Western blotting with CaSR and PKCα antibodies. The results showed significant reduction in the expression of the CaSR in the mesenteric arteries from SS-Casrem1Mcwi rats compared with the SS (Fig. 2A), and down-regulation of expression of PKCα protein following PKCα siRNA treatment of the vessels (Fig. 2B). Western blotting also showed that there were no significant differences in CaSR and PKCα expression between young (<3 months old) rats compared with the aged rats used in this study (Fig. 3).

Normalization of Mounted Mesenteric Arteries. It is important to set a baseline condition in myography studies of isolated vessels in order to acquire reproducible results. To do this, vessels equilibrated in PSS were stretched in a stepwise manner with increasing tension over time until they developed passive tension (Angus and Wright, 2000). Normalization of isolated mesenteric artery segments from SS and SS-Casrem1Mcwi rats were similar (see Supplemental Data). PKCα downregulation did not have any effect on the slopes of the normalization curves. Figure 4 shows resting tensions, after normalization, and tensions resulting from treatment of vessels with 5 μM PE, in SS and SS-Casrem1Mcwi, respectively.

There were no significant differences in resting tensions and PE tensions resulting from either CaSR or PKCα downregulation. No significant changes in PE tensions resulted from treatment of mounted vessels with the PKC inhibitor Gö 6976.

Effects of siRNA Downregulation of PKCα and Pharmacological Inhibition of PKC in Mesenteric Arteries Increased Ca2+ Induced Relaxation. Arteries from SS and SS-Casrem1Mcwi animals that had PKCα downregulated or PKC inhibited showed significant differences in responses to cumulative addition of Ca2+ compared with controls (Fig. 5). Tension changes in these vessels indicate that the nontransfected (control) PE-contracted tissues showed minimal response to Ca2+, with relaxation starting after addition of high [Ca2+]o (Fig. 5, A and C). However, pretreatment of vessels with 5 μM Gö 6976 resulted in increased responses to Ca2+. These increased responses were also observed in PKCα siRNA-treated vessels, which showed responses to much lower [Ca2+]o compared with the nontransfected tissues (Fig. 5, B and D). This effect was enhanced in tissues in which PKCα was downregulated and treated with 5 μM Gö 6976. The [Ca2+]o-response curves from both sets of tissues also indicate the effect of PKCα knockdown and/or PKC inhibition on relaxation response (Fig. 6, A and B). Response curves in PKCα-downregulated arteries were shifted to the left compared with the nontransfected tissues, with combined downregulation and inhibition shifting the response curves further to the left. EC50

Fig. 2. Analysis of expression of CaSR and PKCα in control and PKCα siRNA-treated mesenteric arteries from SS and SS-Casrem1Mcwi rats. Animals were maintained on 0.1% NaCl diet for 8 months and protein extracts from control siRNA-treated mesenteric arteries were analyzed with monoclonal antibodies. CaSR, PKCα and GAPDH bands were analyzed from the separated proteins in the same samples. After separation, proteins were transferred onto membranes and cut into three strips for blotting with monoclonal antibodies to the CaSR (150 kDa), PKCα (80 kDa) and GAPDH (37 kDa). (A) (i) Representative CaSR Western blot, and (ii) bar chart showing densitometric analysis of protein bands from four different Western blot experiments as in (i). Values plotted are means (±S.E.M.) of four experiments. (B) (i) Representative PKCα Western blot, and (ii) bar charts showing densitometric analysis of protein bands from four different Western blot experiments as in (i). Values plotted are means (±S.E.M.) Protein bands were normalized to GAPDH as the loading standard. (*P < 0.05 vs. control; ANOVA followed by multiple comparisons using the Holm-Sidak method).
values for the Ca\textsuperscript{2+} relaxation responses were derived by fitting sigmoid curves to the data (Fig. 6C). No significant differences in vessel responses to Ca\textsuperscript{2+}e were observed between the SS and SS-Casrem1Mcwi tissues regardless of treatment.

**Discussion**

The [Ca\textsuperscript{2+}]\_i is maintained within a narrow range (1.1–1.4 mM) in humans (Hurwitz, 1996), therefore the CaSR must be able to detect small changes in this concentration for receptor activation to be possible. In fact, the CaSR has been shown to detect small changes in Ca\textsuperscript{2+}e (Brown and MacLeod, 2001) and small increases in interstitial fluid Ca\textsuperscript{2+} ([Ca\textsuperscript{2+}]\_ISF) that are within the physiologic range (Breitwieser, 2008). In situ microdialysis studies that measured [Ca\textsuperscript{2+}]\_ISF in the duodenal submucosa and kidney cortex, two tissues that are essential for the regulation of peripheral resistance and BP, showed dynamic changes as a function of the gut lumen [Ca\textsuperscript{2+}]. Increasing gut [Ca\textsuperscript{2+}] from 0 to 6 mM increased the [Ca\textsuperscript{2+}]\_ISF from 1.1 to 1.9 mM (Mupanomunda et al., 1998, 1999, 2000), which is in the range observed to activate the perivascular CaSR expressed in human embryonic kidney (HEK) cells (Awumey et al., 2007), and relaxed isolated mesenteric arteries (Awumey et al., 2008). We have also shown that the CaSR detects decreases in [Ca\textsuperscript{2+}]\_i and an increase in the action potential duration through activation of the nonselective cation channel, which in turn attenuates the impact on release probability at neocortical terminals (Chen et al., 2010). The latter suggests that the CaSR provides presynaptic feedback to alter brain excitability in response to Ca\textsuperscript{2+}. We also found that in HEK-CaSR-EGFP cells expressing the dorsal root ganglia CaSR-EGFP fusion protein, desensitization of the receptor occurs with repeated, prolonged stimulation (Awumey et al., 2007), further suggesting that an understanding of the regulation of this receptor will clarify its role under both normal and hypertensive conditions. Studies have shown that small changes in [Ca\textsuperscript{2+}]\_ISF are enough to activate the CaSR and contribute to vasodilator synthesis under normal conditions (Mupanomunda et al., 1999, 2000; Bukoski, 2001). Other studies have also revealed that a high-salt diet reduced renal [Ca\textsuperscript{2+}]\_ISF and increases systolic BP in Dahl salt-sensitive rats (Palmer et al., 2003; Eley et al., 2008).

The mesenteric arterial network contributes significantly to total peripheral resistance, as it receives about 25% of cardiac output, and so this system is very important for overall regulation of blood pressure (Christensen and Mullvany, 1993). CaSR, and its downstream signaling protein complements, has been shown to play crucial roles in this system and as such is involved in blood pressure regulation (Bukoski et al., 1997; Bukoski, 1998; Wang and Bukoski, 1998; Awumey et al., 2008). Given the key role played by the mesenteric artery CaSR in controlling Ca\textsuperscript{2+}, the regulation...
of its function has important consequences for the entire animal physiology.

PKCα is a critical component of various signaling mechanisms that regulate vascular contractility. It has been shown that PKCα mediates L-type voltage-gated Ca\(^{2+}\) channel control of Ca\(^{2+}\) entry (Navedo et al., 2005; Potts et al., 2012). PKCα is also involved in increasing Ca\(^{2+}\)-sensitizing pathways in the contractile myofilaments coupled to \(\alpha_1\)-adrenergic arterial vasoconstriction (Villalba et al., 2007; Kitazawa and Kitazawa, 2012). Conversely, as we have shown in a previous study, PKCα is also involved in CaSR-signaling mechanisms that reduce Ca\(^{2+}\) mobilization (Sesay et al., 2015). This mechanism involves G\(\delta\) 6976 inhibition of [Ca\(^{2+}\)]\(_{e}\)-induced phosphorylation and translocation of PKCα to the plasma membrane.

In this study we examined the role played by PKCα in decreasing CaSR-mediating relaxation of mesenteric arteries, as well as investigating the effects of reduced expression of CaSR. We performed these studies using isolated arteries from wild-type male SS and SS-Casr<sup>−/−Mcvwi</sup> mutant rats, which have only one functional Casr allele. It is well established that aging results in myriad changes in vascular structure, and such remodeling (Xu et al., 2017) affects endothelial-dependent and -independent relaxations (Muller-Delp et al., 2002; Prisby et al., 2007; Zicha et al., 2012) and Ca\(^{2+}\) homeostasis, although the latter has mainly been shown to occur via an endothelium-dependent mechanism with acetylcholine as the vasodilator agent. We have observed in our laboratory that there is significant decrease in relaxation response of PE-contracted mesenteric arteries as animals get older. However, we did not observe any significant differences in expression levels of CaSR or PKCα in young and old animals (Fig. 3), which suggests that changes in function or activity of these proteins owing to aging contributed to decreased Ca\(^{2+}\)-induced relaxation of phenylephrine-contracted mesenteric arteries.

To accurately and reproducibly conduct mechanical studies on isolated vessels, it is very important to normalize mounted vessel segments to establish standard baseline tension and determine tissue viability. Furthermore, stepwise stretching of the vessel, until a lumen diameter is defined that is comparable to transmural pressure in vivo, is important, as this determines vessel activity and sensitivity to various treatments. Our results show...
that siRNA downregulation of PKCα did not affect basal tensions of both SS and SS-Casrem1Mcwi vessels. There was also no effect of PKCα downregulation on PE tension levels. This is consistent with previous studies showing that PKCα is not directly involved in α1-adrenergic-mediated vasoconstriction (Ohanian et al., 1996). It should also be noted that even though there was reduced expression of CaSR in the arteries from the SS-Casrem1Mcwi animals, this did not result in any significant difference in basal or PE tensions.

As we have previously established, the CaSR-mediated vascular relaxation response in mesenteric arteries is a result of CaSR activity (Awumey et al., 2008, 2013). In these studies, we showed that CaSR-mediated vascular relaxation of precontracted arteries involves CaSR-mediated increase in intracellular [Ca2+] that leads to the generation of cytochrome P450-derived metabolites of the endocannabinoids 2-arachidonoylglycerol and anandamide. Furthermore, endothelial nitric oxide synthase knockout in mice upregulates CaSR expression in mesenteric arteries.

Fig. 5. Effect of downregulation of CaSR and PKCα, and pharmacological inhibition of PKC on Ca2+-induced relaxation of PE-contracted mesenteric arteries. Force tracings showing the effect of cumulative additions of Ca2+ to PE-contracted mesenteric arteries, from SS and SS-Casrem1Mcwi rats, in the absence or presence of 5 μM Gö 6976 on relaxation. (A) SS control; (B) SS + PKCα siRNA; (C) SS-Casrem1Mcwi control; (D) SS-Casrem1Mcwi + PKCα siRNA. PKCα siRNA downregulation and PKC inhibition by Gö 6976 resulted in increased relaxation responses to cumulative additions of Ca2+.
The observed effect of downregulation of PKCa and/or pharmacological inhibition of PKC on mesenteric artery relaxation confirms that PKCa plays an important role in the regulation of CaSR activity, similar to our observation in a previous study (Sesay et al., 2015). It has also been suggested previously that receptor phosphorylation by PKC regulates attenuation of CaSR signaling via a mechanism involving β-arrestin binding to PKC-phosphorylated CaSR and subsequent desensitization to Ca^{2+} (Lorenz et al., 2007). Our results indicate that PKCa mediates relaxation of phenylephrine-contracted mesenteric arteries in response to cumulative addition of Ca^{2+}. Both siRNA downregulation of PKCa and pharmacological inhibition of PKC resulted in significant increases in Ca_{o}^{2+}-induced relaxation of isolated, PE-constricted mesenteric arteries, and, in effect, reversal of the effects of aging on vasodilation in these vessels. PKCa downregulation resulted in increased responsiveness of arteries to Ca^{2+} as illustrated by the reduction in EC_{50} values. The proposed mechanism for such a process is outlined in Fig. 7. It should also be noted that there were no significant differences in responses to Ca^{2+} between mesenteric arteries from SS and SS-Casre^{m1Mcwi} animals (EC_{50} values were similar), indicating that changes in receptor function are the key factor. The current study only involved the use of animals on a low-salt diet, and a future direction would be to investigate whether CaSR plays a more significant role in Ca^{2+}-induced vasodilation when there is exposure to a high-salt diet by comparing responses in tissues from SS and SS-Casre^{m1Mcwi} rats.

In conclusion, our results confirm that PKCa plays an important regulatory role on CaSR signaling in the context of Ca^{2+}-induced vasodilation. Reduction in PKCa activity along with increased exposure to Ca^{2+} could help counteract some of the reduction in vasodilation that occurs because of aging, suggesting a possible direction for combined diet and drug therapeutic studies for the management of hypertension and its related cardiovascular pathologies in aging.