The Role of DPO-1 and XE991-Sensitive Potassium Channels in Perivascular Adipose Tissue-Mediated Regulation of Vascular Tone

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The anti-contractile effect of perivascular adipose tissue (PVAT) is an important mechanism in the modulation of vascular tone in peripheral arteries. Recent evidence has implicated the XE991-sensitive voltage-gated Kv (KCNQ) channels in the regulation of arterial tone by PVAT. However, until now the in vivo pharmacology of the involved vascular Kv channels with regard to XE991 remains undetermined, since XE991 effects may involve Ca2+ activated BKCa channels and/or voltage-dependent Kv1.5 channels sensitive to diphenyl phosphine oxide-1 (DPO-1). In this study, we tested whether Kv1.5 channels are involved in the control of mesenteric arterial tone and its regulation by PVAT. Our study was also aimed at extending our current knowledge on the in situ vascular pharmacology of DPO-1 and XE991 regarding Kv1.5 and BKCa channels, in helping to identify the nature of K+ channels that could contribute to PVAT-mediated relaxation. XE991 at 30 µM reduced the anti-contractile response of PVAT, but had no effects on vasocontraction induced by phenylephrine (PE) in the absence of PVAT. Similar effects were observed for XE991 at 0.3 µM, which is known to almost completely inhibit mesenteric artery VSMC Kv currents. 30 µM XE991 did not affect BKCa currents in Kcnal−/− arteries and wild-type arteries incubated with 1 µM DPO-1 showed normal vasoconstrictions in response to PE in the presence and absence of PVAT. Kv current density and inhibition by 30 µM XE991 were normal in mesenteric artery VSMCs isolated from Kcnal−/− mice. We conclude that Kv channels are involved in the control of arterial vascular tone by PVAT. These channels are present in VSMCs and very potently inhibited by the KCNQ channel blocker XE991. BKCa channels and/or DPO-1 sensitive Kv1.5 channels in VSMCs are not the downstream mediators of the XE991 effects on PVAT-dependent arterial vasorelaxation. Further studies will need to be undertaken to examine the role of other Kv channels in the phenomenon.

Keywords: XE991, KCNQ channels, Kv1.5 channels, adipocyte-derived relaxing factor (ADRF), perivascular adipose tissue (PVAT), BK channels
INTRODUCTION

Over the past decade, various potassium (K⁺) channels have been implicated as important players in the regulation of arterial vascular tone and its control by perivascular adipose tissue (PVAT). Opening of vascular smooth muscle cell (VSMC) K⁺ channels causes K⁺ efflux and membrane hyperpolarization, which leads to reduced Ca²⁺ influx though L-type CaV1.2 channels and consequently arterial relaxation (Nelson and Quayle, 1995). A variety of endogenous vasodilators, such as hypoxia, acidosis, as well as metabolites and autacoids (e.g., adenosine, prostacyclin) act as potent K⁺ channel openers to produce relaxation (Sobey, 2001; Tano and Gollasch, 2014). Noteworthy, many of these substances produce relaxation by opening maxi Ca²⁺ activated (BKCa) K⁺ channels in VSMCs (Bentzen et al., 2014). Only very few substances have been reported to relax vessels by opening arterial smooth muscle voltage-gated Kv channels (Tanaka et al., 2006; Park et al., 2015). Among them adenosine and atrial natriuretic peptide (ANP) act via activation of the KCNQ (Kv7) subfamily of Kv channels (Khanamiri et al., 2013; Stott et al., 2015).

Recent studies have demonstrated a paracrine role for PVAT to produce relaxation of arterial smooth muscle cells in a number of vascular beds (Lohn et al., 2002; Verlohren et al., 2004; Gao et al., 2005; Zavartiszkaya et al., 2013). Certain adipokines, such as adiponectin (Weston et al., 2013), angiotensin-1 to 7 (Lee R. M. K. W. et al., 2011), methyl palmitate (Lee Y.-C. et al., 2011), and notably H₂S (Schleifenbaum et al., 2010) were recently proposed as potential perivascular-derived relaxing factors (PVRFs), which could mediate the anti-contraction properties of PVAT. The paracrine effects of PVAT involve the opening of K⁺ channels, however, the identity of the K⁺ channel subtype(s) involved is still a matter of debate (Tano et al., 2014).

Voltage-gated Kv channels of the KCNQ (Kv7) family have been proposed to play an important role in PVAT control of arterial tone. This conclusion is based on observations demonstrating that the anti-contraction effects of PVAT are inhibited by the pan KCNQ channel blocker XE991 at 30 µM or the pan Kv channel blocker 4-aminopyridine (2 mmol/L; Fésüs et al., 2007; Schleifenbaum et al., 2010; Lee Y.-C. et al., 2011; Zavartiszkaya et al., 2013). XE991 is a widely used pan Kv7 channel blocker, which inhibits Kv7.1 homeric or Kv7.1/ KCNE channels (IC₅₀ of ∼0.8 µM and 11.1 µM, respectively; Wang et al., 2000), KCNQ2/3 channels (EC₅₀ ∼1 µM; Wang et al., 1998), KCNQ4 (EC₅₀ ∼5.5 µM; Sogaard et al., 2001), and KCNQ5 (EC₅₀ ∼65 µM; Schroeder et al., 2000). Noteworthy, XE991 can also inhibit other Kv channels, such as ERG (Kv11; EC₅₀ ∼110 µM) (Elmedyb et al., 2007) and Kv1.2/1.5, Kv2.1/Kv9.3 channels (∼30% inhibition at 10 µM) in heterologous expression systems (Zhong et al., 2010).

However, it is unknown whether XE991 is indeed specific for vascular Kv channels in situ, and does not inhibit native BKCa channels. This is particularly relevant since BKCa channels have been proposed to play a role in PVAT control of arterial tone in other studies (Lynch et al., 2013; Weston et al., 2013), although studies using BKCa deficient mice gave opposing results (Fésüs et al., 2007). A recent study showed that Kv channels in VSMCs of mouse mesenteric arteries are very sensitive to XE991 (EC₅₀ ∼60 nM), suggesting that these channels may contribute to PVAT control of arterial tone (Schleifenbaum et al., 2010, 2014). A very recent study suggested that diphenyl phosphine oxide-1 (DPO-1) sensitive Kv1.5 channels could contribute to the Kv current in VSMC (Fancher et al., 2015).

Therefore, we tested whether Kv1.5 channels are involved in the control of arterial tone and its regulation by PVAT or not. Our study is also aimed at extending our current knowledge on the in situ vascular pharmacology of DPO-1 and XE991 regarding Kv1.5 and BKCa channels, in helping to identify the nature of K⁺ channels that could contribute to PVAT-mediated relaxation.

METHODS

Mouse Model

We used Kcnas⁻/⁻ mice as previously described (Pannasch et al., 2006). The mouse model was evaluated by RT-qPCR (Figure S1). Either litter- or age-matched (10–14 weeks old) male wild-type (129S6 background, previously known as 129SvEv-Ta) mice were used as controls. 250–300 g male Sprague Dawley rats were obtained from Charles River, Germany, Berlin. All experimental procedures were performed in accordance with the German legislation on protection of animals. Animal care followed American Physiological Society guidelines, and local authorities (Landesamt für Gesundheit und Soziales Berlin, LAGeSo) approved all protocols. Mice were housed in individually ventilated cages under standardized conditions with an artificial 12-h dark–light cycle with free access to water and food.

Wire Myography

First order mesenteric arteries were removed immediately after killing the mice or rats under inhalation anesthesia with isoflurane by cervical dislocation, quickly transferred to cold (4°C), oxygenated (95% O₂/5% CO₂) physiological salt solution (PSS) containing (in mmol/L) 119 NaCl, 4.7 KCl, 1.2 KH₂PO₄, 25 NaHCO₃, 1.2 MgSO₄, 1.1 glucose, 1.6 CaCl₂), and dissected into 2 mm rings whereby perivascular fat and connective tissue were either intact [(+)] PVAT or removed (−) PVAT) without damaging the adventitia. Each ring was positioned on two stainless steel wires (diameter 0.0394 mm) in a 5-ml organ bath of a Mulvany Small Vessel Myograph (DMT 610 M; Danish Myo Technology, Denmark). The organ bath was filled with PSS. The bath solution was continuously oxygenated with a gas mixture of 95% O₂ and 5% CO₂, and kept at 37°C (pH 7.4) (Verlohren et al., 2004; Fésüs et al., 2007). The mesenteric rings were placed under a tension equivalent to that generated at 0.9 times the diameter of the vessel at 100 mm Hg by stepwise distending the vessel using LabChart DMT Normalization module. This normalization procedure was performed to obtain the passive diameter of the vessel at 100 mm Hg (Fésüs et al., 2007). The software Chart5 (AD Instruments Ltd. Spechbach, Germany) was used for data acquisition and display. After 60 min equilibration arteries were pre-contracted either with isotonic external 60 mmol/L KCl until a stable resting tension was acquired. The composition of 60 mM KCl (in mmol/L) was 63.7 NaCl, 60 KCl, 1.2 KH₂PO₄, 25 NaHCO₃, 1.2 MgSO₄, 11.1 glucose, and 1.6 CaCl₂. Drugs were
added to the bath solution if not indicated otherwise. Tension is expressed as a percentage of the steady-state tension (100%) obtained with isotonic external 60 mM KCl.

Isolation of Arterial VSMCs

VSMCs from mesenteric arteries were isolated as described (Gollasch et al., 1998; Plüger et al., 2000). Briefly, the arteries were isolated and quickly transferred to cold (4°C) oxygenated (95% O2–5% CO2) PSS. The arteries were cleaned, cut into pieces, and placed into a Ca2+-free Hank's solution (in mmol/L): 55 NaCl, 80 sodium glutamate, 5.6 KCl, 2 MgCl2, 1 mg/ml bovine serum albumin (BSA, Sigma, Taufkirchen), 10 glucose, and 10 HEPES (pH 7.4 with NaOH) containing 0.5 mg/ml papain (Sigma) and 1.0 mg/ml DTT for 50 min at 37°C. The segments then were placed in Hank's solution containing 1 mg/ml collagenase (Sigma, type F and H, ratio 30 and 70%, respectively) and 0.1 mmol/L CaCl2 for 10 min at 37°C. Following several washes in Ca2+-free Hank's solution (containing 1 mg/ml BSA), single cells were dispersed from artery segments by gentle triturating. Cells were then stored in the same solution at 4°C.

Electrophysiology

Voltage dependent potassium (KV) currents and BKCa currents were measured in the conventional whole-cell configuration of the patch-clamp technique at room temperature as previously described (Gollasch et al., 1996; Essin et al., 2007; Schleifenbaum et al., 2014). Patch pipettes (resistance 3–5 MΩ) for recording KV currents were filled with a solution containing (in mmol/L): 130 KCl, 1 MgCl2, 3 Na2ATP, 0.1 Na3GTP, 10 HEPES, and 5 EGTA (pH 7.2; Yeung and Greenwood, 2005). Patch pipettes for recording BKCa currents contained (in mmol/L): 130 KCl, 1 MgCl2, 3 Na2ATP, 0.1 Na3GTP, 10 HEPES, 5 EGTA, and 4.3 CaCl2 (estimated [Ca2+]free, 10⁻⁶ mol/L; pH 7.2). The external bath solution contained (in mmol/L): 126 NaCl, 5 KCl, 1 MgCl2, 0.1 CaCl2, 11 glucose and 10 HEPES (pH 7.2; Yeung and Greenwood, 2005). Holding potential was −60 mV. Whole cell currents were recorded using an Axopatch 200B amplifier (Axon Instruments/Molecular Devices, Sunnyvale, CA, USA) or an EPC 7 amplifier (List, Darmstadt, Germany) and digitized at 5 kHz, using a Digidata 1440A digitizer (Axon CNS, Molecular Devices), and pClamp software versions 10.1 and 10.2 (Schleifenbaum et al., 2014).

RT-qPCR

Total RNA was isolated from snap-frozen heart and aortae tissues with or without Kv1.5 by using the RNeasy RNA isolation kit (Qiagen, Hamburg, Germany) according to the manufacturer’s instruction. Isolated RNA concentration was measured and RNA quality was tested by NanoDrop-1000 spectrophotometer (PeqLab, Erlangen, Germany). For the synthesis of cDNA, equivalent amounts of RNA (2 μg) were used and processed by a high capacity cDNA reverse transcription kit (Life Technologies GmbH, Darmstadt, Germany). Quantitative analysis of target mRNA expression was performed with real-time PCR using the relative standard curve method (Markó et al., 2016). TaqMan or SYBR green analysis was conducted according to the manufacturer’s instructions, using an Applied Biosystems 7500 Sequence Detector (Life Technologies Corporation, Carlsbad, CA, USA). The expression level of the target genes was normalized by the expression of 18S. Primers for were synthesized by Biotez (Berlin, Germany) and the sequences are as follows: Kv1.5 Forward sequence: 5’-GCTACTTGCATCCCTTGAAAT-3’; Reverse sequence: AGTAGTACAAATGCCCCATCGAAGCT, 18S Forward sequence: 5’-ACATCCAAAGGAAGCGACGAC-3’; Reverse sequence 5’-TTTTTGTCACTACCTCCCCGG-3’.

Materials

All salts and other chemicals were obtained from Sigma-Aldrich (Germany) or Merck (Germany). All drugs were freshly dissolved on the day of each experiment according to the material sheet. The following concentrations of drugs were used: phenylephrine (Sigma-Aldrich) ranged from 0.01 to 100 μmol/L, 5-HT from 0.01 to 10 μM, DPO-1 (Tocris) 1 and 10 μmol/L, 100 nmol/L iberiotoxin (Sigma Aldrich). XE991 (Tocris) was applied at concentrations between 0.3 and 30 μM.

Statistics

Data represent mean ± SEM. EC50 values were calculated using a Hill equation: T = (B0 − Be)/([D]/EC50)n + Be, where T is the tension in response to the drug (D); Be is the maximum response induced by the drug; B0 is a constant; EC50 is the concentration of the drug that elicits a half-maximal response (Bychkov et al., 1998). Curve fittings were done by Prism 6 software using non-linear regression. Statistical significance was determined by two-way ANOVA or repeated-measures two-way ANOVA, followed by Bonferroni post hoc test, and using Prism 6 software. In case of unbalanced data, this software uses analysis of “unweighted means” to compare groups. Extra sum-of-squares F-test was performed for comparison of concentration-response curves and their 95% confidence intervals (CI). P-values < 0.05 were considered statistically significant. n represents the number of independent arteries tested or the number of cells measured. All rings were obtained from at least 3 different animals.

RESULTS

Regulation of Arterial Tone by DPO-1

Sensitive Kv1.5 Channels

First, we examined the role of Kv1.5 channels in the regulation of arterial tone by alpha1 adrenoceptor (alpha1-AR) stimulation. In this set of experiments, we used the Kv1.5 channel blocker DPO-1 at concentrations assumed to be specific and potent for Kv1.5 channel inhibition (Stump et al., 2005; Lagrutta et al., 2006; Regan et al., 2006). In the presence of 1 μM DPO-1, mesenteric artery rings without PVAT [(−) PVAT] displayed similar contractions in response to phenylephrine (PE) compared to non-treated (−) PVAT control rings (Figures 1A,B). The 95% CI for EC50 of control and DPO-1 treated rings were 1.21–1.79 μM and 0.78–1.40 μM, respectively. The anti-contractile effects of PVAT were also unchanged by 1 μM DPO-1: the 95% CI for EC50 were 3.99–8.14 μM and 4.99–10.05 μM, respectively. To further confirm the results obtained with the Kv1.5 channel inhibitor,
we performed similar experiments using mesenteric artery rings from Kcna5<sup>−/−</sup> mice. PE-induced vasoconstrictions in (−) PVAT Kcna5<sup>−/−</sup> rings were not different from those observed in (−) PVAT Kcna5<sup>+/+</sup> rings (Figures 1C,D). Similarly, we observed PE-induced vasoconstrictions in (+) PVAT Kcna5<sup>−/−</sup> rings, which were not different from those observed in (+) PVAT Kcna5<sup>+/+</sup> rings (Figures 1C,D). The 95% CI for EC<sub>50</sub> of (−) PVAT and (+) PVAT arteries isolated from Kcna5<sup>−/−</sup> mice were 0.81–1.30 µM and 4.94–7.79 µM, respectively. Data are summarized in Table 1. Experiments on rat mesenteric arteries showed similar results: Cumulative dose-response curves in response to serotonin (5-HT) were similar in vessel rings in the absence or presence of DPO-1 (Figure 1E). Together, the results suggest that K<sub>V</sub>1.5 channels do not play a functionally relevant role in the control of arterial tone by PVAT, α1-AR and 5-HT agonists, in both mouse and rat mesenteric arteries.

**DPO-1 Sensitive K<sub>V</sub> Channels Distinct from K<sub>V</sub>1.5 May Regulate Arterial Tone**

Next, we studied putative non-K<sub>V</sub>1.5 channel dependent effects by using higher concentrations of DPO-1. Figure 2A shows that 1 µM DPO-1 had no effects on basal tone of Kcna5<sup>+/+</sup> mesenteric artery rings with and without PVAT. Surprisingly, application of 10 µM DPO-1 resulted in a stable contraction of Kcna5<sup>+/+</sup> mesenteric arteries without but not with PVAT (Figure 2B). This effect remained stable over 30 min and was observed also on rings isolated from Kcna5<sup>−/−</sup> mice (Figure 2C). Thus, unexpectedly, inhibition of DPO-1 sensitive K<sub>V</sub> channels distinct from K<sub>V</sub>1.5 channels or other pathways could contribute to vascular tone in this preparation.

**Effects of XE991 on K<sub>V</sub> Currents, BK<sub>Ca</sub> Currents and the Anti-Contractile Effects of PVAT**

K<sub>V</sub> currents were recorded in mesenteric artery VSMCs freshly isolated from Kcna5<sup>+/+</sup> and Kcna5<sup>−/−</sup> mice. We did not observe any difference between K<sub>V</sub> current densities in Kcna5<sup>+/+</sup> and Kcna5<sup>−/−</sup> VSMCs. Moreover, K<sub>V</sub> current inhibition by 30 µM XE991 was not different between Kcna5<sup>+/+</sup> and Kcna5<sup>−/−</sup> VSMCs (Figures 3A,B). 30 µM XE991 did not affect basal tone of mesenteric arteries prepared with or without PVAT (Figure 2F).

In order to better understand the effects of XE991, we tested its actions on BK<sub>Ca</sub> currents, potential mediators of the PVAT effect. VSMC Kcna5<sup>+/+</sup> BK<sub>Ca</sub> currents were recorded in the absence and presence of 30 µM XE991. 100 nM iberiotoxin (a potent and highly selective BK<sub>Ca</sub> channel inhibitor) was used as positive control. While 30 µM XE991 did not affect the BK<sub>Ca</sub> current, iberiotoxin almost completely inhibited the BK<sub>Ca</sub> current. These results are consistent with plasma membrane VSMC BK<sub>Ca</sub> channel activity resistant to XE991 in situ, at concentrations up to 30 µM of XE991 (Figures 3C,D).

Additionally, we tested the effects of 30 µM and 0.3 µM XE991 on the paracrine effects of PVAT on arterial tone. We found that XE991 even at the low concentration abolished the anti-contractile effects of PVAT. Interestingly, application of 0.3 and 30 µM XE991 resulted in a similar reduction of the anti-contractile effects of PVAT (Figures 4A,B). The EC<sub>50</sub> 95% CI values were 1.92–3.09 and 1.32–2.02 µM for (+) PVAT rings preincubated with 0.3 µM XE991 and 30 µM XE991, respectively, and 4.18–5.84 µM for (+) PVAT rings in the absence of XE991. (−) PVAT rings showed no difference, regardless of the absence or presence of 0.3 µM or 30 µM XE991. Data
TABLE 1 | EC$_{50}$ and its confidence intervals.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Mouse background</th>
<th>Without PVAT</th>
<th>With PVAT</th>
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<tr>
<td></td>
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<td>EC$_{50}$ µM</td>
<td>95% confidence interval (CI)</td>
</tr>
<tr>
<td>$K_{cna5}^{+/+}$</td>
<td>129SVE-M</td>
<td>1.48</td>
<td>1.21–1.79</td>
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<tr>
<td>$K_{cna5}^{-/-}$</td>
<td>129SVE-M</td>
<td>1.02</td>
<td>0.81–1.30</td>
</tr>
<tr>
<td>$K_{cna5}^{+/+}$ +1 µM DPO-1</td>
<td>129SVE-M</td>
<td>1.04</td>
<td>0.78–1.40</td>
</tr>
<tr>
<td>Control</td>
<td>C57BL/6</td>
<td>0.70</td>
<td>0.57–0.87</td>
</tr>
<tr>
<td>0.3 µM XE991</td>
<td>C57BL/6</td>
<td>0.48</td>
<td>0.30–0.75</td>
</tr>
<tr>
<td>30 µM XE991</td>
<td>C57BL/6</td>
<td>0.38</td>
<td>0.24–0.65</td>
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Data calculated from concentration-response curves to phenylephrine after normalization to maximum response from within each curve. For comparison of data and groups, see text and figures.

DISCUSSION

Perivascular adipose tissue plays a potent anti-contractile role in the control of arterial tone along arterial segments of different vascular beds and species. The main findings of this study are threefold. First, XE991 inhibits the PVAT effect at nanomolar concentrations in mesenteric arteries of mice. Interestingly, similar concentrations were found in earlier studies to inhibit VSMC $K_{V}$ currents (50% inhibition at 60 nM XE991) (Schleifenbaum et al., 2014). Second, $K_{cna5}^{-/-}$ mice exhibited normal VSMC $K_{V}$ currents and arterial contractions in the absence and presence of PVAT, whose effects were insensitive to DPO-1. Third, the KCNQ channel blocker XE991 does not affect plasma membrane VSMC $BK_{Ca}$ channels at concentrations, which inhibit the anti-contractile effects of PVAT. Together, the results of our current study implicate KCNQ-type $K_{V}$ channels in the XE991-mediated inhibition of the PVAT effects. Simultaneously, we exclude $BK_{Ca}$ as well as $K_{V}1.5$ channels as potential downstream candidates in this process.

$K_{V}1.5$ in Regulation of Arterial Tone

In recent studies, $K_{V}1.5$ channels have been shown to determine microvascular tone and the arteriolar response to vasoconstrictors in rat cerebral arteries (Chen et al., 2006; Fancher et al., 2015). Furthermore, $K_{V}1.5$ channels in the heart are essential in coupling myocardial blood flow to cardiac metabolism (Ohanyan et al., 2015). Moreover, hypertension is associated with altered expression of vascular $K_{V}1.5$ channels (Wang et al., 1997; Platoshyn et al., 2001; Cox and Rusch, 2002; Cox et al., 2008; Cidad et al., 2014). Therefore, $K_{V}1.5$ channels may represent interesting putative targets of PVAT and that raised the question of their potential involvement in the regulation of arterial tone by phenylephrine in mouse mesenteric arteries. Our results suggest that $K_{V}1.5$ channels are however not involved. In effect, the anti-contractile effects of PVAT were not different between $K_{cna5}^{-/-}$ and $K_{cna5}^{+/+}$ arteries. Additionally, the $K_{V}1.5$ channel inhibitor DPO-1 at 1 µM displayed no effect on vasoconstrictions in the absence and presence of PVAT. Notably, the mechanism of DPO-1 action (“open channel” blocker) might be a potential confounding factor, since $K_{V}1.5$ channels are activated at $V_{o.5}$ of $-14 mV$ (Grissmer et al., 1994). However, the genetic approach had the
advantage to study vascular effects in the absence of Kv1.5 channels avoiding possible confounders related to membrane potential-dependent drug mechanisms. Furthermore, we did not observe any significant differences in the Kv current density and inhibition by XE991 in Kcna5−/− and Kcna5+/+ VSMCs. Therefore, we conclude that Kv1.5 channels have no apparent role in PVAT-dependent relaxation and are not the XE991 sensitive channels that contribute to this process. This conclusion is in line with our previous results obtained on cloned and heterologously expressed Kv1.5 alpha subunits in HEK293 cells (Schleifenbaum et al., 2014). In these experiments, 100 nM XE991 failed to block Kv1.5 currents. We also observed similar responses of arterial rings without PVAT to PE and 5-HT, regardless of genetic deletion of Kv1.5 alpha subunits or pharmacological blockade of Kv1.5 channels by DPO-1. To our knowledge, this is the first study to firmly establish that Kv1.5 channels are not involved in the regulation of arterial tone of systemic visceral arteries of mice and rats, at least in mesenteric arteries. Our conclusions substantiate the work of other groups, namely that patients with genetic mutations of KCNA5 exhibit pulmonary arterial hypertension and arterial fibrillation but not systemic hypertension (Yang et al., 2009; Wipff et al., 2010; Machado et al., 2015). Together, our data questions the contribution of Kv1.5 channels in a number of small resistance arteries to peripheral arterial resistance. The findings are however not generalizable to all vascular beds as Kv1.5 channels were demonstrated to play important vasoregulatory functions in cerebral arteries and in Gracilis skeletal muscle arteries (Chen et al., 2006; Fancher et al., 2015).

**DPO-1 Sensitive K⁺ Channels and Pathways Distinct from Kv1.5 Involved in Regulation of Arterial Tone**

DPO-1 was described as a specific Kv1.5 inhibitor at micromolar concentrations (Stump et al., 2005; Lagrutta et al., 2006; Regan et al., 2006). It exerts its inhibitory effects through binding...
Other studies have suggested that KCNQ channels are key players in the paracrine role for periadventitial adipose tissue in the regulation of arterial tone (Schleifenbaum et al., 2010; Zavaritskaya et al., 2013; based on mRNA expression levels (see above), KCNQ1, KCNQ4, and/or KCNQ5 channels are likely candidates. This suggestion is also based on the ability of 30 μM XE991 (pan KCNQ blocker) and 2 mmol/L 4-aminopyridine (pan K+ blocker) to block the anti-contractile effects of PVAT. Interestingly, KCNQ channel openers normalized reduced anti-contractile effects of PVAT in a rat model of hypertension (Zavaritskaya et al., 2013), which suggests therapeutic perspectives of KCNQ targeting in cardiovascular disease. It is thus imperative to better understand the actions of these compounds on the vasculature. In order to obtain more information about the potency of XE991 inhibition on PVAT-mediated anti-contractivity, we performed experiments with a 100x lower concentration of XE991. The data show that this considerably reduced concentration still exerted an inhibitory impact on PVAT regulation of arterial tone (Figures 4A,B), while basal tone was unaffected in rings (+) or (−) PVAT (Figure S2). The incomplete inhibition observed, however suggests the possible involvement of additional K+ channels in this process. Furthermore, our data demonstrates that VSMC plasma membrane BKCa channels are not involved in the effects of XE991 on PVAT regulation, since XE991 does not inhibit BKCa currents (this study). This is in line with our previous findings indicating that the paracrine effects of PVAT on arterial tone are normal in the presence of BKCa channel blockers or in arteries that lack BKCa beta1 channel subunits (Fésus et al., 2007; Zavaritskaya et al., 2013).

Previous studies examined the ability of XE991 to inhibit heterologously expressed Kv1.5 alpha subunits. We found that 100 nM and 30 μM XE991 was unable to block monomeric Kv1.5 channels heterologously expressed in HEK293 or CHO cells (Zavaritskaya et al., 2013; Schleifenbaum et al., 2014). Interestingly, Zhong et al. found a small (∼20% at (+) 5 mV) inhibiting effect for 10 μM XE991 on heterologously expressed heterotetrameric Kv1.2/Kv1.5 and Kv2.1/Kv9.3 channel subunits (Zhong et al., 2010). The block of Kv1.2/Kv1.5 channels was voltage dependent, and evident only at voltages positive to -15 mV. Our present study contributes to the debate about the importance of accessory subunits for determining the pharmacological properties of vascular K+ channels in vivo. Since regulatory Kvβ1.3 subunits can decrease the sensitivity of Kv1.5 channels to pharmacological inhibitors such as DPO-1 (Gonzalez et al., 2002; Arias et al.,...
2007; Du et al., 2010), one could argue that DPO-1 is not a reliable tool to study Kv1.5 channels in native tissues. However, we believe that our pharmacological approach in combination with the Kcnal5−/− mouse model firmly demonstrates that the XE991 sensitive regulation of arterial tone by PVAT regulation does not involve native vascular Kv1.5 channels.

CONCLUSION

In conclusion, our results demonstrate that Kv1.5 channels are not involved in the control of mesenteric arterial tone and its regulation by PVAT in mouse and rat mesenteric arteries. The nature of the 10μM DPO-1 sensitive component is unclear, but is most likely related to non-specificity of this drug, for example in targeting vascular Kv1.3 and/or KCNQ channels in situ. Importantly, the inhibitory effects of XE991 on PVAT vasorelaxation are rather related to inhibition of KCNQ-type Kv channels than BKCa channels. These data unequivocally substantiate the hypothesis of different targets of perivascular relaxing factor(s), which employ distinct mechanisms to mediate an anti-contractile effect. Further studies should focus on the enhancement of these relaxing factors, as these will be beneficial for patients with cardiovascular diseases.

REFERENCES

Arias, C., Guizy, M., David, M., Marzian, S., González, T., Decher, N., et al. (2007). Kvbeta1.3 reduces the degree of stereoselective bupivacaine block of Kv1.5 channels. Anesthesiology 107, 641–651. doi: 10.1097/01.anes.0000282100.32923.5c

AUTHOR CONTRIBUTIONS

All authors planned and designed the experimental studies. DT and NW performed the wire myography experiments. MK and JT performed the electrophysiological experiments. DT and MG drafted the article, and all authors contributed to its completion.

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SUPPLEMENTARY MATERIAL

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