Omega-3 fatty acids induce Ca²⁺ mobilization responses in human colon epithelial cell lines endogenously expressing FFA4

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Aim: Free fatty acid receptor 4 (FFA4; formerly known as GPR120) is the G protein-coupled receptor (GPCR) for omega-3 polyunsaturated fatty acids. FFA4 has been found to express in the small intestines and colons of mice and humans. In this study we investigate the effects of omega-3 polyunsaturated fatty acids on FFA4 in human colon epithelial cells in vitro.

Methods: HCT116 and HT-29 human colon epithelial cell lines endogenously expressing FFA4 were used. Intracellular Ca²⁺ concentration ([Ca²⁺]i) was measured in fura 2-AM-loaded cells with fluorescence spectrophotometry. RT-PCR and immunohistochemistry were used to detect FFA4.

Results: Ten to 100 µmol/L of omega-3 polyunsaturated fatty acids α-linolenic acid (αLA) or eicosapentaenoic acid (EPA) induced dose-dependent [Ca²⁺]i increase in HCT116 and HT-29 cells, whereas docosahexaenoic acid (DHA) had no effect. In addition, the omega-6 fatty acids linoleic acid and γ-linoleic acid also dose-dependently increase [Ca²⁺]i, but the mono-unsaturated fatty acid oleic acid and saturated fatty acids such as stearic acid and palmitic acid had no effect. In HCT116 and HT-29 cells, the αLA-induced [Ca²⁺]i increase was partially inhibited by pretreatment with EGTA, phospholipase C inhibitor edelfosine, cADPR inhibitors 8-bro-cADPR or DAB, and abolished by pretreatment with Ca²⁺ ATPase inhibitor thapsigargin, but was not affected by Gαi/o protein inhibitor PTX or IP₃R inhibitor 2-APB.

Conclusion: Omega-3 and omega-6 long-chain polyunsaturated fatty acids (C18-20) induce Ca²⁺ mobilization responses in human colonic epithelial cells in vitro through activation of FFA4 and PTX-insensitive Gαi/o protein, followed by Ca²⁺ release from thapsigargin-sensitive Ca²⁺ stores and Ca²⁺ influx across the plasma membrane.

Keywords: long-chain fatty acid; omega-3; α-linolenic acid; FFA4; Ca²⁺ mobilization; cADPR; human colon epithelial cells

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Introduction

Omega-3 polyunsaturated fatty acids (ω-3 PUFAs) are essential fatty acids with a double bond between the third and fourth carbon atoms from the methyl end (ω end) of the fatty acid carbon chain. Because these fatty acids cannot be synthesized by the human body, the dietary intake of ω-3 PUFAs such as α-linolenic acid (ALA, C18:3), eicosapentaenoic acid (EPA, C20:5), and docosahexaenoic acid (DHA, C22:6) is important. ω-3 PUFAs were initially shown to be beneficial in epidemiological studies conducted in Greenland Inuits. They are clinically prescribed for the prevention of myocardial infarction and the treatment of hypertriglyceridemia. Omega-3 PUFAs are also popularly consumed as functional foods; however, the pharmacological effects of ω-3 PUFAs differ, especially with respect to their anti- and pro-inflammatory effects on the colon. These different effects of ω-3 PUFAs cannot be explained by the accepted mode of action of ω-3 PUFAs, that is, by the biochemical competition of ω-3 PUFAs on enzymes required for inflammatory mediator biosynthesis and the activation of anti-inflammatory PPARγ.

Recently, free fatty acid receptor 4 (FFA4; formerly known as GPR120) was found to act as a G protein-coupled receptor (GPCR) for ω-3 PUFAs. FFA4 was originally cloned as an orphan GPCR, but in 2005, long-chain fatty acids were observed to induce increases in intracellular Ca²⁺ ([Ca²⁺]i) and FFA4 internalization in HEK293 cells exogenously expressing...
FFA4 responds to saturated free fatty acids (C14 to C18) and unsaturated free fatty acids (C16 to C22), including αLA, EPA, and DHA, in HEK293 cells, although αLA was the best agonist in terms of Ca\(^{2+}\) response\(^{10}\). Furthermore, FFA4 expression is abundant in small and large intestines, lungs, and adipose tissues and on macrophages\(^{12,13,15,18}\). In humans, there are two alternative splicing variants of FFA4, short- and long-form FFA4\(^{19,20}\); the long form has additional 16 amino acids in the third intracellular loop compared with the short-form FFA4\(^{19,21}\). In one study, a similar Ca\(^{2+}\) mobilization response to linoleic acid (C18:2n-6) was observed for both isoforms; however, the saturated medium-chain fatty acid capric acid (C10:0) only showed partial agonism for short-form FFA4\(^{22}\). In another study, only long-form FFA4 induced β-arrestin-mediated responses, whereas short-form FFA4 induced G protein-mediated Ca\(^{2+}\) signaling and β-arrestin-mediated FFA4 phosphorylation and internalization\(^{21}\). Interestingly, in the gastrointestinal tract, only the colon expressed both forms of FFA4\(^{22}\).

Since the identification of FFA4 as a GPCR for long-chain PUFAs, FFA4 has been reported to be involved in the fatty acid-stimulated release of glucagon-like peptide-1 (GLP-1) and cholecystokinin (CCK) from enteroendocrine cells\(^{13,23}\). Acid-stimulated release of glucagon-like peptide-1 (GLP-1) and ω-3 PUFAs, FFA4 has been reported to be involved in the fatty acid and reducing metabolic inflammation, a number of selective novel treatments for diabetes by improving insulin sensitivity and type II diabetes\(^{14,15}\). Additionally, genetic studies have shown that FFA4 knockout mice and humans possessing a FFA4 polymorphism associated with reduced signaling are prone to obesity\(^{14}\). Because FFA4 agonists might constitute unique and novel treatments for diabetes by improving insulin sensitivity and reducing metabolic inflammation, a number of selective FFA4 agonists have been developed\(^{24–30}\). However, the functions of FFA4 in the colon have not been investigated.

Because a variety of fatty acids are released during digestion in the gastrointestinal tract, the specificity of endogenous FFA4 for natural nutrient fatty acids in the small and large intestines must be investigated. The different effects of ω-3 PUFAs on colonic inflammation suggested that the different response in colon might be caused by different responses of endogenous FFA4 to individual ω-3 PUFAs in the colon. Therefore, in the present study, we examined the effects of several ω-3 PUFAs in HCT116 and HT-29 human colon epithelial cell lines as a model system of colonic epithelial cells that endogenously express FFA4.

Materials and methods

Materials

αLA, DHA, capric acid, palmitic acid, oleic acid, Fura 2-AM, EGTA, 2-aminoethoxydiphenylborane (2-APB), pertussis toxin (PTX), 8-bromo-cyclic adenosine diphosphate ribose (8-BrcADPR), 2,2′-dihydroxyazobenzene (DAB), and thapsigargin were purchased from Sigma-Aldrich (St Louis, MO, USA). EPA, lauric acid, myristic acid, stearic acid, linoleic acid, γ-linolenic acid, TUG-891, and edelfosine were obtained from Cayman (Ann Arbor, MI, USA).

Cell culture

HCT116 and HT-29 human colon cancer cells were obtained from the American Type Culture Collection (ATCC, Manassas, VA, USA) and maintained in high-glucose DMEM containing 10% (v/v) fetal bovine serum, 100 units/mL penicillin, 50 μg/mL streptomycin, 2 mmol/L glutamine, and 1 mmol/L sodium pyruvate at 37°C in a humidified 5% CO\(_2\)/95% air incubator\(^{31}\).

Measurement of intracellular Ca\(^{2+}\) concentrations

Cells were trypsin-digested, allowed to sediment, and resuspended in HEPES-buffered medium consisting of 20 mmol/L HEPES (pH 7.4), 103 mmol/L NaCl, 4.8 mmol/L KCl, 1.2 mmol/L KH\(_2\)PO\(_4\), 1.2 mmol/L MgSO\(_4\), 0.5 mmol/L CaCl\(_2\), 25 mmol/L NaHCO\(_3\), and 15 mmol/L glucose. The cells were then incubated for 40 min with 5 μmol/L Fura 2-AM. [Ca\(^{2+}\)]\(_i\), was estimated by measuring the changes in Fura 2 fluorescence at an emission wavelength of 510 nm and excitation wavelengths of 340 nm and 380 nm every 0.1 s using a F4500 fluorescence spectrophotometer (Hitachi, Japan). The ratios of fluorescence intensities (λ340/λ380) at these two wavelengths were used as an indicator of [Ca\(^{2+}\)]\(_i\), as previously described\(^{32}\).

Reverse transcription-PCR (RT-PCR)

To assess the expression of FFA4 in HCT116 and HT-29 cells by RT-PCR, first-strand complementary DNA (cDNA) was synthesized using total RNA isolated with TRIzol reagent (Invitrogen, USA). cDNA synthesis from total RNA (1 μg) was performed using Oligo(dt) 15 primer and M-MLV reverse transcriptase (Promega, Madison, WI, USA). Synthesized cDNA products and primers for free fatty acid receptor 1 (FFA1) and FFA4 were used for PCR using an Eppendorf Mastercycler gradient PCR machine (Hamburg, Germany). The primers used to amplify 210, 249, 402, 303, and 238 bp fragments of FFA1, FFA4, short-form FFA4, long-form FFA4, and glyceroldehyde 3-phosphate dehydrogenase (GAPDH) were as follows: FFA1 (sense 5′-GTG TCA CCT GGG TCT GGT CT-3′, antisense 5′-GAG CAG GAG AGA GAG GCT GA-3′), FFA4 (sense 5′-CTT CTT CTC CGA CTT CAA GG-3′, antisense 5′-AGA GGG AGA GCG CTG ATG AA-3′), short-form FFA4 (sense 5′-CGA TTT GCA CAC TGA TTT GGC-3′, antisense 5′-TGC ACA GTG TCA TGT TGT AGA-3′), long-form FFA4 (sense 5′-GCT GTC GTG ACT CAC AGT G-3′, antisense 5′-TGG ACA GTG TCA TGT TGT AGA-3′) and GAPDH (sense 5′-GAG TCA ACG GAT TTG GTC GT-3′, antisense 5′-TTG ATT TTG GAG GGA TCT CG-3′). The PCR reactions were performed with denaturation at 95°C for 30 s, annealing at 57°C for 30 s and 27 cycles for FFA1, annealing at 55°C for 30 s and 30 cycles for FFA4, annealing at 60°C for 30 s and 25 cycles for short-form FFA4, long-form FFA4, and GAPDH, and elongation at 72°C for 30 s. Aliquots of the PCR products (7 μL) were electrophoresed in 1.2% agarose gels and stained with ethidium bromide\(^{33}\).

Immunocytochemistry

Cells were labeled with antibodies against FFA4 (NBPI-00858,
1:500, Novus Biologicals, LLC, CO, USA) and β- arrestin 2 (ab54790, 1:500, Abcam, Cambridge, MA, USA). The secondary antibody used was Alexa Fluor 488-conjugated anti-rabbit IgG (1:1000, Jackson ImmunoResearch, West Grove, PA, USA) and Rhodamine Red™, X-conjugated anti-mouse IgG (1:1000, Jackson ImmunoResearch, West Grove, PA, USA). A confocal scanning module (LSM510, Carl Zeiss, Germany) mounted on a fluorescence microscope (AXIOVERT 100 M, Carl Zeiss, Germany) and a C-Apochromat 40×/1.2 W (Carl Zeiss, Germany) was used[30].

Statistical analysis
The results are expressed as the mean±SEM for the indicated number of determinations. Significant differences were assessed using Student’s t-test, and statistical significance was accepted for P values <0.05.

Results
FFA4 expression in human colonic epithelial cells
Two methods were used to assess FFA4 expression in HCT116 and HT-29 cells. First, RT-PCR was conducted to detect the mRNAs of FFA4 and FFA1. As shown in Figure 1A, FFA4 expression was detected in both cell lines, whereas FFA1 expression was not. Second, FFA4 protein was detected in both cell lines using a FFA4-specific antibody (Figure 1C and 1D). FFA4 protein was weakly detected in plasma membranes and cytosol. Treatment of cells with αLA, the best known agonist of FFA4, caused strong FFA4 aggregation at the cell surfaces in both cell lines (Figure 1C and 1D). Furthermore, αLA induced the co-localization of FFA4 and β-arrestin in both cell types, implying the recruitment of β-arrestin by FFA4 to cell membranes (Figure 1C and 1D). Thus, FFA4 expression and its activation by αLA were observed in both cell lines at the RNA and protein levels. Similarly, EPA and DHA induced the recruitment of β-arrestin in both cell lines (Figure 1C and 1D). However, the response to DHA was weaker than that to αLA or EPA (Figure 1C and 1D).

Due to the two splicing variants of FFA4 in the colon, specific primers for short- and long-form FFA4 were used. As shown in Figure 1B, HCT116 cells expressed only long-form FFA4, whereas HT-29 cells expressed both forms.

Intracellular Ca2+ increase by ω-3 PUFAs in human colonic epithelial cells
Because FFA4 couples to G proteins and increases [Ca2+], in FFA4-overexpressing cells, this Ca2+ response was measured in colonic epithelial cells endogenously expressing FFA4. As shown Figure 2A, the ω-3 PUFAs, αLA (C18:3) and EPA (C20:5) increased [Ca2+], in a concentration-dependent manner in HCT116 cells, whereas DHA (C22:6) did not. The ω-6 fatty, linoleic (C18:2) and γ-linoleic (C18:3) acids increased [Ca2+], (Figure 2A), whereas monounsaturated oleic acid (C18:1) and saturated fatty acids, such as stearic (C18:0), palmitic (C16:0), myristic (C14:0), and lauric (C12:0) acid, did not increase [Ca2+] in HCT116 cells (Figure 2B).

These observations suggested that there is an optimum structure for 18–20 carbon atoms with more than two double bonds and that the location of the unsaturation does not influence endogenous FFA4 activation in colonic cells. TUG-891, an FFA4-specific agonist, increased [Ca2+], in HCT116 cells (Figure 2A)[24, 25]. Although this agonist has been reported to be more potent than αLA in several cell systems[24, 26], it was less potent than other natural PUFAs in HCT116 cells (Figure 2A).

We also examined the Ca2+ response in HT-29 cells. As shown in Figure 2C and 2D, the ω-3 PUFAs, αLA, EPA, linoleic acid, and γ-linoleic acid increased [Ca2+], in a concentration-dependent manner, whereas DHA, stearic acid, palmitic acid, myristic acid, and lauric acid did not. Therefore, the optimum structure for the Ca2+ response in HT-29 cells was the same as that in HCT116 cells, that is, 18–20 carbon atoms and more than 2 double bonds. Further, the Ca2+ response to TUG-891 in HT-29 cells was weaker than that to αLA (Figure 2C), which was in agreement with the results for HCT116 cells. Taken together, these finding suggest that these results are typical for human colonic epithelial cells.

Effects of edelfosine, EGTA, and PTX on αLA-induced Ca2+ response
Because αLA was the best ligand in terms of inducing Ca2+ response in HCT116 and HT-29 cells and FFA4-overexpressing systems, αLA was used in the subsequent studies. To elucidate the mechanism responsible for Ca2+ signaling, cells were treated with specific inhibitors or blockers of Gαi/o-type G proteins, phospholipase C, and extracellular Ca2+, that is, PTX, edelfosine, and EGTA, respectively.

As shown in Figure 3A, treatment of HCT116 cells with EGTA (5 mmol/L for 1 min) partially inhibited the αLA-induced [Ca2+], increases, suggesting that Ca2+ influx across the cell membrane partially contributes to the [Ca2+] increases. In addition, edelfosine (10 μmol/L for 6 h) also partially inhibited the αLA-induced response in HCT116 cells, suggesting the involvement of phospholipase C (Figure 3A). However, PTX (100 ng/mL for 24 h) did not inhibit the Ca2+ response, supporting the notion that Gαi/o proteins are not involved in the αLA-induced response in HCT116 cells (Figure 3A). These results suggest that αLA mobilizes Ca2+ via PTX-insensitive G proteins, likely Gαi/11-type proteins, and phospholipase C and via promoting Ca2+ influx across the plasma membrane.

As shown in Figure 3C, treatment of HT-29 cells with edelfosine or EGTA partially inhibited the αLA-induced [Ca2+] increases, whereas treatment with PTX did not (Figure 3C). Edelfosine inhibition was stronger in HT-29 cells than HCT116 cells (Figure 3). These results suggest that αLA mobilizes Ca2+ via PTX-insensitive G proteins, phospholipase C, and Ca2+ influx across the plasma membrane in both HCT116 and HT-29 cells.

Effects of 2-APB, 8-bromo-cADPR, and thapsigargin on the αLA-induced Ca2+ response
Because external Ca2+ sequestration by EGTA blocked the Ca2+ response by approximately 50%, Ca2+ must have been released...
from internal Ca\^{2+} stores, such as the endoplasmic reticulum (ER). To investigate the mechanism responsible for intracellular Ca\^{2+} signaling, HCT116 and HT-29 cells were treated with specific inhibitors of inositol 1,4,5-trisphosphate receptor (IP\textsubscript{3}R), cyclic ADP ribose receptor (cADPR), and Ca\^{2+} ATPase, that is, 2-APB, 8-bro-cADPR (or DAB), and thapsigargin, respectively. 2-APB did not inhibit the αLA-induced [Ca\textsuperscript{2+}]\textsubscript{i} increases in HCT116 or HT-29 cells (Figure 4A, 4C). However, 8-bro-cADPR and DAB, specific inhibitors of cADPR, which is a receptor for another second messenger for Ca\textsuperscript{2+} signaling, partially inhibited the αLA-induced Ca\textsuperscript{2+} response in both HCT116 and HT-29 cells (Figure 4B, 4D). The depletion of ER Ca\textsuperscript{2+} stores was induced by thapsigargin, and in thapsigargin-treated cells, αLA did not induce a [Ca\textsuperscript{2+}] increase in either cell line (Figure 4B, 4D), suggesting that Ca\textsuperscript{2+} release from the ER is a first step and necessary for Ca\textsuperscript{2+} influx across the plasma membrane. These results suggest that the αLA-induced [Ca\textsuperscript{2+}] increases are induced by cADPR-induced Ca\textsuperscript{2+} release from thapsigargin-sensitive intracellular Ca\textsuperscript{2+} stores and Ca\textsuperscript{2+} influx across the plasma membrane in HCT116 and HT-29 cells.

**Discussion**

In the present study, the effects of long-chain fatty acids were investigated in HCT116 and HT-29 human colonic epithelial cells, which endogenously express FFA4. FFA4 expression has been observed in the small intestines and colons of mice and humans\cite{13, 22}; the present study confirmed the expression of short- and long-form FFA4 in HT-29 cells, which is consistent with a previous report\cite{22}. FFA4 and FFA1 can mediate rapid responses to long-chain (C12–C22) saturated and unsaturated fatty acids\cite{30, 35, 36}. However, HCT116 and HT-29 cells do not express FFA1; thus, long-chain fatty acid-induced [Ca\textsuperscript{2+}]...
increases are presumably mediated through FFA4\textsuperscript{[37].}

Several studies have reported long-chain fatty acid-induced FFA4 activation in exogenously FFA4-expressing HEK293 cells\textsuperscript{[13, 15, 22, 24].} In these systems, FFA4-G\textsubscript{α16} fusion, FFA4-YFP fusion, SRE reporter, or G\textsubscript{α16GUST44} constructs were used to detect FFA4 activation, which is highly sensitive and convenient\textsuperscript{[13, 15, 22, 24].} However, the effects of free fatty acids on cells endogenously expressing FFA4 differ from those in overex-
pression systems. In FFA4-overexpressing systems, saturated fatty acids activated FFA4 but to a lesser extent than did unsaturated long-chain fatty acids\cite{13}. However, in cells endogenously expressing FFA4, saturated long-chain fatty acids did not induce cellular responses in STC-1 cells or RAW264.7 macrophages\cite{13,21}; thus, FFA4 is considered a GPCR for ω-3 PUFAs.

To determine the pharmacological relevance of individual nutrient fatty acids acting through FFA4, the ligand specificity of FFA4 in endogenously FFA4 expressing cells should be assessed. However, to date, αLA or GW9508 (a dual agonist for FFA1 and FFA4) have been typically used\cite{15,29,37}. In the present study, long-chain fatty acids, including ω-3 PUFAs (αLA and EPA) and ω-6 PUFAs (linoleic acid and γ-linolenic acid), increased [Ca$^{2+}$], with the same potency in human colonic epithelial cells. However, saturated fatty acids and monounsaturated fatty acids were inactive. Further, FFA4 was not specific for ω-3 PUFAs but recognized PUFAs with 18-20 carbons and more than 2 unsaturations. The present results using colonic epithelial cells are consistent with those previously obtained using cells endogenously expressing FFA4, such as STC-1 cells and RAW264.7 macrophages\cite{13,15}. This discrepancy between exogenous FFA4 and endogenous FFA4 was also reported by Hudson et al\cite{24}. DHA did not induce a Ca$^{2+}$ response in colonic cells but did do so in cells exogenously or endogenously expressing FFA4\cite{13,15}. Further, DHA induced β-arrestin recruitment in HCT116 and HT-29 cells. These results might be due to long-form FFA4 because in an ectopic expression system, long-form FFA4 induced β-arrestin-mediated responses but not G protein-mediated Ca$^{2+}$ responses\cite{25}. HCT116 cells express only long-form FFA4, whereas HT-29 cells express both isoforms. In addition, TUG891 less potently induced Ca$^{2+}$ mobilization compared with other natural fatty acids, including αLA, in HT-29 and HCT116 cells. Hudson et al demonstrated that TUG891 was more potent than αLA in terms of Ca$^{2+}$ mobilization in cells ectopically or endogenously expressing FFA4\cite{24}. This discrepancy was also observed in RAW264.7 macrophages, which endogenously express FFA4\cite{15,24}. DHA-induced inhibition of TNFα production in macrophages was much greater than those of αLA or TUG891\cite{24}.

FFA4-mediated Ca$^{2+}$ signaling has received little attention in cells endogenously expressing FFA4. In a previous study, Caco-2 intestinal cells, which express FFA4 but not FFA1, were used as endogenous FFA4-expressing cells\cite{28}, and DHA, EPA, and arachidonic acid enhanced Ca$^{2+}$ cytosolic concentrations with similar efficiencies but different kinetics\cite{28}. In the present study, in colonic epithelial cells, the Ca$^{2+}$ response was dependent on Ca$^{2+}$ influx, which is in contrast to the findings observed for Ca$^{2+}$ signaling in STC-1 cells. The involvement of PTX-insensitive Gq/11 G proteins has been reported in STC-1 and 3T3-L1 cells\cite{13,15,29}, which is consistent with our observations in colonic cells. 2-APB only slightly inhibited increase of [Ca$^{2+}$], at maximal Ca$^{2+}$ elevation in ectopic FFA4 expression systems\cite{21}. However, 2-APB had no inhibitory effect on Ca$^{2+}$ elevation in STC-1 or 3T3-L1 cells, which endogenously express FFA4\cite{13,15}, consistent with our observations. Ca$^{2+}$ release from thapsigargin-sensitive Ca$^{2+}$ stores and the involvement of cADPR were shown for the first time to be components of FFA4 signaling. cADP-ribose activates Ca$^{2+}$ release from the sarcoplasmic reticulum or ER through ryanodine receptors\cite{39}. CD38, an ADP-ribose cyclase, is a 45 kDa type II transmembrane multifunctional enzyme that is involved in the formation of cADP-ribose in

![Figure 4. Effects of 2-APB, 8-bro-cADPR, DAB or thapsigargin on the αLA-induced Ca$^{2+}$ responses in human colon epithelial cells. In (A) and (C), HCT116 and HT-29 cells were pretreated with vehicle or 2-APB (100 μmol/L, 15 min), then treated with 50 or 100 μmol/L αLA. In (B) and (D), HCT116 and HT-29 cells were pretreated with vehicle, 8-bro-cADPR (100 μmol/L, 20 min), DAB (1 μmol/L, 30 min) or thapsigargin (1 μmol/L, 30 min), then treated with 50 or 100 μmol/L αLA. Percentage of the αLA-induced Ca$^{2+}$ response compared with digitonin. The data are presented as the mean±SEM of three independent experiments. *P<0.05, **P<0.01 versus non-treated cells.](Image)
mammals\textsuperscript{[39]}. The activation of CD38 and subsequent production of cADPR-ribose have been observed in GPCR signaling, such as that of the GPCRs for angiotensin II in the kidney\textsuperscript{[40]}, oxytocin in the hypothalamus\textsuperscript{[41]}, thromboxane in vascular smooth muscle cells\textsuperscript{[42]} and acetylcholine in adipocytes\textsuperscript{[43]}. Therefore, it would be interesting to investigate how FFA4 activates CD38 to produce cADP-ribose in colonic epithelial cells.

In summary, Ca\textsuperscript{2+} signaling through endogenous FFA4 in colonic epithelial cells exhibited specificity for long-chain polyunsaturated fatty acids with 18–20 carbon atoms and more than 2 unsaturations, which differs from the fatty acid requirements observed in cell exogenously overexpressing FFA4. In particular, DHA did not induce Ca\textsuperscript{2+} signaling but did induce β-arrestin recruitment. Further, Ca\textsuperscript{2+} signaling was composed of Ca\textsuperscript{2+} release from thapsigargin-sensitive Ca\textsuperscript{2+} stores and Ca\textsuperscript{2+} influx, which are dependent on phospholipase C and cADP-ribose (Figure 5).

**Figure 5.** Schematic illustration of Ca\textsuperscript{2+} signaling mechanisms in colon epithelial cells.

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**Author contribution**

Jung-min KIM and Dong-soon IM designed the study; Jung-min KIM, Soo-jin PARK, and Kyoung-pil LEE performed the experiments; and Jung-min KIM, Saeromi KANG, Jin HUANG, Jung-min LEE, Koichi SATO, Hae-young CHUNG, Fumikazu OKAJIMA, and Dong-soon IM participated in the data analysis and drafting of the manuscript.

**Abbreviations**

αLA, α-linolenic acid; GPCR, G protein-coupled receptor; EPA, eicosapentaenoic acid; DHA, docosahexaenoic acid; PUFA, polyunsaturated fatty acids; FFAs, free fatty acid; FFA1, free fatty acid receptor 1; FFA4, free fatty acid receptor 4; LCFA, long-chain fatty acid; 2-APB, 2-aminoethoxydiphenylborane; DAB, 2,2'-dihydroxyazobenzene; PTX, pertussis toxin; 8-bromo-cADPR, 8-bromo-cyclic adenosine diphosphate ribose.

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