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**Recommended Citation**

Lorca, Ramón A.; Prabagaran, Monali; and England, Sarah K., “Functional insights into modulation of BKCa channel activity to alter myometrial contractility.” *Frontiers in Physiology*. 5, 289. (2014).  
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Functional insights into modulation of BK$_{Ca}$ channel activity to alter myometrial contractility

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The large-conductance voltage- and Ca$^{2+}$-activated K$^+$ channel (BK$_{Ca}$) is an important regulator of membrane excitability in a wide variety of cells and tissues. In myometrial smooth muscle, activation of BK$_{Ca}$ plays essential roles in buffering contractility to maintain uterine quiescence during pregnancy and in the transition to a more contractile state at the onset of labor. Multiple mechanisms of modulation have been described to alter BK$_{Ca}$ channel activity, expression, and cellular localization. In the myometrium, BK$_{Ca}$ is regulated by alternative splicing, protein targeting to the plasma membrane, compartmentation in membrane microdomains, and posttranslational modifications. In addition, interaction with auxiliary proteins (i.e., β1- and β2-subunits), association with G-protein coupled receptor signaling pathways, such as those activated by adrenergic and oxytocin receptors, and hormonal regulation provide further mechanisms of variable modulation of BK$_{Ca}$ channel function in myometrial smooth muscle. Here, we provide an overview of these mechanisms of BK$_{Ca}$ channel modulation and provide a context for them in relation to myometrial function.

Keywords: BK$_{Ca}$ channel, ion channel modulation, myometrium, pregnancy, uterine contraction

BK$_{Ca}$ CHANNEL FUNCTION IN MYOMETRIUM

The myometrium, the middle layer of the uterine wall responsible for uterine contractions, undergoes marked structural and functional modifications throughout pregnancy. During most of gestation, the myometrium remains in a quiescent state, whereas at the onset of labor, it becomes highly contractile to deliver the newborn. Regulation of myometrial contractility during pregnancy, and in particular labor, has been the focus of many studies, but the mechanisms controlling the transition from quiescence to contractility are intricate and remain elusive. Moreover, this transition is often mistimed; in the U.S., approximately 12% of babies are born prematurely and up to 10% of pregnancies are described as post-term (Gulmezoglu et al., 2012; Martin and Osterman, 2013). Thus, understanding how this transition is controlled is essential to ensure the health of mothers and newborns.

Uterine contraction is primarily mediated by rises in cytoplasmic Ca$^{2+}$ concentration and activation of Ca$^{2+}$-calmodulin/myosin light chain kinase pathways (Wray, 1993; Bru-Mercier et al., 2012). The mechanisms that elicit increases in intracellular Ca$^{2+}$ levels and contraction in myometrial smooth muscle cells (MSMCs) include: (i) Ca$^{2+}$ influx through voltage-gated Ca$^{2+}$ channels, (ii) agonist (e.g., acetylcholine or ATP) binding to receptor-operated channels, and (iii) binding of agonists (e.g., oxytocin) to receptors that evoke Ca$^{2+}$ release from intracellular stores (Inoue et al., 1992; Wray, 1993; Sanborn, 2000). Additionally, the onset of labor requires the MSMCs to switch from a hyperpolarized to a more depolarized state. This transition is controlled, in part, by a complex regulation of ion channel activity. Multiple types of ion channels are responsible for changes in the membrane potential in MSMCs (Sanborn, 2000; Shmygol et al., 2007a; Chan et al., 2014); potassium channels, in particular, play an important role in controlling membrane potential and attenuating excitation to maintain quiescence in pre-labor MSMCs.

Several lines of evidence indicate that the large-conductance voltage- and Ca$^{2+}$-activated K$^+$ channel (BK$_{Ca}$) is a key regulator of myometrial membrane potential and the maintenance of uterine quiescence. First, the BK$_{Ca}$ channel is one of the most abundant potassium channels in myometrial tissue (Trillharts et al., 1991; Perez et al., 1993; Chan et al., 2014). Second, early reports described an outward K$^+$ current activated by Ca$^{2+}$ influx in MSMCs (Vassort, 1975); pharmacological characterization later attributed this current to the BK$_{Ca}$ channel (Anwer et al., 1993). Third, inhibition of BK$_{Ca}$ depolarizes MSMCs and increases myometrial contractility in both rat and human tissue (Anwer et al., 1993). Fourth, activity of BK$_{Ca}$ channels evokes a large efflux of K$^+$ and repolarization of the membrane. Finally, enhancing BK$_{Ca}$ channel opening has a potent relaxant effect on myometrium from different species (Khan et al., 1998; Choudhury et al., 2011; Xu et al., 2011).

It must be noted that some evidence argues against the importance of the BK$_{Ca}$ channel. For example, mice lacking the BK$_{Ca}$ channel gene, mSlo1, give birth to smaller pups and litters, although they reach term successfully (Meredith et al., 2004); however, compensatory mechanisms to systemic channel ablation have not been addressed. Additionally, a few studies have shown a minimal effect of BK$_{Ca}$ channel blockers or openers on rodent and human myometrial contraction in vitro (Aaronson et al., 2006; Smith et al., 2007; Sadlonova et al., 2011). However, as
we shall see below, this channel is modulated by multiple factors that are difficult to replicate in vitro.

The BKCa channel is formed by homo-tetramers of α-subunits; each subunit comprises seven conserved transmembrane domains (S0 through S6), an extracellular N terminus, and a large C-terminal domain (Wallner et al., 1996; Meera et al., 1997). The C-terminal domain encompasses four hydrophobic segments (S7–S10), two predicted regulators of K+ conductance domains (RCK1 and RCK2), and a Ca2+ sensor domain. The pore-forming α-subunit is frequently associated with various auxiliary subunits, β1–β4 or γ1–γ4 (Knaus et al., 1994b; Wallner et al., 1999; Behrens et al., 2000; Brenner et al., 2000; Uebele et al., 2000; Yan and Aldrich, 2012), which confers further functional diversity.

Several mechanisms have been described to regulate BKCa channel function, such as expression of splice variants, compartmentation in membrane microdomains, posttranslational modifications, interaction with auxiliary proteins, and hormonal regulation. Here, we provide an overview of some of these mechanisms and discuss them in relation to myometrial function. Figure 1 provides a schematic representation of the mechanisms we describe.

**INTRINSIC MECHANISMS OF BKCa CHANNEL MODULATION SPlice VARIANTS**

The gene encoding the BKCa channel (slo1/KCNMA1) was first cloned from *Drosophila* (Atkinson et al., 1991; Adelman et al., 1992), and a mammalian gene was identified later (Butler et al., 1993). The BKCa channel is encoded by a single gene, and alternative splicing allows this channel to respond to a variety of regulatory inputs in a tissue-specific manner. To date, over 30 exons have been reported in the human KCNMA1 gene (http://www.geneCards.org/cgi-bin/cardisp.pl?gene=KCNMA1), leading to a large number of potential isoforms of the channel. Early studies demonstrated that splice variants of the BKCa channel have altered Ca2+ and voltage sensitivities (Tseng-Crank et al., 1994), and key phosphorylation sites are created by the inclusion of certain exons (Tian et al., 2001). In mouse myometrium, the expression of BKCa channel isoforms with low sensitivity to Ca2+ increases at mid-pregnancy (Benkusky et al., 2000). In human myometrium, expression of specific spliced isoforms can be altered during pregnancy and at the junction between non-laboring and laboring states (Curley et al., 2004), allowing the uterus to attain a more excitable state during labor. For example, although the overall levels of BKCa channel transcript and protein decrease as term approaches (Shruti et al., 2012), another splice variant termed SV1. In this protein, 33 amino acids that include an endoplasmic reticulum (ER) retention motif (CVLF) are inserted within the S1 transmembrane domain. Thus, this isoform is retained in the ER, where it acts as a naturally occurring dominant negative (Zarei et al., 2001). Although the role of this isoform in controlling myometrial excitability has not been fully explored, its expression could provide an important mechanism for BKCa channel modulation and regulation of uterine contraction. Table 1 presents a summary of the known myometrial splice variants and their modified functions.

**TRAFFICKING**

Membrane trafficking of the BKCa channel regulates a wide variety of physiological processes including pregnancy (Song et al., 1999), aging (Marijic et al., 2001), and aldosterone-induced K+ secretion from the gut (Sorensen et al., 2008). Two regions that control BKCa channel surface localization are the intracellular C-terminal linker between the RCK1 and RCK2 domains (Lee et al., 2009; Chen et al., 2010) and an actin-binding domain in the C terminus (Zou et al., 2008). In addition, isoforms containing different C-terminal sequences have distinct trafficking to the cell surface (Kim et al., 2007a; Ma et al., 2007).

Variation of the α-subunit by alternative splicing can add or delete signal sequences that modify channel localization by facilitating its retention in or targeting to intracellular organelles, including the ER (Zarei et al., 2001; Chen et al., 2010) and mitochondria (Singh et al., 2013). In rat myometrium, a splice variant containing the SV1 exon is retained in the ER, thereby preventing surface localization and affecting cell excitability (Zarei et al., 2001, 2004). In addition to splicing, co-expression with the auxiliary β1-subunit enhances internalization of the BKCa α-subunit into endosomes, thus controlling its membrane localization (Toro et al., 2006). Likewise, a related β4-subunit has an ER retention signal at its C terminus and prevents the α-subunit from exiting the ER (Shruti et al., 2012). As noted above, ER retention mechanisms have been explored in the myometrium, but their physiological relevance in modulating uterine contractility during pregnancy is still unknown.

Other splice variants that are widely expressed could play an important role in myometrial excitability during gestation, such as the stress axis regulated exon (STREX) isoform, which introduces 59 amino acids into the linker between cytosolic domains S8 and S9 (Saito et al., 1997). This idea is supported by studies showing that the STREX variant is regulated during pregnancy (Benkusky et al., 2000) in mice and rats by adrenocorticotropic hormone, estrogen, and progesterone (Xie and McCobb, 1998; Zhu et al., 2005). Additionally, STREX harbors a consensus PKA phosphorylation motif, whose phosphorylation inhibits channel activity (Tian et al., 2001). STREX expression decreases in rat myometrium during pregnancy, likely due to an estrogenic effect (Zhu et al., 2005) (see Section Hormonal regulation). Although this isoform does not appear to play a dominant role in human myometrium, it may affect myometrial excitability in other species.
Several mechanisms modulate the BKCa channel in the myometrium. Certain splice variants (SV1 and mK44) of the BKCa channel are retained in the endoplasmic reticulum, whereas actin filaments induce traffic of BKCa to the plasma membrane of the myometrial smooth muscle cell (MSMC). Localization of BKCa channels in membrane microdomains (i.e., caveolae) and interaction with caveolin-1 and -2 and actin filaments modulate the channel's activity. The BKCa auxiliary \(\beta_1\)- and \(\beta_2\)-subunits modify channel activation by direct interaction and, in the case of \(\beta_1\), by inducing its internalization to endosomes. Novel BKCa auxiliary \(\gamma\)-subunits are expressed in the uterus, but their significance for MSMC excitability has not been assessed. The vasoactive molecules nitric oxide (NO) and epoxyeicosatrienoic acid (5,6-EET) induce relaxation of the myometrium likely by modulation of BKCa channel activity. The steroid hormones 17\(\beta\)-estradiol (E2) and progesterone (P4) are important in maintaining pregnancy and inducing labor. These hormones modulate activity of the BKCa channel in several ways: directly modulating BKCa channel activity, inducing proteosomal degradation of the channel, and regulating expression of the genes encoding the BKCa \(\alpha\)-subunit (\(KCNMA1\)/mSlo1) or \(\beta\)-subunits (\(KCNMB1\) and \(KCNMB2\)). Another pregnancy-related hormone, human chorionic gonadotropin (hCG), modulates BKCa channel activity to induce relaxation of the myometrium. Several G-protein coupled receptors (GPCRs) regulate BKCa channel activity in MSMCs. Norepinephrine (NE) and nociceptin bind their receptors, \(\beta_2\)- and \(\beta_3\)-adrenoceptors (\(\beta_2\)- and \(\beta_3\)-AR) and the orphan opioid receptor-like 1 (ORL1), respectively, and thereby activate G-proteins (G\(_{\alpha}\), G\(_{\beta\gamma}\)). This leads to adenyl cyclase (AC) production of cyclic AMP (cAMP), which activates protein kinase A (PKA) and modulates BKCa channel activity. Oxytocin and melatonin stimulate oxytocin receptor (OTR) and melatonin receptors 1 and 2 (MT1 and MT2), respectively, and thereby induce G\(_{\alpha}\)q/11-dependent activation of phospholipase C (PLC). This leads to production of diacylglycerol (DAG), which in turn causes protein kinase C (PKC)-dependent phosphorylation of the BKCa channel. PLC also produces inositol 1,4,5-triphosphate (IP3) from membrane-bound phosphatidylinositol 4,5-bisphosphate (PIP2) and thereby brings about Ca\(^{2+}\) release from the sarcoplasmic reticulum. In addition to activation by Ca\(^{2+}\) release from intracellular stores, the BKCa channel is activated by Ca\(^{2+}\) influx from nearby voltage- or ligand-gated Ca\(^{2+}\) channels (VGCC and LGCC, respectively). Corticotropin-releasing hormone (CRH) binds to its receptors CRH-R1 and CRH-R2, which are linked to multiple signaling pathways and induce up- or down-regulation of BKCa channel activity. Finally, a particular BKCa channel (mitoBKCa) targets to the inner membrane of mitochondria and may influence MSMC contractility.

**Table 1 | BKCa channel splice variants expressed in the myometrium.**

| Splice variant name | Affected domain | Number of amino acids added | Functional modification | References |
|---------------------|-----------------|-----------------------------|------------------------|------------|
| mK44 | S0-S1 loop | 44 | decreased voltage and Ca\(^{2+}\) sensitivity, endoprotease cleavage | Korovkina et al., 2001, 2006; Curley et al., 2004 |
| SV1 | S1 | 33 | endoplasmic reticulum retention | Zarei et al., 2001, 2004 |
| STREX | S8-S9 loop | 59 | increased voltage and Ca\(^{2+}\) sensitivity, switches from PKA activation to inhibition | Saito et al., 1997; Benkusky et al., 2000; Tian et al., 2001; Zhu et al., 2005 |

**MITOCHONDRIAL LOCALIZATION**

A mitochondrial BKCa (mitoBKCa) channel was first identified by patch clamp studies performed on mitoplasts prepared from human glioma cells (Siemen et al., 1999). The structure of mitoBKCa is similar to the plasmalemmal BKCa except for the inclusion of a mitochondrial-targeting sequence, DEC, in the C-terminal region (Singh et al., 2013). Located in the inner mitochondrial membrane, mitoBKCa channels appear to...
be structurally and functionally coupled to the respiratory chain (Bednarczyk et al., 2013). In cardiac myocytes, activation of mitoBKCa channels attenuates mitochondrial Ca\(^{2+}\) overload (Sato et al., 2005). A similar effect is observed after activation of mitochondrial ATP-sensitive K\(^+\) channels, but these effects seem to be independent (Sato et al., 2005). The link between the mitoBKCa channel and myometrial function has not been explored. However, disruption of mitochondrial function decreases the amplitude and frequency of spontaneous contractions in non-pregnant mouse uterus, and some data suggest that this effect is, at least in part, mediated by Ca\(^{2+}\)-activated K\(^+\) channels, such as the BKCa channel (Gravina et al., 2010). Notably, the effect occurs through modulation of Ca\(^{2+}\) influx and membrane potential. The idea that mitoBKCa functions in the myometrium is appealing. For example, activation of mitoBKCa improves mitochondrial respiratory function and thus protects the heart from ischemic injury (Xu et al., 2002). Moreover, mitoBKCa channels are more sensitive to hypoxia than plasma membrane BKCa channels in glioma cells (Gu et al., 2014), suggesting functional differences between these forms. Therefore, further work is required to determine (i) whether the mitochondria-dependent modulation of Ca\(^{2+}\) levels and uterine contractility changes during pregnancy, and (ii) whether mitoBKCa function affects mitochondria to accommodate changes in Ca\(^{2+}\) dynamics in the myometrium.

**MEMBRANE COMPARTMENTATION**

Localization of proteins in cholesterol- and sphingolipid-rich membrane microdomains has been proposed as a mechanism to modulate membrane excitability and intracellular signaling (Razani et al., 2002). Several lines of evidence indicate that such microdomains play important roles in controlling myometrial excitability. First, the number of a specific type of microdomain, caveolae, increases in myometrial cells toward the end of pregnancy (Turi et al., 2001). Second, two isoforms of the scaffolding proteins that form caveolae, caveolin-1, and caveolin-2, are down regulated by estrogen (Turi et al., 2001) and labor (Chan et al., 2014). Third, deletion of membrane cholesterol and consequent disruption of membrane microdomains, induces an increase in uterine contractions and Ca\(^{2+}\) transients (Smith et al., 2005). Finally, multiple studies have shown that BKCa channels localize to membrane microdomains in both cells used for heterologous expression and smooth muscle cells (Bravo-Zehnder et al., 2000; Babiychuk et al., 2004). For example, co-localization of BKCa channels with downstream effectors and other receptors in caveolae alters channel function in vascular smooth muscle cells (Lu et al., 2010).

The discrete membrane localization of the BKCa channel with its effectors and regulators might be an important mechanism to modulate BKCa function in myometrium. In support of this idea, a sub-population of BKCa channels in MSMCs localizes to caveolae where they associate with both structural components of caveolae, caveolin-1, and caveolin-2, and cytoskeletal proteins, α- and γ-actin (Brainard et al., 2005). Specific down-regulation of caveolin-1 decreases BKCa currents and alters localization of BKCa channels from detergent-resistant to detergent-soluble membrane microdomains (Brainard et al., 2009). This effect is also observed by deleting the entire caveolin-binding motif in the C terminus of the BKCa channel (Alioua et al., 2008) or by mutating key amino acids in this region (Brainard et al., 2009). Moreover, disruption of caveolae by depletion of membrane cholesterol or depolymerization of the actin cytoskeleton increases BKCa activity in human MSMCs (Brainard et al., 2005). Conversely, cholesterol depletion decreases BKCa activity in rat MSMCs (Shmygol et al., 2007b). These contradictory observations might be explained if the cholesterol-depleting agent used in both studies differentially affected other membrane-bound proteins such as Ca\(^{2+}\) or K\(^+\) channels (Levitan et al., 2010). Nonetheless, it is tempting to speculate that differential localization of BKCa isoforms within caveolar domains of the plasma membrane partially explains the Ca\(^{2+}\)-insensitive BKCa currents that are observed in laboring myometrium (Khan et al., 1993).

**POSTRANSLATIONAL MODIFICATIONS**

The BKCa channel possesses numerous phosphorylation sites, and the phosphorylation state of these residues can regulate channel activity (Toro et al., 1998; Schubert and Nelson, 2001; Kyle et al., 2013). Below, we discuss three potential kinase modulators of BKCa channel activity in the myometrium: protein kinase A (PKA), protein kinase C (PKC), and protein kinase G (PKG).

In the myometrium, the association of PKA with the plasma membrane is regulated by progesterone and labor (Ku and Sanborn, 2002; Ku et al., 2005). Activation of the PKA pathway by cyclic AMP contributes to uterine quiescence during pregnancy through phosphorylation of various proteins (Lopez Bernal, 2007; Tyson et al., 2008). The BKCa channel is one such target; in non-pregnant myometrium, PKA inhibits BKCa channels, whereas in pregnant myometrium, phosphorylation by PKA activates the channel (Perez and Toro, 1994). This disparity may be explained by the fact that, as mentioned in section Splice variants, different splice variants of the BKCa channel respond in distinctive ways to PKA modulation (Tian et al., 2001; Zhou et al., 2001).

PKC is a serine/threonine kinase activated by increasing intracellular levels of diacylglycerol or Ca\(^{2+}\). In vascular SMCs, PKC directly phosphorylates the BKCa channel α-subunit, reducing its activity (Schubert and Nelson, 2001; Zhou et al., 2010). In these cells, PKC can also reduce BKCa channel activity indirectly by decreasing the release of Ca\(^{2+}\) sparks from the sarcoplasmic reticulum (Bonev et al., 1997; Hristov et al., 2014). Although the PKC modulation of agonist-dependent myometrial contractions has been explored (Phillippe, 1994; Breuiller-Fouche et al., 1998; Eude et al., 2000), the role of BKCa channels in this process remains elusive.

PKG, a serine/threonine-specific protein kinase that is activated by intracellular cyclic GMP, enhances BKCa activity by direct phosphorylation of serine residues (Alioua et al., 1998; Kyle et al., 2013). In SMCs, PKG has been shown to activate BKCa channels (Robertson et al., 1993; Archer et al., 1994; Zhou et al., 1996). Likewise, PKG enhances the activity of BKCa channels originally cloned from myometrium and subsequently expressed in a heterologous system (Zhou et al., 1998). Furthermore, PKG activation increases the activity of BKCa channels in myometrium (Zhou et al., 2000b), suggesting a role for PKG in maintaining uterine quiescence by modulation of BKCa.
channel activity. Functional contraction studies aimed at dissecting the effects of PKG on BKCa currents in non-pregnant and pregnant myometrium are required to elucidate whether this interaction has a role in the myometrium during pregnancy or labor.

**EXTRINSIC MECHANISMS OF BKCa CHANNEL MODULATION INTERACTION WITH AUXILIARY PROTEINS**

The pore-forming BKCa channel α-subunits can associate with and be regulated by auxiliary β- and γ-subunits (Knaus et al., 1994b; Tanaka et al., 1997; Yan and Aldrich, 2012). Four distinct β-subunits proteins (β1-4) have been found to regulate the function and localization of the BKCa channel α-subunit (Knaus et al., 1994a; Wallner et al., 1999; Behrens et al., 2000; Brenner et al., 2000; Uebele et al., 2000). We will focus on the β1- and β2-subunits as these are expressed in MSMCs (Behrens et al., 2000; Chan et al., 2014). In addition, four members of a γ-subunit family, also known as leucine-rich repeat-containing (LRRC) proteins, that associate with the BKCa channel α-subunits: LRRC26 (γ1), LRRC52 (γ2), LRRC55 (γ3), and LRRC38 (γ4) (Yan and Aldrich, 2012) will be examined.

**β-subunits**

The β1-subunit is the predominant β-subunit in the myometrium. Association with β1 decreases the voltage dependency and enhances the apparent Ca2+ sensitivity of the BKCa channel α-subunits (McManus et al., 1995; Wallner et al., 1995; Tanaka et al., 1997; Lorca et al., 2014). The β1-subunit also modulates the membrane trafficking (Toro et al., 2006; Kim et al., 2007b), mobility (Yamamura et al., 2012), pharmacology (Giangiocomo et al., 2000), and alcohol and estrogen sensitivity (Valverde et al., 1999; Feinberg-Zadek and Treistman, 2007) of the α-subunits. In human myometrium, expression of both α- and β1 -subunits decreases at the onset of labor (Matharoo-Ball et al., 2003; Gao et al., 2009; Chan et al., 2014). Their association with one another is not altered at this time (Matharoo-Ball et al., 2003), suggesting that dissociation of BKCa channels from accessory β1-subunits is not a mechanism to alter channel activity during pregnancy. However, certain variants of the BKCa channel α-subunit can be modulated differentially by the β1-subunit (Lorca et al., 2014), thus acting to fine tune the properties of BKCa to best fulfill its cell type-specific functions.

Similarly to β1, β2 increases BKCa channel Ca2+ and voltage sensitivity (Wallner et al., 1999), although the mechanisms of modulation may differ (Orio and Latorre, 2005; Yang et al., 2008; Lee et al., 2010). In addition to enhancing the activity of the α-subunit, the β2-subunit inactivates the channel currents by N-type inactivation (Wallner et al., 1999; Xia et al., 2003). Consistent with the idea that β2 inhibits uterine contractility during pregnancy, progesterone (which is high until the end of pregnancy) increases the expression of the BKCa α-subunit but decreases expression of β2 in MSMCs (Soloff et al., 2011).

**γ-subunits**

The γ1–γ4 subunits belong to a subgroup of the LRRC protein family, the “Elron” cluster, so named because they contain only the extracellular LRR region (Dolan et al., 2007). The effect of these auxiliary proteins on BKCa activity is remarkable, inducing shifts between −140 mV and −20 mV in the channel’s voltage-activation curve in the absence of Ca2+ (Yan and Aldrich, 2012), thus providing strong modulation of channel function. In particular, the γ1-subunit enhances the voltage-dependency of BKCa channel activation, allowing activation at resting membrane potential and intracellular Ca2+ concentrations (Yan and Aldrich, 2010). This effect requires at least four γ-subunits to associate with the pore forming α-subunits (Gonzalez-Perez et al., 2014). The γ1-subunit also reduces the sensitivity of the BKCa channel to its opener mellatoxin (Almassy and Begenisich, 2012). Likewise, the γ2-subunit has been shown to modulate a BKCa-related pH-sensitive channel (Slo3) in sperm (Yang et al., 2011).

An extensive study by Yan and Aldrich (2012) showed that all four γ-subunits are expressed in the human uterus. This finding is intriguing because myometrial BKCa channel activity is significantly higher in women at labor than in non-pregnant women; in fact, at labor, BKCa activity is independent of intracellular Ca2+ (Khan et al., 1993). Thus, it is feasible that increased activity of the BKCa channel in labor is mediated by γ-subunit association. Further analysis of the biophysical properties of the myometrial BKCa channel at different gestational stages is necessary to elucidate its modulation by γ-subunits.

**MODULATION BY G-PROTEIN COUPLED RECEPTORS**

**Adrenergic modulation**

Catecholamines, such as epinephrine and norepinephrine, have been well described to play a pivotal role in controlling uterine contraction through various G protein-coupled receptors (GPCRs), specifically the α- and β-adrenergic receptors (AR) (Bulbring and Tomita, 1987). Activation of α- and β-AR trigger two main signaling pathways: (i) activation of Gα1 or Gq-protein, activation/inhibition of adenylyl cyclase (AC), and changes in cyclic AMP (cAMP) levels, and (ii) activation of Gα11-protein, production of inositol 1,4,5-trisphosphate (IP3) and diacylglycerol (DAG), and an increase in intracellular Ca2+.

Clinically, β-AR agonists have been used as tocolytic agents, inducing relaxation of the myometrial smooth muscle through membrane hyperpolarization. However, the adverse cardiovascular and metabolic side effects in the mother and fetus (Jeyabalan and Caritis, 2002; Berkman et al., 2003) have dampened their effectiveness and limited their usage. Hence, a better understanding of the pathways downstream of adrenergic signaling might aid the design of new tocolytic agents. Interestingly, one of the main effectors of adrenergic signaling pathways involved in myometrial contractility is the BKCa channel.

In both the myometrium and lipid bilayers isolated from MSMCs, activation of β-AR increases Ca2+-activated K+ currents, which are likely mediated by BKCa channels (Toro et al., 1990; Anwer et al., 1992). Moreover, selective activation of β2-AR increases AC activity, resulting in increased cAMP levels, activation of PKA, and increased BKCa currents (Zhou et al., 2000a). When both α2- and β2-AR are stimulated in MSMCs from a pregnant woman, a synergistic increase in BKCa current is observed, likely due to concomitant activation of AC by both Gβγ2-subunit and Gaα (Zhou et al., 2000a). Two findings further support
this observation: (i) β2-AR and the BKCa channel physically interact, and (ii) activation of β2-AR relaxes pregnant human myometrium, and this relaxation is attenuated by the BKCa channel blocker paxilline (Chanrachakul et al., 2004). Conversely, α2-AR stimulation antagonizes β2-AR in MSMCs from non-pregnant women. Therefore, a precise balance between α2- and β2-AR activity during pregnancy leads to increased BKCa channel function.

Interestingly, β2-AR and BKCa channels seem to be part of a macromolecule complex involving the A-kinase anchoring protein (AKAP79/150), PKA, and L-type Ca2+ channels (Liu et al., 2004), making the control of BKCa channel activity by phosphorylation and Ca2+ more efficient. Expression of AKAP79 and PKA are significantly lower in myometrial tissues from women in labor than in tissue from women not in labor (Ku et al., 2005). It has been proposed that these complexes are linked to caveolins and/or actin filaments (Lu et al., 2006), as observed for BKCa channel-angiotensin II signaling (Lu et al., 2010), and that disruption of these complexes and reduction of BKCa activity could lead to increased contractions at term.

Similar to the effects of β2-AR, selective stimulation of β3-AR activates single-channel and whole-cell BKCa currents in isolated human MSMCs (Doheny et al., 2005). Moreover, β3-AR activation inhibits both spontaneously occurring and oxytocin-induced contractions of myometrial strips from pregnant women, an effect that is abolished by blocking BKCa channels with iberiotoxin (Doheny et al., 2005). Hence, the adrenergic modulation of myometrial activity involves BKCa channel modulation and seems to vary according to the type of AR that is activated and the physiological state of the myometrium.

**Modulation by other G-protein coupled receptors**

The association of BKCa channels with, and their regulation by, GPCRs has been well established in other tissues. For example, M2 muscarinic receptors inhibit BKCa currents in tracheal SMCs (Zhou et al., 2008), whereas the G protein-coupled estrogen receptor 1 stimulates BKCa activity in coronary SMCs (Yu et al., 2011). Here we discuss five GPCRs that have been linked to uterine function: oxytocin, prostaglandin F2α, corticotropin-releasing hormone, nociceptin, and melatonin receptors.

The neuromodulator oxytocin increases the force and duration of myometrial contractions and is a widely used uterotonic to induce labor (Hawkins and Wing, 2012). The oxytocin receptor (OTR) is coupled to Gq/11 protein and mediates both activation of the phospholipase C (PLC)/DAG/PKC pathway (Morrison et al., 1996) and IP3-induced intracellular Ca2+ increase (McKellen et al., 1999; Willets et al., 2009). OTR-dependent increases in intracellular Ca2+ lead to activation of BKCa channels (Zhou et al., 2007), which may serve as a negative feedback for oxytocin-induced uterine contractions. Further understanding of oxytocin’s effects on BKCa channel activity will hopefully lead to strategies to avoid some of the side effects associated with the use of this labor-inducing drug.

Prostaglandins (PGs), derivatives from arachidonic acid, participate in several physiological processes, including regulation of smooth muscle contractility (Wong and Vanhoutte, 2010) and inflammation (Ricciotti and FitzGerald, 2011). The prostaglandin F2α (PGF2α) is a potent uterotonic (Crankshaw and Dyal, 1994), and the levels of both PGF2α and its receptor (FP) rise in the amniotic fluid at the onset of labor (Dray and Frydman, 1976; Brodt-Eppley and Myatt, 1999). Activation of the FP receptor, which is coupled to Gα protein, leads to increases in IP3, DAG, and intracellular Ca2+ levels. During labor, PGF2α also regulates the expression of uterine contraction-associated proteins, such as connexin 43, OTR, and FP receptor, thus promoting uterine contractility (Xu et al., 2013). Inhibition of the FP receptor by the specific antagonist THG113 prevents pre-term labor in mouse (Peri et al., 2002) and induces marked relaxation of human myometrial tissue (Doheny et al., 2007). These effects may be explained by the fact that THG113 induces activation of BKCa channels in human MSMCs. However, the detailed mechanism of BKCa channel activation by this agent remains elusive (Doheny et al., 2007). Further studies will be necessary to determine the precise relationship between BKCa channel activity and signaling by PGF2α or other PGs in the myometrium.

Corticotropin-releasing hormone (CRH), a polypeptide expressed in the placenta and uterus, activates the CRH receptors (CRH-R) expressed in the myometrium (Warren and Silverman, 1995). The plasma levels of CRH and its affinity for its receptors increase during pregnancy (Goland et al., 1986; Campbell et al., 1987; Hillhouse et al., 1993). CRH-R activation induces contraction of myometrium through different G-protein coupled signaling pathways, such as AC/cAMP/PKA and PLC/DAG/PKC (Grammatopoulos, 2007), an effect that appears specific to term pregnancy (Simpkin et al., 1999). CRH-Rs associate with the BKCa channel, and the two major subtypes, CRH-R1 and CRH-R2, regulate the expression of BKCa in MSMCs in a complicated manner (Xu et al., 2011). During pregnancy, CRH increases BKCa expression via CRH-R1, whereas it decreases BKCa expression via CRH-R2. Conversely, after onset of labor, CRH-R1 decreases BKCa expression, whereas CRH-R2 increases BKCa expression (Xu et al., 2011). These findings indicate that a finely tuned regulation of BKCa activity by CRH could control the transition of the myometrium from a quiescent to contractile state. How this occurs is yet to be fully defined.

Nociceptin is an opioid-related neuropeptide that is expressed in the uterus where it acts as a relaxant (Klugovits et al., 2010; Deak et al., 2013). The effect of nociceptin in myometrium is likely mediated by binding to its receptor, the orphan opioid receptor-like 1 (ORL-1), which is a Gβ and Gδ coupled receptor that regulates AC activity. In term pregnant rat uterus, activation of ORL-1 by nociceptin stimulates the production of cAMP (Klugovits et al., 2010). Interestingly, the relaxant effect of nociceptin is diminished by application of paxilline, a selective blocker of BKCa channels, suggesting that nociceptin-induced relaxation involves activation of BKCa channels (Klugovits et al., 2010).

Melatonin, a monoamine that regulates circadian rhythms, is expressed by pregnant human myometrium. In the myometrium, signaling via melatonin receptors-1 and -2 (MT1 and MT2) (Schlabritz-Loutsevitch et al., 2003) elicits several cellular signaling pathways, including inhibition of AC/cAMP formation and stimulation of Ca2+ transients through the PLC/IP3 pathway (Witt-Enderby et al., 2003). Melatonin increases BKCa channel activity in MSMCs in a PLC-dependent manner (Steffens et al., 2014).
suggesting a role of melatonin in regulating myometrial excitability. However, melatonin can also enhance oxytocin-induced contraction of MSMCs (Sharkey et al., 2009). Both BK_{Ca} channels and melatonin are modulators of circadian rhythm behavior (Arendt and Skene, 2005; Meredith et al., 2006), which might impact the timing of parturition (Olcese et al., 2013), so additional evaluation of the effects of melatonin on BK_{Ca} channel activity and its role on uterine contractility might be necessary.

**HORMONAL REGULATION**

Numerous hormones regulate BK_{Ca} channel expression and activity in different tissues. Two relevant steroid hormones in the uterus, estrogens and progesterone, are key regulators for both maintaining uterine quiescence during pregnancy and for inducing labor at term. Although the levels of both hormones increase during pregnancy in humans (Boroditsky et al., 1978; Buster et al., 1979; Montelongo et al., 1992), changes in responsiveness of the target cells are key for their function. Here, we discuss ways in which BK_{Ca} might contribute to myometrial cell responsiveness to estrogens, progesterone, and also the hormone human chorionic gonadotropin (hCG).

The steroid hormone 17β-estradiol (E2) helps maintain pregnancy. As such, circulating E2 levels rise throughout pregnancy (Boroditsky et al., 1978; Buster et al., 1979; Montelongo et al., 1992), and the activity of the estrogen receptor α (ERα) is increased in myometrium near term (Mesiano and Welsh, 2007; Welsh et al., 2012). E2 regulates expression of the BK_{Ca} channel by species-specific mechanisms. For example, expression of the mouse BK_{Ca} gene (mSlo1) is up-regulated by E2 through activation of ERα and binding to estrogen response elements in the mSlo1 promoter (Kundu et al., 2007). Expression of the human homolog (KCNMA1 or hSlo1) is also up-regulated by E2 interaction with ERα, but through the phosphatidylinositol 3-kinase 3-pathway (Danesh et al., 2011). Furthermore, E2 activation of ER decreases expression of the STREX variant in rat myometrium, mimicking the effect of pregnancy on this variant (Zhu et al., 2005). In addition, E2 augments the expression of the BK_{Ca} auxiliary β1-subunit in mouse uterus (Benkusky et al., 2002). Although less studied, the estrogen receptor β (ERβ) has also been suggested to play a role in myometrial quiescence and labor (Wu et al., 2000). Furthermore, ERβ is necessary for the E2-induced increase in BK_{Ca} currents in a neuronal cell line (Nishimura et al., 2008), but whether ERβ modulates myometrial BK_{Ca} currents has not been studied.

Although not yet fully explored, it is feasible that, at the onset of labor, E2 triggers activation of BK_{Ca} channel activity directly rather than by activation of ERα and up-regulation of BK_{Ca} gene expression in MSMCs. This is a strong possibility because BK_{Ca} channel expression is reduced at the end of pregnancy (Matharoo-Ball et al., 2003; Gao et al., 2009; Chan et al., 2014). Additionally, E2 can increase BK_{Ca} channel activity both in the presence (Valverde et al., 1999; De Wet et al., 2006) or absence (Wong et al., 2008) of the auxiliary β1-subunit by directly binding to the channel. An E2-dependent increase in BK_{Ca} channel activity has also been observed in uterine vascular SMCs (Hu et al., 2011). However, a lower concentration of E2 reduces BK_{Ca} currents and induces proteosomal degradation of the BK_{Ca} α-subunit (Korovkina et al., 2004). Hence, further studies are necessary to address the physiological significance of the E2-BK_{Ca} channel interaction in the myometrium.

Myometrial quiescence during pregnancy is, in part, attributable to high plasma levels of the steroid hormone progesterone. Progesterone acts through its receptor PR to inhibit expression of contraction-associated proteins such as OTR, connexin 43, and cyclooxygenase-2, a key enzyme in the biosynthesis of prostaglandins (Renthal et al., 2010; Williams et al., 2012). Progesterone has been shown to inhibit BK_{Ca} channel currents in human sperm (Mannowitz et al., 2013) as well as in heterologous expression systems (Wong et al., 2008), suggesting a direct interaction between PR and the BK_{Ca} α-subunit. However, other evidence indicates that progesterone regulates expression of BK_{Ca}. For example, longer progesterone treatment increases mRNA and protein expression of the BK_{Ca} α-subunit in human immortalized SMCs. Likewise, progesterone treatment decreases the expression of the β2-subunit (Soloff et al., 2011) without changing the expression of β1-subunit in mouse uterus (Xu et al., 2011). Although the effects of progesterone are wide and complex in the myometrium, elucidation of its effects on BK_{Ca} channel activity and expression will help to inform our understanding of the regulation of myometrial function by this hormone.

The human chorionic gonadotropin (hCG) is a glycoprotein produced mainly by the placenta. In addition to its role in sustaining early pregnancy, hCG may also participate in maintaining uterine quiescence during pregnancy. One study reported that hCG induces a potent relaxation of human myometrium in vitro, an effect partially attributable to an hCG-dependent increase in BK_{Ca} currents in MSMCs (Doheny et al., 2003). Simultaneously, another study found that certain unidentified choriionic-derived factors reduce oxytocin-mediated contraction in guinea pig myometrium in a paracrine manner, an effect that involves the activation of myometrial BK_{Ca} channels (Carvajal et al., 2003). Thus, BK_{Ca} channel seems to be a predominant effector of the uterorelaxant effects of choriionic-derived factors, including hCG.

**OTHER MODULATORS**

Other modulators of vascular smooth muscle such as nitric oxide (NO) and certain eicosanoids have been reported to change BK_{Ca} channel activity in the myometrium. NO is a gaseous molecule that acts as a potent vasodilator mainly via activation of soluble guanylyl cyclase and production of cGMP in smooth muscle. NO production increases during pregnancy (Choi et al., 2002), and decreases toward labor, suggesting a role in regulating uterine contractility. NO has been shown to increase the open probability of the BK_{Ca} channel in human SMCs (Shimano et al., 2000), but whether this occurs by a direct interaction or by cGMP-dependent pathways is unknown.

Another modulator of BK_{Ca} channels in the myometrium is the non-prostanoid eicosanoid, 5,6-epoxyeicosatrienoic acid (5,6-EET), a metabolite of arachidonic acid. The 5,6-EET isomer, the most abundant eicosanoid isomer in myometrial tissue (Zhang et al., 2007), reduces oxytocin-induced contractions in human...
pregnant myometrium by increasing $\text{BK}_{\text{Ca}}$ currents (Pearson et al., 2009). Additional studies should elucidate the nature of this interaction and its physiological significance in the myometrium, as well as in other tissues.

**CONCLUDING REMARKS**

During pregnancy, the myometrium must remain in a quiescent, relaxed state, and the MSMCs must remain hyperpolarized. At term, however, the MSMCs convert to a more depolarized state to allow the myometrium to become contractile. Modulation of $\text{BK}_{\text{Ca}}$ channel function is pivotal for proper regulation of both these states. Thus, enhanced activity of $\text{BK}_{\text{Ca}}$ channels might underlie myometrial quiescence during pregnancy. Conversely, reduced activity of this channel might result in earlier labor, and failure to properly modulate channel activity at the end of labor might interfere with the transition to a contractile state. Thus, it is perhaps not surprising that so many mechanisms function to regulate the $\text{BK}_{\text{Ca}}$ channel and thus fine-tune the excitability of the myometrium. In addition to those regulators that are known to regulate $\text{BK}_{\text{Ca}}$ in the myometrium, numerous modulators of $\text{BK}_{\text{Ca}}$ channel activity have been described in different tissues and under different physio(patho)logical states. Complete understanding of these modulatory mechanisms will provide opportunities to develop precise treatments for labor mistiming and dysfunction.

**ACKNOWLEDGMENTS**

We thank Dr. Deborah J. Frank for critical reading of the manuscript. Funded by the National Institutes of Health (5R01HD037831 grant to Sarah K. England).

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