Multiplex GPCR screen reveals reliably acting agonists and a Gq-phospholipase C coupling mode of GPR30/GPER1

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Abbreviations: cAMP, 3',5'-cyclic adenosine monophosphate; CFP, enhanced cyan fluorescent protein; DAG, diacylglycerol; EPAC, exchange protein activated by cAMP; ER, endoplasmic reticulum; FLIPR, fluorescence imaging plate reader; FRET, Förster resonance energy transfer; GPCR, G protein-coupled receptor; GPER1, G protein-coupled estrogen receptor 1; InsP3, inositol-1,4,5-trisphosphate; [Ca²⁺]i, intracellular Ca²⁺ concentration; PIP₂, phosphatidylinositol-4,5-bisphosphate; PLC, phospholipase C; PKC, protein kinase C; PTX, pertussis toxin; YFP, enhanced yellow fluorescent protein
Abstract

G protein-coupled receptors (GPCR) constitute the most versatile family of pharmacological target proteins. For some “orphan” GPCR, no ligand or drug-like modulator is known. In this study, we have established and applied a parallelized assay to co-screen 29 different human GPCR. Three compounds, chlorhexidine, Lys-05, and 9-aminoacridine triggered transient Ca\(^{2+}\) signals linked to the expression of GPR30. GPR30, also named G protein-coupled estrogen receptor 1 (GPER1), was reported to elicit increases in cAMP in response to 17\(\beta\)-estradiol, 4-hydroxytamoxifen, or G-1. These findings could, however, not be reproduced by other groups, and the de-orphanisation of GPR30 is, therefore, intensely disputed. The unbiased screen and following experiments in transiently or stably GPR30-overexpressing HEK293 cells did not show responses to 17\(\beta\)-estradiol, 4-hydroxytamoxifen or G-1. A thorough analysis of the activated signalling cascade revealed a canonical G\(_{\text{q}}\)-coupled pathway, including phospholipase C, protein kinase C and ERK activation, receptor internalisation, and sensitivity to the G\(_{\text{q}}\) inhibitor YM-254890. When expressed in different cell lines, the localisation of a fluorescent GPR30 fusion protein appeared variable. An efficient integration into the plasma membrane and stronger functional responses were found in HEK293 and in MCF-7 cells, whereas GPR30 appeared mostly retained in endomembrane compartments in Cos-7 or HeLa cells. Thus, conflicting findings may result from the use of different cell lines. The newly identified agonists and the finding that GPR30 couples to G\(_{\text{q}}\) are expected to serve as starting point for identifying physiological responses that are controlled by this GPCR.

Significance Statement

We have identified and thoroughly characterized novel and reliably acting agonists of the G protein-coupled receptor GPER1/GPR30. Applying these agonists, we demonstrate that GPR30 couples to the canonical G\(_{\text{q}}\)-phospholipase C pathway and is rapidly internalized upon continuous exposure to the agonists.
Introduction

Representing one of the largest and most versatile groups of pharmacologically addressable target proteins, non-olfactory G protein-coupled receptors are amongst the most intensively studied signalling proteins in mammals (Sriram and Insel, 2018). Thus, tremendous efforts have been undertaken to identify physiological and pharmacological modulators of hitherto “orphan” GPCRs, with many substantial successes being reported within the last decades (Laschet et al., 2018; Hauser et al., 2020). Nonetheless, almost 100 orphan GPCRs are still awaiting the unequivocal assignment of cognate agonists and physiological and pathophysiological functions governed by them. There are also “de-orphanized” GPCRs whose assigned agonists or sites of expression are not reliably reproducible by other laboratories (Laschet et al., 2018), leading to partly confusing results pertaining to postulated receptor functions and proposed benefits of their modulation by pharmacological intervention. Finally, although not de-orphanizing GPCRs by identifying a physiological agonist, screening activities with or without prior virtual in-silico pre-screening have been instrumental in identifying drug-like compounds that exert agonistic effects or an inverse agonism towards individual orphan GPCRs.

We have established a Ca\(^{2+}\) influx-based academic screening infrastructure to identify cation channel-modulating activities in various compound libraries, comprising FDA-approved drugs, bioactive natural compounds, toxins, and chemically diverse drug-like compounds. To expand the range of investigated target structures, we conducted a first screening on GPR34, a GPCR whose de-orphanisation as a lysophosphatidyl-L-serine receptor (Sugo et al., 2006) has been questioned (Ritscher et al., 2012). Although screening results were valid, this screen failed to identify novel modulators. We therefore decided to explore the possibility to set up a highly parallelized co-screening that may become more successful in identifying novel agonists of orphan or poorly validated GPCRs in an unbiased fashion.

Typically, a high-throughput screening (HTS) for GPCR agonists or antagonists requires the generation of a cell line that stably expresses a recombinant GPCR of interest either alone or together with promiscuously coupling G\(\alpha_{15/16}\) subunits or with chimeric G protein \(\alpha\) subunits.
that form a complex with endogenously expressed \( \beta \gamma \) subunits. \( \mathrm{G}_\alpha_{15/16} \) or chimeric \( \mathrm{G}_\alpha_{q/i} \) subunits can be activated by GPCRs even if the receptor would otherwise couple to the \( \mathrm{G}_q \) or \( \mathrm{G}_i/o \) families of heterotrimeric G proteins (Liu et al., 1995; Offermanns and Simon, 1995). At the effector side, \( \mathrm{G}_\alpha_{15/16} \) or chimeric \( \mathrm{G}_\alpha_{q/i} \) subunits activate phospholipases C (PLC), giving rise to formation of inositol-1,4,5-trisphosphate (InsP\(_3\)) and Ca\(^{2+}\) release via InsP\(_3\)-receptors that can be detected by means of fluorescent indicator dyes with exceptionally high signal-to-noise ratio (Kostenis et al., 2005). In preliminary co-transfection experiments, we added increasing numbers of GPCR-encoding plasmid constructs to transfection mixes that also contained expression plasmids that encode \( \mathrm{G}_\alpha_{15} \) and \( \mathrm{G}_\alpha_{16} \). Since functional signals were robustly detectable in a 384-well screening format with up to 15 co-expressed GPCR constructs, including \( \mathrm{G}_q \)-coupling FP\(_1\) formyl peptide and ET\(_B\) endothelin receptors, and the \( \mathrm{G}_q \)-coupling V\(_{2A}\) vasopressin receptor, we embarked on a multiplex GPCR screen with two sets of expression plasmids that encode 15 or 14 GPCRs, each. The sets were assembled based on the orphan character or a poorly identified function of the GPCR, or by a lack of drug-like modulators.

Among the co-screened receptors, GPR30 has been tentatively de-orphanized as a plasma membrane- or endo-membrane-resident estrogen receptor and, therefore re-named by the IUPHAR as G protein-coupled estrogen receptor 1 or GPER1. While initial reports provided evidence for \( \mathrm{G}_q \) coupling, leading to cAMP formation (Filardo et al., 2002), or a non-canonical signalling pathway that includes phospholipase C-independent release of Ca\(^{2+}\) from internal storage organelles and formation of phosphatidylinositol-3,4,5-trisphosphate in the nucleus (Revankar et al., 2005), other studies found neither an activation by estrogens nor by other recently reported GPER1 agonists (Otto et al., 2008; Tutzauer et al., 2021). Due to the inconclusive data of agonist activities and downstream coupling, we included GPER1 in our unbiased screening, and found no agonistic activity of estrogens or other reported GPER1 agonists. Instead, we identified three non-steroidal drug-like compounds with agonistic properties towards GPR30. The signalling cascade was identified as a canonical \( \mathrm{G}_q/\mathrm{PLC} \)-dependent pathway, leading to PIP\(_2\) hydrolysis, Ca\(^{2+}\) release from thapsigargin-sensitive
stores, and protein kinase C activation. In addition, the newly identified GPR30 agonists efficiently trigger receptor clustering and internalisation as a hallmark of effective agonism of the used ligands.

**Materials and Methods**

**Chemicals**

Chlorhexidine, Lys05, 9-aminoacridine, 17β-estradiol, 4-hydroxytamoxifen, fulvestrant, oleuropein, 3-hydroxytyrosol, niacin, niacin amide U-73122 as well as U-73433 were purchased from Sigma Aldrich (Munich, Germany). G-1 was ordered from Tocris (Wiesbaden-Nordenstadt, Germany) and YM-254890 was supplied by Biomol (Hamburg, Germany).

**Molecular Biology Methods**

Human Estrogen receptor 1 (GPER1/GPR30) cloned into pcDNA3.1 was purchased from the cDNA Resource Center (Bloomsburg, USA). Subcloning into a custom-made pcDNA3-YFP vector (Schaefer et al., 2001) was carried out by PCR and primers (5’-gctgagatccatagtcgtg and 5’-gccctctagatgcacggcactg) to remove the stop codon, followed by digestion with Eco-RI/Xba-I. The gel-purified fragment was then ligated by T4 ligase into pcDNA3-YFP, and the absence of mutations was ascertained by sequencing the entire open reading frame.

**Cell culture and Transfections**

HEK293 and HeLa cells were cultured in Earle’s Minimum essential Medium (MEM; Sigma, Munich, Germany), whereas COS-7 and MCF-7 cells were grown in DMEM and RPMI-1640 medium (Sigma, Munich, Germany), respectively. All media were supplemented with 10% fetal calf serum (Gibco Thermo Fisher Scientific, Darmstadt, Germany), 2 mM L-glutamine, 100 U/ml penicillin and 0.1 mg/ml streptomycin.
For primary screening, HEK293 cells were seeded into 6 cm culture dishes and transfected with a mixture of 14 or 15 GPCRs, FP1 formyl peptide receptor, YFP-tagged ETB endothelin receptor and Gα15/Gα16-encoding cDNA plasmids, using the transfection reagent Lipofectamin 2000 (Invitrogen, Thermo Fisher Scientific, Germany). The total cDNA plasmid amount per transfection was 9.6 or 10.2 µg, and each single plasmid construct was added at an amount of 600 ng or 300 ng (GPR1, GPR4, GPR12, GPER1, Gα15, Gα16). A reduced cDNA amount was selected for the four GPCR isoforms because they suppressed signals of control receptors when transfected at higher amounts. For confocal laser-scanning microscopy and single cell [Ca2+]i imaging experiments, cells were plated onto 25 mm poly-L-lysine-coated glass coverslips. If required, these cells were transiently transfected with 2 µg of the respective pcDNA construct applying jetPEI Polyplus (PEQLAB, Erlangen, Germany) 24 hours after cell plating. To obtain a stably human GPR30-expressing HEK293 cell line (HEK293hGPR30-YFP), cells were transiently transfected, and the growth medium was supplemented with 1 mg/ml geneticin. Stably transfected colonies were generated with a limiting dilution method and verified by fluorescence microscopy and functional assays. All cells were maintained at 37°C and in a 5% CO2-aerated, humidified atmosphere.

**Fluorometric [Ca2+]i imaging**

All fluorometric Ca2+ assays were performed in HEPES-buffered saline (HBS), containing 132 mM NaCl, 6 mM KCl, 1 mM MgCl2, 1 mM CaCl2, 5.5 mM D-glucose and 10 mM HEPES, adjusted to pH 7.4 with NaOH. For measurements in a Ca2+-free buffer, we used a modified HBS in which CaCl2 was omitted and 200 µM EGTA were added before readjusting the pH. For the primary screen, to generate concentration response curves or in multiwell assays applying various GPCR signalling inhibitors, a custom-made Fluorescence Imaging Plate Reader (FLIPR) built into a robotic liquid handling station (Freedom Evo 150, Tecan, Männedorf, Switzerland) was used as previously described (Häfner et al., 2019). To this end, transiently or stably transfected HEK293 cells were detached with trypsin and loaded with 4 µM fluo-4/AM (Invitrogen) in HBS, containing 1% bovine serum albumin for 30 min at 37°C.
Cells were washed by centrifugation, resuspended in HBS, and dispensed into pigmented clear-bottom 384-well plates (Greiner, Frickenhausen, Germany). After mounting plates onto the FLIPR, fluorescence signals were continuously recorded with a Zyla 5.5 camera (Andor, Belfast, UK) and under the control of Micromanager software (Edelstein et al., 2010). Fluo-4 was excited at 460-480 nm by using a projection of a light-pipe-homogenized array of light-emitting diodes, and emission was detected through a 515 nM long-pass filter. After recording an initial baseline in each experiment, compounds of Selleckchem library or serially prediluted agonists or modulators were pipetted with a 96-tip multichannel arm (MCA96, Tecan) in 4 quadrant steps (Q1 to Q4). Finally, fluorescence intensities were calculated from image stacks for each single well with ImageJ software, corrected for background signals and normalized to the initial intensities (F/F₀). Generation of concentration response curves was done by fitting Hill equations (Eₘᵢₙₚ, Eₘₐₓₑₓ, Eₛₑ₅₀ and Hill coefficient n) to the data.

Single-cell [Ca²⁺]i imaging analyses were performed on an inverted epifluorescence microscope (Carl Zeiss, Jena, Germany), and calibrated as described (Lenz et al., 2002). To this end, HEK293, COS-7, HeLa or MCF-7 cells seeded onto 25 mm coverslips were loaded with 4 µM fura-2/AM (AAT Bioquest) in HBS, containing 0.2% BSA for 30 min at 37°C. Then, cells were rinsed, coverslips were mounted in a HBS-filled bath chamber and sequentially excited at wavelengths of 340 nm, 358 nm, and 380 nm. Fluorescence emission was detected at 505-550 nm with a cooled CCD camera. After baseline recording, chlorhexidine, Lys05, 9-aminoacridine or thapsigargin were added and Ca²⁺ signals were monitored. Note, when 9-aminoacridine was applied, cells were loaded with 4 µM fluo-4/AM instead of fura-2/AM, because this compound is fluorescent when excited at wavelengths that heavily overlap with those of the fura-2 excitation spectrum. Consequently data are not expressed as [Ca²⁺], but as relative increases in fluorescence intensities.

Laser scanning microscopy and translocation assays

The subcellular distribution of human GPR30 in various cell lines was visualized in living cells with an inverted confocal laser scanning microscope (LSM510-META, Carl Zeiss,
Oberkochen, Germany) using a 100x/1.46 alpha Plan-Apochromat objective and applying pinhole settings to yield optical slices with a thickness of 0.9-1.1 μM. Imaging of GPR30 internalization and cell blebbing during agonist stimulation was carried out by recording time series with one picture per minute.

Time lapse analysis of CFP-PLCδ1(PH) and PKCe-CFP translocation was also assessed with a 100x/1.46 alpha Plan-Apochromat objective, but on an inverted epifluorescence microscope (Carl Zeiss, Jena, Germany) equipped with a monochromator (Polychrome V, TillVision, Gräfelfing, Germany) and a cooled charge-coupled device camera (IMAGO-QE, TillVision). HEK293,hGPR30-YFP cells grown on coverslips were transfected with cDNA plasmids encoding CFP-tagged PLCδ1(PH) or PKCe 24 h prior to the experiments as previously described (Sinnecker and Schaefer, 2004). Coverslips were superfused with 5 μM chlorhexidine or Lys05, and translocation was recorded by CFP excitation at 410 nm, and filtering the emission at 450-500 nm. To analyse the relative membrane association over the time, ratios of mean CFP fluorescence intensities over regions of interest defined over the plasma membrane (F_{pm}) and over the cytosol (F_{cyt}) regions were calculated. Finally, data were normalized to the initial ratios measured before the application of GPR30 agonists.

Fluorometric analysis of cAMP formation

Monitoring of cAMP formation in HEK293,hGPR30-YFP cells during GPR30 activation was performed using the fluorescence resonance energy transfer (FRET) sensor EPAC (mTurquoise2Δ-Epac(CD, ΔDEP)_td^{S173}Venus, (Klarenbeek et al., 2015)). All measurements were done in HBS on an inverted epifluorescence microscope (Carl Zeiss, Jena, Germany) equipped with a 25x/0.8 Plan-Neofluar objective, 24 hours after transfecting cells with 2 μg of the EPAC biosensor-encoding cDNA plasmid. The sensor was sequentially imaged at three different spectral settings to obtain CFP-, YFP- and FRET-prevalent settings: i) excitation at 410 nm and emission at 450-500 nm, ii) excitation at 515 nm and emission at 530-600 nm, and iii) excitation at 410 nm and emission at 530-600nm. Image triplets were obtained every s. After recording the baseline for 90 s, the respective GPCR agonist was added at the
indicated final concentrations. After correction for background signals, mTurquoise and Venus fluorescence intensities, and FRET efficiencies were calculated by multivariate linear regression analysis that compensates for channel cross-talk and differences in brightness of mTourquise, Venus, and mTourquise-Venus-FRET as described earlier (Lenz et al., 2002; Hellwig et al., 2004)

**Imaging of ERK activity with a FRET-based biosensor**

Analysis of extracellular-signal regulated kinase (ERK) activation after GPR30 stimulation was executed using a cDNA plasmid encoding the cytosolic ERK activity reporter 4 (cytoEKAR4), which contains an ERK substrate peptide and reports its phosphorylation by an increase in the intramolecular fluorescence resonance energy transfer (FRET) efficiency (Keyes et al., 2020). GPR30-expressing or parental HEK293 cells were transfected with 2 µg of the biosensor plasmid and measured after 24 hours on an inverted epifluorescence microscope (Carl Zeiss, Jena, Germany) equipped with a 25x/0.8 Plan-Neofluar objective. Fluorescence was excited at 410 nm, and images were sequentially obtained through emission band pass filters at 450-490 nm and 530-600 nm mounted in a motorized filter wheel (Lambda 10-2, Sutter Instruments, Novato, CA, USA). For analysis, emission ratios of background-corrected signals were calculated and finally normalized to initial signals. To determine statistical differences after addition of chlorhexidine, Lys05, or EGF in comparison to basal FRET signals, photobleaching was corrected by fitting the data of unstimulated controls to a single exponential decay function.
Results

Identification of novel GPR30 agonists by a multiplexed GPCR screen.

To identify novel agonists that act on orphan or poorly characterized G protein-coupled receptors (GPCRs), we simultaneously transfected HEK293 cells with two groups of various GPCRs (Fig. 1A) and subjected them to a medium-throughput Ca²⁺ assay, applying 4,770 compounds of the Selleckchem bioactive compound library. The two distinct transfection mixes served to further increase the number of screened target structures, but also served as a counterscreen to omit compounds that exert off-target effects or stimulate receptors and ion channels expressed by the parental HEK293 cell line. Since some of the orphan GPCRs might not couple to G proteins that activate phospholipases C (PLC) and Ca²⁺ release from the endoplasmic reticulum, we additionally co-transfected the cells with the murine G protein α subunit Gα₁₅ and its human counterpart Gα₁₆. As previously described, both Gα₁₅ and Gα₁₆ not only redirect receptor signalling of Gₛ- or Gᵢ-coupled receptors to PLC activation and subsequent Ca²⁺ mobilization, but also enhance PLC stimulation mediated by Gᵦ₁₄- or Gα₁₁-coupled GPCRs (Offermanns and Simon, 1995). To control for the efficiency of Gα₁₅/Gα₁₆-dependent conversion of signalling towards Ca²⁺ signals, we added the cDNA encoding the FP₁ formyl peptide receptor and the YFP-tagged ET₆ endothelin receptor as positive controls into each transfection mix. The screening was valid when transfected HEK293 cells expressed the YFP-fused ET₆ receptor, and each transfected and fluo-4/AM-loaded cell batch responded with a substantial Ca²⁺ signal upon addition of 10 nM endothelin-1 and 100 nM fMLP (data not shown). During acute addition of compounds of the Selleckchem library at a final concentration of 20 µM to cells that were transfected with mixture 1 (Fig. 1B-E), we recorded GPCR-characteristic immediate and transient fluorescence signals in wells that received chlorhexidine, Lys05 or 9-aminoacridine. This prompted us to identify the cDNA plasmids in transfection mixture 1 that confer the responsiveness to these compounds. After two rounds of generating cDNA mixes with lower complexity of added GPCR- and G protein-encoding plasmids, we revealed the single human GPER1-encoding plasmid to correlate
with the responses to all three compounds independently of co-expressed Ga15/16 (Suppl. Fig. 1, 2). At a concentration of 10 µM, none of the three ligands caused a substantial Ca²⁺ mobilisation in cells that expressed any of the other co-screened receptors in the presence or in the absence of co-expressed Ga15 and Ga16. Interestingly, published GPR30 agonists such as 17β-estradiol, 4-hydroxymethotamoxifen, fulvestrant, hydroxytyrosol, quercetin, oleuropein, niacin or niacin amide that were all included in the used compound library did not elicit agonist-like properties during the primary screening.

Validation of chlorhexidine, Lys05 and 9-aminoacridine as GPR30 agonists

For hit validation, we subcloned the purchased cDNA of human GPER1 into a custom-made pcDNA3-YFP vector to visualize the receptor expression and its cellular localisation by monitoring the YFP fluorescence of the C-terminally tagged fusion protein. The generated plasmid construct (hGPR30-YFP) was used to generate a stably transfected HEK293 cell line (HEK293hGPR30-YFP). The major subcellular localisation of heterologously expressed hGPR30 seemed to be in the plasma membrane with minor amounts of the YFP-tagged receptor protein residing in the endoplasmic reticulum as detected by confocal laser scanning microscopy in living cells (Fig. 2A).

To assess the potency and efficacy of the newly identified GPR30 agonists, we loaded HEK293hGPR30-YFP with fluo-4/AM and measured the Ca²⁺ responses in our fluorescence imaging plate reader during application of serially diluted agonist concentrations. Lys05 exerted the highest potency with an EC₅₀ of 270 nM, followed by the most efficient agonist chlorhexidine (EC₅₀ = 750 nM). Since 9-aminoacridine is a strongly fluorescent dye and to monitor for possible unspecific Ca²⁺ signals, we also applied the three compounds to the parental HEK293 cell line. We did not obtain any detectable rise in [Ca²⁺], when we incubated these cells with chlorhexidine, Lys05 or 9-aminoacridine within a concentration range of 0.02 to 40 µM (Fig. 2B). Next, we imaged GPR30 activation in adherent single GPR30-overexpressing HEK293 cells to estimate the levels of [Ca²⁺] reached by addition of 5 µM chlorhexidine, and Lys05 with the latter reaching somewhat lower maximal F/F₀ signals in
multiwell assays. During stimulation, all cells responded with uniform and transient \([\text{Ca}^{2+}]_i\) signals that peaked after 5-15 s and almost decayed to baseline levels within 120 s, thereby excluding toxic effects on the cells. With regard to peak \([\text{Ca}^{2+}]_i\), the higher efficacy of chlorhexidine compared to Lys05 was confirmed by the calibrated single cell \([\text{Ca}^{2+}]_i\) analysis. Single cell \(\text{Ca}^{2+}\) imaging with 9-aminoacridine required the use of the indicator dye fluo-4 because the fluorescence excitation spectrum of 9-aminoacridine interferes with that of fura-2 (Fig. 2D). It should, therefore be regarded as qualitative rather than quantitative data. When comparing concentration response curves obtained in multiwell assays with fluo-4-loaded HEK293\(_{\text{hGPR30-YFP}}\) cells, we found that \(\text{F/F}_0\) values levels at saturating 9-aminoacridine concentrations ranged between those of chlorhexidine and Lys05. In parental HEK293 cells, 5 µM of the respective compounds failed to induce detectable increases in \([\text{Ca}^{2+}]_i\) in cell suspensions or in single cell assays (see Fig. 2B-F). To test whether the identified agonists may act in an allosteric manner in relation to each other, we generated concentration response curves with and without addition of different submaximally effective concentrations of the respective other agonists. In case of a positive allosteric modulation, we would expect a shift of half-maximally effective concentrations to lower values. In none of the tested combinations, we observed such signs of allosteric modulation (Suppl. Fig. 3). As shown in Fig. 2B, high concentrations of Lys05 caused a partial inhibition of \([\text{Ca}^{2+}]_i\) signals, which was also evident when applied in combination with chlorhexidine (see Suppl. Fig 3A,C).

Since none of the previously reported GPR30 agonists appeared active in the primary multiplexed GPCR screening, we selected some relevant and most frequently used GPR30-activating drugs (Rosano et al., 2016) and generated concentration-response curves using our stably transfected HEK293\(_{\text{hGPR30-YFP}}\) cell line as well as parental HEK293 cells. Surprisingly, only 4-hydroxytamoxifen, and niacin amide led to an increase in fluorescence intensities when added at concentrations higher than 10 µM (Suppl. Fig. 4). Since they did so in HEK293\(_{\text{hGPR30-YFP}}\) cells, but also in untransfected parental HEK293 cells, we consider them as presumably hGPR30-unrelated background signals. Other reported GPR30 agonists, including 17β-estradiol and G-1 that have been described to mobilize \(\text{Ca}^{2+}\) in MCF-7 and
SKBr3 cells (Ariazi et al., 2010), were inactive in HEK293<sub>hGPR30-YFP</sub> cells as well as in parental HEK293 cells over the entire range of applied concentrations (Suppl. Fig. 4A,B). If previously reported GPR30 agonists were biased to induce a G<sub>i</sub> coupling mode of the receptor, [Ca<sup>2+</sup>], assays might require a G<sub>q</sub> priming (Pfeil et al., 2020) or co-expression with the promiscuously coupling G proteins to detect a receptor activation by these agonists. However, neither G<sub>q</sub> priming via stimulation of an endogenous muscarinic receptor with 100 µM carbachol did nor co-expression of G<sub>α<sub>15</sub></sub> and G<sub>α<sub>16</sub></sub> led to Ca<sup>2+</sup> signals upon challenging GPR30-expressing HEK293 cells with 17ß-estradiol, G-1 or several other reported GPR30 agonists (Suppl. Fig. 4). Notably, the same G<sub>q</sub> priming procedure or co-expression of G<sub>α<sub>15</sub></sub> and G<sub>α<sub>16</sub></sub> enhanced Ca<sup>2+</sup> signals elicited via a G<sub>i</sub>-coupled fMLP receptor.

**Inhibition of GPR30-triggered Ca<sup>2+</sup> signals by Gq, PLC and inositol-1,4,5-trisphosphate (InsP<sub>3</sub>) receptor inhibitors**

Signalling of G<sub>q</sub>/G<sub>i</sub>-coupling GPRCs typically triggers a Ca<sup>2+</sup> release from inositol-1,4,5-trisphosphate (InsP<sub>3</sub>)-sensitive Ca<sup>2+</sup> stores. To strengthen the assumption that chlorhexidine, Lys05 and 9-aminoacridine mediate Ca<sup>2+</sup> release from InsP<sub>3</sub>-sensitive stores, we repeated microfluorometric single-cell [Ca<sup>2+</sup>]i analyses using a Ca<sup>2+</sup>-free bath solution. As expected, the Ca<sup>2+</sup> mobilisation response remained detectable under this condition with response amplitudes of about 2- to 2.5-fold compared to the respective basal levels (Fig. 3). Moreover, we depleted these stores by preincubating cells for 5 min with 2 µM thapsigargin, an inhibitor of endoplasmic reticulum Ca<sup>2+</sup>-ATPases. In thapsigargin-treated HEK293<sub>hGPR30-YFP</sub> cells, chlorhexidine, Lys05 or 9-aminoacridine failed to elicit [Ca<sup>2+</sup>]i signals, indicating that their signalling critically relies on the canonical PLC- and InsP<sub>3</sub>-dependent Ca<sup>2+</sup> mobilisation pathway. To characterize GPR30 signalling in more detail, we incubated HEK293<sub>hGPR30-YFP</sub> cells either with the G<sub>q</sub> inhibitor YM-254890 (1 µM), the phospholipase C inhibitor U-73122 (10 µM) or its inactive analog U-73343 (10 µM), and with the InsP<sub>3</sub> receptor inhibitor 2-APB (100 µM) for 5 min. Then, GPR30 was challenged with the three new identified agonists. In contrast to solvent-treated control cells, Ca<sup>2+</sup> rises were prevented when applying the
inhibitors. U-73343 showed a very slight reduction of the maximal control signal during activation by Lys05 or 9-aminoacridine (Fig. 4). Since GPR30-dependent [Ca\textsuperscript{2+}] signals were fully abrogated by the G\textsubscript{q} inhibitor YM-254890, we assume that GPR30 activates phospholipase C and Ca\textsuperscript{2+} mobilisation involves a G\textsubscript{q} coupling component. Since a combined G\textsubscript{q}/G\textsubscript{i} coupling mode may be sensitive to YM-254890 as well (Pfeil et al., 2020), we used a pretreatment with pertussis toxin (PTX) that uncouples GPCRs from G\textsubscript{a\,16} proteins and, thus, disrupts receptor signalling via G\textsubscript{i}. To this end, we transiently co-transfected HEK293 cells with GPR30 and the FP\textsubscript{1} and ET\textsubscript{B} receptors as positive controls for exclusively (FP\textsubscript{1}) or predominantly (ET\textsubscript{B}) G\textsubscript{i}-coupling receptors. The G\textsubscript{q}-coupled muscarinic M\textsubscript{3} acetylcholine receptor that is endogenously expressed in our HEK293 cell line served as a control for a PTX-resistant pathway. After treatment of cells with 100 ng/ml PTX or its solvent for 18-20 h added to the culture medium, responses elicited by the GPCR agonists were analysed in multiwell Ca\textsuperscript{2+} measurements. PTX-treated cells did not respond to 100 nM fMLP and endothelin-1 (10 nM) signals were diminished by about 50% compared to untreated controls, thereby confirming the coupling behaviour of pure G\textsubscript{i} or mixed G\textsubscript{q}/G\textsubscript{i} coupling known for formyl peptide and endothelin receptor type B receptors. Activation of GPR30 applying either 5 \mu M chlorhexidine, Lys05 or 9-aminoacridine, and carbachol (100 \mu M)-induced M\textsubscript{3} activation were unaffected by pretreatment with PTX (Fig. 5). We therefore conclude that hGPR30 genuinely couples to the G\textsubscript{i} signalling cascade when challenged with the newly identified agonists.

**Activation of GPR30 results in phosphoinositide hydrolysis and diacylglycerol (DAG) formation.**

In general, agonist binding to a G\textsubscript{i}-coupling receptor results in an immediate activation of phospholipases C that hydrolyse phosphatidylinositol-4,5-bisphosphate (PIP\textsubscript{2}) to InsP\textsubscript{3} and diacylglycerol (DAG). Since Revankar et. al (Revankar et al., 2005) described an inefficacy of PLC inhibitor U73122 on blocking GPR30-initiated calcium mobilization and thereby suggested a divergent signalling pathway, we extended the analysis of hGPR30 coupling to
PLC applying more direct methods. PIP$_2$ hydrolysis and DAG formation can be monitored by subcellular translocation of well-characterized biosensor proteins. The plasma membrane PIP$_2$ content is reflected by the association of a cyan fluorescent protein (CFP)-fused pleckstrin homology domain of PLC-$\delta_1$ (CFP-PLC-$\delta_1$(PH)) to the plasma membrane. Upon PLC-mediated PIP$_2$ hydrolysis, CFP-PLC-$\delta_1$(PH) translocates to the cytosol. Conversely, a translocation of CFP-tagged DAG-sensitive novel protein kinase C $\varepsilon$ isoform (PKC$\varepsilon$-CFP) from the cytosol to the plasma membrane indicated DAG formation by PLC.

We transfected a CFP-PLC-$\delta_1$(PH)-encoding plasmid into HEK293$_{hGPR30-YFP}$ cells, and imaged the CFP-PLC-$\delta_1$(PH) distribution during addition of chlorhexidine or Lys05 by confocal microscopy and by epifluorescence time-lapse microscopy (Fig. 6A-F). Within a few seconds after agonist application, the plasma membrane association of CFP-PLC-$\delta_1$(PH) was markedly reduced and partly recovered within the following 5 min. Measurements of DAG formation were also performed by a translocation assay. Accordingly, we tracked transiently transfected PKC$\varepsilon$-CFP which was recruited from the cytosol to the plasma membrane upon application of chlorhexidine or Lys05 (Fig. 6G-L). Finally, we transiently expressed CFP-PLC-$\delta_1$(PH) and PKC$\varepsilon$-CFP in parental HEK293 and repeated the experiments. None of the proteins and agonists exerted detectable changes in the distribution of the biosensor proteins in the absence of GPR30 expression, while stimulation of a co-transfected histamine H$_1$ receptor served as a positive control (Suppl. Fig. 5).

**Cyclic adenosine monophosphate does not rise after stimulation with GPR30 agonists.**

The discovery of GPR30 as a putative membrane-resident estrogen receptor started with the observation that estrogen could activate adenylyl cyclase activity in MCF-7 cells, giving rise to the production of 3',5'-cyclic adenosine monophosphate (cAMP) (Aronica et al., 1994). Later on, the GPR30 cDNA was cloned out of this cell line (Carmeci et al., 1997). Finally, Thomas et al. (Thomas et al., 2005) identified GPR30 as a G protein-coupled membrane receptor that is directly activated by estradiol and triggered increases in cytosolic cAMP.
concentrations. The cAMP generation mediated by GPR30 could, likewise, be confirmed applying other agonists like G-1 or tamoxifen (Mo et al., 2013). Hence, we determined the cAMP formation in HEK293_{hGPR30-YFP} cells during stimulation with chlorhexidine or Lys05. As highly sensitive and cAMP-specific detection method, we applied FRET measurements, using the well-established EPAC-derived cAMP biosensor that allows a time-resolved detection of cAMP formation in living cells (Klarenbeek et al., 2015). Since elevation of cAMP would cause a decline in FRET efficiencies, we first validated the EPAC sensor by utilizing ß-adrenergic and adenosine receptor agonists that act on Gs-coupled receptors that are endogenously expressed in HEK293 cells. The addition of epinephrine or adenosine rapidly and robustly reduced the initial FRET efficiency of 63 to 64% about 36% or 18% whereas solvent controls led only to decrease in FRET efficiency, caused by photobleaching of the FRET acceptor (Fig. 7B,C). FRET signals upon addition of 5 µM 17ß-estradiol or G-1 did not display discernible differences to those observed after addition of HBS buffer. Likewise, the addition of chlorhexidine and Lys05 gave rise to FRET signals that were not different from those in solvent-treated controls (Fig. 7A,C). To assess whether a coupling to the cAMP cascade may be restricted to certain cell types, we repeated assays in MCF7 cells that have been reported to express GPR30 (Carmeci et al., 1997). Neither 17ß-estradiol nor G-1 induced a cAMP response as indicated by a co-expressed EPAC-derived cAMP biosensor (Suppl. Fig. 6). We, thus, exclude a predominant coupling of hGPR30 to the Gs-/adenylyl cyclase/cAMP pathway when challenged with previously reported or newly identified GPR30 agonists.

**ERK activation assay**

Coupling to the Ras-Raf-MEK-ERK pathway is a typical hallmark of G_q-coupled receptors. To assess the activity of this cascade in HEK293 cells, we co-expressed GPR30 with a cytosolic FRET-based ERK biosensor protein (cytoEKAR4) that reports the phosphorylation state of an ERK substrate by an increase in the intramolecular FRET efficiency (Keyes et al., 2020). As shown in Fig. 8A-D, 5 µM chlorhexidine or 5 µM Lys05 caused an increase in FRET
signals with a maximum appearing about 10 min after agonist application and an amplitude, reaching about 40%-60% of responses that were exerted by 100 ng/ml recombinant epidermal growth factor (EGF) as a positive control. Responses to chlorhexidine or Lys05 were absent in HEK293 cells that expressed the reporter protein, but no GPR30 (see Fig. 8E-H).

Rapid internalization of GPR30 and potential coupling to \( \text{Ga}_{12/13} \)

A characteristic feature of efficient and sustained GPCR activation is given by the receptor internalization, which uncouples the GPCR from G protein signalling and may be followed either by terminal degradation in lysosomes or by receptor recycling back to the plasma membrane. To follow these processes, we imaged the subcellular localisation of the YFP-fused hGPR30 during prolonged agonist application by using confocal laser scanning microscopy. Upon addition of 5 µM chlorhexidine or Lys05 that cause comparable amplitudes of \( \text{Ca}^{2+} \) responses, a clustered ("patchy") distribution and first distinct internalization patterns were already observable 2 minutes after agonist application (Fig. 9A,B). Within 10-20 min, hGPR30-YFP was almost quantitatively removed from the plasma membrane in chlorhexidine- or Lys05-treated cells. 9-aminoacridine seemed to be more slowly acting, but within 20 minutes, GPR30 followed the same clustered distribution and substantial internalisation as seen with the other two agonists (Fig. 9C). In the transmitted light channel, a secondary finding while imaging chlorhexidine- or Lys05-stimulated HEK293 cells overexpressing hGPR30 was a marked membrane blebbing. To visualize the blebbing events independently of hGPR30 clustering and internalisation, we stably transfected HEK293\(_{\text{hGPR30-YFP}}\) cells with an expression plasmid that encodes a CAAX-box-modified and thereby membrane-targeted CFP. During hGPR30 internalization mediated by chlorhexidine or Lys05, the CFP-CAAX protein indicated distinct bleb-like bulges in the plasma membrane (Fig. 10) that may reflect a rearrangement of the cortical actin network (Charras, 2008). Since GPCR coupling to \( \text{Ga}_{12/13} \) is known to affect the actin cytoskeleton through the downstream effectors RhoA and ROCK (Purvanov et al., 2014; Vanderboor et al., 2020), we
applied the ROCK inhibitors Y-27632 or fasudil to affirm this assumption. Both blockers prevented bleb formation (data not shown). Thus, we propose that, besides $G_q$ coupling, hGPR30 may also activate heterotrimeric G proteins of the $G_{12/13}$ family, which is a frequently observed dual coupling pattern for $G_q$-linked GPCRs.

**Transiently transfected GPR30 pattern and calcium signals differ in various cell types**

In the past, results of GPR30 localization assays revealed conflicting patterns with reports on a predominant localisation in the endoplasmic reticulum, or in the plasma membrane (Revankar et al., 2005; Bologa et al., 2006; Funakoshi et al., 2006; Filardo et al., 2007; Otto et al., 2008). Since variations in the cellular localisation patterns may depend on the cell types they are investigated in, we transiently transfected the expression plasmid encoding YFP-tagged hGPR30 into HeLa, COS-7, and MCF-7 cells which endogenously express GPR30. Surprisingly, the plasma membrane localisation of transiently expressed hGPR30-YFP in HEK293 cells was less prominent than in our stable HEK293hGPR30-YFP cell line, and only observable in cells that express only small amounts of the fusion protein (Fig. 11A). When compared to the other cell lines, HEK293 cells followed by MCF-7 were visually the cell type with the highest abundance of hGPR30-YFP in the plasma membrane. In COS-7 and in HeLa cells, hGPR30-YFP seemed to be retained in the endoplasmic reticulum, as indicated by the reticular pattern and nuclear membrane residence of intracellularly retained hGPR30-YFP proteins (Fig. 11D,G).

To examine whether the cellular distribution affects the efficacy of chlorhexidine or Lys05 to elicit functional Ca$^{2+}$ mobilisation signals, we performed single cell [Ca$^{2+}$]i imaging experiments in all investigated cell types. After transient transfection of GPR30, chlorhexidine and Lys05 elicited a rise in basal [Ca$^{2+}$]i in all cell lines. In HEK293 and MCF-7 cells, 62%-67% of the transfected cells (as detected by their yellow fluorescence) responded to the addition of chlorhexidine or Lys05 with increases in [Ca$^{2+}$]i by more than 100 nM over their basal [Ca$^{2+}$]. In HeLa cells, rises in [Ca$^{2+}$]i occurred in 40%-64% of transfected cells, but often with a delayed response when compared to HEK293 or MCF-7 cells (Fig. 11H,I).
functional GPR30 activation in COS-7 cells by chlorhexidine or Lys05 could only provoked in 16%-25% of GPR30-expressing cells (Fig. 11E,F). This observation was in line with the observed higher efficiency in plasma membrane targeting of the protein in HEK293 or MCF-7 cells compared to COS-7 and HeLa cells. Parental HEK293 (Fig. 2), or parental COS-7 and HeLa cells (data not shown) did not respond to the two GPR30 agonists. Parental MCF-7 cells showed transient and inhomogeneous [Ca^{2+}]_i signals to the addition of 5 μM chlorhexidine that were also obtained when applying 0.05% DMSO as solvent control (Suppl. Fig. 7). Notably, agonist-induced [Ca^{2+}]_i signals in transiently hGPR30-YFP-overexpressing MCF-7 signals were more uniform and stronger than in the untransfected or mock-transfected parental cell line. Taken together, we conclude that the newly identified GPR30 agonists, albeit eliciting more variable results in transiently transfected cells, were effective specific for GPR30 regardless of which cell line we used. Furthermore, diverse findings in past could rely on the use of various cell types in different laboratories.

4. Discussion

In this study, we identified three novel GPR30 agonists by performing an unbiased multiplexed screen of 31 GPRCs, including numerous orphan members. Our screening assay was based on measurement of intracellular Ca^{2+} concentrations with co-expressed G protein α subunits 15/16 to enforce a convergence of GPCR signalling towards PLC activation with subsequent Ca^{2+} signals. Until now, GPR30 has been described as a receptor that induces cAMP production via a G_s pathway (Kanda and Watanabe, 2003; Thomas et al., 2005; Mo et al., 2013). Astonishingly, it has also been described to induce a Ca^{2+} mobilization in a PLC-independent manner (Revankar et al., 2005; Bologa et al., 2006; Ariazi et al., 2010) in both native and in GPR30-overexpressing cells. In addition, GPR30 mediates ERK-1/2 phosphorylation as well as phosphoinositide 3-kinase (PI3K) activation via trans-activating epidermal growth factor receptors in breast cancer cell lines or in GPR30-overexpressing COS-7 cells (Filardo et al., 2000; Revankar et al., 2005). Of note, reported GPR30 agonists (Rosano et al., 2016) which are included in our Selleckchem library failed to
elicit increases in $[\text{Ca}^{2+}]_i$ despite favouring promiscuous coupling via $\text{Go}_{15/16}$. By contrast, three compounds that have previously not been reported as GPCR agonists, namely chlorhexidine, Lys05 and 9-aminoacridine, emerged as agonists with secondary screening results showing that GPR30 was the common target GPCR for all three compounds. Although the newly identified agonists may share structural motifs with an as yet unidentified physiological GPR30 agonist, the assumption of a unified pharmacophore must not hold true. Notably, the AT$_1$ receptor as closest relative of GPR30 is a peptide receptor.

Following experiments provided several lines of evidence that signaling downstream of GPR30 was relayed via a canonical G$_q$-linked, PLC-dependent pathway, leading to Ca$^{2+}$ mobilisation, recruitment of diacylglycerol-sensitive PKC isoforms, and activation of the ERK pathway. Since previous studies did not show such canonical signaling properties, the different observations may deserve a closer analysis. In our hands, inhibitors of G$_q$, PLC and InsP$_3$ receptors reliably and completely blocked Ca$^{2+}$ signals regardless of which agonist we used. Depletion of InsP$_3$-sensitive Ca$^{2+}$ stores by pretreating GPR30-expressing cells with thapsigargin abolished chlorhexidine-, Lys05- and 9-aminoacridine-induced Ca$^{2+}$ responses. Other groups negated efficacy of a PLC inhibitor U73122 (Revankar et al., 2005) or got variable results when applying IP$_3$ receptor inhibitors 2-APB or xestopongin C in different cell types (Ariazi et al., 2010). Performing complementary CFP-PLC-$\delta_1$(PH) and PKC$_\varepsilon$-CFP translocation assays that indicate PIP$_2$ hydrolysis and generation of diacylglycerols, respectively, our study demonstrates robust coupling of GPR30 to PLC. A canonical PLC-driven Ca$^{2+}$ mobilisation response typically consists in a transient increase in $[\text{Ca}^{2+}]_i$ lasting for about 1-2 min and terminating in slightly elevated levels. In GPR30-expressing HEK293 cells, we observed such a uniform time course in all imaged cells upon stimulation with the newly identified agonists. In previous studies using 17$\beta$-estradiol, 4-hydroxytamoxifen or G-1, single cell $[\text{Ca}^{2+}]_i$ imaging experiments showed atypical kinetic properties (Revankar et al., 2005; Bologa et al., 2006) or variable kinetic properties depending on the agonists and cell types used (Ariazi et al., 2010). When added at concentrations $> 10$ µM, tamoxifen induced delayed and long lasting Ca$^{2+}$ signals in GPR30-
overexpressing as well as in parental HEK293 cells, confirming earlier reports that found that
tamoxifen and its metabolite interfere with cytosolic Ca\(^{2+}\) homeostasis in an estrogen
receptor or GPR30-independent fashion (Zhang et al., 2000; Bollig et al., 2007; Asp et al.,
2013). Our finding that 17\(\beta\)-estradiol and G-1 did not elicit Ca\(^{2+}\) responses in
HEK293\(_{\text{hGPR30-YFP}}\) cells is in line with observations in heterologously GPR30-expressing CHO-
K1 cells (Otto et al., 2008). In MCF-7 cells, the reported GPR30 agonist G-1 induces Ca\(^{2+}\)
efflux from the endoplasmic reticulum (ER) that is associated with ER stress and cell death
(Vo et al., 2019). When applied concentrations that activate GPR30, chlorhexidine and Lys05
identified in this study rather elicited an increase in metabolic activity reminiscent of the co-
mitogenic activity of numerous G\(_q\)-coupled receptors, including the GPR30-related AT\(_1\)
angiotensin-II receptor (Forrester et al., 2018). Although the initial characterisation of G-1
included data that demonstrate a competition for binding of an estradiol derivative to GPR30,
other studies failed to reproduce 17\(\beta\)-estradiol binding to GPR30 (Otto et al., 2008). Similar
results were obtained by Pedram et al. (Pedram et al., 2006). Thus, the specific binding of
estrogens to GPR30 is not undisputed.

Since initial evidence has suggested that activation of GPR30 triggers increases in cAMP
concentrations, we wondered whether our GPR30 agonist may exert such a biased agonism
towards PLC while maintaining some coupling to the G\(_s\)-cAMP pathway. To test this
hypothesis, we used the EPAC-based sensitive cAMP-reporting biosensor. In
HEK293\(_{\text{hGPR30-YFP}}\) cells, this sensor was capable of detecting cAMP formation triggered by the
endogenously expressed adenosine receptor or the \(\beta_2\) adrenoceptor. In the same cells,
neither recently reported (17\(\beta\)-estradiol, G-1) nor our newly identified GPR30 agonists
chlorhexidine and Lys05 evoked detectable changes in cAMP levels. This observation
corroborates findings that COS-7 or HEK293 cells heterologously expressing GPR30 lacked
enhanced cAMP formation after treatment with 17\(\beta\)-estradiol or G-1 (Otto et al., 2008;
Broselid et al., 2014). Moreover, the latter authors observed a GPR30-mediated, but again
17\(\beta\)-estradiol- or G-1-independent constitutive inhibition of cAMP formation, and increased
cAMP levels after siRNA knockdown of native GPR30 in MDCK cells. Recently, it has
become clear that some GPCR agonists may shift the signalling towards specific G-protein families or arrestins. This phenomenon is commonly referred to as “biased agonism” (Bock and Bermudez, 2021). Although we cannot exclude that the newly identified GPR30 agonists may exert a biased agonism, the coupling of three chemically distinct agonists towards a canonical $G_q$ pathway argues against such signaling bias.

There are also inconsistent data regarding the subcellular localization of GPR30. Several studies demonstrated that GPR30 is localized to the ER (Revankar et al., 2005; Bologa et al., 2006; Otto et al., 2008; Lin et al., 2009) or in the Golgi complex (Sakamoto et al., 2007). Other groups found GPR30 integrated into the plasma membrane (Thomas et al., 2005; Funakoshi et al., 2006; Filardo et al., 2007; Mo et al., 2013). Upon expression in different cell lines, we observed a YFP-tagged GPR30 mainly in the ER and in the plasma membrane, but the balance was strongly dependent on the cell type used. A pronounced plasma membrane localization was observable in HEK293 and MCF-7 cells, especially in cells that expressed low amounts of the protein. In COS-7 and HeLa cells, GPR30-YFP mostly accumulated in perinuclear endomembrane compartments. Such cell type- and expression density-dependent effects may explain the diverging observations especially when using transiently transfected cells.

The identification of reliably acting GPR30 agonists that initiate a canonical $G_q$- and PLC-linked signalling pathway may pave the way towards an investigation of real physiological functions of this GPCR and to overcome the state of contradictory results in the field. A genetic knock-in mouse model, which harbours a lacZ reporter in the GPR30 locus, has revealed a major expression in vascular endothelial cells of multiple tissues but also in smooth muscle cells and in pericytes of brain vessels (Isensee et al., 2009). Female GPR30 knockout mice showed a blood pressure elevation at the age of 9 months (Mårtensson et al., 2009). In conjunction with the flow-induced upregulation of GPR30 expression in HUVEC (Takada et al., 1997), this finding implies that GPR30 may play a role in regulating endothelial functions. Furthermore, the ubiquitous expression profile and the similarity to the $G_{q\gamma}$ and $G_{12/13}$-coupling AT$_1$ receptor (Feng and Gregor, 1997) would fit to a model that
GPR30 is expressed in blood vessels. Recently, Tutzauer et al. attempted to confirm a vasodilatory function of GPR30 by measuring the relaxation of caudal arteries from wild-type as well as from GPR30 knockout mice while treating them with the previously proposed GPR30-specific agonists G-1 and 17β-estradiol. They found that arteries from GPR30-deficient mice relaxed with the same potency and efficacy than in wild-type mice. In addition, various cellular expression models showed no effects of G-1 or 17β-estradiol and prompted them to state that “classifying GPR30 as an estrogen receptor and G-1 as a specific GPR30 agonist is unfounded” (Tutzauer et al., 2021). Based on our data, we agree with their conclusion and hope that the discovery of a reliably acting GPR30 agonist and a fundamental change of the induced canonical Gq-phospholipase C signaling pathway may be instrumental in more unambiguously the physiological functions of GPR30.

**Authorship Contributions**

Participated in research design: Urban, and Schaefer

Conducted experiments: Urban, and Leonhardt

Performed data analysis: Urban, and Schaefer

Wrote or contributed to the writing of the manuscript: Urban, and Schaefer
References


Conflict of Interest

The authors declare no conflicts of interest.

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Figure legends

Figure 1: Identification of new GPR30 agonists by a multiplexed GPCR screening.
(A) HEK293 cells were transiently transfected with cDNA plasmid mixtures, encoding the indicated GPCRs, the FP1 formyl peptide receptor, the C-terminally YFP-fused ET\textsubscript{B} endothelin receptor, and the G protein \( \alpha_{15} \) and \( \alpha_{16} \) subunits. Transfection mix 2 (right panel) contained the same amounts of cDNA plasmids, but 14 other GPCRs to be screened. (B-E) After 24 hours, both cell samples were subjected to a screen for novel GPCR agonists performing fluorometric Ca\textsuperscript{2+} assays in a 384-well microplate format. Cells were detached by trypsinization, and loaded for 30 min with the Ca\textsuperscript{2+} indicator fluo-4/AM. After centrifugation and resuspension in a HEPES-buffered saline (HBS), cells were dispensed into black pigmented, transparent bottom 384-well plates. The multiwell plates were positioned on a fluorescence imaging plate reader (FLIPR) built into a robotic liquid handling station. A 96-tip multichannel arm was used to inject and mix the 4,718 compounds of a bioactive compound library (Selleckchem) at a final concentration of 20 \( \mu \)M, solvent controls or control agonists in four quadrant steps (Q1 to Q4). To identify primary hits, wells showing a typical transient GPCR-induced rise in fluorescence intensity were compared between the two transfection mixtures. Chlorhexidine (B), Lys05 (C) and 9-aminoacridine (D) were the only compounds that elicited a robust [Ca\textsuperscript{2+}] signal in cells transfected with mix 1 (black lines) but not after transfection with mix 2 (grey lines). (E) Chemical structures of the three screening hits.

Figure 2: [Ca\textsuperscript{2+}]\textsubscript{i} measurements in HEK293 cells stably expressing the human GPR30 during stimulation with new GPR30 agonists.
(A) Confocal laser-scanning microscopy of living HEK293 cells stably overexpressing YFP-tagged human GPR30 (HEK293\textsubscript{HGR30-YFP}). Nuclei were counterstained with Hoechst 33258 and excited with a 405-nm laser. Bars: 30-\( \mu \)m scale. (B) Potency and efficacy of chlorhexidine, Lys05 and 9-aminoacridine were determined in multiwell Ca\textsuperscript{2+} assays, using a fluorescence imaging plate reader device. Fluo-4-loaded HEK293\textsubscript{HGR30-YFP} (black symbols
and lines) or parental HEK293 (grey symbols and lines) cell suspensions were exposed to
the serially diluted compounds, and Ca\(^{2+}\) signals were obtained as increases in fluorescence
intensities compared to the respective basal intensities before agonist application (F/F\(_0\)). The
indicated half-maximally effective concentrations (EC\(_{50}\)) were calculated by modelling the
concentration-dependent peak Ca\(^{2+}\) responses (F\(_\text{Peak}\)/F\(_0\)) with a four-parameter Hill equation.
Hill slopes were 0.98, 1.12, and 1.77 for chlorhexidine, Lys05 and 9-aminoacridine,
respectively. Data represent means and S.E. of 6–10 independent biological experiments
performed in technical duplicates, each. (C-D) Microfluorometric single cell analysis of Ca\(^{2+}\)
signals in HEK293\(_{\text{hGPR30-YFP}}\) cells (upper panels) or in parental HEK293 cells (lower panels)
during application of chlorhexidine, Lys05 or 9-aminoacridine. Cells were loaded with fura-
2/AM (C) or fluo-4/AM (D) and challenged with 5 µM of respective agonist. Shown is a
representative measurement of 150-200 cells (grey lines), each. Averaged time courses for
[Ca\(^{2+}\)] or relative fluorescence intensities (F/F\(_0\)) are depicted as black lines.

Figure 3: Single cell analysis of hGPR30-induced [Ca\(^{2+}\)] signals in the absence of
extracellular Ca\(^{2+}\) and after depletion of thapsigargin-sensitive intracellular Ca\(^{2+}\)
stores.
Microfluorometric analysis of [Ca\(^{2+}\)] in HEK293\(_{\text{hGPR30-YFP}}\) cells as described in Figure 2C, but
in a nominally Ca\(^{2+}\)-free bath solution. (A, C, E) Representative experiments depicting
application of 5 µM chlorhexidine, Lys05 or 9-aminoacridine to HEK293\(_{\text{hGPR30-YFP}}\) cells without
(left panels) and with prior incubation with 2 µM thapsigargin (right panels). Grey lines depict
responses in single cells, black line: average signal of all cells measured in this single
biological experiment (B, D, F) Statistical analysis of [Ca\(^{2+}\)], signals (means and S.D.)
obtained in 4-5 independent biological experiments, performed as shown in (A, C, E), each.
Bars represent the time points as indicated in (A, C, E). Increases in [Ca\(^{2+}\)], after agonist
stimulation (time points 4 versus 3) were seen in Ca\(^{2+}\)-free buffer (white bars), but not when
applied after store depletion with thapsigargin (black bars). #,*: p < 0.05, Student’s t-test with
paired data; n.s.: no statistically significant difference.
Figure 4: GPR30-induced Ca\(^{2+}\) release is suppressed by Gq, PLC and InsP\(_3\) receptor inhibitors.

(A) Representative FLIPR analyses of fluo-4-loaded HEK293\(_{hGPR30-YFP}\) cell suspensions after 5 minutes of preincubation without (HBS control) and with 1 \(\mu\)M YM-254890 (Gq inhibitor), 100 \(\mu\)M 2-APB (IP\(_3\) receptor inhibitor), 10 \(\mu\)M U-73122 (PLC inhibitor), or U-73343 (inactive U-73122 analog). GPR30 was activated either by chlorhexidine (left panel), Lys05 (middle panel) or 9-aminoacridine (right panel). Shown are the kinetics of relative fluorescence intensities during stimulation, each condition as duplicate. Pipetting artifacts caused during compound application are not deleted. (B) Aggregated data (means and S.D.; \(n = 3\) independent biological experiments performed in technical duplicates, each) of peak fluorescence intensities (\(F_{peak}/F_0\)) measured as shown in (A). All blockers acting on G\(_q\) mediated Ca\(^{2+}\) release were effective (# or *: \(p < 0.05\) by one-way ANOVA with Dunn–Šidák post-hoc test). Note that U-73343 only suppressed a minor fraction of Lys05- and 9-aminoacridine-induced responses, and effects on chlorhexidine-stimulated cells were statistically not significant (n.s.).

Figure 5: Effect of pertussis toxin (PTX) on GPR30-induced [Ca\(^{2+}\)]\(_i\) signals.

Similar FLIPR experiments as in Figure 4 but with HEK293 cells that transiently expressed human GPR30, the ET\(_B\) receptor, and the FP\(_1\) formyl peptide receptor. Six hours after transfection, PTX (100 ng/ml) was added to the culture medium and incubated overnight to deactivate G\(_{\alpha_{i/o}}\) proteins by ADP ribosylation. The next day, cells were loaded with fluo-4 and subjected to multiwell Ca\(^{2+}\) imaging. (A, B) Shown are time courses of [Ca\(^{2+}\)]\(_i\), obtained in a representative experiment during the addition of 5 \(\mu\)M 9-aminoacridine, 5 \(\mu\)M chlorhexidine, 5 \(\mu\)M Lys05, or the control agonists 100 \(\mu\)M carbachol, 10 nM endothelin-1, and 100 nM fMLP. Orange lines: data from 4 wells containing PTX-treated cells; black lines: 4 wells with untreated control cells from same transfection day. To exclude confounding effects of different cell numbers in single wells, the [Ca\(^{2+}\)]\(_i\) was calibrated in each well at the end of the experiment. To this end, 0.04% Triton X-100 and 10 mM EGTA were sequentially added in
order to expose the indicator to high (1 mM) and to very low (< 20 nM) Ca\(^{2+}\) concentrations, respectively. (C) Statistical analysis of PTX-treated (black bars) and -untreated cells (white bars). Shown are means and S.D. (n = 4 independent biological experiments, each performed in duplicates) of maximal [Ca\(^{2+}\)]_i increases (Δ[Ca\(^{2+}\)]_i) after adding the indicated agonists. Differences (#: p < 0.05, Dunn–Šidák post-hoc test) were only registered during activation of G\(_i\)-coupling ET\(_B\) or FP\(_1\) receptors, but not after stimulating endogenous muscarinic acetylcholine receptors or after applying hGPR30 agonists (n.s.: statistically not significant).

**Figure 6: Imaging of CFP-PLC-δ\(_1\)(PH) and PKC\(_{\varepsilon}\)-CFP translocation in HEK293\(_{hGPR30-YFP}\) cells induced by chlorhexidine and Lys05 addition.**

HEK293\(_{hGPR30-YFP}\) cells were transiently transfected with cDNA plasmids encoding the pleckstrin homology domain of phospholipase C-δ1 N-terminally fused to CFP (CFP-PLC-δ\(_1\)(PH); A-F) or a protein kinase C\(_{\varepsilon}\) C-terminally fused to CFP (PKC\(_{\varepsilon}\)-CFP; G-L). (A, D, G, J) Confocal microscopy images of the CFP-fused translocating biosensor proteins in unstimulated (left panels), and in chlorhexidine- or Lys05-stimulated cells (right panels). Bars: 20-µm scale. (B, E, H, K) Typical time courses of relative changes of PLC-δ\(_1\)(PH) or PKC\(_{\varepsilon}\) fluorescence signals measured by time-lapse epifluorescence microscopy in regions of interest defined over the plasma membrane (F\(_{pm}\)) and the cytosol (F\(_{cyt}\)) of the same cells, expressed as ratios and normalized to the initial values. Shown are data from 5-6 independent experiments, comprising 4-9 cells measured cells, each. (C, F, I, L) Statistical comparison (p < 0.05, Student’s t-test with unpaired data: #) of strongest PLC-δ\(_1\)(PH) or PKC\(_{\varepsilon}\)-CFP translocation effects seen in GPR30-expressing (GPR30) or in parental HEK293 (control) cells after addition of chlorhexidine (C, I) or Lys05 (F, L), observed in n = 5-6 independent experiments, each.
Figure 7: Förster resonance energy transfer (FRET)-based measurement of 3‘,5’-cyclic adenosine monophosphate (cAMP) formation during application of GPR30 agonists using an EPAC-derived biosensor.

A possible impact of GPR30 agonists on intracellular cyclic adenosine monophosphate formation was evaluated by transiently transfecting HEK293hGPR30-YFP cells with a cDNA encoding an established EPAC-based FRET biosensor. (A) After 24 hours, FRET efficiencies in 34-36 single cells (grey lines) and their averaged values (black lines) were recorded before and during application of 17ß-estradiol, G-1, chlorhexidine or Lys05 as indicated by the horizontal bars. Note the slight linear decline, which is caused by photobleaching the FRET acceptor YFP. (B) To validate cAMP measurements, positive controls with epinephrine and adenosine activating endogenously expressed β-adrenergic and adenosine receptors, respectively, were carried out. (C) Means and S.D. obtained from 4-6 independent biological experiments performed as in (A, B). #: differences to buffer (HBS)-treated controls at time point (2); p < 0.05). n.s.: no statistically significant differences to buffer controls.

Figure 8: Imaging of GPR30-induced ERK activity by using a FRET-based biosensor.

HEK293hGPR30-YFP cells (A) or parental HEK293 (B) cells were transiently transfected with cDNA plasmids encoding a cytosolic ERK activity reporter 4 (cytoEKAR4) to investigate the effect of chlorhexidine and Lys05 on ERK activity. Shown are exemplary measurements of FRET signals obtained from 46-77 single cells (grey lines) and their averaged values (black lines), respectively. As positive controls, experiments with recombinant human EGF (100 ng/ml), activating endogenously expressed EGF receptors were performed. The slight linear decline is caused by photobleaching of the FRET acceptor YFP during the experiment. (C, D) For statistical analysis, averaged values were obtained from 5-6 independent biological experiments performed as shown in (A, B), corrected for photobleaching, and FRET signals before (white bars) and 10 minutes after agonist addition (black bars) were compared. Increases in FRET signals after addition of chlorhexidine or Lys05 were recorded in
HEK293<sub>hGPR30-YFP</sub> cells (C; #: p < 0.05., One-Way ANOVA Dunn-Šidák) whereas parental HEK293 cells (D) showed no statistically significant ERK activation (n.s.).

**Figure 9: Rapid and efficient internalization of hGPR30 in the continuous presence of newly identified agonists.**

Image series of hGPR30-YFP were taken by confocal laser-scanning microscopy in living HEK293<sub>hGPR30-YFP</sub> cells immediately before (0 min) and at the indicated times after stimulating cells with either 5 µM chlorhexidine (A), Lys05 (B) or 9-aminoacridine (C). Bars: 10-µm scale. Note that receptor clustering at or close to the plasma membrane precedes the internalisation.

**Figure 10: Plasma membrane blebbing responses after hGPR30 stimulation with chlorhexidine and Lys05.**

Confocal laser scanning images like shown in Figure 8, but with HEK293<sub>hGPR30-YFP</sub> cells that were additionally stably co-transfected with a cDNA plasmid encoding a CAAX-box-modified and thereby plasma membrane-targeted cyan fluorescent protein (CFP-CAAX). Shortly after GPR30 activation with 5 µM chlorhexidine (A) or Lys05 (B), and during receptor clustering (upper panels), the CFP-delineated plasma membrane showed dynamic blebbing events (middle panels). Lower panels: overlay of YFP and CFP signals. Bars: 10-µm scale.

**Figure 11: Subcellular localisation and [Ca<sup>2+</sup>], responses of transiently overexpressed hGPR30 in various cell lines.**

The cellular localisation of human GPR30 and functional responsiveness to chlorhexidine and Lys05 were examined in HEK293 (A-C), COS-7 (D-F), HeLa (G-I), and MCF-7 cells (J-L). (A, D, G, J) Representative confocal microscopy images of hGPR30-YFP in different cell lines 24 hours after transient transfection. Bars: 20-µm scale. (B, E, H, K) Fluorometric single-cell [Ca<sup>2+</sup>], analysis in hGPR30-YFP-expressing HEK293, COS-7, HeLa or MCF-7 cells was performed as described in Figure 2C. Shown are exemplary measurements during...
chlorhexidine (left panels) or Lys05 (right panels) application. (C, F, I, L) Means and S.D. of the percentage of transfected cells that responded during application of the indicated hGPR30 agonists with increases in intracellular Ca\(^{2+}\) concentration by more than 100 nM. Data represent 4-6 independent measurements performed as in (B, E, H, K).
Figure 2

A

B

C

D

HEK293

hGPR30

Hoechst

merge

[Ca²⁺]i, (nM)

5 µM chlorhexidine

5 µM Lys05

5 µM 9-aminoacridine

F/F₀

HEK293

hGPR30-YFP

HEK293 parental

50 s

30 s

30 s

30 s

EC₅₀ = 0.75 µM

EC₅₀ = 0.27 µM

EC₅₀ = 1.78 µM

n.a.

n.a.

n.a.
Figure 4

A

5 μM chlorhexidine

5 μM Lys05

5 μM 9-aminoacridine

B

F_0 / F_0

60 s

HBS control
YM-254890
U-73433
U-73122
2-APB

chlorhexidine

Lys05

9-aminoacridine

# p < 0.05 vs. HBS control

* p < 0.05 vs. YM-254890
Figure 5

A

9-aminoacridine

chlorhexidine

Lys05

carbachol

\[ [Ca^{2+}]_i, \text{(nM)} \]

30 s

100

150

200

250

300

B

endothelin-1

fMLP

\[ [Ca^{2+}]_i, \text{(nM)} \]

30 s

100

150

200

250

300

C

\[ \Delta [Ca^{2+}]_i, \text{(nM)} \]

n.s.

n.s.

n.s.

n.s.

n.s.

# p < 0.05 vs. control

control

PTX

endothelin-1
Figure 7

A

5 μM 17β-estradiol

5 μM G-1

5 μM chlorhexidine

5 μM Lys05

FRET efficiency, (%)

60 s

B

10 μM epinephrine

20 μM adenosine

FRET efficiency, (%)

60 s

C

# p < 0.05 vs. HBS control
Figure 8

A

HEK293_hGPR30-YFP:

- 100 ng/ml EGF
- 5 μM chlorhexidine
- 5 μM Lys05
- solvent

B

HEK293_parental:

- 100 ng/ml EGF
- 5 μM chlorhexidine
- 5 μM Lys05
- solvent

C

HEK293_hGPR30-YFP

# p < 0.05 vs. basal

basal stimulus

D

HEK293_parental

# p < 0.05 vs. basal

basal stimulus
Figure 9

A  5 µM chlorhexidine

0 min  2 min  5 min  10 min  20 min

B  5 µM Lys05

0 min  2 min  5 min  10 min  20 min

C  5 µM 9-aminoacridine

0 min  2 min  5 min  10 min  20 min
Figure 10

A

basal | 5 μM chlorhexidine

hGR30-YFP

CFP-CAAX

merge

B

basal | 5 μM Lys05

hGR30-YFP

CFP-CAAX

merge
Figure 11

A. HEK293

B. HEK293

5 μM chlorhexidine

5 μM Lys05

C. HEK293

Δ[Ca^{2+}] > 100 nM (% of transf. cells)

D. COS-7

E. COS-7

5 μM chlorhexidine

5 μM Lys05

F. COS-7

Δ[Ca^{2+}] > 100 nM (% of transf. cells)

G. HeLa

H. HeLa

5 μM chlorhexidine

5 μM Lys05

I. HeLa

Δ[Ca^{2+}] > 100 nM (% of transf. cells)

J. MCF-7

K. MCF-7

5 μM chlorhexidine

5 μM Lys05

L. MCF-7

Δ[Ca^{2+}] > 100 nM (% of transf. cells)