The β4-Subunit of the Large-Conductance Potassium Ion Channel KCa1.1 Regulates Outflow Facility in Mice

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Received: August 20, 2019
Accepted: January 9, 2020
Published: March 23, 2020

Citation: Bertrand JA, Schicht M, Stamer WD, et al. The β4-subunit of the large-conductance potassium ion channel KCa1.1 regulates outflow facility in mice. Invest Ophthalmol Vis Sci. 2020;61(3):41. https://doi.org/10.1167/iovs.61.3.41

PURPOSE. The large-conductance calcium-activated potassium channel KCa1.1 (BKCa, maxi-K) influences aqueous humor outflow facility, but the contribution of auxiliary β-subunits to KCa1.1 activity in the outflow pathway is unknown.

METHODS. Using quantitative polymerase chain reaction, we measured expression of β-subunit genes in anterior segments of C57BL/6J mice (Kcnnb1-4) and in cultured human trabecular meshwork (TM) and Schlemm's canal (SC) cells (KCNMB1-4). We also measured expression of Kcnma1/KCNNMA1 that encodes the pore-forming a-subunit. Using confocal immunofluorescence, we visualized the distribution of β4 in the conventional outflow pathway of mice. Using iPerfuson, we measured outflow facility in enucleated mouse eyes in response to 100 or 500 nM iberiotoxin (IbTX; N = 9) or 100 nM martentoxin (MarTX; N = 12). MartTX selectively blocks β4-containing KCa1.1 channels, whereas IbTX blocks KCa1.1 channels that lack β4.

RESULTS. Kcnnb4 was the most highly expressed β-subunit in mouse conventional outflow tissues, expressed at a level comparable to Kcnma1. β4 was present within the juxtacanalicular TM, appearing to label cellular processes connecting to SC cells. Accordingly, KCNNB4 was the most highly expressed β-subunit in human TM cells, and the sole β-subunit in human SC cells. To dissect functional contribution, MarTX decreased outflow facility by 35% (27%, 42%; mean, 95% confidence interval) relative to vehicle-treated contralateral eyes, whereas IbTX reduced outflow facility by 16% (6%, 25%).

CONCLUSIONS. The β4-subunit regulates KCa1.1 activity in the conventional outflow pathway, significantly influencing outflow function. Targeting β4-containing KCa1.1 channels may be a promising approach to lower intraocular pressure to treat glaucoma.

Keywords: trabecular meshwork, outflow facility, ion channels, mechanotransduction, mouse models

Intraocular pressure (IOP) is determined by aqueous humor outflow facility. With decreasing facility, IOP becomes elevated, and elevated IOP is the major risk factor for glaucoma. The trabecular meshwork (TM) and inner wall endothelium of Schlemm's canal (SC) regulate outflow facility.1,2 Although the precise mechanism of facility regulation is not fully understood,3 volume, stiffness, and contractility of TM and SC cells are known to play important roles.4–8

The large-conductance calcium-activated potassium channel KCa1.1 (BKCa, maxi-K) regulates cell volume and contractility in smooth muscle cells,9 as well as in TM and SC cells.5,10–12 The KCa1.1 channel opener, NS1619, increases outflow facility in porcine anterior segments.13 NS1619 also inhibits the decrease in outflow facility following perfusion with hypotonic saline in bovine anterior segments3 and, likewise, decreases TM cell volume13 and smooth muscle cell contractility.14 Conversely, blocking KCa1.1 with iberiotoxin (IbTX) potentiates the facility decrease in response to hypotonic saline5 and inhibits the cell volume decrease in response to NS1619.13 IbTX also inhibits the facility increasing effect of nitric oxide donors in porcine anterior segments.15 KCa1.1 is thus involved in outflow facility regulation, apparently by regulating the volume or contractility of SC or TM cells.

KCa1.1 is composed of four α-subunits that form the potassium-selective transmembrane pore. Membrane depolarization or increased cytosolic calcium may activate KCa1.1, leading to channel opening, potassium efflux, and membrane depolarization.16 Association between α and auxiliary β-subunits, of which there are four types (β1–4),17 regulates KCa1.1 sensitivity to voltage and calcium. β-subunits are differentially expressed in a tissue-specific manner.
manner and affect the pharmacology of KCa1.1. For example, \( \beta_3 \) renders KCa1.1 relatively resistant to IbTX but sensitive to martentoxin (MarTX), which has a smaller effect on KCa1.1 channels lacking \( \beta_3 \).\(^{14-20}\)

In this study, we examine the expression of genes encoding the \( \beta \)-subunits of KCa1.1 in mouse anterior segments (\( Kcnmb1-4 \)) and in human TM and SC cells (\( KCNMB1-4 \)). We focus on \( \beta_4 \), examining its localization in the TM and inner wall endothelium of SC. Using MarTX, we examine the influence of \( \beta_4 \) on outflow facility in enucleated mouse eyes. We also examine the effect of IbTX to investigate the influence of KCa1.1 channels that lack \( \beta_4 \) on outflow facility.

**METHODS**

**Gene Expression**

We used quantitative polymerase chain reaction (qPCR) to measure the expression of \( Kcnma1 \) and \( Kcnmb1-4 \) in mouse anterior eye segments and \( Kcnma1 \) and \( Kcnmb1-4 \) in cultured human TM and SC cells. For mouse anterior segments, C57BL/6J mice (\( N = 3 \), 13-week-old males, Charles River UK Ltd., Margate, UK) were euthanized by cervical dislocation. Eyes were enucleated, trimmed of extraocular tissue, and hemisected at the equator. The lens was removed, and the anterior segments homogenized in TRizol using a rotor-stat tissue homogenizer (Ultra-Turrax T10; VWR, Leicestershire, UK). Total RNA was extracted using PureLink RNA spin columns following manufacturer protocols (ThermoFisher Scientific, Waltham, MA, USA). RNA content was measured using a spectrophotometer (NanoDrop ND-1000; ThermoFisher Scientific), and 2 \( \mu \)g of RNA was used to synthesize cDNA by reverse transcription (SuperScript VILO; ThermoFisher Scientific). qPCR was carried out using TaqMan master mix and primers (see Supplementary Table S1). \( GAPDH/Gapdh \) was used as the reference gene. cDNA was analyzed in triplicate (QuantStudio 6 Flex; Applied Biosystems, ThermoFisher Scientific). Expression level relative to \( GAPDH/Gapdh \) was calculated using the \( \Delta \Delta C_t \) method. Homogenized mouse brain tissue, which expresses \( Kcnma1 \) and \( Kcnmb4 \),\(^ {21} \) was used as a positive control. Mouse 3T3-L1 fibroblasts (passage 25), which do not express KCa1.1 channels,\(^ {22} \) were used as a negative control. As the anterior segment contains various tissues, this approach was unable to attribute expression to TM or SC directly. Further, pooling tissues together may mask the actual gene expression within the TM or SC.

Human TM and SC cells were isolated and characterized from human donor eyes following established techniques.\(^ {23-26} \) Cells were grown to confluency in T25 flasks and lysed using TRizol. RNA extraction and quantification followed the methods described earlier for mouse anterior segments. These studies used TM cell strains TM86, TM93, and TM134 from donors aged 3 months, 35, and 51 years, respectively, and SC cell strains SC56 and SC67 from donors aged 29 and 44 years, respectively. TM and SC cells were used between passage 4 and 6. EA.hy926 human endothelial cells (ATCC CRL-2922; LGC standards, Middlesex, UK) were used at passage 8 as a positive control for \( Kcnma1 \) and \( Kcnmb4 \) expression.\(^ {27} \)

**Microscopy**

Whole globes from three adult mice (C57BL/6J) were fixed in 4% paraformaldehyde (Roth, Karlsruhe, Germany) for 4 hours and washed in PBS. The eyes were hemisected at the equator, and 10 \( \mu \)m sagittal cryostat sections were cut. The sections were incubated in BLOTTO’s Blocking Buffer (ThermoFisher Scientific) at room temperature for 1 hour to reduce nonspecific staining. Following three washes in Tris-buffered PBS, specimens were incubated with the primary antibody (Table 1) at 4°C overnight, washed three times with PBS, and incubated with a secondary antibody (goat anti-rabbit Alexa 488; Invitrogen A11070; 1:1000) for 75 minutes. For double immunolabeling, specimens were washed three times with PBS and incubated with the second primary antibody (Table 1) at 4°C overnight. After washing three times with PBS, sections were incubated with secondary antibody (goat anti-rat Cy3; Dianova, Dianova GmbH, Hamburg, Germany 112-169-003; 1:1000) for 1 hour. Sections were mounted on glass slides with a 1:1 mixture of PBS and glycerol containing DAPI to label cell nuclei (10 \( \mu \)L of 2 mg/mL). The slides were examined with a Keyence Biorevo BZ9000 microscope (Keyence, Neu-Isenburg, Germany).

For electron microscopy, one MarTX perfused mouse eye (100 nM) and its paired contralateral vehicle perfused eye, were postfixed in OsO\(_4\) and dehydrated. Whole eyes were embedded in Epon resin and 1 \( \mu \)m semithin sagittal sections were cut using an ultramicrotome (Ultractum; Reichert Jung, Vienna, Austria). Semithin sections were stained with toluidine blue and examined with a transmission electron microscope (JEM 1400 plus; JEOL, MA, USA). Four regions were examined per eye.

**Outflow Facility Measurements**

We measured the effect of IbTX and MarTX on outflow facility in enucleated eyes from C57BL/6J mice (13-week-old males; Charles River UK Ltd., Margate, UK). We used a paired experimental design, in which one eye was perfused with IbTX or MarTX and the contralateral eye perfused with vehicle. We measured the relative difference in outflow facility between treated and untreated paired eyes. All procedures on living mice were carried out under the authority of a United Kingdom Home Office project license and adhered to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research.

IbTX was purchased from Tocris Bioscience (Abingdon, UK). MarTX was custom synthesized by Peptide Protein Research Limited (Farham, UK) with the sequence FLGIDVKCFASSECWTACKKVTGSGQGKCQNNQCRCY,\(^ {29} \) as determined by Ji et al.\(^ {29} \) This sequence contains the N-terminal phenylalanine, which may be lacking from some commercial suppliers, but is critical for MarTX function.\(^ {29} \) MarTX was modified by the addition of propargyl (Pra) to the lysine at position 7 with the sequence FLGIDV[Pra]CFASSECWTACKKVTGSGQGKCQNNQCRCY. Pra labeling was chosen because it is compatible with click-chemistry, and thereby allows fluorescent click labeling to localize MarTX in fixed specimens. Separate studies revealed successful MarTX labeling in fixed EA.hy926 cells, but labeling was undetectable within the mouse TM in situ (data not shown).

For perfusions, mice were humanely culled by cervical dislocation. Eyes were enucleated, affixed to a support platform using tissue glue, and submerged in PBS at 35°C. Using a micromanipulator and dissection microscope, the anterior
βᵣ-Subunit of KCₐ,1.1 Regulates Outflow Facility

Table 1. Antibodies Used for Immunofluorescence Microscopy

<table>
<thead>
<tr>
<th>Protein</th>
<th>Host Species</th>
<th>Company, Catalog Number</th>
<th>Dilution in PBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Anti-KCa₁.1 βᵣ</td>
<td>Rabbit</td>
<td>Alomone Labs; APC-061</td>
<td>1:50</td>
</tr>
<tr>
<td>PICAM-1/CD31</td>
<td>Rat</td>
<td>Biolegend; 102401; Clone C390</td>
<td>1:50</td>
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</tbody>
</table>

Table 2. Expression of Genes Encoding the KCa₁.1 Channel α-Subunit and the Four β-Subunits in Mouse Tissues (N = 3 mice) and Human Cells Measured by qPCR

<table>
<thead>
<tr>
<th>Gene Expression</th>
<th>Mouse Tissue</th>
<th>Human Cells</th>
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<tbody>
<tr>
<td></td>
<td>Kcnma1</td>
<td>Kcnmb1</td>
</tr>
<tr>
<td>Brain</td>
<td>+</td>
<td>+</td>
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<tr>
<td>Anterior Segment</td>
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Positive (+) indicates all samples tested gave Ct values lower than 35 cycles. Positive/negative (+/-) indicates that at least one sample tested gave a Ct value between 35 and 40 cycles. If all samples tested gave Ct values greater than 40 cycles, they were considered indistinguishable from background and marked negative (−). Full details of Ct values are available in Supplementary Figure S1.

Results

Gene Expression

By qPCR, we detected positive expression (Ct < 35) of Kcnma1, Kcnmb1, and Kcnmb4 in mouse anterior segments (N = 3; Table 2 and Supplementary Fig. S1A). Kcnmb2 and Kcnmb3 had Ct values higher than 35 and 40, respectively, and were thus considered low expression or below the limit of quantification. ΔCt values (ΔCt = Ct[gene] – Ct[Gapdh]) for Kcnma1 and Kcnmb4 were similar for mouse anterior segments (7.6 and 8.5, respectively), whereas ΔCt for Kcnmb1 was greater (10.1), indicating roughly four-fold lower expression (Supplementary Fig. S1A). Homogenized mouse brain was positive for all genes except Kcnmb3, which was expressed at low levels. Mouse 3T3-L1 fibroblasts expressed low levels of Kcnma1 and Kcnmb4. Kcnmb1-3 were below the limit of quantification (40 cycles).

Human TM cells expressed KCNMA1, KCNMB1, and KCNMB4, but low levels of KCNMB2 and undetectable levels of KCNMB3 (Table 2 and Supplementary Fig. S1B). Human SC cells expressed KCNMA1 and KCNMB4, but no other β-subunit genes (Table 2 and Supplementary Fig. S1B). βᵣ was the most highly expressed β-subunit in TM cells, and the sole β-subunit in SC cells. EAHY926 cells, used as a positive control, primarily expressed KCNMA1 and KCNMB4. TM and SC cells express similar amounts of KCNMA1 relative to EAHY926 cells, but several-fold higher levels of KCNMB4 (Supplementary Fig. S1B).

We then analyzed published microarray data (GEO ID: GSE32169) from primary human TM cells deposited by Porter et al. Consistent with our qPCR data described earlier, KCNMB4 was the most highly expressed β-subunit gene, with expression levels comparable to KCNMA1. KCNMB1 and KCNMB3 were expressed at lower levels, and reported in terms of the geometric mean and the 95% confidence interval on the mean.

chamber was cannulated within 10 to 15 minutes of death using a 33-gauge beveled metal needle (NanoFil, NF35BV-2; World Precision Instruments, Sarasota, FL, USA) connected to the iPerfusion system (Bioengineering Department, Imperial College London, UK). The vehicle was Dulbecco’s PBS containing divalent cations and 5.5 mM glucose (collectively referred to as DBG) that was passed through a 0.2-μm filter prior to use. Paired eyes were perfused with either DBG or DBG containing IbTX or MarTX. We examined the effect of a power-law relationship of the form

\[ Q = C_p \left( \frac{P}{P_r} \right)^b P \]  

The fitting yields \( C_p \), which represents the value of outflow facility at a reference pressure \( P_r \) of 8 mm Hg, and \( b \) that characterizes the nonlinearity of the \( Q-P \) relationship. We then calculated the relative difference in \( C_p \) between treated and untreated contralateral eyes, defined as the ratio of \( C_p \) in the treated eye relative to that in the contralateral control eye minus unity. We tested whether the relative difference in facility was statistically different from zero using a weighted t-test on the log-transformed data, as previously described. Facility values and relative changes in facility were then converted back into the linear domain and reported in terms of the geometric mean and the 95% confidence interval on the mean.

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and KCNMB2 was the lowest expressed (Supplementary Fig. S1C). These data show that β4 is the most highly expressed auxiliary β-subunit of the KCa1.1 channel in mouse anterior segments, as well as in cultured human TM and SC cells.

Immunofluorescence Localization

We then examined the localization of β4 within the conventional outflow pathway of C57BL/6J mice using confocal immunofluorescence (Fig. 1). β4 was observed in the TM, labeling subendothelial cells underlying the inner and outer walls of SC. Continuous bands of β4 labeling were observed in the internal TM, suggestive of labeling along trabecular beams. Punctate labeling of β4 was observed along the inner and outer walls of SC, identified by CD31. The punctate β4 labeling along SC endothelium often appeared as extensions of β4 labeling within the subendothelial space, suggestive of functional processes connecting subendothelial or juxtacanalicular cells to the basal surface of SC endothelium.32–34 β4 labeling was also observed along ciliary process capillaries, the ciliary epithelium, and in nerve bundles within the sclera and cornea. Moderate β4 labeling was observed in the ciliary muscle.

Outflow Facility

We then examined the effect of two KCa1.1 blockers, IbTX and MarTX, on outflow facility in enucleated mouse eyes using the iPerfusion system.29 IbTX predominately blocks KCa1.1 channels that contain only α-subunits or α+β1 subunits, but IbTX does not effectively block KCa1.1 that contain β4.35 In response to 100 or 500 nM IbTX, outflow facility decreased by 16% [6%, 25%] (geometric mean, [95% confidence interval]) relative to contralateral eyes that were perfused with vehicle (P < 0.0001, n = 12; Figs. 2C, 2D) relative to vehicle-treated contralateral eyes. Cr for MarTX-treated eyes was 4.3 [3.2, 5.5] nL/min/mm Hg compared with 6.7 [5.5, 8.0] nL/min/mm Hg for vehicle-treated eyes. The effect of MarTX on Cr was significantly greater than that of IbTX (P = 0.01, unpaired two-tailed t-test).

To examine whether MarTX induces cellular toxicity in the outflow pathway, we used transmission electron microscopy to visualize the ultrastructure of the TM in a pair of eyes perfused with MarTX or vehicle. There were no obvious morphological differences between MarTX and vehicle-perfused eyes. In both cases, the inner wall of SC appeared continuous, and the juxtacanalicular connective tissue (JCT) contained loose extracellular matrix interspersed by JCT cells that extended connections to the inner wall and TM beams (Figs. 3A, 3C). The mitochondria appeared normal without any evidence of swelling that would indicate toxicity, and cell membranes and cell–cell connections appeared intact (Figs. 3B, 3D). This suggests that MarTX does not induce an overtly toxic effect in the outflow pathway.

MarTX is a potent and selective blocker of β4-containing KCa1.1 channels.19 In response to 100 nM MarTX, outflow facility decreased by 35% [27%, 42%] (P < 0.0001, n = 9 pairs; paired two-tailed t-test; Figs. 2A, 2B). Data for both concentrations were pooled together because there was no statistical difference between 100 and 500 nM IbTX (P = 0.6; n = 4 and 5) for the present data (unpaired two-tailed t-test). Cr for IbTX-treated eyes was 5.0 [3.8, 6.2] nL/min/mm Hg versus 5.9 [4.8, 7.1] nL/min/mm Hg for vehicle-treated eyes.

Discussion

The large-conductance calcium-activated potassium channel KCa1.1 is a known regulator of outflow facility. Opening KCa1.1 with NS1619 increases outflow facility in porcine anterior segments.13 Conversely, blocking KCa1.1 with IbTX prevents the increase in outflow facility following treatment with nitric oxide15 or perfusion with hypotonic saline.5 Here we show that blocking KCa1.1 with either IbTX or MarTX, independent of nitric oxide or any other stimulus, decreases outflow facility in enucleated mouse eyes. Thus across different species, opening the KCa1.1 channel coincides with increasing outflow facility, whereas blockade of the KCa1.1 channel corresponds with decreasing outflow facility.

KCa1.1 may modulate outflow facility by influencing cell contractility. Opening KCa1.1 leads to potassium efflux and membrane hyperpolarization that inactivates voltage-gated calcium channels.16 The associated reduction in cytosolic concentration of calcium leads to a reduction in contractility and opening of KCa1.1 channels.

Figure 1. Localization of β4 in the iridocorneal angle of the mouse eye. Boxed region in (A) is shown magnified in (B). Labeling of β4 is shown in green, CD31 in red, and nuclei stained by DAPI in blue. AC, anterior chamber; CM, ciliary muscle; CP, ciliary process; CE, ciliary epithelium; C, ciliary process capillary. Arrows show areas of colocalization of β4 with CD31 along the inner and outer walls of SC.

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Figure 2. Representative flow-pressure (Q-P) plots of eyes treated with IbTX (A) or MarTX (C) versus vehicle-perfused contralateral eyes. Error bars are 95% confidence intervals. Shaded regions represent the best estimate of the sample distributions, with the central white line representing the geometric mean. Dark central bands represent the 95% confidence interval on the mean, and the outer white lines represent the limits encompassing 95% of the population. Green squares in (B) correspond to data obtained from 500 nM IbTX and black circles from 100 nM. The C_r values appearing in (A, C) correspond to the Q-P data shown in each plot, in units of nL/min/mm Hg.

β4-Subunit of KCa1.1 Regulates Outflow Facility

Activity of KCa1.1 is regulated by auxiliary β-subunits that affect channel sensitivity to intracellular calcium and membrane voltage.16,17 Of the four known β-subunits, we show that β4 is the most highly expressed in the anterior segment of the mouse eye. In cultured human SC cells, we show that β4 appears to be the sole β-subunit, and β4 is the primary β-subunit expressed by human TM cells. The β-subunit expression profile influences the pharmacology of the KCa1.1 channel. IbTX and MarTX, for example, are venomous scorpion toxins that are evolutionarily selected to be highly specific for particular β-subunit combinations of KCa1.1. IbTX completely blocks ion channels composed solely of pore-forming α-subunits that are present in all KCa1.1 channels, but IbTX only partially blocks β1-containing KCa1.1 channels (by ~50%) and ineffectively blocks β1-containing KCa1.1 channels (by ~20%).18 MarTX, in contrast, is highly selective for β1-containing KCa1.1 channels, with an IC50 value of 21 to 78 nM.15,16 MarTX has a negligible effect on KCa1.1 channels containing only α-subunits.19 MarTX also has a negligible effect on β1-containing KCa1.1 channels for concentrations up to 400 nM with low cytoplasmic calcium.20 However, with high cytoplasmic calcium, MarTX enhances β1-containing KCa1.1 channel activity with an EC50 of 495 nM.35 Taken together, the 100 nM concentration of MarTX used in this study should have had little effect on β1-containing KCa1.1 channels, as β1 was the second most highly expressed β-subunit after β4 in TM cells and in mouse anterior segments.

In response to IbTX, we measured a significant decrease in outflow facility in enucleated mouse eyes. This suggests that at least some of the channels involved in facility regulation are IbTX-sensitive (i.e., β4-deficient), consistent with prior reports.5,6 However, MarTX, which selectively blocks β1-containing KCa1.1 channels, had a nearly twofold larger facility reduction relative to IbTX (~35% vs. ~16% average reduction). Although the MarTX and IbTX experiments were performed in separate cohorts such that the data are not directly comparable, the larger facility effect observed with MarTX suggests that the majority of KCa1.1 channels involved in outflow facility regulation contain the β4-subunit. However, further study would be necessary to confirm within the same cohort whether MarTX

Calcium leads to relaxation in smooth muscle cells.9 Similarly, opening KCa1.1 leads to relaxation in TM and ciliary muscle cells and a reduction in calcium-induced actin polymerization.7,35 Cell relaxation is typically associated with increasing outflow facility, as occurs following treatment with rho kinase inhibitors36,37 or nitric oxide.38,39

Alternatively, KCa1.1 channel opening may lead to water efflux across the cell membrane and a reduction in TM and SC cell volume.5,4 In some cases, a widening of open spaces in the juxtacanalicular TM.40 Consistent with this notion, the increase in outflow facility following perfusion with hypertonic saline coincides with a widening of open spaces in the juxtacanalicular TM.40 Similarly, treatment with nitric oxide decreases cell volume in TM and SC cells in vitro, and the time scale for cell volume change corresponds to the time scale for changing outflow facility.6,15 Blocking KCa1.1 with IbTX inhibits both the effect of nitric oxide on TM and SC cell volume and on outflow facility.6,13,15 Thus KCa1.1 channel opening appears to increase outflow facility by promoting cellular volume reduction and/or cell relaxation in the outflow pathway. Conversely, blocking KCa1.1 with IbTX or MarTX should decrease outflow facility by inhibiting relaxation and/or cell volume decrease. In addition, because cell volume regulation is tightly coupled to mechanical stretch and contractility experienced by TM cells,41 it may not be possible to attribute the effects of KCa1.1 to cell volume or contractility alone.

Other potassium ion channels, in addition to KCa1.1, have similar effects on outflow facility. Opening the ATP-sensitive inward rectifier potassium channel 11 (Kir6.2) with cromakalim,42 or its prodrug CKLP1,43 increases outflow facility in human anterior segments and reduces IOP in wild-type mice, but not in homozygous null mice lacking Kir6.2.42 Despite the IOP-lowering effect of cromakalim/CKLP1, there was no detectible effect of CKLP1 on pressure-dependent outflow facility in either enucleated or in vivo mice,35 leading the authors to conclude that K_w opening by CKLP1 may affect distal outflow.

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Investigative Ophthalmology & Visual Science

β4-Subunit of KCa1.1 Regulates Outflow Facility

Activity of KCa1.1 is regulated by auxiliary β-subunits that affect channel sensitivity to intracellular calcium and membrane voltage.16,17 Of the four known β-subunits, we show that β4 is the most highly expressed in the anterior segment of the mouse eye. In cultured human SC cells, we show that β4 appears to be the sole β-subunit, and β4 is the primary β-subunit expressed by human TM cells. The β-subunit expression profile influences the pharmacology of the KCa1.1 channel. IbTX and MarTX, for example, are venomous scorpion toxins that are evolutionarily selected to be highly specific for particular β-subunit combinations of KCa1.1. IbTX completely blocks ion channels composed solely of pore-forming α-subunits that are present in all KCa1.1 channels, but IbTX only partially blocks β1-containing KCa1.1 channels (by ~50%) and ineffectively blocks β1-containing KCa1.1 channels (by ~20%).18 MarTX, in contrast, is highly selective for β1-containing KCa1.1 channels, with an IC50 value of 21 to 78 nM.15,16 MarTX has a negligible effect on KCa1.1 channels containing only α-subunits.19 MarTX also has a negligible effect on β1-containing KCa1.1 channels for concentrations up to 400 nM with low cytoplasmic calcium.20 However, with high cytoplasmic calcium, MarTX enhances β1-containing KCa1.1 channel activity with an EC50 of 495 nM.35 Taken together, the 100 nM concentration of MarTX used in this study should have had little effect on β1-containing KCa1.1 channels, as β1 was the second most highly expressed β-subunit after β4 in TM cells and in mouse anterior segments.

In response to IbTX, we measured a significant decrease in outflow facility in enucleated mouse eyes. This suggests that at least some of the channels involved in facility regulation are IbTX-sensitive (i.e., β4-deficient), consistent with prior reports.5,6 However, MarTX, which selectively blocks β1-containing KCa1.1 channels, had a nearly twofold larger facility reduction relative to IbTX (~35% vs. ~16% average reduction). Although the MarTX and IbTX experiments were performed in separate cohorts such that the data are not directly comparable, the larger facility effect observed with MarTX suggests that the majority of KCa1.1 channels involved in outflow facility regulation contain the β4-subunit. However, further study would be necessary to confirm within the same cohort whether MarTX

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truly has additive inhibitory effects beyond ibTX. Regardless, the magnitude of the facility reduction measured in response to MarTX was comparable to that previously reported in response to sphingosine 1-phosphate, reduced temperature, and prolonged exposure to dexamethasone. Thus β₄-containing KCa1.1 channels appear to be centrally important for the maintenance of outflow because blocking these channels significantly disrupts outflow function.

Using confocal microscopy, we localized expression of β₄ to the juxtacanalicular TM, with punctate labeling observed along the endothelium of SC. This labeling pattern was consistent with β₄ expression along cell processes that connect juxtacanalicular TM cells with inner wall cells. These processes experience significant biomechanical deformation in response to IOP elevation. As the juxtacanalicular TM and inner wall of SC are the primary sites of outflow resistance generation, this localization suggests a mechanosensory and regulatory role for β₄. Specifically, we postulate the existence of a stretch-sensitive feedback loop whereby β₄-containing KCa1.1 channels are opened in response to IOP-induced stretch in the juxtacanalicular TM, triggering signaling pathways that lead to increased outflow facility to oppose the elevation in IOP. Previous studies have provided evidence that KCa1.1 channels in bovine TM are directly sensitive to stretch, independent of cytosolic calcium levels. Even if KCa1.1 channels are not directly stretch-activated, KCa1.1 may be activated by elevated intracellular calcium that often occurs in response to stretch or other mechanical stimulation. Consequently, we hypothesize that the association with particular β-subunits influence the mechanosensitivity of KCa1.1 in the juxtacanalicular TM. For example, the β₄-subunit regulates shear and stretch-mediated mechanotransduction in intercalated cells of the kidney collecting duct. Similarly, β₄ may influence mechanotransduction via KCa1.1 in the juxtacanalicular TM.

Stretch induces secretion of several compounds from TM cells that increase outflow facility, such as adenosine triphosphate, metalloproteinases, and vascular endothelial growth factor. As KCa1.1 appears to be involved in the stretch response in TM cells, it is possible that blocking KCa1.1 may suppress stretch-induced release of these compounds to oppose the facility increase. KCa1.1 is also involved in homeostatic regulation of cell volume, as occurs during the regulatory volume decrease following hypotonic shock. As regulatory volume decrease is associated with increasing outflow facility, blocking KCa1.1 could potentially affect cell volume regulation in the TM to affect outflow facility.

CONCLUSIONS

We have shown that β₄ is the primary β-subunit of KCa1.1 expressed in outflow pathway tissues. Blockade of β₄...
containing KCa₄.1 channels with MarTX leads to a physiologically significant decrease in outflow facility, which appeared to be larger than observed when blocking KCa₄.1 channels that lack β₂ with IbTX. The β₂-subunit is localized to the juxtacanalicular TM and inner wall of SC, where it may influence the response of these tissues to IOP-induced stretch or shear stress. The β₂-subunit is thus important for outflow regulation, potentially by influencing mechanotransduction via KCa₄.1. Compounds that modulate β₂-KCa₄.1 activity should therefore be explored as an approach to improve outflow and lower IOP for glaucoma therapy.

**References**


