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High Extracellular Ca\textsuperscript{2+} Stimulates Ca\textsuperscript{2+}-Activated Cl\textsuperscript{−} Currents in Frog Parathyroid Cells through the Mediation of Arachidonic Acid Cascade

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Abstract

Elevation of extracellular Ca\textsuperscript{2+} concentration induces intracellular Ca\textsuperscript{2+} signaling in parathyroid cells. The response is due to stimulation of the phospholipase C/Ca\textsuperscript{2+} pathways, but the direct mechanism responsible for the rise of intracellular Ca\textsuperscript{2+} concentration has remained elusive. Here, we describe the electrophysiological property associated with intracellular Ca\textsuperscript{2+} signaling in frog parathyroid cells and show that Ca\textsuperscript{2+}-activated Cl\textsuperscript{−} channels are activated by intracellular Ca\textsuperscript{2+} increase through an inositol 1,4,5-triphosphate (IP\textsubscript{3})-independent pathway. High extracellular Ca\textsuperscript{2+} induced an outwardly-rectifying conductance in a dose-dependent manner (EC\textsubscript{50} ~ 6 mM). The conductance was composed of an instantaneous time-independent component and a slowly activating time-dependent component and displayed a deactivating inward tail current. Extracellular Ca\textsuperscript{2+}-induced and Ca\textsuperscript{2+} dialysis-induced currents reversed at the equilibrium potential of Cl\textsuperscript{−} and were inhibited by niflumic acid (a specific blocker of Ca\textsuperscript{2+}-activated Cl\textsuperscript{−} channel). Gramicidin-perforated whole-cell recording displayed the shift of the reversal potential in extracellular Ca\textsuperscript{2+}-induced current, suggesting the change of intracellular Cl\textsuperscript{−} concentration in a few minutes. Extracellular Ca\textsuperscript{2+}-induced currents displayed a moderate dependency on guanosine triphosphate (GTP). All blockers for phospholipase C, diacylglycerol (DAG) lipase, monoacylglycerol (MAG) lipase and lipoxygenase inhibited extracellular Ca\textsuperscript{2+}-induced current. IP\textsubscript{3} dialysis failed to induce conductance increase, but 2-arachidonoylglycerol (2-AG), arachidonic acid and 12S-hydroperoxy-5Z,8Z,10E,14Z-eicosatetraenoic acid (12(S)-HPETE) dialysis increased the conductance identical to extracellular Ca\textsuperscript{2+}-induced conductance. These results indicate that high extracellular Ca\textsuperscript{2+} raises intracellular Ca\textsuperscript{2+} concentration through the DAG lipase/lipoxygenase pathway, resulting in the activation of Cl\textsuperscript{−} conductance.

Introduction

Parathyroid hormone (PTH) regulates extracellular free Ca\textsuperscript{2+} concentration ([Ca\textsuperscript{2+}]\textsubscript{o}) in cooperation with 1,25-dihydroxycholecalciferol (1,25-(OH)\textsubscript{2}D\textsubscript{3}) and calcitomin. On the other hand, [Ca\textsuperscript{2+}]\textsubscript{i}, regulates the secretion of PTH from parathyroid cells through an extracellular Ca\textsuperscript{2+}-sensing receptor (CaR) [1,2]. High [Ca\textsuperscript{2+}]\textsubscript{o} inhibits the secretion, whereas low [Ca\textsuperscript{2+}]\textsubscript{i} enhances the secretion. It is believed that extracellular Ca\textsuperscript{2+} binds to CaR, and as a consequence inhibits the secretion of PTH via intracellular free Ca\textsuperscript{2+} concentration ([Ca\textsuperscript{2+}]\textsubscript{i}). However, the molecular mechanism by which [Ca\textsuperscript{2+}]\textsubscript{i} regulates the secretion is not well elucidated.

The CaR belongs to the family G of G protein-coupled receptors (GPCRs) and has a large extracellular domain that binds external Ca\textsuperscript{2+} and other CaR agonists. The CaR controls various signaling pathways [3–5]. Calcium binding to the receptor results in G protein-dependent activation of phosphatidylinositol-specific phospholipase C (PI-PLC) causing accumulation of inositol 1,4,5-triphosphate (IP\textsubscript{3}) and diacylglycerol (DAG) and promoting rapid release of Ca\textsuperscript{2+} from its intracellular stores [6,7]. The CaR-mediated activation of PI-PLC in parathyroid cells is a direct G protein-mediated process, while activation of phospholipase A\textsubscript{2} (PLA\textsubscript{2}) and D by high [Ca\textsuperscript{2+}]\textsubscript{o} are probably indirect, through the mediation of PLC-dependent activation of protein kinase C [4].

DAG can be utilized for 2-arachidonoylglycerol (2-AG) generation [8]. PLC hydrolyzes phosphatidylinositol and produces arachidonic acid-containing DAG. Then, DAG is converted into 2-AG by the action of DAG lipase. Next, 2-AG is hydrolyzed by monoacylglycerol (MAG) lipase and yields arachidonic acid. Finally, arachidonic acid is oxidized by cyclooxygenase (COX), lipoxygenase (LO) or epoxysgenase (cytochrome P450).

The mitogen-activated protein kinase (MAP kinase) pathways are found in bovine parathyroid cells [9]. MAP kinase is activated by dual tyrosine and threonine phosphorylation [10]. Phosphorylated MAP kinase can phosphorylate cytosolic phospholipase A\textsubscript{2} (cPLA\textsubscript{2}) [11]. In bovine parathyroid cells, the MAP kinase is activated by CaR [9]. There are several mechanisms by which
which is depolarized by extracellular Ca$^{2+}$ (EC) solution (10 mM Ca$^{2+}$) to outwardly rectifying (6 mM Ca$^{2+}$) configuration in normal saline solution, the whole-cell current-difference between conventional and perforated conditions in frog parathyroid cells displayed a resting potential of about −66 mV, input resistance of 13 GΩ and membrane capacitance of 8 pF. There was no difference between conventional and perforated conditions in those properties. After attaining the perforated whole-cell configuration in normal saline solution, the whole-cell current-voltage (I/V) relationships produced by a voltage ramp (167 mV/s) from −100 to +100 mV were almost linear in normal saline solution (data not shown).

When the extracellular Ca$^{2+}$ concentration was increased from 1.8 mM to a higher concentration, frog parathyroid cells displayed a sustained inward current at a holding potential of −54 mV (Figure 2A). I/V relationships produced by a voltage ramp indicated an outwardly rectifying property in high Ca$^{2+}$ saline solution (Figure 2B). However, at 10 mM Ca$^{2+}$, linear I/V relationships were observed in 5 of 10 cells. The magnitude of the current increased in a dose-dependent manner of Ca$^{2+}$ (Figure 2C). The apparent EC$_{50}$ for extracellular Ca$^{2+}$ was about 6 mM. The biophysical properties of extracellular Ca$^{2+}$-induced currents elicited by voltage steps between −104 mV and +96 mV for 400 ms from a holding potential of −94 mV were examined. Frog parathyroid cells displayed transient inward currents and subsequent sustained leak currents in response to depolarizing steps in normal saline solution (Figure 2D). We have reported previously that the transient inward currents were the tetrodotoxin (TTX)-sensitive, voltage-gated Na$^{+}$ currents [24]. When extracellular Ca$^{2+}$ was increased to 6 mM, slowly developing but sustained outward currents appeared in response to depolarizing steps (Figure 2E). Deactivating inward tail currents were also observed on the return to −84 mV from depolarizing potentials (Figure 2F). Outward currents were composed of an instantaneous time-independent component and a slowly activating time-dependent component. The steady-state I/V relationships measured at the end of the pulse changed from almost linear characteristic (normal saline) to outwardly rectifying (6 mM Ca$^{2+}$) (Figure 2F). The activation and deactivation time constants did not show clear dependence on the voltage (Figure 2G). Extracellular 6 mM Ca$^{2+}$ shifted the threshold of the voltage for the activation of transient inward Na$^{+}$ currents from −54 mV to −44 mV reversibly. This shift may be due to the change of surface charge elicited by high Ca$^{2+}$. The biophysical properties of extracellular Ca$^{2+}$-induced currents suggested the appearance of Ca$^{2+}$-activated Cl$^{-}$ current [29]. Niflumic acid (0.1 mM), a specific blocker of Ca$^{2+}$-activated Cl$^{-}$ channel, inhibited extracellular Ca$^{2+}$-induced currents completely (n = 5) (Figure 3A and B). The currents had the reversal potential of −14±3 mV (n = 7) close to the E$_{Cl}$ (−7 mV). When intracellular Cl$^{-}$ concentration decreased from 104 to 10 mM, the reversal potential shifted to −69±3 mM (n = 5) when E$_{Cl}$ was set to −66 mV (Figure 3C). Prevention of the permeation of Cl$^{-}$ through the patch membrane using gramicidin instead of amphotericin B caused the reversal potential of intracellular Ca$^{2+}$-induced current to change from −25±2 mV in early stage (1 min) to −58±3 mV in steady state (3 min) (n = 4) (Figure 3D). When the pipette was filled with a modified Ca$^{2+}$, low Cl$^{-}$ (10 mM) internal solution (E$_{Cl}$ = −63 mV) containing 0.8 mM Ca$^{2+}$ without EGTA, frog parathyroid cells displayed a gradual increase in outward-rectifying current (Figure 3E and F). The outward-rectifying current was strongly inhibited by niflumic acid (Figure 3E) and the niflumic acid-sensitive current had a mean reversal potential of −65±2 mV (n = 5) (Figure 3F).
Nominal Ca\(^{2+}\)-free 10 mM Ba\(^{2+}\) solution without Na\(^{+}\) also induced a conductance increase and the currents had the reversal potential close to E\(_{Cl}\) (Figure S1A and B). Even though extracellular Ca\(^{2+}\) was eliminated by 1 mM EGTA, a Ca\(^{2+}\)−deficient 10 mM Ba\(^{2+}\) solution could induce the outwardly-rectifying current as well as the Ba\(^{2+}\) solution containing 1.8 mM Ca\(^{2+}\) did (Figure S1C, D and E). Extracellular 6 mM Sr\(^{2+}\) displayed about half of the potency of 6 mM Ca\(^{2+}\). Extracellular 0.1 mM Gd\(^{3+}\) did not induce any response in frog parathyroid cells, while the drug inhibited extracellular Ca\(^{2+}\)-induced current strongly, although a previous study has reported that...
Ga<sup>3+</sup> induced a large response in Xenopus oocytes injected with cRNA for bovine Ca<sup>2+</sup>-sensing receptor [1]. Spermine (1 mM) also did not induce any response in frog parathyroid cells. NPS R-467 (0.1 mM) induced the outwardly rectifying currents in 2 of 4 cells when E<sub>Cl</sub> was set to −63 mV, but other R-467-insensitive cells displayed a moderate response to extracellular 10 mM Ca<sup>2+</sup>.

**Effects of Intracellular Drugs Related to Phospholipase C on Extracellular Ca<sup>2+</sup>-induced Current**

After attaining the conventional whole-cell configuration with a standard K<sup>+</sup> internal solution without GTP, frog parathyroid cells still displayed a sustained inward current of −88±10 pA (n = 16) at −54 mV in response to extracellular 10 mM Ca<sup>2+</sup>, although repetitive recordings were impossible. In the conventional mode, the effects of drugs were estimated by the different responses of different populations of cells. When the internal Ca<sup>2+</sup>-buffer of 1 mM EGTA was replaced with 10 mM BAPTA, the extracellular 10 mM Ca<sup>2+</sup>-induced current decreased to 16% of the controls (Figure 4). During washout, a slowly developing but transient conductance increase always appeared (Figure 4A and B). In the present study, further analysis of the response was avoided. Addition of 10 μM U73122 (an inhibitor of phospholipase C) into the internal solution decreased the current response to 36% of the controls, which was a significant decreases, but U73343 (a weak analog of U73122) did not affect the current response. Addition of 1 mM GTP and 1 mM GDP<sub>b</sub>S did not change the magnitude of the current significantly. However, there was a significant difference in current magnitudes between GTP and GDP<sub>b</sub>S. Thus, extracellular Ca<sup>2+</sup>-induced current had a moderate dependency on GTP (Figure 4C). Even when the pipette contained 50 μM inositol 1,4,5-trisphosphate, frog parathyroid cells did not display any response, but the cells showed an inward current of −103±20 pA (n = 7) at −54 mV in response to extracellular 10 mM Ca<sup>2+</sup> (Figure 5A and B). When 50 μM 2-arachidonoylglycerol (2-AG) was dialyzed into the cells, the drug induced a slowly developing inward current of −205±59 pA at −54 mV in 3 of 4 cells within an hour after dissolving the drug in the pipette solution (Figure 5C and D), but the cells (6 cells) did not respond after an hour from dissolving the drug in the pipette solution. Internal 2-arachidonoylglycerol ether (2-AG ether, a chemically stable analog of 2-AG) did not induce any response in the cells (n = 6, Figure 5E and F). Although 2-AG is an endogenous agonist of the cannabinoid-1 (CB<sub>1</sub>) receptor, external 2-AG ether (50 μM) and Win55,212-2 (10 μM, cannabinoid receptor agonist) did not induce a conductance increase.

Figure 3. The dependence of the reversal potentials of extracellular Ca<sup>2+</sup>-induced and Ca<sup>2+</sup> dialysis-induced currents on intracellular Cl<sup>−</sup> concentration. (A) The pen recording of the inhibitory effect of niflumic acid on extracellular Ca<sup>2+</sup>-induced current measured at a holding potential of −54 mV. (B) The plot of the whole-cell current/voltage (I/V) relationships produced by a voltage ramp of the extracellular Ca<sup>2+</sup>-induced currents obtained from the pen recording on the upper. (C) The shift of the reversal potential of extracellular Ca<sup>2+</sup>-induced current in another cell. Intracellular Cl<sup>−</sup> concentration was reduced from 104 to 10 mM. In Figure 3A, B and C, the pipette solution contained amphotericin B (133 μg/ml). (D) The gramicidin-perforated whole-cell current/voltage (I/V) relationships by a voltage ramp of the extracellular Ca<sup>2+</sup>-induced currents. Only in this case, the pipette solution contained gramicidin (100 μg/ml). (E) The pen recording of intracellular 0.8 mM Ca<sup>2+</sup>-induced current and its inhibition with niflumic acid. (F) The plots of I/V relationships produced by a voltage ramp of Ca<sup>2+</sup> dialysis-induced currents. I/V relationships labeled a–d were obtained at the time indicated by the same letters on the pen recording.

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Figure 4. Effects of intracellular drugs on extracellular Ca\(^{2+}\)-induced current. (A) The pen recording of the inhibitory effect of internal 10 mM BAPTA on extracellular Ca\(^{2+}\) (A) The plot of the whole-cell current/voltage (I/V) relationships produced by a voltage ramp. (C) Comparison of the effects of intracellular drugs on extracellular 10 mM Ca\(^{2+}\)-induced current measured at −54 mV. (B) The plot of the whole-cell current/voltage (I/V) relationships in response to depolarizing steps and deactivating tail currents in the cells, but the drug decreased extracellular Ca\(^{2+}\)-induced current to 5% of the controls (Figure 7A and C). Washout recovered the response to 48% of the controls. It is known that ETYA is a non-specific inhibitor of phospholipase A\(_2\) (PLA\(_2\)), epoxygenase (cytochrome P-450), cyclooxygenase (COX) and lipooxygenase (LO). Baicalein (20 μM, an inhibitor of 12/15-lipoxygenase) decreased the current magnitude to 64% of the controls and the moderate inhibition was significant (Figure 7C), MS-PPOH (20 μM, an inhibitor of epoxygenase) and dicrofenac (20 μM, an inhibitor of cyclooxygenase) did not inhibit the extracellular Ca\(^{2+}\)-induced current (Figure 7C).

Effects of intracellular arachidonic acid and 12(S)-HPETE

Intracellular dialysis of 50 μM arachidonic acid induced slow developing inward current and the response was decreased by ETYA to 6% of the controls in six cells (Figure 7D and F). Baicalein (20 μM) and niflumic acid (100 μM) also decreased the arachidonic acid-induced currents to 28% and 11% of the controls, respectively (Figure 7F). The reversal potentials of arachidonic acid-induced currents shifted in accordance to the equilibrium potential of Cl\(^-\) (EC\(_{50}\)) (Figure S2). Internal arachidonic acid also elicited slowly activating time-dependent outward currents in response to depolarizing steps and deactivating tail currents on the return to −84 mV from depolarized potentials (Figure 8B). Both components of the currents were greatly inhibited by baicalein (Figure 8C and D, three cells). In steady state during arachidonic acid dialysis, some cells displayed a linear current/voltage (I/V) relationships in response to depolarizing steps. Ca\(^{2+}\)-free saline solution containing 1 mM EGTA gradually decreased the arachidonic acid-induced current to 20% of the control (n = 3), suggesting that the IP\(_3\)-independent Ca\(^{2+}\) store might be depleted by sustained action of an arachidonic acid metabolite. Intracellular dialysis of 12 (S)-HPETE at very low concentration also induced time-dependent outward currents and deactivating tail currents (Figure 8F). The apparent EC\(_{50}\) for intracellular 12 (S)-HPETE was about 700 pM (Figure 8H). Intracellular dialysis of 1 μM 15(S)-HETE elicited the response (−67±31 pA, n = 5) equivalent to that of 300 nM 12(S)-HPETE (−62±11 pA, n = 6).

Effects of MAP Kinase Cascade Inhibitor on Extracellular Ca\(^{2+}\)-induced Current

It has been reported that extracellular Ca\(^{2+}\) activates MAP kinase and phospholipase A\(_2\) via protein tyrosine kinase (PTK) as...
well as protein kinase C (PKC) in bovine parathyroid cells [9]. When genistein (40 mM, an inhibitor of PTK) was added to the external solution, extracellular Ca$_{2+}$-induced current decreased to 6% of the controls (Figure S3A and E). Washout of the drug recovered the current response to 87% of the controls. External PDBu (10 mM, an activator of PKC) did not evoke the current response, although the drug induced very slowly developing inhibition of voltage-gated Na$_{+}$ currents (the time constant of about 10 min) [24]. External PD98059 (50 mM, an inhibitor of MAP kinase) also decreased extracellular Ca$_{2+}$-induced current to 31% of the controls (Figure S3C and E). The current response recovered to 57% of the controls after washout.

**Discussion**

The present study shows that frog parathyroid cells can respond to high extracellular Ca$_{2+}$, resulting in an activation of Ca$_{2+}$-activated Cl$^{-}$ conductance. High extracellular Ca$_{2+}$ increased intracellular Ca$_{2+}$ concentration ([Ca$^{2+}$]$_{i}$), but the increase was independent of inositol 1,4,5-trisphosphate (IP$_{3}$). Alternatively, the PLC-DAG-MAG pathway may produce arachidonic acid in frog parathyroid cells. Since ETYA (a non-metabolizable analog of arachidonic acid) could not elicit the current response, arachidonic acid also may not be an intracellular mediator for raising [Ca$^{2+}$]$_{i}$. An arachidonic acid metabolite produced by the action of baicalein-sensitive 12-/15-lipoxygenase may increase [Ca$^{2+}$]$_{i}$. 12-lipoxygenase produces 12(S)-HPETE, while 15-lipoxygenase produces 15(S)-HETE. In the present study, 12(S)-HPETE as well as 15(S)-HETE elicited Ca$_{2+}$-activated Cl$^{-}$ currents. In porcine parathyroid cells, high extracellular Ca$^{2+}$ and arachidonic acid inhibit PTH secretion and baicalein restores the secretion [30]. Both 12(S)-HPETE and 15(S)-HETE inhibit the PTH secretion [31]. No effect of IP$_{3}$ dialysis suggests other targets for the lipid messenger than the endoplasmic reticulum. The intra-granular Ca$^{2+}$ concentration in secretory cells is lower than that in the endoplasmic reticulum but higher than that in the cytosol [32]. 12(S)-HPETE may affect the secretory granules, resulting in the inhibition of PTH secretion.

In murine parotid and pancreatic acinar cells, arachidonic acid activates Ca$^{2+}$-selective channels in plasma membrane [38]. The Ca$^{2+}$ entry through the channels increases [Ca$^{2+}$]$_{i}$. It is claimed

![Figure 5. Effects of intracellular 1,4,5-IP$_{3}$, 2-AG and 2-AG ether.](image-url)
that the molecular architecture of the arachidonate-regulated Ca\(^{2+}\)-selective channel is a pentameric assembly of Orai1 and Orai3 subunits [39]. In olfactory transduction, odorant-induced currents in olfactory receptor neurons are amplified by Ca\(^{2+}\)-activated Cl\(^{-}\) current [40]. The transduction currents are divided into cyclic nucleotide-gated cationic and Ca\(^{2+}\)-activated Cl\(^{-}\) conductance. In the present study, Ba\(^{2+}\) in Ca\(^{2+}\)-free saline solution containing 1 mM EGTA also could elicit Ca\(^{2+}\)-activated Cl\(^{-}\) current in frog parathyroid cells. Furthermore, high extracellular Ca\(^{2+}\) and intracellular arachidonic acid could induce almost only niflumic acid-sensitive currents. An arachidonic acid metabolite may not induce the Ca\(^{2+}\) entry through Ca\(^{2+}\)-permeable channels in the plasma membrane, but the metabolite may release Ca\(^{2+}\) from an unknown novel store independent of IP\(_3\). This mechanism for [Ca\(^{2+}\)] increase without Ca\(^{2+}\) entry may make the precise monitoring of [Ca\(^{2+}\)] possible. On the other
hand, the IP3-independent Ca\(^{2+}\) store should be refilled by an innate mechanism. In the present experiment, the wash-out of Ca\(^{2+}\)-free saline solution for 10 minutes did not recover the arachidonic acid-induced current. Lu et al. [23] identified expression and association of TRPC channels with Orai1 and STIM1 in human parathyroid.

Figure 7. Effects of arachidonic acid-related drugs on the current signals. (A) The pen recording of the inhibitory effect of ETYA on extracellular Ca\(^{2+}\)-induced current at −54 mV. (B) The plots of the whole-cell I/V relationships during control, ETYA application and wash-out. The relationships were obtained from the pen recording on the upper. (C) Comparison of the effects of external 20 μM ETYA, 20 μM baicalein, 20 μM MS-PPOH and 20 μM diclofenac on extracellular Ca\(^{2+}\)-induced current at −54 mV. In Figure 7A, B and C, the pipette solution contained amphotericin B (133 μg/ml). (D) The pen recording of the current signal measured at −54 mV during 50 μM arachidonic acid dialysis. (E) The plots of the whole-cell I/V relationships during arachidonic acid dialysis. I/V relationships were obtained from the pen recording on the upper. (F) Comparison of effects of external 20 μM ETYA, 20 μM baicalein and 100 μM niflumic acid on intracellular arachidonic acid-induced current at −54 mV.

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EC$_{50}$ of extracellular Ca$^{2+}$ for inhibition of human PTH secretion is about 1.2 mM [41]. On the other hand, Xenopus oocytes injected with cRNA prepared from bovine CaR displayed an EC$_{50}$ of 5 mM extracellular Ca$^{2+}$ for stimulation of Ca$^{2+}$-activated Cl$^{-}$ current under the condition of resting 0.5 mM Ca$^{2+}$ [42]. In the frogs, the actual relationship between extracellular...
Ca\(^{2+}\) concentration and PTH secretion is unknown. Normal saline in the present study contained 1.8 mM Ca\(^{2+}\). The higher EC\(_{50}\) (6 mM) in this study suggests that the isolated parathyroid cells might fairly desensitize during exposure to 1.8 mM Ca\(^{2+}\). Bovine parathyroid cells also displayed the desensitization of the intracellular Ca\(^{2+}\) response during sustained extracellular Ca\(^{2+}\) stimulation [25]. Nevertheless, we cannot deny that PTH secretion in the frog can be inhibited by extracellular Ca\(^{2+}\) between 2 mM and 3 mM.

Ca\(^{2+}\)-activated Cl\(^{-}\) channels carry out the important functions in several tissues including fluid secretion from exocrine gland, amplification of olfactory transduction and block of polypharmacy in amphibian oocytes [43]. Recently, the Tmem16 family is recognized to possess characteristics most similar to the native channels [44–46]. Similar channels may be expressed in the plasma membrane of frog parathyroid cells. However, the relation between Ca\(^{2+}\)-activated Cl\(^{-}\) channels and inhibition of PTH secretion is unknown. In secretory glands, a low pH of secretory vesicles makes them ready to release their contents. Acidification of secretory granules for release, which is constructed by Cl\(^{-}\) extracellular Ca\(^{2+}\) influx, reduces intracellular Cl\(^{-}\) neutralization. In accordance with this mechanism, procedures reducing intracellular Cl\(^{-}\) concentration decrease influx of Cl\(^{-}\) through granular Cl\(^{-}\) channels, resulting in inhibition of exocytosis [48]. In the present study, we tried the prevention of the Cl\(^{-}\) permeation through the patch membrane using gramicidin instead of amphotericin B to estimate natural intracellular Cl\(^{-}\) concentration. The reversal potentials of extracellular Ca\(^{2+}\)-induced currents shifted from −25 mV in early stage (1 min) to −58 mV in steady state (3 min). This suggests that initial concentration of intracellular Cl\(^{-}\) was 51 mM, and that the concentration decreased to 14 mM in a few minutes. We suppose that the decrease of intracellular Cl\(^{-}\) concentration in parathyroid cells also may inhibit influx of Cl\(^{-}\) through granular Cl\(^{-}\) channels. The inhibition may lead to the reduction in priming of PTH secretory granules for release, which is constructed by Cl\(^{-}\)-dependent proton pumping.

Kifor et al. [9] reported that high extracellular Ca\(^{2+}\) regulates MAP kinase through the mediation protein kinase C (PKC) and protein tyrosine kinase (PTK) in bovine parathyroid cells, resulting in PLA\(_2\) activation. In the present study, genistein greatly decreased extracellular Ca\(^{2+}\)-induced current. Genistein is an isoflavone that interacts with several molecules in living cells. Genistein affects voltage-gated Na\(^{+}\) current in the neurons through PTK-dependent and kinase-independent mechanisms [49]. Similarly, genistein greatly decreased voltage-gated Na\(^{+}\) current in frog parathyroid cells to 2% of the controls (data not shown). Alternatively, genistein also may affect PLC\(_{\gamma}\), because PLC\(_{\gamma}\) has Src homology, which has tyrosine kinase activity [50]. Further study using a specific inhibitor for PTK should be performed in order to elucidate PTK-dependent mechanisms.

In conclusion, frog parathyroid cells use a novel mechanism for extracellular Ca\(^{2+}\)-sensing.

Materials and Methods

Cell preparation

Adult bullfrogs (Rana catesbeiana) weighing 250–550 g were used for the experiment over the course of a year. The experiments were performed in accordance with the Guidelines for Animal Experimentation of Nagasaki University with approval of the Institutional Animal Care and Use Committee. The keeping of bullfrogs (invasive alien species) was approved by the Ministry of the Environment of Japan (approval number 06000204). Parathyroid cells were isolated from the parathyroid glands of decapitated and pithed animals. Two pairs of the oval parathyroid glands in both sides were quickly dissected from the precordial region which lie near the ventral branchial bodies and attached to the carotid arteries [51]. The glands were cut into small pieces in Ca\(^{2+}\)-free saline containing 2 mM EDTA and incubated for 10–12 min in 2 ml of same saline containing 10 mM L-cysteine and 10 units/ml papain (Sigma, St. Louis, MO, USA). The glands were then rinsed with normal saline. The individual cells were dissociated by gentle trituration in normal saline. Isolated parathyroid cells displayed an oval shape, with a diameter of about 10 µm [24].

Electrophysiological recording

Voltage-clamp recording was performed in whole-cell configuration [52] using a CEZ 2300 patch-clamp amplifier (Nihon Kohden, Tokyo, Japan) or an EPC-7 plus amplifier (HEKA Elektronik, Lambrecht, Germany). The patch pipettes were pulled from Pyrex glass capillaries containing a fine filament (Summit Medical, Tokyo, Japan) with a two-stage puller (Narishige PD-5, Tokyo, Japan). The tips of the electrodes were heat-polished with a microforge (Narishige MF-80). The resistance of the resulting patch electrode was 5–10 MΩ when filled with internal solution. The formation of 5–20 GΩ seals between the patch pipette and the cell surface was facilitated by applying weak suction to the interior of the pipette. The patch membrane was broken by applying strong suction, resulting in a sudden increase in capacitance. Amphotericin B (133–160 µg/ml, Sigma) or gramicidin (100 µg/ml, Sigma) was added to the pipette solution when using the perforated method [53]. The perforated whole-cell condition was obtained within 5 min of the establishment of a GΩ seal. Recordings were made from parathyroid cells that had been allowed to settle on the bottom of a chamber placed on the stage of an inverted microscope (Olympus IMT-2, Tokyo, Japan). The recording pipette was positioned with a hydraulic micromanipulator (Narishige WR-83). The current signal was low-pass-filtered at 5 kHz, digitized at 125 kHz using a TL-1 interface (Axon Instruments, Union City, CA, USA), acquired at a sampling rate of 0.25–5 kHz using a computer running the pCLAMP 5.5 software (Axon Instruments), and stored on a hard disk. The pCLAMP was also used to control the digital-analogue converter for the generation of the clamp protocol. The indifferent electrode was a chlorided silver wire. The voltages were corrected for the liquid junction potential between external solution and internal solution. Capacitance and series resistance were compensated for, as appropriate. The whole-cell current-voltage (I/V) relationship was obtained from the current generated by the 167 mV/s voltage ramp from −100 to +100 mV. In some case, the current-voltage relationship was obtained from the current generated the 400 ms voltage-step pulses between −104 and +96 mV in 20 mV increments from a holding potential of −84 mV. Input resistance was calculated from the slope conductance generated by the voltage ramp from −104 to −54 mV. Data were analyzed with pCLAMP and Origin 7.5 and 8.0 (Origin Lab, Northampton, MA, USA). Unless stated otherwise, the data are presented as means ± S.E.M., significance was tested by Student’s t test and a difference was considered significant if P<0.05.

Measurement of [Ca\(^{2+}\)]\(_i\) using fura-2

Dissociated parathyroid cells in normal saline solutions collected into the recording chamber were incubated at room
temperature in 10 μM fura-2 acetoxymethyl ester (fura-2 AM, Dojindo Laboratories, Kumamoto, Japan) with 0.02% cremophore EL (Nacalai, Kyoto, Japan) and washed thoroughly with normal saline after 30 min. Cell adhesion, concanavalin A (type IV, Sigma) was coated to the bottom of the recording chamber to immobilize the cells during the experiment. A chamber containing fura-2-loaded cells was placed on the stage of an inverted microscope (Diaphot 300, Nikon, Tokyo, Japan). A 100-W xenon lamp emitted the excitation light. The fluorescence was imaged using a silicon-intensified target (SIT) camera (C2400-08, Hamamatsu Photonics, Hamamatsu, Japan) and digitized to 8 bits per pixel with an Argus 50 image processor system (Ratio imaging program, version 3.5, Hamamatsu). A PC controlled the filter and intensifier gains. Imaging data were stored on magneto-optical disks. Changes in fluorescence ratios of excitation at 340 nm and 380 nm light pulses were measured in the selected areas to determine [Ca2+]r responses. We used a light-attenuating filter for 340 nm excitation light to balance the brightness of the two images. Measurements were taken only after first 2 h after completion of loading the fura-2 due to the reduction in fura-2 level. Measurement of fluorescence ratios under a continuous perfusion with normal saline solution was carried out for 5 min to confirm the stable basal level before applying any chemical. Switching between solutions was electronically controlled.

Solution and drugs

Normal saline solution consisted of (in mM): NaCl, 115; KCl, 2.5; CaCl2, 1.8; Hepes, 10; glucose, 20; pH 7.2. The pH of normal saline and other solution was adjusted by Tris base. The external Na+-free 10 mM Ba2+ solution was prepared by the replacement of Na+ by Ca2+ with NMDG+ and Ba2+. The solution exchange was done by gravity flow. For stock solution, spermine tetrahydrochloride (100 mM, Sigma) and ruthenium red (10 mM, Sigma) were dissolved in deionized water. WIN 55,212-2 mesylate (10 mM, Tocris, Bristol, UK), phorbol 12,13-dibutyrate (PDBu, 10 mM, Sigma), U73122 (5 mM, Tocris and Sigma), U73343 (2 mM, Calbiochem, San Diego, USA), ryanodine (20 mM, Sigma), 1-octanol-2-acetyl-sn-glycerol (OAG, 50 mM, Sigma), arachidonic acid (50 mM, Sigma and Cayman, Ann Arbor USA), RHC-80267 (10 mM, Calbiochem), tetrathydrodipristatin (10 mM, Sigma), 5,8,11,14-eicosatetraynoic acid (ETYA, 20 mM, Sigma), baicalein (50 mM, Cayman), MS-POH (10 mM, Cayman), dicrofenac (50 mM, Cayman), genistein (20 mM, Sigma), PD98059 (50 mM, Cayman), and m-3M3PBS (50 mM, Tocris) were dissolved in dimethylsulphoxide (DMSO). 2-arachidonoylglycerol (2-AG, 26.4 mM) dissolved in acetonitrile, 2-arachidonoylglycerol ether (2-AG ether, 13.7 mM), 12S-hydroperoxy-5Z,8Z,10E,14Z-eicosatetraenoic acid (12(S)-HPETE, 297 μM) and 15S-hydroxy-5Z,8Z,11Z,13E-eicosatetraenoic acid (15(S)-HETE, 312 μM) dissolved in ethanol and methyl arachidonoyl fluorophosphonate (MAFP, 27 mM) dissolved in methyl acetate were purchased from Cayman. Samples of the stock solutions were added to normal saline solution or internal solution to give the desired final concentrations. NPS R-467 (100 μM, NPS Pharmaceuticals, Salt Lake City, USA), NPS S-467 (100 μM, NPS Pharmaceuticals), and niflumic acid (100–300 μM, Sigma) were directly dissolved in normal saline solution. The standard K+ internal solution contained (in mM): KCl, 100; CaCl2, 0.1; MgCl2, 2; EGTA, 1; Hepes, 10; pH 7.2. In some experiments, internal K+ was replaced with Cs+ and Cl− was replaced with gluconate−. BAPTA (10 mM, Sigma), GTP (1 mM, Sigma), GDPβS (1 mM, Sigma), 1,4,5-IP3 (50 μM, Sigma) and cyclic AMP (1 mM, Sigma) were dissolved in internal solution.

All experiments were carried out at room temperature (20–25°C).

Supporting Information

Figure S1 Extracellular Ba2+-induced current in frog parathyroid cells. (A) The plot of the whole-cell current/voltage (I/V) relationship produced by a voltage ramp. Extracellular cations (Na+, K+, and Ca2+) other than Ba2+ were replaced with NMDG+. (B) The shift of the reversal potential of extracellular Ba2+-induced current in another cell. Intracellular Cl− concentration was reduced from 104 to 10 mM. (C) Extracellular Ba2+-induced current in the condition of external Ca2+ elimination with EGTA. (D) The I/V relationship of the difference between a and b in the pen recording C. (E) Comparison of extracellular Ba2+-induced currents measured at −54 mV with and without extracellular Ca2+. The pipette solution contained amphotericin B (133 μg/ml). (EPS)

Figure S2 Effects of baicalein and niflumic acid on intracellular arachidonic acid-induced currents. (A) The plot of the whole-cell currents/voltage (I/V) relationships produced by a voltage ramp of internal arachidonic acid-induced currents under the condition of high intracellular Cl− concentration (ECl− = −4 mV) and the inhibition with 20 mM baicalein. (B) The similar relationships under the condition of low intracellular Cl− (ECl− = −63 mV). (C) Inhibition of the internal arachidonic acid-induced currents with 100 μM niflumic acid. (EPS)

Figure S3 Effects of genistein and PD98059 on extracellular Ca2+-induced current. (A) The pen recording of the inhibitory effect of external genistein on extracellular Ca2+-induced current at −54 mV. (B) The plots of the whole-cell I/V relationships during control, genistein application and wash-out. The relationships were obtained from the pen recording on the upper part. (C) The pen recording of the inhibitory effect of external PD98059 on extracellular Ca2+-induced current at −54 mV. (D) The plots of the whole-cell I/V relationships during control, PD98059 application and wash-out. The relationships were obtained from the pen recording on the upper part. (E) Comparison of the effects of genistein and PD98059 on extracellular Ca2+-induced current at −54 mV. The pipette solution contained amphotericin B (133 μg/ml). (EPS)

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Author Contributions

Conceived and designed the experiments: YO. Performed the experiments: YO KGI. Analyzed the data: YO KGI RF. Contributed reagents/materials/analysis tools: YO KT. Wrote the paper: YO KGI TM HH RF KT.
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