

Pharmacological Characterization of Membrane-Expressed Human Trace Amine-Associated Receptor 1 (TAAR1) by a Bioluminescence Resonance Energy Transfer cAMP Biosensor

Larry S. Barak, Ali Salahpour, Xiaodong Zhang, Bernard Masri, Tatyana D. Sotnikova, Amy J. Ramsey, Jonathan D. Violin, Robert J. Lefkowitz, Marc G. Caron, and Raul R. Gainetdinov

Departments of Cell Biology (L.S.B., A.S., X.Z., B.M., T.D.S., A.J.R., M.G.C., R.R.G.) and Biochemistry (J.D.V., R.J.L.) and the Howard Hughes Medical Institute (J.D.V., R.J.L.), Duke University, Durham, North Carolina

Received May 15, 2008; accepted June 3, 2008

ABSTRACT

Trace amines are neurotransmitters whose role in regulating invertebrate physiology has been appreciated for many decades. Recent studies indicate that trace amines may also play a role in mammalian physiology by binding to a novel family of G protein-coupled receptors (GPCRs) that are found throughout the central nervous system. A major obstacle impeding the careful pharmacological characterization of trace amine associated receptors (TAARs) is their extremely poor membrane expression in model cell systems, and a molecular basis for this phenomenon has not been determined. In the present study, we show that the addition of an asparagine-linked glycosylation site to the N terminus of the human trace amine associated receptor 1 (TAAR1) is sufficient to enable its plasma membrane

expression, and thus its pharmacological characterization with a novel cAMP EPAC (exchange protein directly activated by cAMP) protein based bioluminescence resonance energy transfer (BRET) biosensor. We applied this novel cAMP BRET biosensor to evaluate the activity of putative TAAR1 ligands. This study represents the first comprehensive investigation of the membrane-expressed human TAAR1 pharmacology. Our strategy to express TAARs and to identify their ligands using a cAMP BRET assay could provide a foundation for characterizing the functional role of trace amines in vivo and suggests a strategy to apply to groups of poorly expressing GPCRs that have remained difficult to investigate in model systems.

Trace amines (TAs) are biogenic amines that include tyramine, tryptamine, octopamine, and β -phenylethylamine (β -PEA). TAs are found in the mammalian central nervous system at substantially lower levels than such typical transmitters as norepinephrine, serotonin, and dopamine (Boulton, 1980; Premont et al., 2001; Branchek and Blackburn, 2003; Berry, 2004; Grandy, 2007). TA dysregulation has been linked to various psychiatric and neurological disorders, in-

cluding schizophrenia and Parkinson's disease. As such, the TAs offer tempting targets for ameliorating the symptoms of central nervous system diseases when used in combination with standard therapies or for reducing doses and hence the side effects that accompany the long-term use of some currently prescribed medications. This is particularly relevant for Parkinson's disease, where long-term L-DOPA therapy often produces drug-related dyskinesias (Hornykiewicz, 2002; Fahn, 2003; Mercuri and Bernardi, 2005).

Trace amines are structurally related to several psychotropic molecules that naturally occur in plants, including amphetamine-like compounds. Amphetamines are recognized inhibitors of inward monoamine transport (Jones et al., 1998), and it was generally proposed that TAs also affect the monoamine system indirectly via interaction with plasma membrane transporters, such as the dopamine transporter

This work was supported by National Institutes of Health grants NS19576 and 1U01-DA022950, and by the Michael J. Fox Foundation for Parkinson's Research. A.S. was supported by a fellowship from Canadian Institutes of Health Research. B.M. is supported by a European Marie-Curie Outgoing International Fellowship (FP6-2005-Mobility-6).

L.S.B. and A.S. contributed equally to this work

Article, publication date, and citation information can be found at <http://molpharm.aspetjournals.org>.
doi:10.1124/mol.108.048884.

ABBREVIATIONS: TA, trace amine; β -PEA, β -phenylethylamine; GPCR, G-protein coupled receptor; TAAR, trace amine-associated receptor; β TAAR1, human TAAR1 with the first nine amino acids of the human β 2-AR inserted at the N terminus; h, human; BRET, bioluminescence resonance energy transfer; EPAC, exchange protein directly activated by cAMP; HA, hemagglutinin; PCR, polymerase chain reaction; HEK, human embryonic kidney; PBS, phosphate-buffered saline; MEM, minimal essential medium; GFP, green fluorescent protein; β 2-AR, β 2-adrenergic receptor; MDMA, methylenedioxymethamphetamine; DA, dopamine; IBMX, 3-isobutyl-1-methylxanthine; MT, methoxytyramine.

(Sotnikova et al., 2004). In this view, the TAs function simply as neuromodulators of conventional mammalian brain amine transmitters, and at physiological levels, TAs generally should have only minor effects on neuronal excitability in the absence of conventional monoamines. However, binding sites for tryptamine, tyramine and β -PEA have been reported in rat brain and a family of trace amine G-protein-coupled receptors (GPCRs) has been recently identified in rodents and humans (Borowsky et al., 2001; Bunzow et al., 2001; Lindemann and Hoener, 2005; Grandy, 2007). Thus solid support exists for a potential direct behavioral mechanism in which trace amines influence neuronal activity.

In humans, six trace amine-associated receptors (TAARs) and three pseudogenes have been identified (Lindemann and Hoener, 2005). Similar to their mouse counterparts on chromosome 10, human TAARs are coded for by intronless genes clustered tightly on chromosome 6. TAAR1 is the best characterized of them (Borowsky et al., 2001; Bunzow et al., 2001; Grandy, 2007). TAAR1 couples to G_s , and when assessed using cAMP, is activated by TAs such as β -PEA in addition to metabolites of catecholamines, amphetamines (including MDMA), and other compounds known to affect monoaminergic transmission (Borowsky et al., 2001; Bunzow et al., 2001; Kim and von Zastrow, 2001; Scanlan et al., 2004; Lindemann and Hoener, 2005; Miller et al., 2005; Grandy, 2007; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007).

In the brain, the mRNA for TAAR1 is distributed throughout the limbic system and in regions containing catecholaminergic cell bodies and their projections (Borowsky et al., 2001; Bunzow et al., 2001; Lindemann and Hoener, 2005; Xie et al., 2007). Thus, TAAR1 is well positioned to modulate locomotor, emotional, and motivated behaviors that are traditionally associated with monoaminergic activity. Recent evidence indicates that at least some TAARs can also serve as a new class of chemosensory receptors in mammals (Liberles and Buck, 2006). Because an imbalance in the function of TAs might have important implications in the pathogenesis of several disorders, finding selective small-molecule agonists and antagonists for these receptors could provide novel approaches to disease management. However, a major obstacle in studying and screening TA receptors is their extremely poor plasma membrane expression in heterologous cell systems (Borowsky et al., 2001; Bunzow et al., 2001; Lindemann and Hoener, 2005; Miller et al., 2005; Grandy, 2007; Wainscott et al., 2007; Wolinsky et al., 2007), a scenario remarkably similar to that of the large GPCR subfamily of chemosensory odorant receptors (Saito et al., 2004; Zhuang and Matsunami, 2007).

The human variant of the TAAR1 has remained even more difficult to express in model systems than its poorly expressed rodent analog (Lindemann and Hoener, 2005; Grandy, 2007), thus impeding measurements of biochemical and pharmacological properties of this receptor. To improve our ability to study hTAAR1, we investigated potential reasons for the poor hTAAR1 expression. In this report, we demonstrate that an *N*-glycosylated variant of the human TAAR1 expresses at the plasma membrane of HEK-293 cells well enough to be studied using antibody labeling. We have determined in this system that hTAAR1 can interact with β -arrestin2. Moreover, we have used an *N*-glycosylated variant of the human TAAR1 for identifying and studying TAAR1 ligands by constructing a novel

cell-based screening assay that employs a bioluminescence resonance energy transfer (BRET) exchange protein activated by cAMP (EPAC) cAMP biosensor.

Materials and Methods

Materials. Anti-HA antibody was from Roche Applied Sciences (Indianapolis, IN) and goat anti-mouse Alexa Fluor 568 antibody from Invitrogen (Carlsbad, CA). Plasmids containing the cDNA for the human trace amine receptor were obtained from the cDNA resource center at the University of Missouri-Rolla and the American Type Culture Collection (Manassas, VA). Sources of cell culture reagents and buffers were from Invitrogen and Sigma (St. Louis, MO), and fetal bovine serum from JRH Biosciences (Lenexa, KS). The enhanced green fluorescent protein plasmid was obtained from Clontech (Mountain View, CA). All compounds used in this study were obtained from Sigma.

Construction of Expression Vectors. A cDNA leader sequence containing the triple-HA epitope was constructed using the polymerase chain reaction for insertion into the plasmid pcDNA3. Full-length human TAAR1 cDNA without a stop codon was amplified by PCR with 5' and 3' in-frame restriction enzyme sites of EcoRI and KpnI, respectively. A cDNA encoding GFP in the absence of its initiation start codon was amplified by PCR with 5' (in-frame) and 3' (downstream of stop codon) restriction enzyme sites of KpnI and XbaI, respectively. Enzyme-digested TAAR1 and GFP PCR products were ligated into EcoRI and XbaI restriction enzyme sites of pcDNA3 vector with N-terminal triple HA tag to generate the triple HA- β 2N9-TAAR1-GFP construct. The cDNA corresponding to the first nine amino acids of the β 2-adrenergic receptor was inserted in-frame between the triple HA and TAAR1.

For the GFP-negative construct, the GFP moiety was removed from the above construct by PCR amplification using 5' T7 promoter sequence primer upstream of triple-HA sequence and 3' primer containing a stop codon followed by the restriction enzyme site of XbaI. The PCR product was then digested with HindIII (upstream of triple HA sequence) and XbaI, and subcloned into the pcDNA3 vector. Two complementary sequences encoding the EcoRV/EcoRI-digested β 2N9 DNA fragment were allowed to anneal in buffer containing 10 mM Tris-EDTA, pH 8.0, and 50 mM NaCl and were ligated into EcoRV/EcoRI restriction enzyme sites. The cDNA illustrative of these modifications is shown below; upper case characters correspond to the three triple-HA inserts, and the last segment corresponds to the β 2-adrenergic receptor. The corresponding cDNA sequence is: [tcaccatggtgtagctaccacTACGATGTTCTGACTATGCGggcTATCCCTATGACGTCCCGGACTATGCaggtatccTATCCATATGACGTTCCAGATTACGCCagatctgatataTGGGGCAACCCGGGAACGGCAGCGCCgaattcATGATGCCCTTTTGGC]. The translated sequence is: (s t m a s Y P Y D V P D Y a g Y P Y D V P D Y a g s Y P Y D V P D Y a r s d i M G Q P G N G S A e f M M P F C).

The BRET-based cyclic AMP biosensor (Ponsioen et al., 2004; Holz et al., 2006; Jiang et al., 2007) was constructed by the modification of ICUE2, an existing FRET-based intramolecular biosensor in which enhanced cyan fluorescent protein and citrine flank residues 149 to 881 of Epac1 (exchange proteins directly activated by cAMP) (DiPilato et al., 2004; Violin et al., 2008). The enhanced cyan fluorescent protein moiety of ICUE2 was removed by BamHI and KpnI restriction and replaced with a humanized *Renilla reniformis* luciferase gene that was PCR-amplified from pRhLuc-C1 (PerkinElmer Life and Analytical Sciences) and was engineered with BamHI and KpnI restriction sites that preserve the frame of translation. Primers for the PCR amplification of Rhuc were 5'-GGATCCATGACCAGCAAGGTGTACGACC and 5'-GGTACCCCCCTGCTCGTTCTTCA-GCAC.

Cell Culture and Transfection of Cell Lines. Cells were cultured in MEM supplemented with 10% fetal bovine serum and 1:100

penicillin/streptomycin in a humidified 5% CO₂ atmosphere. Transfections were carried out by the calcium phosphate precipitation method. HEK-293T cells or U2OS cells were transfected with aliquots containing 1 to 2 μ g of β -arrestin2 cDNA and/or 5 μ g of receptor cDNA per milliliter. Cells were plated for immunofluorescence studies into the wells of 35-mm glass-bottomed Matek dishes containing 2 ml of MEM/10% fetal bovine serum. Transfection solution (125 μ l) was added for a period lasting between 6 h and overnight, after which the transfection solution was replaced with fresh serum containing media. For BRET studies, the HEK-293T cells were transfected with 5 μ g of cDNA in 1 ml of transfection solution in 100-mm plastic dishes overnight and selected to permanently express the EPAC sensor using phleomycin (Zeocin; 200–400 μ g/ml). These cells were transfected as mentioned above with TAAR1 for evaluation of compounds in the screening assay.

Fluorescence Microscopy. Cells were plated at a density of 2 to 4 $\times 10^4$ /well in 35-mm Matek glass cover-slip-bottomed dishes. Anti-HA antibody was diluted 1:400. Alexa Fluor 568 goat anti-mouse antibody was used at a 1:1500 dilution. Fixed cells were first washed twice in PBS followed by incubation with 4% paraformaldehyde for 15 min at room temperature, rewashed, and then incubated for 40-min intervals in PBS with 2% bovine serum albumin with either anti-HA or, subsequently, secondary antibody using an intervening three washes with PBS between antibody treatments. Live cells were incubated with the same antibody dilutions in MEM at room temperature or 37°C. β -Arrestin translocation was assessed as described previously (Barak et al., 1997). Cells were examined with a Zeiss LSM-510 confocal microscope equipped with a 100 $\times$ /numerical aperture 1.4 oil objective using excitation at 488 nm for the GFP tag and excitation at 568 nm for Alexa Fluor 568 antibody, and using the accompanying fluorescein and rhodamine emission filter sets, respectively.

Immunoblotting. HEK-293T cells were transfected with the various HA-tagged receptor subtypes and lysed the following day in a buffer containing 20 mM Tris, pH 7.5, 150 mM NaCl, 1 mM EDTA, and 1% Triton X-100. Cell lysates were analyzed by SDS-polyacrylamide gel electrophoresis and immunoblotted with anti-HA antibody at a dilution of 1:5000.

BRET Screening Assays. HEK-293T cells permanently transfected with the EPAC sensor and transiently with the TAAR1 were split into 96-well plates at 15 to 20 $\times 10^4$ cells per well. On the following day, they were washed twice with PBS, and 80 μ l of PBS containing calcium and magnesium was added to each well followed by addition of 10 μ l of a 50 μ M coelenterazine solution (final concentration, 5 μ M). After 10-min incubation, either 10 μ l of vehicle or 10 $\times$ concentrated solution of drug in PBS was added, and the plate was then placed into a Mithras LB940 instrument (Berthold Technologies, Bad Wildbad, Germany) that allowed the sequential integration of the luminescent signals detected in the 465 to 505 nm and 505 to 555 nm windows using filters with the appropriate band pass and by using MicroWin 2000 software (Berthold Technologies). The BRET signal is determined by calculating the ratio of the light emitted at 505 to 555 nm to the light emitted at 465 to 505 nm.

Results

Expression of TAAR1 Receptors in Fixed HEK-293T Cells. Receptors of the human trace amine family have been notoriously difficult to express in model cell systems and are comparable in this regard with odorant receptors (Lindemann and Hoener, 2005; Grandy, 2007; Zhuang and Matsu-nami, 2007). Our initial attempts at expression were also disappointing, but in the process of evaluating TAAR1 plasma membrane expression, we noted a marked absence of glycosylated bands that are common to other rhodopsin-family GPCRs. Moreover, in silico prediction suggested that the N terminus of TAAR1 should be poorly glycosylated. There-

fore, in an attempt to augment TAAR1 glycosylation and the subsequent expression of the receptor at the plasma membrane (Fig. 1A), the first nine amino acids of the human β 2-adrenergic receptor (β 2-AR) were inserted between the HA tag and the N terminus of TAAR1, creating the HA- β TAAR1 (note that an initial attempt to augment expression using the N-terminal rhodopsin signal sequence proved unsuccessful). This nine-residue segment contains an asparagine glycosylation site at position 6 (Rands et al., 1990). Moreover, for the β 2-AR, this glycosylation enhances receptor expression at the plasma membrane (Rands et al., 1990). Without the added insert, we observed for a TAAR1-GFP chimera a homogeneous intracellular GFP distribution consistent with degraded TAAR1 (Fig. 1B, top left) or receptor trapped in the endoplasmic reticulum (Fig. 1B, top right). With addition of the first nine amino acids of the human β 2-adrenergic receptor, we observed a substantial accumulation, at 24 h, of what appears to be plasma membrane-localized receptor at the edge of the cells, with loss of the majority of internal staining (Fig. 1B, bottom). Immunoblotting of cell lysates for HA antibody (Fig. 1C) demonstrates extended bands for both GFP and non-GFP receptor variants characteristic of glycosylated receptor that runs above sharper-well defined bands typically characteristic of the immature receptor isoforms (Sadeghi et al., 1997; Barak et al., 2001). In addition, paraformaldehyde fixation without a permeabilization step of the HA-tagged β TAAR1 transfected cells indicates that the HA tag on the receptor is located at the external face of the plasma membrane (Fig. 1D).

Expression of TAAR1 in Live Cells. To estimate the expression level of the β TAAR1 and verify its orientation and integrity in the plasma membrane, we performed live cell immunofluorescence labeling with anti-HA antibody. Figure 2A shows the relative expression of HA tagged β 2-AR (Fig. 2A, left) compared with the HA- β TAAR1 GFP and non-GFP variants (Fig. 2A, middle and right). A more substantial expression of fluorescence associated with the β 2-AR is evident, as is a smaller expression level for the non- β TAAR1-GFP variant compared with the GFP version. The ability of GFP tagging to stabilize the expression of the β TAAR1 was also apparent from the immunoblotting in Fig. 1B. Labeling N-terminal plasma membrane receptor in live cells with antibody can result in receptor aggregation, and this inhomogeneous distribution can be used to verify the intactness of the receptor construct (Barak et al., 1997). Figure 2B shows that in nonpermeabilized live antibody-labeled cells, the C-terminal GFP distribution coincides with the HA epitope distribution, indicating that a fully formed full-length receptor is being expressed at the plasma membrane. Our ability to express β TAAR1 at the plasma membrane is not simply confined to HEK cells, in that transient labeling of the cell edge by β TAAR1 can also be demonstrated in a U2OS cell line (Fig. 2C). To demonstrate receptor functionality, we evaluated whether the β TAAR1 could undergo desensitization to known agonists using a β -arrestin2-GFP translocation assay. However, because of the relatively smaller expression levels of the β TAAR1, we first aggregated the receptors using mouse monoclonal anti-HA and Alexa Fluor 568 goat anti-mouse antibodies. As seen in Fig. 2D, the aggregated β TAAR1 in the presence of *p*-tyramine results in the translocation of a small amount of β -arrestin2-GFP, indicating that β TAAR1 can recruit β -arrestin2 similar to other GPCRs.

However, this modest translocation resembles that of the dopamine D3 receptor, which is known to desensitize relatively poorly in a β -arrestin-dependent manner (Kim et al., 2001, 2005). In addition, the reduced translocation may also be indicative of the lesser expression of β TAAR1 relative to the β 2-AR. Although the β -arrestin translocation assay can be used to measure receptor activation, evaluate both agonists, and antagonists at many receptors, in this case, the weak response precludes using the direct visualization assay for this receptor variant. Therefore, we investigated a novel cAMP signaling sensor that could function well at these smaller but still greatly improved TAAR1 expression levels.

BRET Sensor for Measuring TAAR1 in Real Time in Live Cells. cAMP production provides sufficient amplification to measure the functional activity of TAAR1 and so far has been the only practical way to approach the pharmacological study of this very poorly expressed receptor. A significant limitation of current methods to measure cAMP in cells for compound library screening is the extended activation period necessary to accumulate enough of the second messenger product to measure in antibody mediated assays. Here we evaluated a biosensor for real time screening of cAMP production in TAAR1-transfected cells. The cAMP

BRET biosensor was generated by modification of the original ICUE2 cAMP FRET biosensor (Violin et al., 2008). The sensor consists of an N-terminal truncated variant of the EPAC tagged with the *R. reniformis* luciferase and a yellow fluorescent protein variant (citrine) attached at the N and C termini, respectively (Fig. 3A). Upon binding cAMP, the signal of the biosensor decreases because of a conformational change that presumably increases the distance between the *R. reniformis* luciferase donor and the yellow fluorescent protein acceptor. The utility of the biosensor for measuring β TAAR1 cAMP signaling in real time is demonstrated in Fig. 3B, where application of 1 μ M β -PEA, a TAAR1 agonist, produces a sustained reduction in the BRET signal for β TAAR1 (wild-type TAAR1 did not produce changes in the BRET signal; data not shown). Moreover, the addition of IBMX to the incubation media resulted in a significant increase of the BRET signal to β -PEA (Fig. 3B) and isoproterenol (not shown), without changing the EC_{50} values of responses to either ligands (data not shown). The enhancement of the BRET signal with IBMX is consistent with its role as a phosphodiesterase inhibitor that prevents cAMP degradation. Figure 3C shows that, by increasing the β -PEA concentration, a concomitant increase in the β TAAR1 BRET signal

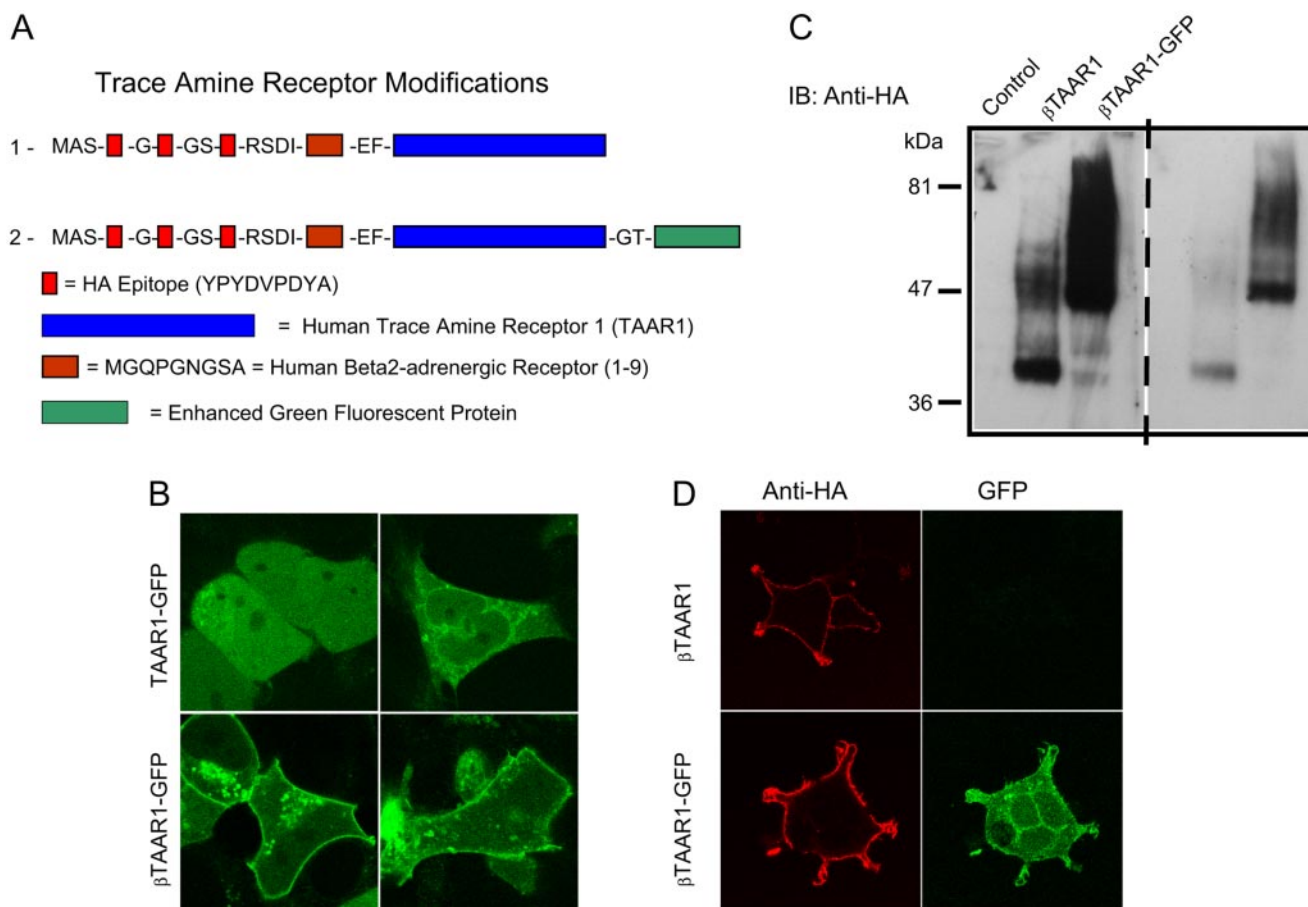


Fig. 1. Expression of the TAAR1 in HEK-293 Cells. A, pictured are the two variants of the human trace amine receptor that were used throughout the study. Insertion of the nine-amino-acid proximal portion of the human β 2-adrenergic receptor into the N terminus of the TAAR1 was a key to stabilizing it at the plasma membrane. B, confocal micrograph of the fluorescence distribution of GFP in HEK-293 cells transfected with 5 μ g of cDNA of the GFP variants of the TAAR1 without and with (β TAAR1) the β 2-adrenergic receptor insert. C, Western Blot for the HA epitope of the triple HA-tagged, β 2-adrenergic receptor (amino acids 1–9) modified TAAR1 variants transiently expressed in HEK-293 cells. Note that the right image represents the same blot with a lower exposure period. D, immunostaining using mouse anti-HA antibody followed by goat anti-mouse Alexa Fluor 568 secondary antibody of fixed, nonpermeabilized HEK cells transiently expressing either the β TAAR1 (top), or the β TAAR1 conjugated to GFP (bottom).

occurs and that the resulting signal amplitude remains stable for at least 20 min after induction of cAMP. In contrast, in these HEK-293 cells isoproterenol stimulation of the endogenous β 2-AR produces a transient change in the BRET signal that is maximal at 400 s and then returns slowly toward baseline (Fig. 3D), an indication of a desensitization of the signaling apparatus and a reduction in cAMP concentration (Violin et al., 2008).

Taken together, the β -arrestin/ β TAAR1 translocation and the cAMP BRET data indicate that the β TAAR1 has poorer affinity for β -arrestin2 than does the β 2-AR. To confirm a β TAAR1/ β -arrestin desensitization response by BRET, we transiently overexpressed both proteins in the same cell (Fig. 3E). In the presence of overexpressed β -arrestin2, a return to baseline (i.e., desensitization) of the β -PEA-mediated BRET signal, as well as a reduction in the magnitude of the BRET signal, is apparent after 5 min.

To demonstrate the general utility of the EPAC BRET sensor for determining cAMP concentrations, we cotransfected the sensor with the G_i -coupled D2 dopamine (DA) receptor, expecting that prestimulation of the cells by DA would dampen their cAMP responsiveness. Figure 3F demonstrates that increasing concentrations of DA diminish the magnitude of an isoproterenol-induced BRET signal toward control levels without significantly changing the time it takes the signal to desensitize.

Specificity of BRET Signaling of β TAAR1 in HEK-293 Cells. The sensitivity of the BRET EPAC assay enables measurement of the signaling of endogenous receptors (Fig.

3D). To verify the absence of TAAR1 signaling in HEK/EPAC cells not containing transfected β TAAR1 cDNA, we compared the isoproterenol and β -PEA response of non-receptor-transfected (mock) cells to cells transfected with β TAAR1 cDNA. Isoproterenol signaling was the same in both cell populations (Fig. 4A), whereas only the β TAAR1-transfected cells produced an EPAC signal significantly above baseline after β -PEA stimulation. The very small rise in the β -PEA signal in mock cells at high agonist concentrations may be due to activation of endogenous adrenergic receptors.

Activation of the β TAAR1 by TAAR1 Agonists β -PEA and *d*-Amphetamine. The endogenous trace amine β -PEA is the best established agonist of TAAR1 (Borowsky et al., 2001; Bunzow et al., 2001; Lindemann and Hoener, 2005; Miller et al., 2005; Grandy, 2007; Wainscott et al., 2007; Wolinsky et al., 2007). The effects of amphetamine on behavior have historically been attributed to the release of internal stores of dopamine (Jones et al., 1998). However, recent observations indicated that amphetamine derivatives can also directly activate TAAR1 (Bunzow et al., 2001; Miller et al., 2005; Grandy, 2007; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007). Therefore, by using the EPAC cell line, the ability of these two compounds to induce cAMP production through the β TAAR1 was tested (Fig. 4B). Moreover, to confirm the results, we also measured the cAMP response in HEK cells using the standard cAMP column assay developed by Salomon et al. (1974) (Fig. 4C). The results of the column and BRET measurements are shown in Table 1. They are quali-

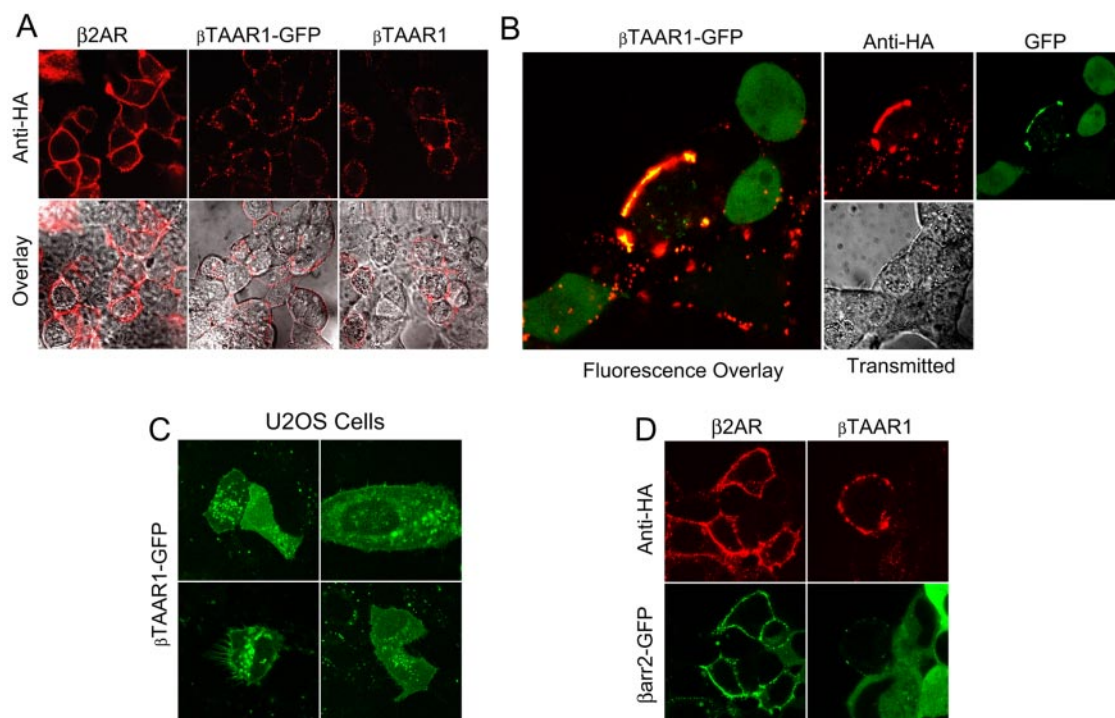


Fig. 2. Expression levels, distribution, and function of the β TAAR1 in live HEK cells. A, immunofluorescence and transmitted light images of Alexa Fluor 568 immuno-stained HA- β 2AR (leftmost images), β TAAR1-GFP (middle images), and β TAAR1 (rightmost images). Images using live HEK-293 cells expressing labeled receptors were acquired on a Zeiss LSM 510 confocal microscope using a 100 $\times$ /1.4 numerical aperture oil objective. B, overlay of Alexa Fluor 568, anti-HA immunostaining, and GFP imaging of the β TAAR1-GFP receptor. Images were acquired as above in live HEK cells plated and transfected in 35-mm glass-bottomed dishes (Matek). C, imaging of β TAAR1-GFP receptor in live U2OS cells transfected using calcium phosphate protocol with β TAAR1-GFP receptor as in B. Receptor can be seen as enhanced fluorescence at the edge of the cells. D, translocation of β -arrestin2-GFP was measured in cells transfected with β 2AR (leftmost images) or the β TAAR1 (rightmost images). Live cells were imaged after labeling with monoclonal anti-HA antibody followed by Alexa Fluor 568 goat anti-mouse antibody (top), and treatment for 30 min at 37°C with either 20 μ M isoproterenol (β 2AR) or 20 to 50 μ M *p*-tyramine for the β TAAR1. β -Arrestin2-GFP translocation is shown at the bottom (green).

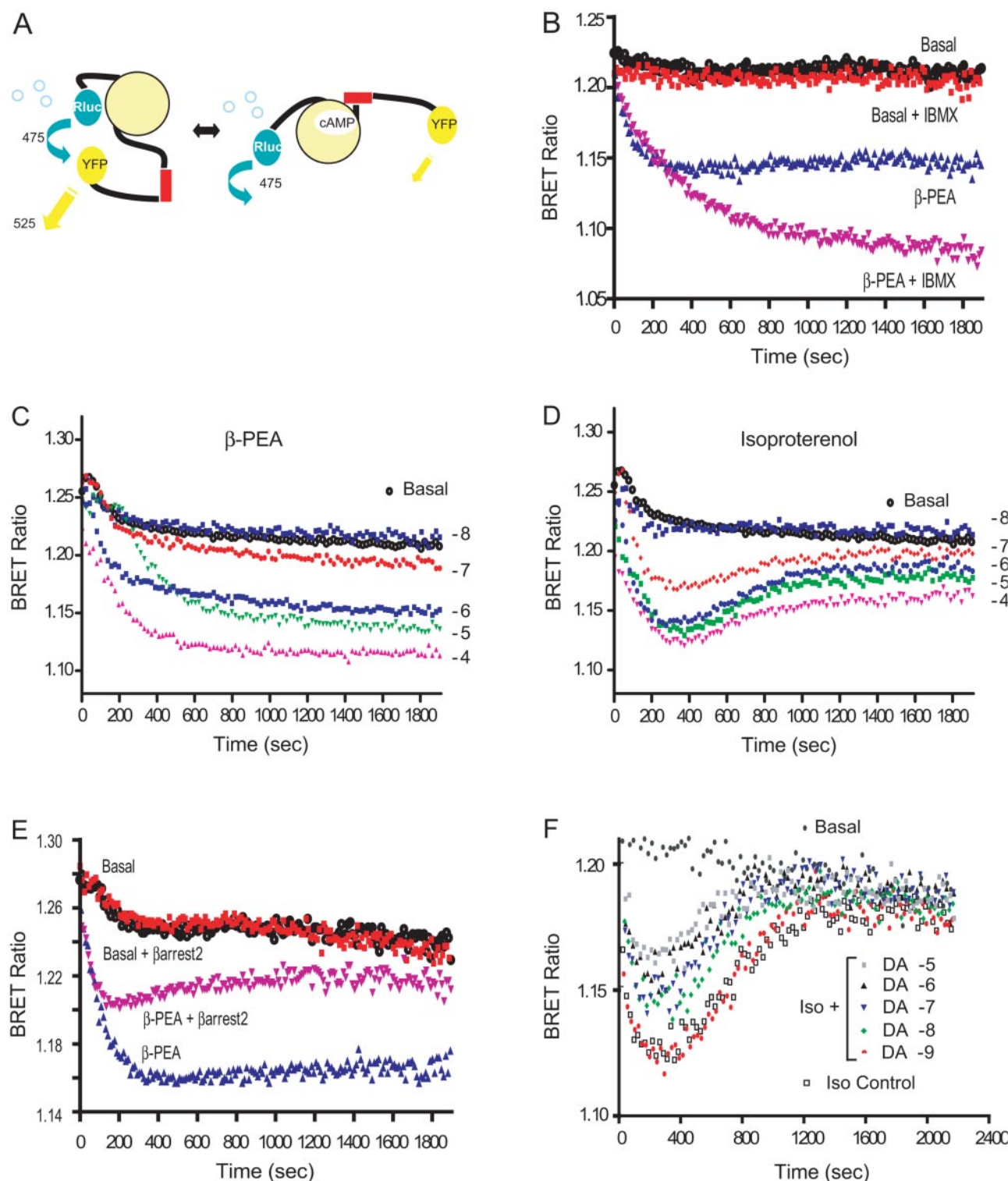


Fig. 3. Evaluation of cAMP response in HEK-293 cells using an EPAC BRET biosensor. **A**, diagram of the postulated molecular rearrangement of the full-length EPAC protein with and without cAMP present. **B**, time course of the BRET response computed as the ratio of YFP/Rluc emissions (see *Materials and Methods*) in HEK-293 cells transfected with the β TAAR1 and permanently expressing the BRET biosensor (clone 8). To generate the β -PEA curve, the cells were exposed to 10 μ M compound in PBS containing calcium and magnesium (see *Materials and Methods*), and 5 μ M coelenterazine at room temperature. The lower β -PEA curve reflects the increased levels of cAMP in the presence of IBMX (0.5 mM). **C**, time course of the BRET sensor response to cAMP accumulation after exposure to various doses of β -PEA in clone 8 cells expressing β TAAR1 receptor. **D**, an analogous time course graph is generated for cAMP production secondary to isoproterenol exposure of endogenous β 2-adrenergic receptors in the clone 8 HEK cells. **E**, the desensitizing effects of β -arrestin2 (β arrest2) cotransfection on the cAMP response of 10 μ M β -PEA treated β TAAR1 results in an upward deflection of the BRET response curve. **F**, the G_i-coupled D2 dopamine receptor was coexpressed in HEK-293 cells expressing the EPAC BRET biosensor and endogenous β -adrenergic receptor. Increasing concentrations of dopamine preceding isoproterenol stimulation of the β -adrenergic receptors results in decreased cAMP production and deflection of the BRET response upwards toward the measured basal cAMP response profile.

tatively similar, with the BRET assay yielding EC_{50} values for cAMP activation that are shifted to the left by 3- to 4-fold.

BRET Measurement of TAAR1 for Screening. The above results indicated that the TAAR1 BRET assay should be sensitive and specific enough for general screening of TAAR1 ligands using a higher throughput format. Therefore, we measured the dose response of approximately 40 more compounds that could be potential ligands of the TAAR1 in antagonist and agonist assays. Some examples of these studies are plotted in Fig. 4D. Although

among these compounds we detected no antagonist [based on their ability to counteract a β -PEA-induced BRET signal (data not shown)], we found several compounds that induced relatively potent agonist activity (Table 2) supporting previous reports on activity of these compounds at TAAR1 receptors (Bunzow et al., 2001; Miller et al., 2005; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007). A list of compounds that exerted no activity at β TAAR1 in the BRET assay is presented in Table 3.

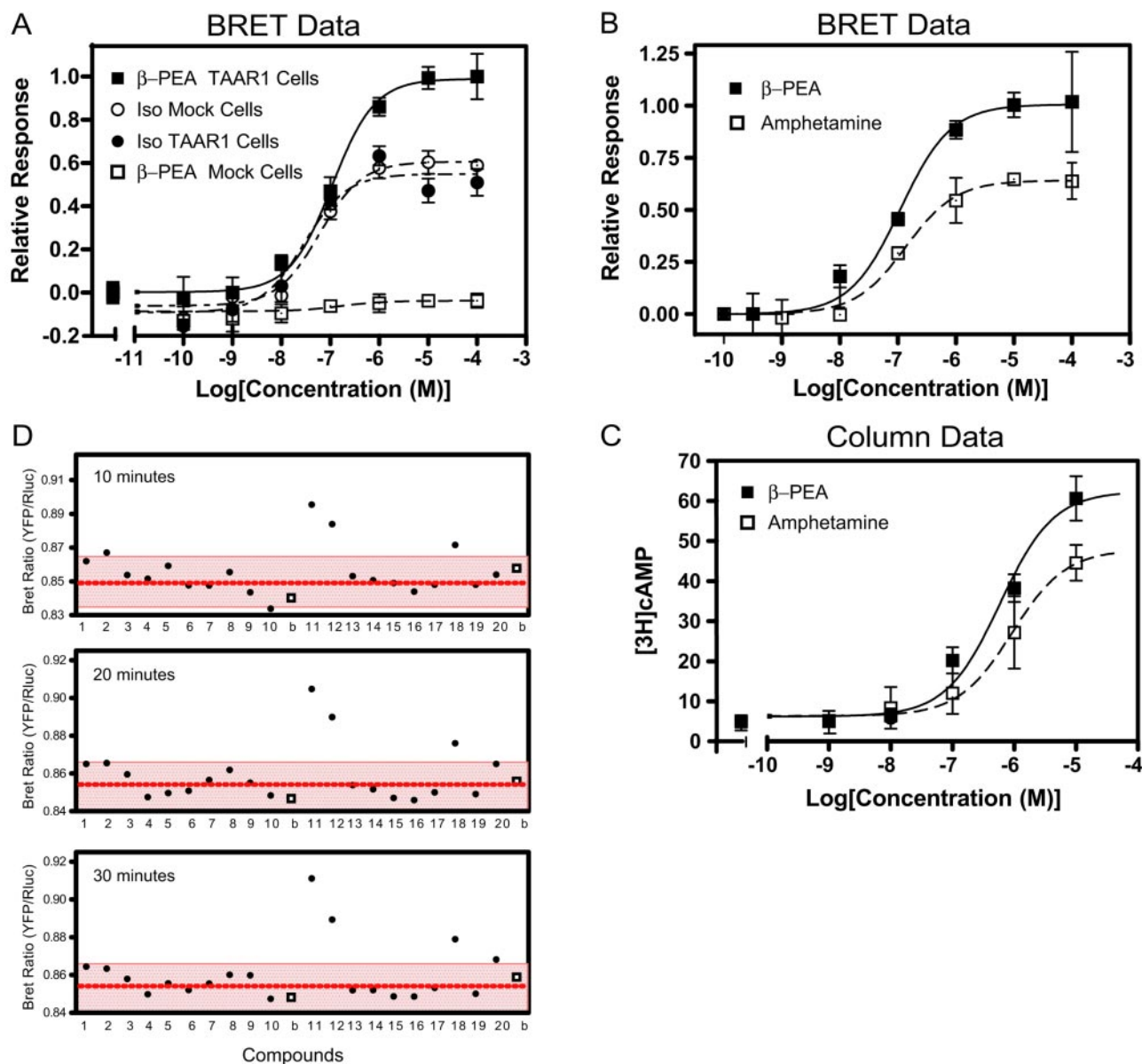


Fig. 4. EPAC response in HEK-293 cells with stimulation of endogenous and transfected receptors. A, clone 8 HEK-293 cells permanently expressing Rluc-EPAC-YFP and endogenous receptors only (mock) or expressing in addition transfected β TAAR1 were exposed to differing concentrations of isoproterenol or β -PEA for 5 and 15 min, respectively, at room temperature. Data are presented as the relative change $\pm$ S.E.M. from the baseline level BRET measurements, and results are the average of two (iso Mock) to four independent experiments. B, clone 8 cells expressing the β TAAR1 were exposed to varying concentrations of β -PEA and *d*-amphetamine for 15 min at room temperature. Results are presented as mean $\pm$ S.E.M. change from baseline BRET signaling and represent two independent experiments performed in duplicate. C, Dowex and Alumina column chromatography was used to measure [3 H]cAMP accumulation in HEK-293 cells transfected with the β TAAR1 receptor and treated with the concentrations of compounds shown in the Figure for 15 min at room temperature. Results are the mean $\pm$ S.E.M. of two (*d*-amphetamine) or three (β -PEA) independent experiments performed in duplicate. D, example of TAAR1 BRET assay screening test for TAAR1 ligands. Twenty compounds were tested in this experiment at a single concentration (10 μ M). Measurements were performed 10, 20, and 30 min after addition of compounds. b, vehicle baseline; compound 11, β -PEA; compound 12, *l*-amphetamine; compound 18, *d*-methamphetamine. Stippled area around the baseline represents 95% confidence interval for vehicle response. On the basis of the data presented in this report, we estimated Z-score as 0.6.

Discussion

Trace amine-associated receptors, like olfactory receptors, are notoriously difficult to express in heterologous cell systems. This poor cell surface expression has been a major limitation for understanding TAAR1 biology and evaluating TAAR1 selective ligands. In fact, up to this point, there has been no compelling direct evidence in the literature to suggest that the intact human TAAR1 could be expressed at sufficient amounts in a cell system, particularly at the plasma membrane compartment (Borowsky et al., 2001; Bunzow et al., 2001; Scanlan et al., 2004; Lindemann and Hoener, 2005; Miller et al., 2005; Grandy, 2007; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007). Our data with HA-tagged and GFP-modified human TAAR1 provides evidence that glycosylation-stabilized expression of the receptor can occur in cells at levels sufficient for characterizing receptor biology and developing reliable in vitro cellular assays without modifying intracellular loops, developing human-rat chimeras (Lindemann and Hoener, 2005; Grandy, 2007), or coexpressing human TAAR1 with rat $G\alpha_s$ (Wainscott et al., 2007). Furthermore, we devised and validated a novel BRET cAMP biosensor cellular assay that permits high-throughput screening for TAAR1 agonists and antagonists. Although β TAAR1 expression was 5- to 10-fold lower than what can be achieved with the β 2-adrenergic receptor, we observed that an N- β 2-AR peptide modified TAAR1 enables observable plasma membrane expression for which limited β -arrestin translocation occurs.

The ability of the human TAAR1 to activate adenylyl cyclase with previously identified agonists was assessed by standard methods using column chromatography and by a novel BRET method employing an EPAC biosensor. The two distinct techniques were in agreement that human TAAR1 in HEK cells responds to β -PEA and *d*-amphetamine, similar to what has been reported for rodent receptors or rodent modified human variants (Borowsky et al., 2001; Bunzow et al., 2001; Lindemann and Hoener, 2005; Miller et al., 2005; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007). Although the measurement of cAMP using chromatography is not well suited to high-throughput screening, we observed that the BRET method described here can be applied to large-scale screening for GPCR ligands. In fact, in our initial BRET cAMP screening, we confirmed agonistic activity at human TAAR1 of several other compounds, including the trace amines octopamine and tryptamine, the amphetamine derivatives *l*-amphetamine, *d*-methamphetamine, (+)-MDMA, and phentermine, and the catecholamine metabolites 3-MT and 4-MT (Bunzow et al., 2001; Lindemann and Hoener, 2005; Reese et al., 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007). It has been noted previously that activity of these compounds at TAAR1 can differ significantly among

different species (Lindemann and Hoener, 2005; Grandy, 2007; Wainscott et al., 2007). Accordingly, we observed that although these compounds were active at human TAAR1 with potencies generally similar to that observed in rodent, Rhesus monkey (*Macaca mulatta*) and chimeric human-rodent receptors (Bunzow et al., 2001; Lindemann and Hoener, 2005; Grandy, 2007; Wainscott et al., 2007; Wolinsky et al., 2007; Xie and Miller, 2007; Xie et al., 2007), several important differences were also noted. In particular, the most efficacious compound at human TAAR1 appeared to be *l*-amphetamine, followed by *d*-methamphetamine, with activities at least equal to or exceeding that of β -PEA. It is interesting also that trace amines octopamine and tryptamine showed partial agonist activity at human TAAR1 with potencies that were somewhat higher than those observed in previous studies with human-rat chimeric receptors (Lindemann and Hoener, 2005; Grandy, 2007; Wainscott et al., 2007). Finally, these studies also confirmed activity of catecholamine metabolites 3-MT and 4-MT at human TAAR1 (Bunzow et al., 2001; Grandy, 2007; Wainscott et al., 2007), raising an intriguing question on physiological roles that may be mediated by these metabolites via activation of TAAR1 receptors. By assessing the capability of compounds to reduce β -PEA-induced BRET signaling, we also sought to identify antagonists of TAAR1, but in a small list of compounds tested, no such activity was found. Tests of larger libraries of compounds for TAAR1 activity by using this assay are clearly warranted and are being performed currently in our lab.

It is noteworthy that the BRET method has been used for high-throughput screening of chemokine receptor CCR5 antagonists using a variant of a BRET-sensitive β -arrestin2 recruitment assay (Hamdan et al., 2005). During the course of this work, a similar BRET sensor for cAMP, CAMYEL (cAMP sensor using YFP-Epac-RLuc), was developed independently for characterizing cAMP synthesis stimulated via a sphingosine 1-phosphate/G13 pathway (Jiang et al., 2007). Moreover, the modified EPAC cAMP sensor, described here, has shown recently great utility to monitor dynamics of β 2AR desensitization in live cells by fluorescence resonance energy transfer (Violin et al., 2008). The BRET data in our study indicate that the TAAR1-induced cellular concentration of cAMP is stable over an extended period. In contrast, under similar assay conditions, β 2AR cAMP production decreases relatively rapidly presumably as a result of more pronounced receptor desensitization (Jiang et al., 2007; Violin et al., 2008). The TAAR1 behaves in this regard similarly to the dopamine D3 receptor, which also shows no discernable desensitization in HEK 293 cells (Kim et al., 2001, 2005).

In conclusion, we expressed human TAAR1 receptor in HEK cells at the plasma membrane at levels enabling biologic characterization and the development of a BRET signaling cellular assay for large-scale screening of TAAR1

TABLE 1

Comparison of activity of β -PEA and *d*-amphetamine at TAAR1 as measured by column cAMP assay and BRET assay

Values are estimated from experiments presented in Fig. 4, B and C.

Compounds	Column Assay		BRET Assay	
	EC ₅₀	Efficacy (Proportion of β -PEA)	EC ₅₀	Efficacy (Proportion of β -PEA)
	<i>M</i>	%	<i>M</i>	%
β -PEA	$5.8 \pm 0.58 \times 10^{-7}$	100	$1.08 \pm 0.29 \times 10^{-7}$	100
<i>d</i> -Amphetamine	$9.3 \pm 2.79 \times 10^{-7}$	73.9 $\pm$ 12.6	$1.36 \pm 0.14 \times 10^{-7}$	62.6 $\pm$ 1.7

ligands. Identification of selective ligands of the TAAR1 would be critical for investigating the functional role of this receptor in mammalian physiology in vivo and/or managing human disorders in which abnormalities in TA physiology may occur. The use of the BRET EPAC biosensor described here may become an effective approach to identify selective agonists and antagonists of a wide range of GPCRs in general. Compared with other available cAMP assays, the described BRET assay provides a user-friendly opportunity for real-time dynamic assessment of cAMP production rather than single-endpoint analysis of total accumulated cAMP. In addition, the strategy applied to express TAAR1 in HEK cells may be applicable to other GPCRs, such as olfactory receptors that exhibit very limited expression at the plasma membrane in model systems.

TABLE 2

List of TAAR1 agonists identified in BRET assay

Dose-response curves were generated as in Fig. 4B by measuring responses from 10^{-4} to 10^{-10} M for each compound. Results of at least two independent experiments are presented. Note that no response was observed in mock cells not transfected with β TAAR1.

Compounds	EC ₅₀	Efficacy (Proportion of β -PEA)
	<i>M</i>	%
<i>p</i> -Tyramine	$3.24 \pm 0.39 \times 10^{-7}$	101.7 ± 2.3
Octopamine	$1.66 \pm 0.74 \times 10^{-6}$	63.6 ± 1.9
Tryptamine	$1.95 \pm 0.49 \times 10^{-6}$	82.6 ± 4.7
<i>l</i> -Amphetamine	$2.45 \pm 0.14 \times 10^{-7}$	127.9 ± 4.1
(+)-MDMA	$3.70 \pm 0.54 \times 10^{-7}$	89.6 ± 6.3
<i>d</i> -Methamphetamine	$1.31 \pm 0.19 \times 10^{-6}$	107.7 ± 5.1
Phentermine	$1.08 \pm 0.04 \times 10^{-6}$	87.7 ± 1.1
3-MT	$2.81 \pm 0.24 \times 10^{-6}$	63.7 ± 5.4
4-MT	$2.87 \pm 0.04 \times 10^{-6}$	74.4 ± 3.74

TABLE 3

Compounds that did not show activity (agonist or antagonist) at TAAR1 in EPAC BRET assay

Dose-response curves were generated as in Fig. 4B by measuring responses from 10^{-4} to 10^{-10} M for each compound. In antagonist assay, the ability of compounds to counteract BRET signal induced by 10μ M β -PEA was evaluated. At least two tests were performed.

Compounds
L-DOPA
D-DOPA
Bupropion
Spermidine
Spermine
Haloperidol
α -Methyl-serotonin
Morphine
Naltrexone
Naloxone
Methadone
L-Tyrosine
Methylphenidate
Phentolamine
2-Methyl-6-(phenylethynyl)-pyridine
Zonisamide
Lamotrigine
Modafinil
D-Phenylalanine
5-Methoxy- <i>N,N</i> -dimethyltryptamine
3-Methoxy-L-tyrosine
<i>L</i> -threo-3,4-Dihydroxyphenylserine
Pergolide
Propranolol
Atropine
Capsaicin
Capsazepine

Acknowledgments

We thank Ava Sweeney, Katherine Clark, and Yushi Bai for excellent technical assistance in performing these experiments.

References

- Barak LS, Ferguson SS, Zhang J, and Caron MG (1997) A β -arrestin/green fluorescent protein biosensor for detecting G protein-coupled receptor activation. *J Biol Chem* **272**:27497–27500.
- Barak LS, Oakley RH, Laporte SA, and Caron MG (2001) Constitutive arrestin-mediated desensitization of a human vasopressin receptor mutant associated with nephrogenic diabetes insipidus. *Proc Natl Acad Sci U S A* **98**:93–98.
- Berry MD (2004) Mammalian central nervous system trace amines. Pharmacologic amphetamines, physiologic neuromodulators. *J Neurochem* **90**:257–271.
- Borowsky B, Adham N, Jones KA, Raddatz R, Artymyshyn R, Ogozalek KL, Durkin MM, Lakhilani PP, Bonini JA, Pathirana S, et al. (2001) Trace amines: identification of a family of mammalian G protein-coupled receptors. *Proc Natl Acad Sci U S A* **98**:8966–8971.
- Boulton AA (1980) Trace amines and mental disorders. *Can J Neurol Sci* **7**:261–263.
- Branchek TA and Blackburn TP (2003) Trace amine receptors as targets for novel therapeutics: legend, myth and fact. *Curr Opin Pharmacol* **3**:90–97.
- Bunzow JR, Sonders MS, Arttamangkul S, Harrison LM, Zhang G, Quigley DI, Darland T, Suchland KL, Pasumamula S, Kennedy JL, et al. (2001) Amphetamine, 3,4-methylenedioxyamphetamine, lysergic acid diethylamide, and metabolites of the catecholamine neurotransmitters are agonists of a rat trace amine receptor. *Mol Pharmacol* **60**:1181–1188.
- DiPilato LM, Cheng X, and Zhang J (2004) Fluorescent indicators of cAMP and Epac activation reveal differential dynamics of cAMP signaling within discrete subcellular compartments. *Proc Natl Acad Sci U S A* **101**:16513–16518.
- Fahn S (2003) Description of Parkinson's disease as a clinical syndrome. *Ann NY Acad Sci* **991**:1–14.
- Grandy DK (2007) Trace amine-associated receptor 1-Family archetype or iconoclast? *Pharmacol Ther* **116**:355–390.
- Hamdan FF, Audet M, Garneau P, Pelletier J, and Bouvier M (2005) High-throughput screening of G protein-coupled receptor antagonists using a bioluminescence resonance energy transfer 1-based beta-arrestin2 recruitment assay. *J Biomol Screen* **10**:463–475.
- Holz GG, Kang G, Harbeck M, Roe MW, and Chepurly OG (2006) Cell physiology of cAMP sensor Epac. *J Physiol* **577**:5–15.
- Hornykiewicz O (2002) L-DOPA: from a biologically inactive amino acid to a successful therapeutic agent. *Amino Acids* **23**:65–70.
- Jiang LI, Collins J, Davis R, Lin KM, DeCamp D, Roach T, Hsueh R, Rebrés RA, Ross EM, Taussig R, et al. (2007) Use of a cAMP BRET sensor to characterize a novel regulation of cAMP by the sphingosine 1-phosphate/G₁₃ pathway. *J Biol Chem* **282**:10576–10584.
- Jones SR, Gainetdinov RR, Wightman RM, and Caron MG (1998) Mechanisms of amphetamine action revealed in mice lacking the dopamine transporter. *J Neurosci* **18**:1979–1986.
- Kim KA and von Zastrow M (2001) Old drugs learn new tricks: insights from mammalian trace amine receptors. *Mol Pharmacol* **60**:1165–1167.
- Kim KM, Gainetdinov RR, Laporte SA, Caron MG, and Barak LS (2005) G protein-coupled receptor kinase regulates dopamine D3 receptor signaling by modulating the stability of a receptor-filamin- β -arrestin complex. A case of autoreceptor regulation. *J Biol Chem* **280**:12774–12780.
- Kim KM, Valenzano KJ, Robinson SR, Yao WD, Barak LS, and Caron MG (2001) Differential regulation of the dopamine D2 and D3 receptors by G protein-coupled receptor kinases and β -arrestins. *J Biol Chem* **276**:37409–37414.
- Liberles SD and Buck LB (2006) A second class of chemosensory receptors in the olfactory epithelium. *Nature* **442**:645–650.
- Lindemann L and Hoener MC (2005) A renaissance in trace amines inspired by a novel GPCR family. *Trends Pharmacol Sci* **26**:274–281.
- Mercuri NB and Bernardi G (2005) The 'magic' of L-dopa: why is it the gold standard Parkinson's disease therapy? *Trends Pharmacol Sci* **26**:341–344.
- Miller GM, Verrico CD, Jassen A, Konar M, Yang H, Panas H, Bahn M, Johnson R, and Madras BK (2005) Primate trace amine receptor 1 modulation by the dopamine transporter. *J Pharmacol Exp Ther* **313**:983–994.
- Ponsioen B, Zhao J, Riedl J, Zwartkruis F, van der Krogt G, Zaccolo M, Moolenaar WH, Bos JL, and Jalink K (2004) Detecting cAMP-induced Epac activation by fluorescence resonance energy transfer: Epac as a novel cAMP indicator. *EMBO Rep* **5**:1176–1180.
- Premont RT, Gainetdinov RR, and Caron MG (2001) Following the trace of elusive amines. *Proc Natl Acad Sci U S A* **98**:9474–9475.
- Rands E, Candelore MR, Cheung AH, Hill WS, Strader CD, and Dixon RA (1990) Mutational analysis of β -adrenergic receptor glycosylation. *J Biol Chem* **265**:10759–10764.
- Reese EA, Bunzow JR, Arttamangkul S, Sonders MS, and Grandy DK (2007) Trace amine-associated receptor 1 displays species-dependent stereoselectivity for isomers of methamphetamine, amphetamine, and para-hydroxyamphetamine. *J Pharmacol Exp Ther* **321**:178–186.
- Sadeghi HM, Innamorati G, and Birnbaumer M (1997) Maturation of receptor proteins in eukaryotic expression systems. *J Recept Signal Transduct Res* **17**:433–445.
- Saito H, Kubota M, Roberts RW, Chi Q, and Matsunami H (2004) RTP family members induce functional expression of mammalian odorant receptors. *Cell* **119**:679–691.
- Salomon Y, Londos C, and Rodbell M (1974) A highly sensitive adenylate cyclase assay. *Anal Biochem* **58**:541–548.
- Scanlan TS, Suchland KL, Hart ME, Chiellini G, Huang Y, Krucich PJ, Frascarelli S, Crossley DA, Bunzow JR, Ronca-Testoni S, et al. (2004) 3-Iodothyronamine is an endogenous and rapid-acting derivative of thyroid hormone. *Nat Med* **10**:638–642.

- Sotnikova TD, Budygin EA, Jones SR, Dykstra LA, Caron MG, and Gainetdinov RR (2004) Dopamine transporter-dependent and -independent actions of trace amine beta-phenylethylamine. *J Neurochem* **91**:362–373.
- Violin JD, DiPilato LM, Yildirim N, Elston TC, Zhang J, and Lefkowitz RJ (2008) β_2 -Adrenergic receptor signaling and desensitization elucidated by quantitative modeling of real-time camp dynamics. *J Biol Chem* **283**:2949–2961.
- Wainscott DB, Little SP, Yin T, Tu Y, Rocco VP, He JX, and Nelson DL (2007) Pharmacologic characterization of the cloned human trace amine-associated receptor1 (TAAR1) and evidence for species differences with the rat TAAR1. *J Pharmacol Exp Ther* **320**:475–485.
- Wolinsky TD, Swanson CJ, Smith KE, Zhong H, Borowsky B, Seeman P, Branchek T, and Gerald CP (2007) The Trace Amine 1 receptor knockout mouse: an animal model with relevance to schizophrenia. *Genes Brain Behav* **6**:628–639.
- Xie Z and Miller GM (2007) Trace amine-associated receptor 1 is a modulator of the dopamine transporter. *J Pharmacol Exp Ther* **321**:128–136.
- Xie Z, Westmoreland SV, Bahn ME, Chen GL, Yang H, Vallender EJ, Yao WD, Madras BK, and Miller GM (2007) Rhesus monkey trace amine-associated receptor 1 signaling: enhancement by monoamine transporters and attenuation by the D2 autoreceptor in vitro. *J Pharmacol Exp Ther* **321**:116–127.
- Zhuang H and Matsunami H (2007) Synergism of accessory factors in functional expression of mammalian odorant receptors. *J Biol Chem* **282**:15284–15293.

Address correspondence to: Marc G. Caron, Box 3287, Duke University, Durham, NC 27710. E-mail: m.caron@cellbio.duke.edu
