

Differential effects of ginsenoside metabolites on slowly activating delayed rectifier K⁺ and KCNQ1 K⁺ channel currents

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Channels formed by the co-assembly of the KCNQ1 subunit and the mink (KCNE1) subunit underline the slowly activating delayed rectifier K⁺ channels (I_{Ks}) in the heart. This K⁺ channel is one of the main pharmacological targets for the development of drugs against cardiovascular disease. *Panax ginseng* has been shown to exhibit beneficial cardiovascular effects. In a previous study, we showed that ginsenoside Rg3 activates human KCNQ1 K⁺ channel currents through interactions with the K318 and V319 residues. However, little is known about the effects of ginsenoside metabolites on KCNQ1 K⁺ alone or the KCNQ1 + KCNE1 K⁺ (I_{Ks}) channels. In the present study, we examined the effect of protopanaxatriol (PPT) and compound K (CK) on KCNQ1 K⁺ and I_{Ks} channel activity expressed in *Xenopus* oocytes. PPT more strongly inhibited the I_{Ks} channel currents than the currents of KCNQ1 K⁺ alone in concentration- and voltage-dependent manners. The IC₅₀ values on I_{Ks} and KCNQ1 alone currents for PPT were 5.18±0.13 and 10.04±0.17 μM, respectively. PPT caused a leftward shift in the activation curve of I_{Ks} channel activity, but minimally affected KCNQ1 alone. CK exhibited slight inhibition on I_{Ks} and KCNQ1 alone K⁺ channel currents. These results indicate that ginsenoside metabolites show limited effects on I_{Ks} channel activity, depending on the structure of the ginsenoside metabolites.

Keywords: *Panax ginseng*, Ginsenoside metabolites, Slowly activating delayed rectifier K⁺ channels (I_{Ks}), Human heart

INTRODUCTION

KCNQ1 was first discovered by positional cloning [1]. Coassembly with the β-subunit KCNE1 modified a very slowly activating delayed rectifier K⁺ current, I_{Ks} , with no apparent pattern of inactivation [2-5]. Physiologically, I_{Ks} channels involve repolarization of cardiac action potentials, modulation of H⁺ secretion into the stomach, secretion of Cl⁻ into the colon, and secretion of K⁺ into the stria media of the inner ear [6-8]. In particular, I_{Ks} channels constitute the major outward current involved in ventricular repolarization and HERG (I_{Kr}) channels [9-11]. Dysfunction or mutation of delayed rectifier K⁺ chan-

nels (I_{Ks} and I_{Kr}) underlines the long QT syndrome (LQT) with increased risk of Torsades de Pointes [11-13]. Since arrhythmia is one of the major causes of sudden cardiac death worldwide [14], KCNQ K⁺ and hERG channels are primary pharmacological targets for the development of therapeutic drugs against cardiovascular disease, including arrhythmia.

Ginseng, the root of *Panax ginseng* Meyer, is a representative herbal medicine and exhibits a variety of pharmacological effects, including antistress, antifatigue, anticancer, and antidiabetes mellitus [15]. Ginsenosides (also

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called ginseng saponins), as a representative ingredient of ginseng, also exhibit antihypertension and cardio-protective effects [16-18]. For example, administration of ginseng extract shortened action potential duration and ginsenoside Re regulates the I_{kr} and I_{Ks} channel currents of guinea pig myocytes [19,20].

In a previous study, we showed that ginsenoside Rg3 activated human cardiac I_{Ks} channel currents in concentration- and voltage-dependent manners [21]. Moreover, we demonstrated that ginsenoside Rg3 enhanced the outward currents (I_{HERG}) and transient tail currents (I_{tail}). Rg3 induced a large persistent deactivating-tail current ($I_{deactivating-tail}$) and significantly decelerated the deactivating current decay [22]. According to the number and position of sugar moieties, ginsenosides are divided into two main categories (i.e., the 20[S]-protopanaxadiol [PPD] and 20[S]-protopanaxatriol [PPT] families). On the other hand, ginsenosides are metabolized by colonic bacteria [23]. The intestinal bacterial metabolites, including compound K (CK), PPD, and PPT, were easily absorbed and appeared in the plasma of rats or humans after the oral administration of ginsenosides [23-26].

In the present study, we examined the effects of ginsenoside metabolites such as PPT and CK on I_{Ks} and KCNQ1 K^+ alone channel activity by using the *Xenopus* oocyte gene-expression system. We found that CK and PPT exhibited a differential effect on I_{Ks} and KCNQ1 K^+ alone channel activity and further discussed the role of ginsenoside metabolites in cardiovascular systems.

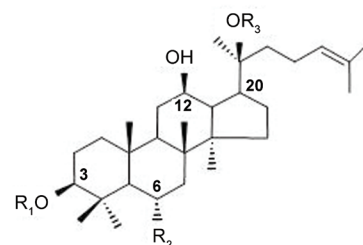
MATERIALS AND METHODS

Materials

Ginsenoside metabolites, such as CK and PPT, were provided by the AMBO Institute (Seoul, Korea) (Fig. 1). The cDNAs for human KCNQ channels (Gene Bank ID. NM_000218) were kindly provided by Dr. Pongs (University of Hamburg, Germany). Other agents were purchased from Sigma-Aldrich (St. Louis, MO, USA).

Preparation of *Xenopus* oocytes and microinjection

X. laevis frogs were purchased from *Xenopus* I (Ann Arbor, MI, USA). Their care and handling procedures were performed in accordance with the institutional guidelines of Konkuk University. For the isolation of oocytes, frogs were anesthetized with an aerated solution of 3-amino benzoic acid ethyl ester, followed by the removal of ovarian follicles. The oocytes were treated with collagenase, and then agitated for 2 h in a Ca^{2+} -free



Ginsenosides	R1	R2	R3
CK	-H	-H	-Glc
Rg3	-Glc ₂ -Glc	-H	-H
PPD	-H	-H	-H
PPT	-H	-OH	-H

Fig. 1. Chemical structures of ginsenoside Rg3 and ginsenoside metabolites used in this study. CK, compound K; PPD, protopanaxadiol; PPT, protopanaxatriol; Glc, glucopyranoside.

medium containing 82.5 mM NaCl, 2 mM KCl, 1 mM $MgCl_2$, 5 mM HEPES, 2.5 mM sodium pyruvate, 100 units/mL penicillin, and 100 μ g/mL streptomycin. Stage V–VI oocytes were collected and stored in a ND96 medium (in mM: 96 NaCl, 2 KCl, 1 $MgCl_2$, 1.8 $CaCl_2$, and 5 HEPES, pH 7.5) supplemented with 50 μ g/mL gentamicin. The oocyte-containing solution was maintained at 18°C with gentle continuous shaking and renewed daily. Electrophysiological experiments were performed within 5 to 6 d of oocyte isolation, with ginsenoside metabolites applied to the bath. For K^+ channel experiments, Kv channel-encoding cRNAs (40 nL) were injected into the animal or the vegetal pole of each oocyte 1 d after isolation using a 10- μ L microdispenser (VWR Scientific, San Francisco, CA, USA) fitted with a tapered glass pipette tip (15 to 20 μ m in diameter) [27].

Data recording

A custom-made Plexiglas net chamber was used for two-electrode voltage-clamp recordings as previously reported [27]. The oocytes were impaled with 2 microelectrodes filled with 3M KCl (0.2 to 0.7 M Ω), and electrophysiological experiments were carried out at room temperature by using an Oocyte Clamp (OC-725C; Warner Instruments, Hamden, CT, USA). Stimulation and data acquisition were controlled with a pClamp 8 (Axon Instruments, Union City, CA, USA). For most electrophysiological experiments, oocytes were initially perfused with a ND96 solution (in mM: 96 NaCl, 3 KCl, 2 $CaCl_2$, 5 HEPES, pH 7.4 with NaOH) to obtain control-current recordings. The oocytes were then clamped at a holding potential of -90 mV. The membrane potential

was depolarized to 0 mV for 4 s, followed by repolarization to -60 mV at 20-s intervals, and the currents were recorded.

Data analysis

To obtain the concentration-response curve of the effects of CK and PPT on the K⁺ current from the human KCNQ K⁺ channel, the peak amplitudes at different concentrations of CK and PPT were plotted. The Origin software (Origin, Northampton, MA, USA) was used to fit the plot to the Hill equation: $y/y_{\max} = [A]^{nH}/([A]^{nH} + [IC_{50}]^{nH})$, where y is the peak current at a given concentration of CK and PPT, y_{max} is the maximal peak current, IC₅₀ is the concentration of CK and PPT producing a half-maximal effect, [A] is the concentration of CK and PPT, and nH is the Hill coefficient. All values are presented as

mean±SEM. The significance of differences between the mean control and treatment values was determined using Student's *t*-test. A *p*-value of <0.05 was considered statistically significant.

RESULTS AND DISCUSSION

Effects of protopanaxatriol and compound K on I_{Ks}

We first examined the effect of the ginsenoside metabolites PPT and CK on the I_{Ks} channel currents by using a *Xenopus* oocyte gene-expression system. As shown in previous reports, I_{Ks} channel currents were recorded using a two-electrode voltage-clamp recording technique at room temperature. In these experiments, cells were held at -80 mV and depolarized to +30 mV for 2.5 s to elicit the currents. The currents evoked by this voltage-clamp

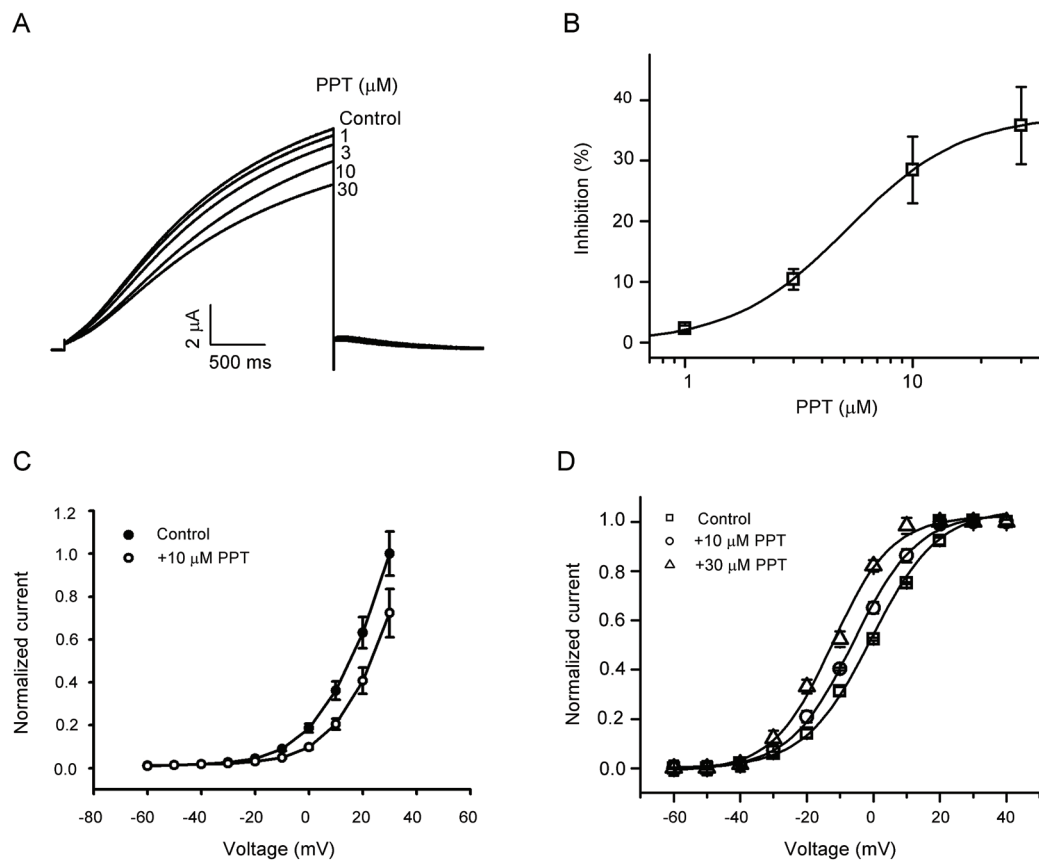


Fig. 2. Effects of protopanaxatriol (PPT) on I_{Ks} channel currents. (A) The representative traces on I_{Ks} channel current blocks by different concentrations of PPT. Currents were in response to 2.5-s voltage steps up to +30 mV from a holding potential of -80 mV. (B) Concentration-response curves of PPT on I_{Ks} and KCNQ1 alone channel currents. Solid lines have been fitted to the Hill equation as described in Materials and Methods. Oocytes were clamped at the same as described for (A), and evoked every 10 s. (C) Current-voltage (I-V) relationships of I_{Ks} channel in the absence (●) or presence (○) of 10 μM PPT. Voltage pulses of 3-second duration were applied in 10-mV increments and at 10-second intervals from a holding potential of -80 mV. The peaks of the evoked currents, normalized to the peak current evoked by the voltage step to +30 mV in the absence of PPT, were used in the I-V plot. (D) An example of I_{Ks} channel currents recorded before (control) and after modification by 10 and 30 μM PPT. Currents recorded during 3-second depolarizing pulses to membrane potentials of -60 to +50 mV, applied from a holding potential of -80 mV. Tail currents were measured at -70 mV. Voltage-dependent activation curves were determined from the normalized amplitudes of tail currents. Data were fitted to a Boltzmann function. Data represent the mean±SEM (n=6-7).

protocol were slowly activating delayed rectifier K⁺ channel (I_{Ks}) currents with no apparent inactivation (Fig. 2A) [3]. PPT inhibited I_{Ks} in a concentration-dependent manner over a range of concentrations (i.e., 1 to 30 μ M) (Fig. 2A). The IC_{50} and Hill coefficient for the PPT block of I_{Ks} were 5.18 ± 0.13 μ M and 1.72 ± 0.05 , respectively (Fig. 2B). The effect of PPT on the current-voltage relationship of the I_{Ks} channel was estimated by normalizing current values plotted against the test potential in the absence and presence of 10 μ M PPT [21]. Normalized currents were obtained from the peak current amplitudes in response to depolarizing pulses, in the range of -60 to +30 mV in 10-mV increments with a holding potential of -80 mV. The blockage of I_{Ks} at 10 μ M PPT was voltage dependent (Fig. 2C). Next, we examined the effects of PPT on the voltage dependency of steady-state channel activation. As described above, a voltage-clamp protocol consisted of 3-s depolarizing steps from -60 to +40 mV (10-mV increments and 10-s intervals with a holding potential of -80 mV) was used to determine the

activation of I_{Ks} channels. The activation of I_{Ks} channels was fitted to a Boltzmann function. As shown in Fig. 2D, 10 and 30 μ M PPT shifted $V_{g0.5}$ in the hyperpolarizing direction (control, -0.62 ± 1.12 mV; 10 and 30 μ M PPT, -5.93 ± 0.66 mV, -12.25 ± 0.86 mV, respectively; $n=5$, $p<0.05$). Interestingly, CK exhibited only a slight inhibition of I_{Ks} in a concentration-dependent block, the I-V relationship, and the G-V curve (Fig. 3). Thus, ginsenoside-induced regulations on I_{Ks} might be derived from PPT rather than from protopanaxadiol ginsenoside metabolites (i.e., PPD).

Effects of protopanaxatriol and compound K on KCNQ1 alone K⁺ channel activity

We next examined the effect of PPT and CK on KCNQ1 alone channel currents. Similar to the I_{Ks} channels, PPT also exhibited the concentration-dependent inhibition of KCNQ1 alone K⁺ channel currents and showed by 5% inhibition of the KCNQ1 alone K⁺ channel current (Fig. 4A, B). The fitting curve of PPT for IC_{50}

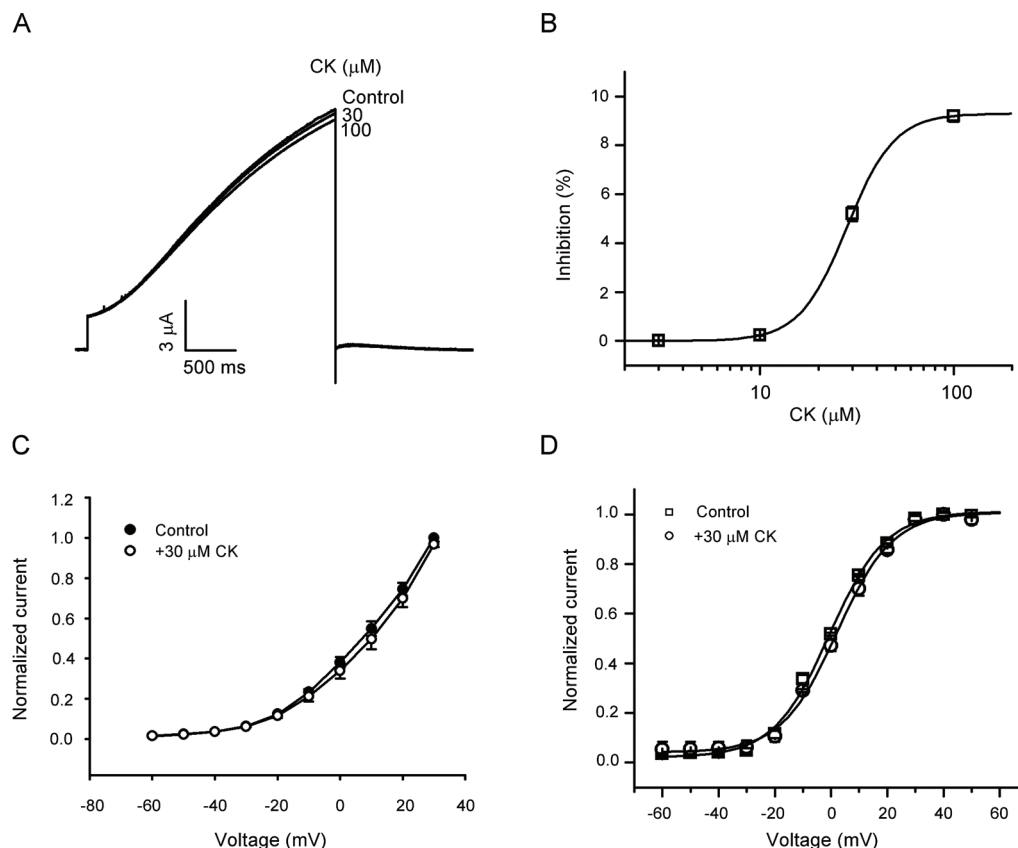


Fig. 3. Effects of compound K (CK) on I_{Ks} channel currents. (A) Representative current traces on I_{Ks} channel inhibitions by different concentrations of CK. (B) Concentration-response curves of CK on I_{Ks} channel currents. (C) I-V relationships for KCNQ1 plus KCNE1 channel currents measurement at the end of the 3-second test pulse before and after application of 30 μ M CK. (D) The steady-state activation curve for I_{Ks} channel currents by 30 μ M CK. Protocols were the same as described for Fig. 2. Data are represented by the mean \pm SEM ($n=7$).

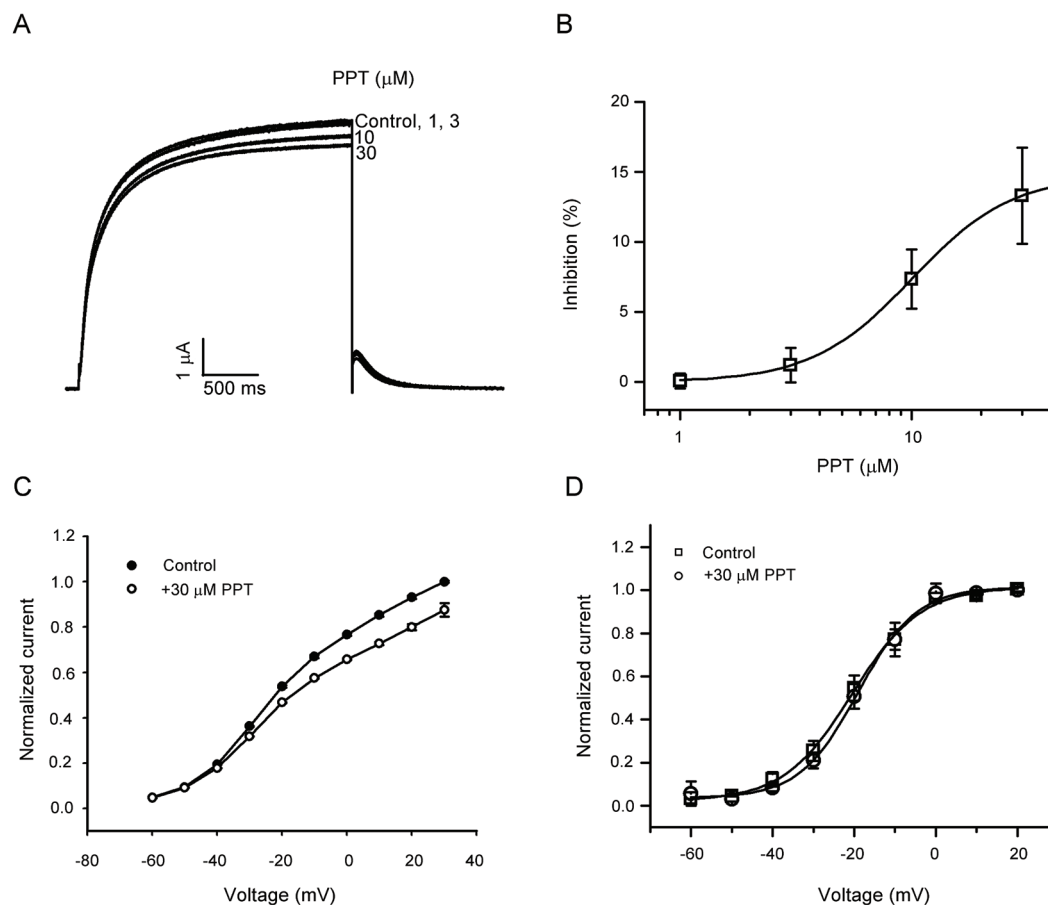


Fig. 4. Effects of protopanaxatriol (PPT) on KCNQ1 alone channel. (A) The representative traces on KCNQ1 alone channel current inhibition by different concentrations of PPT. Protocols were the same as described for Fig. 2. (B) Concentration-response curves of PPT on KCNQ1 alone channel currents. (C) Current-voltage (I-V) relationships of KCNQ1 alone channels in the absence (●) or presence (○) of 30 μM PPT. (D) Example of KCNQ1 channel currents recorded before (control) and after modification by 30 μM PPT. Protocols were the same as described for Fig. 2. Data represent the mean±SEM ($n=5-7$).

was 10.0 ± 0.17 μM with a Hill coefficient of $h=2.01 \pm 0.06$ ($n=5$) (Fig. 4B). The current-voltage relationship was examined, and the current responses evoked by voltage steps (i.e., a series of voltage pulses of 3-s duration given in 10-mV increments and 10-s intervals with a holding potential of -80 mV) were used to construct the I-V curve. KCNQ1 alone K^+ current by PPT observed voltage-dependent inhibition (Fig. 4C). Unlike the I_{Ks} channels, the effect of PPT on the KCNQ1 alone K^+ channel induced a minimal shift in the G-V curve (Fig. 4D). Fig. 5 shows the effects of the ginsenoside metabolite CK on KCNQ1 alone K^+ currents. CK also had no effect on KCNQ1 alone as it did on the I_{Ks} channels. The IC_{50} was 27.65 ± 0.05 μM with a Hill coefficient of $h=3.04 \pm 0.03$ ($n=7$) (Fig. 5B). CK minimally affected the current-voltage relationship and voltage-dependent activation (Fig. 5C, D). Thus, these results suggest that KCNQ1 alone is more sensitive to PPT than CK with regard to blocking.

In vitro and *in vivo* studies have shown that an orally administered ginsenoside was metabolized and finally converted to aglycone such as CK, which has a glucose residue at the C-20 of PPD or PPT [23]. Recent reports have shown that such ginsenoside metabolites might exhibit pharmacological effects [23,28,29]. However, relatively little is known about the effects of ginsenoside metabolites on K^+ ion channel activity, such as I_{Ks} in the heart.

We have previously reported that ginsenoside Rg3 activated human KCNQ1 K^+ channel currents through interactions with the K318 and V319 residues [21]. In the present study, we examined the effects of ginsenoside metabolites such as CK and PPT on human KCNQ1 K^+ channel activity. We found that ginsenoside metabolites showed a differential effect of PPT on I_{Ks} and KCNQ1 alone K^+ channels currents. Thus, we observed that PPT inhibited I_{Ks} and KCNQ1 alone K^+ channels currents

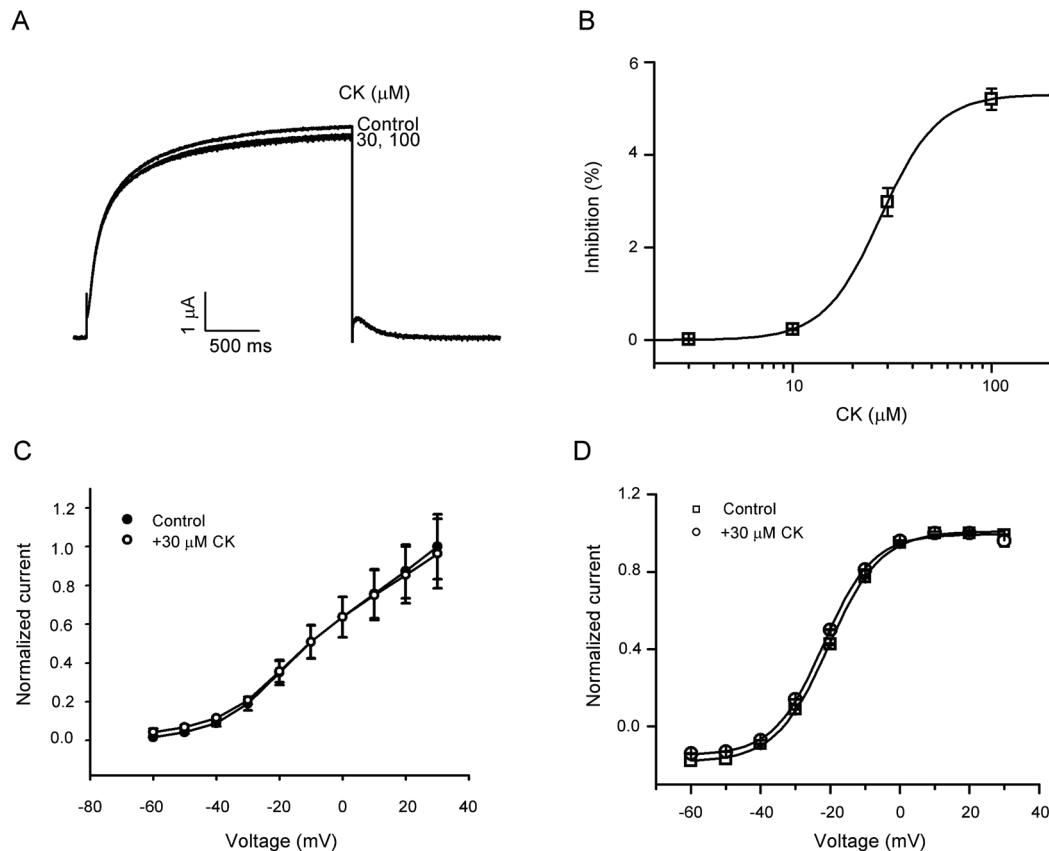


Fig. 5. Effects of compound K (CK) on KCNQ1 alone channel currents. (A) Representative current traces on KCNQ1 alone channel inhibition by different concentrations of CK. (B) Concentration-response curves of CK on KCNQ1 alone channel currents. (C) I-V relationships for KCNQ1 alone channel currents measurement at the end of the 3-second test pulse before and after application of 30 μM CK. (D) The steady-state activation curve for KCNQ1 alone channel currents by 30 μM CK. Protocols were the same as described for Fig. 2. Data are represented by the mean \pm SEM ($n=6$).

in both concentration- and voltage-dependent manners, but the PPT blockade of the I_{Ks} current had an IC_{50} value of $5.18 \pm 0.13 \mu\text{M}$, which was 2-fold less than that of KCNQ1 alone K^+ current. In addition, we found that steady-state activation curves of I_{Ks} channel currents by PPT shifted in the direction of hyperpolarization in a dose-dependent manner, but the KCNQ1 alone K^+ channel currents rarely did. This observation suggests that PPT affects the steady-state activation of I_{Ks} channels only. Taken together, these results suggest that the KCNE1 subunit has an important role in PPT-induced regulation of the I_{Ks} channel.

Native cardiac I_{Ks} channels are involved in cardiac diseases such as arrhythmia [30]. I_{Ks} channel regulators are clinically important for the treatment of cardiac diseases [31,32]. In a previous study, we reported that ginsenoside metabolites exhibited differential regulations on $I_{\text{deactivating-tail}}$ of the HERG K^+ channel [22]. CK induced a persistent $I_{\text{deactivating-tail}}$ and caused a leftward shift of steady-state, voltage-dependent activation. In contrast to CK, PPT

caused an acceleration of $I_{\text{deactivating-tail}}$ decay. In the present study, we found that PPT mainly inhibited the I_{Ks} K^+ channel, caused a leftward shift in the activation curve of the I_{Ks} channel, and minimally affected KCNQ1 alone. Therefore, when KCNQ1 co-assembled with KCNE1, the sensitivity to PPT increased 2-fold, thus indicating that ginsenoside metabolites exhibit a differential effect on HERG K^+ and I_{Ks} channels.

In previous studies, we also showed that ginsenoside metabolites such as CK, PPD, and PPT regulate ion channels and receptors. PPT, but not CK, induced an inhibition of the voltage-dependent L-type Ca^{2+} channel currents [33]. We have found that CK, but not PPT, inhibited a neuronal Nav1.2 channel [34]. In contrast, M4, but not CK, caused an inhibition of *N*-methyl-D-aspartic acid receptor-mediated currents [35]. In the present study, CK exhibited a negligible effect on both I_{Ks} and KCNE K^+ channel currents. Thus, ginsenoside metabolite-induced regulations on various ion channels and receptors might be dependent on ion channel or receptor types.

In summary, our results show that PPT, rather than CK, is the main component in the inhibition of I_{Ks} channels. Further, different types of ginsenoside metabolites exhibit differential effects on the regulation of I_{Ks} and KCNQ1 K^+ channels.

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