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RESEARCH PAPER

Functional efficacy of adenosine A_{2A} receptor agonists is positively correlated to their receptor residence time

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BACKGROUND AND PURPOSE

The adenosine A_{2A} receptor belongs to the superfamily of GPCRs and is a promising therapeutic target. Traditionally, the discovery of novel agents for the A_{2A} receptor has been guided by their affinity for the receptor. This parameter is determined under equilibrium conditions, largely ignoring the kinetic aspects of the ligand-receptor interaction. The aim of this study was to assess the binding kinetics of A_{2A} receptor agonists and explore a possible relationship with their functional efficacy.

EXPERIMENTAL APPROACH

We set up, validated and optimized a kinetic radioligand binding assay (a so-called competition association assay) at the A_{2A} receptor from which the binding kinetics of unlabelled ligands were determined. Subsequently, functional efficacies of A_{2A} receptor agonists were determined in two different assays: a novel label-free impedance-based assay and a more traditional cAMP determination.

KEY RESULTS

A simplified competition association assay yielded an accurate determination of the association and dissociation rates of unlabelled A_{2A} receptor ligands at their receptor. A correlation was observed between the receptor residence time of A_{2A} receptor agonists and their intrinsic efficacies in both functional assays. The affinity of A_{2A} receptor agonists was not correlated to their functional efficacy.

CONCLUSIONS AND IMPLICATIONS

This study indicates that the molecular basis of different agonist efficacies at the A_{2A} receptor lies within their different residence times at this receptor.

Abbreviations

ADA, adenosine deaminase; BCA, bicinchoninic acid; CHAPS, 3-[(3-cholamidopropyl) dimethylammonio]-1-propanesulfonate; CI, cell index; HEK293hA_{2A}R, human embryonic kidney 293 cells stably expressing the hA_{2A} receptor; k_3, the association rate constant of the unlabelled ligand; k_4, the dissociation rate constant of the unlabelled ligand; RT, residence time; Z, cell-electrode impedance; ZM241385, 4-(2-[7-amino-2-(2-furyl)[1,2,4]triazolo[2,3-*a*][1,3,5]triazin-5-ylamino]ethyl)phenol

Introduction

Extracellular adenosine is a ubiquitous local hormone that has been reported to play an important physiological role in numerous tissues, for instance in the sleep/wake cycle and in inflammation. The nucleoside can bind and activate four subtypes of adenosine receptors (Fredholm *et al.*, 2001; 2011). These are the adenosine A_1, A_{2A}, A_{2B} and A_3 receptors, which

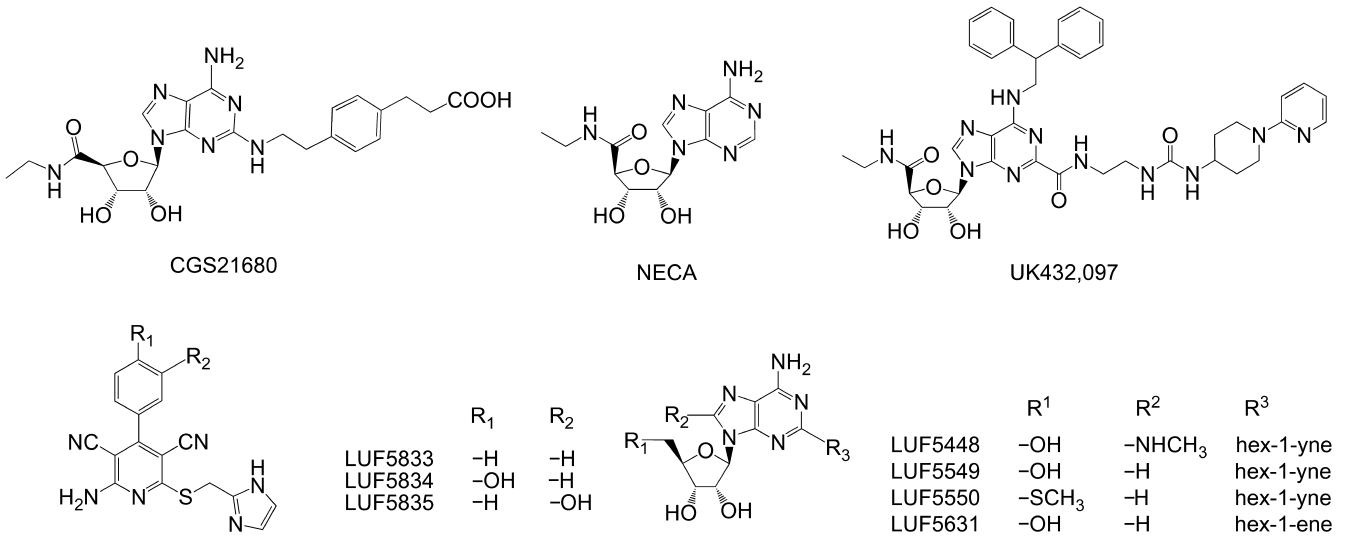

Figure 1
Chemical structures of the 10 A_{2A} receptor agonists used in this study.

belong to the superfamily of GPCRs. The adenosine A_1 and A_3 receptors are mainly coupled to the enzyme adenylate cyclase in an inhibitory fashion via a G_i protein, whereas the A_{2A} and A_{2B} receptors stimulate this enzyme via a G_s protein (Gao and Jacobson, 2007). In this study, we focused on agonists for the human adenosine A_{2A} receptor (hA_{2A} receptor), which have clinical relevance in various pathological conditions such as respiratory disorders and inflammatory conditions (Jacobson and Gao, 2006).

Traditionally, drug discovery campaigns for A_{2A} receptor (and other GPCRs) agents usually include the identification of lead compounds in a dose-dependent assessment of activities (i.e. EC_{50} or K_i values) under equilibrium conditions. The binding kinetics of the drug–target interaction are usually not taken into account. However, awareness of the importance of binding kinetics has started to increase because accumulating evidence (Swinney, 2004; Copeland *et al.*, 2006; Tummino and Copeland, 2008; Zhang and Monsma, 2009) suggests that the *in vivo* effectiveness of ligands may be attributed to the time ligands reside at their receptor. The duration a drug stays in a complex with the target is defined as 'drug–target residence time', which equals the reciprocal of the dissociation rate constant ($1 \cdot k_{off}^{-1}$) (Copeland, 2005).

A recent study at the muscarinic M_3 receptor showed a tight correlation between receptor residence time and agonist efficacy (Sykes *et al.*, 2009). This finding suggests that the molecular basis behind ligand efficacy may be inextricably linked to the ligand-receptor residence time. To verify this possible relationship, we determined the binding kinetics of 10 A_{2A} receptor agonists from different chemical classes (Figure 1) and extensively explored the putative relationship to their functional efficacies at the hA_{2A} receptor. The agonist-binding kinetics were quantified using a competition association method (Motulsky and Mahan, 1984), which we adopted and further optimized into a fast, medium-throughput format. The efficacies of the A_{2A} receptor agonists were measured, for the first time, in a novel label-free impedance-based assay and in a 'traditional' cAMP assay.

Methods

Chemicals and reagents

[^{3}H]-ZM241385 (specific activity 28.4 Ci mmol^{-1}) was purchased from ARC Inc. (St. Louis, MO, USA). Unlabelled ZM241385 was a gift from Dr S. M. Poucher (AstraZeneca, Macclesfield, UK). CGS21680 was a gift from Dr R. A. Lovell (Ciba-Geigy, Summit, NJ, USA). 5′-N-ethylcarboxamidoadenosine (NECA) was purchased from Sigma-Aldrich (Steinheim, Germany), UK432,097 was purchased from Axon (Groningen, the Netherlands). LUF5448 and LUF5631 were synthesized in our laboratory as described previously by van Tilburg *et al.* (2003); LUF5549 and LUF5550 were described by van Tilburg *et al.* (2002); LUF5833, LUF5834 and LUF5835 were described by Beukers *et al.* (2004). GTP was purchased from Acros Organics (Geel, Belgium). Adenosine deaminase (ADA) was purchased from Boehringer Mannheim (Mannheim, Germany). Bicinchoninic acid (BCA) and BCA protein assay reagent were obtained from Pierce Chemical Company (Rockford, IL, USA). HEK293 cells stably expressing the hA_{2A} receptor ($HEK293hA_{2A}R$) were kindly provided by Dr J Wang (Biogen/IDEC, Cambridge, MA, USA). All other chemicals were of analytical grade and obtained from standard commercial sources.

Cell culture

$HEK293hA_{2A}R$ cells were grown in culture medium consisting of Dulbecco's modified eagle's medium supplemented with 10% newborn calf serum, 50 μg·mL^{-1} streptomycin,

50 IU·mL^{-1} penicillin, and 500 μg·mL^{-1} G418 at 37°C and 7% CO_2. Cells were subcultured twice a week at a ratio of 1:8 on 10 cm ø plates.

Cell membrane preparation

HEK293hA_{2A}R cells were grown to 80–90% confluency and detached from plates by scraping them into 5 mL PBS. Detached cells were collected and centrifuged at 700× *g* for 5 min. Pellets derived from 30 plates (15 cm ø) were pooled and resuspended in 20 mL of ice-cold 25 mM Tris-HCl buffer, pH 7.4. An UltraThurrax was used to homogenize the cell suspension. Membranes and the cytosolic fraction were separated by centrifugation at 100 000× *g* in a Beckman Optima LE-80 K ultracentrifuge at 4°C for 20 min. The pellet was resuspended in 10 mL of Tris buffer and the homogenization and centrifugation step was repeated. Tris buffer (10 mL) was used to resuspend the pellet and ADA was added (0.8 IU·mL^{-1}) to break down endogenous adenosine. Membranes were stored in 250 μL aliquots at –80°C. Membrane protein concentrations were measured using the BCA method (Smith *et al.*, 1985).

Radioligand saturation and displacement assays

Membrane aliquots containing 20 μg of protein were incubated in a total volume of 100 μL of assay buffer {25 mM Tris-HCl, pH 7.4, supplemented with 5 mM $MgCl_2$ and 0.1% (w v^{-1}) 3-[(3-cholamidopropyl) dimethylammonio]-1-propanesulfonate (CHAPS)} at 5°C for 2 h to ensure the equilibrium was reached at all concentrations of radioligand. For saturation experiments, a range of concentrations (~0.2–10 nM) of [^{3}H]-ZM241385 was used. Non-specific binding was determined at three concentrations of radioligand in the presence of 100 μM CGS21680. Radioligand displacement experiments were performed using 11 concentrations of competing ligand in the presence of 5.5 nM [^{3}H]-ZM241385. In such experiments, ZM241385 and NECA were tested in the absence or presence of 100 μM GTP. Non-specific binding was determined in the presence of 100 μM CGS21680 and represented less than 10% of the total binding. [^{3}H]-ZM241385 did not bind specifically to membranes prepared from parental HEK293 cells. Incubations were terminated by rapid vacuum filtration to separate the bound and free radioligand through a 96-well GF/B filter plates using a Perkin Elmer Filtermate-harvester (Perkin Elmer, Groningen, the Netherlands) after the indicated incubation time. Filters were subsequently washed three times with ice-cold wash buffer (25 mM Tris HCl, pH 7.4, supplemented with 5 mM $MgCl_2$). The filter-bound radioactivity was determined by scintillation spectrometry using the P-E 1450 Microbeta Wallac Trilux scintillation counter (Perkin Elmer).

Radioligand association and dissociation assays

Association experiments were performed by incubating membrane aliquots, containing 20 μg of protein, in a total volume of 100 μL of assay buffer (25 mM Tris-HCl, pH 7.4, supplemented with 5 mM $MgCl_2$ and 0.1% CHAPS) at 25 or 5°C with 5.5 nM [^{3}H]-ZM241385. The amount of radioligand bound to the receptor was measured at different time intervals during incubation for 30 min at 25°C or 2 h at 5°C. Dissociation experiments were performed by pre-incubating membrane aliquots containing 20 μg of protein in a total volume of 100 μL of assay buffer (25 mM Tris-HCl, pH 7.4, supplemented with 5 mM $MgCl_2$ and 0.1% CHAPS) either at 25°C for 30 min or at 5°C for 2 h with 5.5 nM [^{3}H]-ZM241385. After the pre-incubation, the dissociation was initiated by addition of 1 μM of unlabelled ZM241385 in 5 μL. The amount of radioligand still bound to the receptor was measured at various time intervals for a total duration of 30 min at 25°C or 4 h at 5°C to ensure that [^{3}H]-ZM241385 was fully dissociated from the hA_{2A} receptor. Incubations were terminated and samples were obtained as described in the previous paragraph (Radioligand saturation and displacement assays).

Radioligand competition association assay

The binding kinetics of unlabelled ligands were determined at 5°C using the competition association assay developed by Motulsky and Mahan (1984). In the standard assay, three different concentrations of unlabelled ZM241385 or NECA were tested, namely at one-, three- and 10-fold its K_i value. For NECA, its kinetics were also determined in the presence of 100 μM GTP. We also assessed binding kinetics in a simplified one-concentration competition association assay, at only 10-fold of the respective K_i value of the unlabelled ligands. The experiment was initiated by adding membrane aliquots containing 20 μg of protein at different time points. Incubations were terminated and samples were obtained as described above (Radioligand saturation and displacement assays).

Label-free whole-cell analysis (xCELLigence RTCA system)

Whole-cell assays were performed on the xCELLigence RTCA system (Yu *et al.*, 2006; Xi *et al.*, 2008). Briefly, a monolayer of cells adheres to an arrayed microelectrode embedded at the bottom of each well of an E-plate 96 (Roche Applied Science, Mannheim, Germany), which is compatible with the xCELLigence RTCA system. Upon activation of GPCR-mediated signalling, cell morphology changes and thereby affects the local ionic environment at the cell–electrode interface. This leads to an increased electronic readout of cell-sensor impedance (Z), which is displayed in real time as the cell index (CI). Specifically, the CI value at each time point is defined as $(Z_i\text{-}Z_0)$ Ω /15 Ω, where Z_i is the impedance at each individual time point, and Z_0 is the impedance derived from electrode/solution interface in the absence of cells before the start of the experiment. Thus, a loss of adhesion would generate a lower CI; an increase in cell adhesion, which is typically seen with GPCR-mediated activation (Scandroglio *et al.*, 2010; Denelavas *et al.*, 2011; Flynn *et al.*, 2011), results in an overall increase in the CI.

HEK293hA_{2A}R cells were cultured as a monolayer on 10-cm ø culture plates to 80–90% confluency and subsequently harvested and centrifuged twice at 200× *g* for 5 min. Initially, 45 μL of culture media was added to wells in E-plates 96 to obtain background readings (Z_0) followed by the addition of 50 μL of cell suspension containing 20 000 cells per well. The E-plate containing the cells was left at

room temperature for 15 min before being placed on the recording device station in the incubator at 37°C in 5% CO_2. Afterwards, cell attachment, spreading and proliferation were continuously monitored every 30 min. The cells were cultured until the end of log phase (~18–20 h) to obtain an optimal assay window. Prior to agonist application the interval between two measurements was adjusted to 1 min. Subsequently 5 µL compound solution (final concentration of 0.5 % DMSO) or vehicle control was added to each well, after which the CI was recorded for 30 min. For data analysis, the individual CI traces were normalized, by subtracting the baseline (vehicle control), to correct for any agonist-independent signals.

cAMP assay

HEK293hA_{2A}R cells were cultured as a monolayer on 10 cm ø culture plates to 80%–90% confluency. Cells were harvested and centrifuged twice at 200× *g* for 5 min. The amount of cAMP produced was determined with the LANCE cAMP 384 kit (Perkin Elmer). In short, 2500 cells per well were pre-incubated for 45 min at 37°C and subsequently at room temperature for three hours with a range of agonist concentrations. cAMP generation was performed in the medium containing cilostamide (50 µM), rolipram (50 µM) and ADA (0.8 IU·mL^{-1}). The incubation was stopped by adding detection mix and antibody solution, according to the instructions of the manufacturer. The generated fluorescence intensity was quantified on the EnVision® Multilabel Reader (Perkin Elmer). cAMP production by agonists tested at 100-fold their K_i value on the parental HEK293 cell line represented less than 5% of maximal stimulation of cAMP production by 10 µM CGS21680 at the cells expressing the adenosine A_{2A} receptor.

Data analysis

All experimental data were analysed by using GraphPad Prism 5.0 (GraphPad Software Inc., San Diego, CA, USA). K_D and B_{max} values of [^{3}H]-ZM241385 at hA_{2A} receptor membranes were obtained by computational analysis of saturation curves. IC_{50} values obtained from competition displacement binding data were converted to K_i values using the Cheng-Prusoff equation (Cheng and Prusoff, 1973). Association data were fitted using one-phase exponential association. Values for k_{on} were obtained by converting k_{obs} values using the following equation:

$$k_{on} = (k_{obs} - k_{off})/[\text{radioligand}]$$

where k_{off} values were assessed from independent dissociation experiments. Dissociation data were fitted using one-phase exponential decay. The association and dissociation rates were used to calculate the 'kinetic K_D' using the following equation:

$$K_D = k_{off}/k_{on}$$

Association and dissociation rates for unlabelled ligands were calculated by fitting the data in the competition association model using 'kinetics of competitive binding' (Motulsky and Mahan, 1984):

$$K_A = k_1[L] + k_2$$

$$K_B = k_3[I] + k_4$$

$$S = \sqrt{(K_A - K_B)^{2+4k_1 \cdot k_3 \cdot L \cdot I \cdot 1e^{-18}}}$$

$$K_F = 0.5(K_A + K_B + S)$$

$$K_S = 0.5(K_A + K_B - S)$$

$$Q = \frac{B_{\max} \cdot k_1 \cdot L \cdot 1e^{-9}}{K_F - K_S}$$

$$Y = Q \cdot \left(\frac{k_4 \cdot (K_F - K_S)}{K_F \cdot K_S} + \frac{k_4 - K_F}{K_F} e^{(-K_F \cdot X)} - \frac{k_4 - K_S}{K_S} e^{(-K_S \cdot X)} \right)$$

Where X is the time (min), Y is the specific [^{3}H]-ZM241385 binding (dpm), k_1 and k_2 are the k_{on} (M^{-1} min^{-1}) and k_{off} (min^{-1}) of [^{3}H]-ZM241385, respectively, determined from the radioligand association and dissociation assays, L the concentration of [^{3}H]-ZM241385 used (nM), B_{max} the total binding (dpm) and I the concentration unlabelled ligand (nM). Fixing these parameters allows the following parameters to be calculated: k_3, which is the k_{on} value (M^{-1} min^{-1}) of the unlabelled ligand and k_4, which is the k_{off} value (min^{-1}) of the unlabelled ligand. EC_{50} and E_{max} values in label-free whole-cell assay were obtained by analysing the normalized CI traces using RTCA Software 1.2 (Roche Applied Science) to obtain peak responses within 30 min after compound addition. These peak values were exported to Prism 5.0, which yielded dose–response curves and were analysed by nonlinear regression.

The relative efficacies (τ) of agonists in label-free whole-cell experiment and cAMP assay were also evaluated. Data were fitted to the operational model of Black and Leff (1983), which correlates a biological effect E with agonist concentration [A] as a function of three parameters: E_m, K_A, and τ:

$$E = \frac{E_m \cdot \tau \cdot [A]}{K_A + (\tau + 1)[A]}$$

where E_m, the operational maximum, represents the maximum possible effect in the tissue. K_A is the dissociation constant of agonist and τ is the relative efficacy. The E_m value was generated by fitting the dose–response curve for the full agonist (i.e. UK432,097). Its best-fit values were recorded to fit dose–response curves of partial agonists and other full agonists by global fitting in the operational model in Prism 5.0 to generate their relative efficacies. All values obtained are

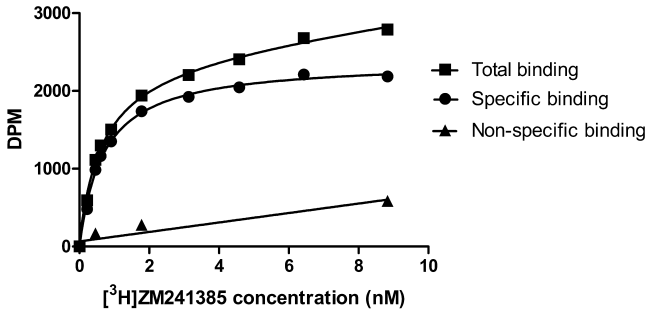

Figure 2

Saturation experiment for [^{3}H]-ZM241385 (~0.2–10 nM, final concentration) binding to HEK293hA_{2A}R membranes at 5°C; total binding, non-specific binding and specific binding are shown. Representative graph from one experiment performed in duplicate.

means of at least three independent experiments performed in duplicate.

Results

Quantification of the K_D and B_{max} of [^{3}H]-ZM241385 in saturation experiments

Saturation binding experiments were performed with [^{3}H]-ZM241385 at 5°C. The result of a representative saturation experiment is shown in Figure 2. [^{3}H]-ZM241385 bound to a single class of binding sites at HEK293hA_{2A}R membranes. The K_D value was determined as 0.60 ± 0.07 nM and B_{max} was 1.9 ± 0.04 pmol·mg^{-1} protein. The K_D value for [^{3}H]-ZM241385 obtained with these experiments was used to derive K_i values from IC_{50} values for ten A_{2A} receptor agonists, as well as the unlabelled antagonist ZM241385 (see later).

Quantification of the affinity (K_i) of A_{2A} receptor ligands in displacement experiments

Displacement experiments with several A_{2A} receptor ligands were performed to determine their affinities to the hA_{2A} receptor. All compounds produced a concentration-dependent inhibition of specific [^{3}H]-ZM241385 binding (Figure 3) and their affinities are detailed in Tables 1 and 3. Among all the ligands tested, ZM241385 showed the highest affinity for the hA_{2A} receptor with a K_i value of 0.4 ± 0.03 nM (Table 1) in the absence of 100 μM GTP; its K_i value determined in the presence of 100 μM GTP was the same (0.4 ± 0.02 nM, Figure 3A). Similarly, there was no significant difference between the kinetic or K_i values of NECA tested in the absence or presence of 100 μM GTP (Tables 2 and 3, Figure 3A). Affinities of other A_{2A} receptor agonists were determined and showed a range of K_i values in the lower to higher nanomolar range (Table 3). The agonist with the lowest affinity was CGS21680 (K_i = 376 ± 12 nM), while the agonist with the highest affinity was LUF5835 (K_i = 15 ± 4 nM). In general, the affinities of the ribose-containing agonists (e.g. LUF5448) were lower than those of the non-ribose agonists (e.g. LUF5833), as shown in Table 3.

Quantification of the association [k_{on} (k_1)] and dissociation rates [k_{off} (k_2)] of [^{3}H]-ZM241385 at different temperatures

To optimize the experimental conditions of the kinetic binding assays, [^{3}H]-ZM241385 association and dissociation experiments were carried out at both 25 and 5°C. At both temperatures, the association and dissociation curves of [^{3}H]-ZM241385 at the hA_{2A} receptor were monophasic. At 25°C (Figure 4A), [^{3}H]-ZM241385 had a very fast association (k_{on} = 2.4 ± 0.05 × 10^8 M^{-1}·min^{-1}) and dissociation rate (k_{off} = 0.48 ± 0.03 min^{-1}). Decreasing the experimental temperature to 5°C resulted in slower binding kinetics of [^{3}H]-ZM241385 with an association rate of 1.5 ± 0.06 × 10^7 M^{-1}·min^{-1} and a dissociation rate of 0.01 ± 0.00 min^{-1} (Figure 4B, Table 1). We also conducted experiments at 15°C; the kinetic rates determined were also fast (data not shown). Based on these initial tests, we chose 5°C as the standard experimental condition for this study because it enabled better accuracy and reproducibility of kinetic data.

Validation and optimization of the competition association assay at the hA_{2A} receptor

With the predetermined k_{on} (k_1) and k_{off} (k_2) values of [^{3}H]-ZM241385 from association and dissociation experiments, k_{on} (k_3) and k_{off} (k_4) values of unlabelled ligands could be determined by fitting the kinetic parameters into the model of 'kinetics of competitive binding' described in methods. Firstly, we validated the competition association assay at the hA_{2A} receptor using unlabelled ZM241385. Its k_{on} (k_3) and k_{off} (k_4) values determined in this assay were 2.0 ± 0.2 × 10^7 M^{-1}·min^{-1} and 0.02 ± 0.00 min^{-1}, respectively (Figure 5, Table 1), which corresponded rather well to the kinetic rates determined in 'traditional' association and dissociation experiments described in the previous paragraph (k_{on} = 1.50 ± 0.06 × 10^7 M^{-1}·min^{-1}, k_{off} = 0.011 ± 0.001 min^{-1}). Moreover, the 'kinetic K_D' (0.95 ± 0.20 nM) derived from the competition association assay for unlabelled ZM241385 was similar to the affinity constant (K_i = 0.40 ± 0.03 nM) obtained from displacement experiments and the dissociation constant (K_D) derived from saturation experiments (0.60 ± 0.07 nM, Table 1). Taken together, this proved that the competition association assay can be applied to determine the binding kinetics of unlabelled ligands at the hA_{2A} receptor. Secondly, we modified the assay and improved its throughput by reducing the three-concentration–dependent method to a one-concentration–based method. Instead of testing at concentrations equivalent to one-, three- and 10-fold, the K_i value of unlabelled ZM241385, we only used 10-fold K_i. The latter yielded an assay window distinguishable from both the baseline and the control curve (Figure 5). Specifically, the data analysed at 10-fold K_i alone of unlabelled ZM241385 showed a comparable result (k_{on} = 2.8 ± 0.5 × 10^7 M^{-1}·min^{-1}, k_{off} = 0.03 ± 0.01 min^{-1}) to that generated in a standard (three concentration) competition association experiment (Table 1). Next to that, we also determined the effect of GTP (100 μM) on the binding kinetics of an unlabelled agonist, NECA. Its k_{on} and k_{off} values determined in the standard three-concentration competition association assay in the absence

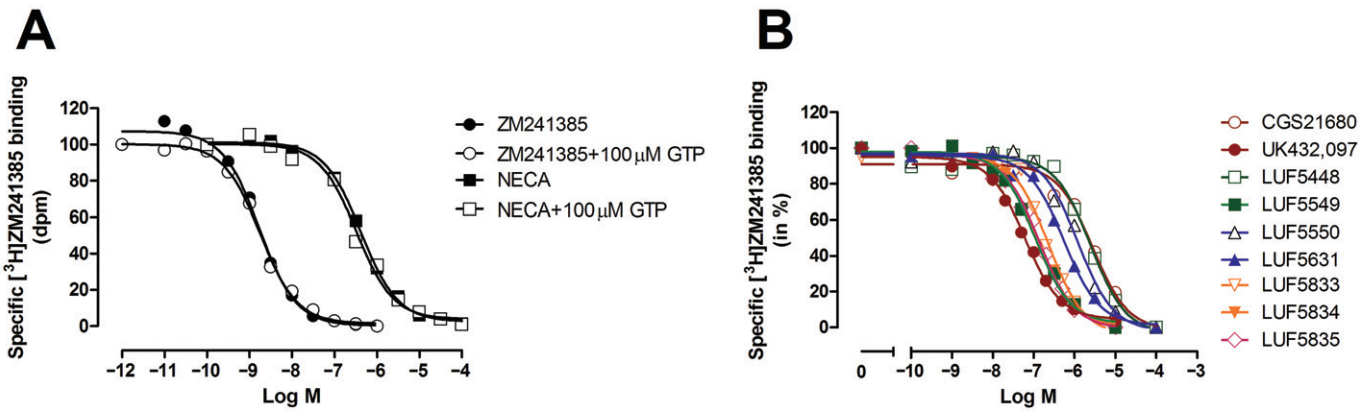

Figure 3

(A) Displacement of specific [^{3}H]-ZM241385 binding from the hA_{2A} receptor by ZM241385 and NECA in the absence (closed symbols) or presence of 100 μM GTP (open symbols). (B) Displacement of specific [^{3}H]-ZM241385 binding from the hA_{2A} receptors by the other nine agonists. Representative graphs from one experiment performed in duplicate.

Table 1

Comparison of the affinity, dissociation constants and kinetic rates of reference antagonist ZM241385 obtained in different radioligand binding assays

Assay	K_D/K_i (nM)	k_{on} ($M^{-1}\cdot min^{-1}$)	k_{off} (min^{-1})
Saturation binding[a]	0.60 ± 0.07	N.A	NA
Displacement[b]	0.40 ± 0.03	N.A	NA
Association and dissociation[c]	0.70 ± 0.01	1.5 ± 0.1 × 10^7	0.01 ± 0.00
Standard competition association[d]	0.95 ± 0.2[f]	2.0 ± 0.2 × 10^7	0.02 ± 0.00
Simplified competition association[e]	0.89 ± 0.3[f]	2.8 ± 0.5 × 10^7	0.03 ± 0.01

Values are means ±SEM of three separate experiments each performed in duplicate.
NA, not applicable.
[a][^{3}H]-ZM241385 (~0.2–10 nM) binding to HEK293hA_{2A} membranes at 5°C
[b]Displacement of specific [^{3}H]-ZM241385 binding from the hA_{2A} receptors at 5°C.
[c]Association and dissociation of [^{3}H]-ZM241385 at the hA_{2A} receptors at 5°C.
[d]The binding kinetics of unlabelled ZM241385 were determined by adding a concentration equivalent to 1-, 3- and 10-fold the K_i value of unlabelled ZM241385 at 5°C.
[e]The binding kinetics of unlabelled ZM241385 were determined by adding a concentration equivalent to only 10-fold the K_i value of unlabelled ZM241385 at 5°C.
[f]'kinetic K_D' = k_{off}/k_{on}.

of GTP were 8.1 ± 1 × 10^5 $M^{-1}\cdot min^{-1}$ and 0.04 ± 0.01 min^{-1} (Table 2, Figure 6A), which were similar to these values determined in the presence GTP (k_{on} = 9.8 ± 1 × 10^5 $M^{-1}\cdot min^{-1}$, k_{off} = 0.04 ± 0.01 min^{-1}, Table 2, Figure 6B). Furthermore, k_{on} and k_{off} values of unlabelled NECA assessed by using a concentration of 10-fold its K_i only, either in the absence or presence of 100 μM GTP, showed comparable results to that determined by the standard assay mentioned earlier (Table 2). It is also noteworthy that the calculated kinetic K_D values from the one-concentration approach in the absence (K_D = 58 nM) or presence (K_D = 52 nM) of GTP are almost identical to the affinity determined in the displacement experiments (K_i = 64 ± 1 nM). Thus, the simplified one-concentration competition association assay in the absence of 100 μM GTP was used to determine the binding kinetics of other unlabelled agonists in the rest of this study.

Quantification of the binding kinetics of unlabelled ligands using the simplified competition association assay

By using the simplified competition association assay, the on- and off-rates of 10 A_{2A} receptor agonists were determined. Notably, a good correlation (Figure 7B, r^2 = 0.99, P < 0.0001) was observed between the affinities (K_i) determined in equilibrium-binding studies and K_D values derived from the competition association assays (Table 3). This further proved that the simplified model is able to accurately quantify the

Table 2

The binding kinetics of reference agonist NECA in the absence or presence of 100 μM GTP

Assay	Control k_{on} (M^{-1}·min^{-1})	k_{off} (min^{-1})	+100 μM GTP k_{on} (M^{-1}·min^{-1})	k_{off} (min^{-1})
Standard competition association[a]	8.1 ± 1.0 × 10^5	0.04 ± 0.01	9.8 ± 1.0 × 10^5	0.04 ± 0.01
Simplified competition association[b]	5.0 ± 0.6 × 10^5	0.03 ± 0.01	9.1 ± 2.0 × 10^5	0.05 ± 0.01

Values are means ±SEM of three separate experiments each performed in duplicate.
[a]The binding kinetics of unlabelled NECA in the absence or presence of 100 μM GTP were determined by adding a concentration equivalent to 1-, 3- and 10-fold the K_i value of unlabelled NECA in the absence or presence of 100 μM GTP at 5°C.
[b]The binding kinetics of unlabelled NECA in the absence or presence of 100 μM GTP were determined by adding a concentration equivalent to only 10-fold the K_i value of unlabelled NECA in the absence or presence of 100 μM GTP at 5°C.

Table 3

Binding parameters for agonists at HEK293hA_{2A}R derived from the simplified competition association assay and equilibrium radioligand displacement experiments

Cpd	k_{on} (M^{-1}·min^{-1})[a]	k_{off} (min^{-1})[a]	RT (min)[b]	Kinetic K_D (nM)[c]	K_i (nM)[d]
CGS21680	5.0 ± 1.0 × 10^4	0.02 ± 0.00	53 ± 0.2	380 ± 0.3	376 ± 12
NECA	5.0 ± 0.6 × 10^5	0.03 ± 0.01	35 ± 0.2	58 ± 0.2	64 ± 1
UK432,097	5.0 ± 0.8 × 10^5	0.004 ± 0.00	250 ± 0.8	8.0 ± 0.8	22 ± 5
LUF5448	2.8 ± 0.1 × 10^5	0.06 ± 0.02	16 ± 0.3	225 ± 0.3	219 ± 15
LUF5549	2.4 ± 0.5 × 10^6	0.04 ± 0.01	24 ± 0.2	17 ± 0.2	24 ± 7
LUF5550	8.0 ± 2 × 10^5	0.09 ± 0.02	12 ± 0.2	110 ± 0.3	126 ± 10
LUF5631	8.0 ± 2 × 10^5	0.05 ± 0.02	21 ± 0.4	60 ± 0.5	44 ± 9
LUF5833	8.5 ± 3 × 10^6	0.16 ± 0.08	6.3 ± 0.5	19 ± 0.6	17 ± 4
LUF5834	1.1 ± 0.4 × 10^7	0.23 ± 0.10	4.2 ± 0.4	21 ± 0.6	16 ± 5
LUF5835	1.6 ± 0.8 × 10^7	0.29 ± 0.10	3.4 ± 0.3	18 ± 0.6	15 ± 4

Data are shown as mean ± SEM of three separate experiments each performed in duplicate.
[a]k_{on} and k_{off} of unlabelled A_{2A}R agonists were determined in one-concentration competition association assay.
[b]RT = $1/k_{off}$.
[c]Kinetic $K_D = k_{off}/k_{on}$.
[d]Displacement of specific [^{3}H]ZM241385 binding from the hA_{2A}R at 5°C.

association and dissociation rates of unlabelled ligands. Two distinct patterns of [^{3}H]-ZM241385 binding were found in the presence of the agonists, which are depicted in Figure 7A: (i) the specific binding of [^{3}H]-ZM241385 approached its equilibrium slowly and more gradually if [^{3}H]-ZM241385 dissociated slower than the competitor ($k_2 < k_4$, e.g. LUF5834); and (ii) the specific binding [^{3}H]-ZM241385 became biphasic with a typical 'overshoot' followed by a continuous decline towards equilibrium if [^{3}H]-ZM241385 dissociated faster than the competitor ($k_2 > k_4$, e.g. UK432,097). In accordance with these observations, UK432,097 had a much slower off-rate (k_{off} = 0.004 ± 0.003 min^{-1}) than [^{3}H]-ZM241385 (k_{off} = 0.01 ± 0.00 min^{-1}). LUF5834 (k_{off} = 0.23 ± 0.10 min^{-1}) or LUF5550 (k_{off} = 0.09 ± 0.02 min^{-1}) dissociated much faster from the receptor than [^{3}H]-ZM241385. Furthermore, it follows from Table 3 that the values for binding kinetics of ribose-containing agonists were significantly different from those of non-ribose agonists. For instance, LUF5631 was 10-fold slower in association and 3.3-fold slower in dissociation compared with LUF5833.

Quantification of functional efficacies of A_{2A} receptor agonists in a label-free whole-cell assay

Changes in cell morphology by the addition of CGS21680 and other A_{2A} receptor agonists to HEK293hA_{2A}R cells were assessed in real time with the impedance-based assay system. Typically, upon agonist addition to HEK293hA_{2A}R cells, the impedance (displayed as CI) resulted in an immediate dose-dependent increase to a peak level. After that, the CI trace decreased and gradually reached a plateau without returning to the baseline when monitored over a period of 30 min. A representative measurement of CGS21680-induced impedance changes is plotted in Figure 8A. Concentration-effect curves were obtained from peak analysis of corresponding agonist-induced CI changes (Figure 8B). Agonist potencies,

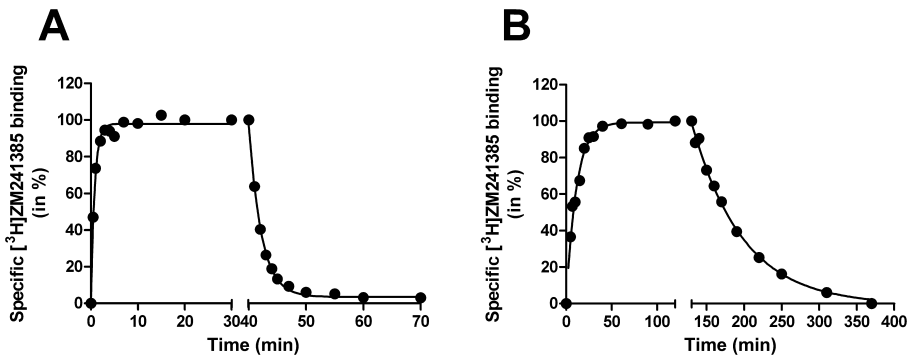

Figure 4

The association and dissociation of [^{3}H]-ZM241385 at the hA_{2A} receptor at (A) 25°C and (B) 5°C. Representative graphs from one experiment performed in duplicate.

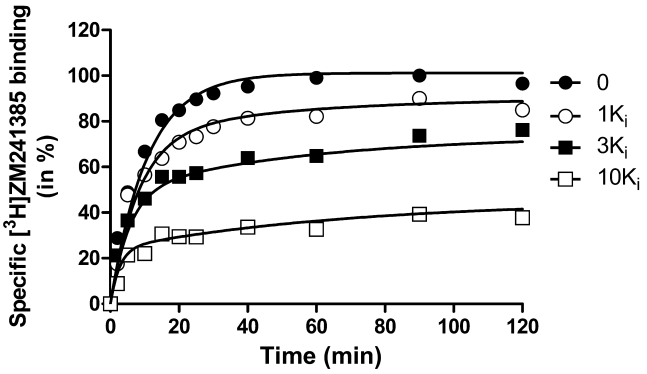

Figure 5

Competition association experiment with [^{3}H]-ZM241385 in the absence of ligand and in the presence of onefold K_i value, threefold K_i value or tenfold K_i value of unlabelled ZM241385. Representative graphs from one experiment performed in duplicate (see Table 1 for kinetic values).

intrinsic efficacies and their relative efficacies (τ) analysed in the operational model are detailed in Table 4. Specifically, among all tested agonists, UK432,097 had the highest efficacy, with a value of 114 ± 4 % compared with the reference agonist CGS21680 (set at 100%). Efficacies of other ribose-containing agonists LUF5448, LUF5549, LUF5550 and LUF5631 were 83 ± 5, 92 ± 4, 63 ± 6 and 91 ± 8%, while the efficacies of the non-ribose agonists LUF5833, LUF5835 and LUF5834 were 54 ± 9, 47 ± 6 and 54 ± 8%, respectively. In Figure 9A and B, correlations are shown between the agonist efficacy and either their affinities or receptor residence times respectively. It follows from Figure 9A that there was very little correlation between the affinity of the agonists and their efficacy, if at all (r^2 = 0.13, P = 0.32). Interestingly, when the efficacy of each agonist was compared with the logarithm of its residence time (Figure 9B), a much better correlation was obtained (r^2 = 0.90, P < 0.0001), where the highest efficacy ligand UK432,097 had the longest residence time of 250 ± 0.8 min. In addition, no correlation was observed between functional potency and the logarithm of its residence time (r^2 = 0.077, P = 0.44). The ranking of the relative efficacy, τ, is quite comparable with the intrinsic efficacy, where UK432,097 had the highest τ-value of 51 ± 5; LUF5550 had the lowest value of 0.7 ± 0.07 (Table 4). Similarly, a positive link between receptor residence time and relative efficacy was observed (r^2 = 0.60, P < 0.01).

Quantification of functional efficacies of A_{2A} receptor agonists in a cAMP assay

The functional efficacy of all A_{2A} receptor agonists was tested in a classic cAMP assay as well. The cAMP production was stimulated by adding increasing concentrations of different agonists. The effects were normalized and are shown as a percentage of maximal stimulation of cAMP production by 10 μM CGS21680 (=100%). Among all tested agonists (Figure 8C, Table 4), UK432,097 had the highest efficacy of 115 ± 2% in this assay. Efficacies of ribose-containing agonists LUF5448, LUF5549, LUF5550 and LUF5631 were 84 ± 3, 71 ± 6, 39 ± 1 and 67 ± 5%, while the efficacies of the non-ribose agonists LUF5833, LUF5834 and LUF5835 were 38 ± 2, 50 ± 1 and 58 ± 2%, respectively. Notably, the ranking of the agonists by their efficacy measured in the cAMP assay is quite comparable with the efficacy-ranking obtained with the impedance-based assay (Figure 9D, r^2 = 0.79, P < 0.001). Similarly, a positive link between the functional efficacy and the logarithm of a compound's residence time was observed in this assay as well (Figure 9C, r^2 = 0.74, P < 0.001), while no correlation was observed between functional efficacy and the logarithm of its K_i value (r^2 = 0.10, P = 0.40). The ranking of the relative efficacy, τ, in this assay is also quite comparable with that obtained from the whole-cell impedance-based assay, where UK432,097 had the highest (τ = 14 ± 5) and LUF5550 had the lowest relative efficacy (τ = 0.5 ± 0.04; Table 4). These relative efficacies were again closely correlated to the receptor residence times of the agonists in the present study (r^2 = 0.80, P < 0.001).

Discussion

In this study, the binding kinetics of unlabelled A_{2A} receptor ligands were determined for the first time using the competi-

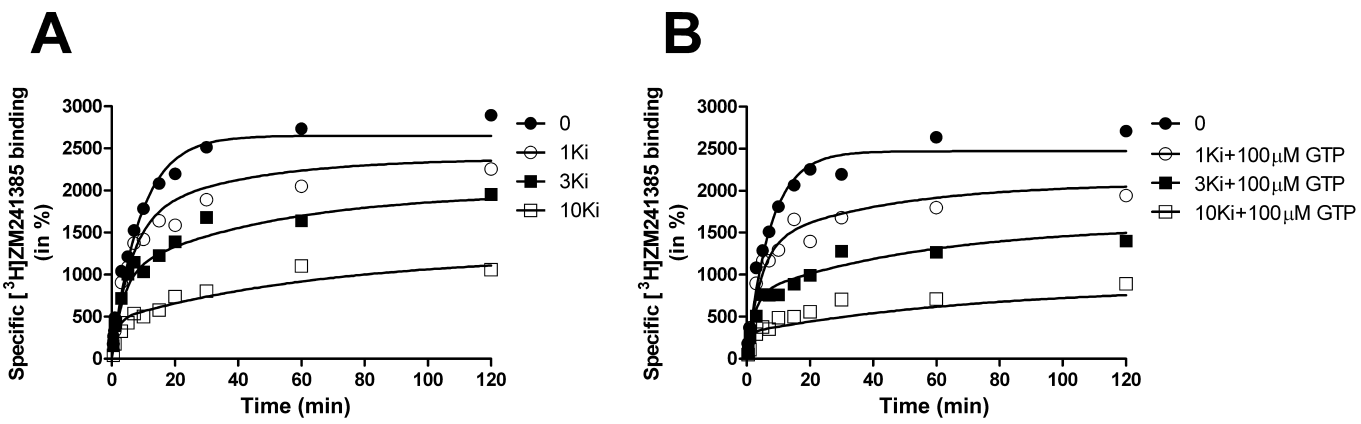

Figure 6

[^{3}H]-ZM241385 competition association experiments in the absence (A) or presence (B) of 100 μM GTP with NECA concentrations 1-, 3- or 10-fold its K_i value. Data were fitted to the equations described in the methods to calculate NECA's k_{on} and k_{off} values in the absence or presence of GTP. Representative graphs from one experiment performed in duplicate (see Table 2 for kinetic values).

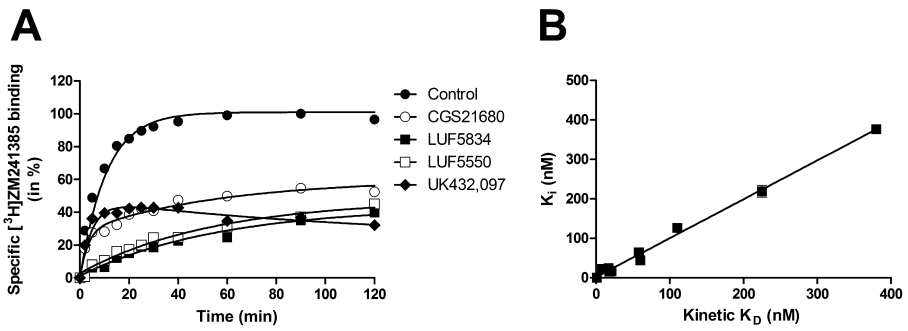

Figure 7

(A) [^{3}H]-ZM241385 competition association binding in the absence of ligand and in the presence of unlabelled CGS21680, LUF5834, LUF5550 or UK432,097. Data were fitted to the equations described in the methods to calculate the k_{on} and k_{off} values of unlabelled ligands. Representative graphs from one experiment performed in duplicate (see Table 3 for kinetic values). (B) Correlation between affinities (K_i) and 'kinetic K_D' values of all the tested compounds. K_i values were taken from the displacement experiments at equilibrium and K_D values were derived from the competition association experiments.

tion association assay method (Motulsky and Mahan, 1984) at the hA_{2A} receptor. This approach has been shown to be highly accurate in determining the binding kinetics at the β-adrenoceptor (Affolter *et al.*, 1985; Contreras *et al.*, 1986) and more recently, at the muscarinic M_3 receptor (Dowling and Charlton, 2006; Sykes *et al.*, 2009). However, the standard model is laborious and time consuming when the kinetics of multiple compounds need to be determined because it implies the use of three concentrations of each unlabelled ligand. In this study, the tested agonists were considered competitive with the radioligand as they fully displaced [^{3}H]-ZM241385 from the receptor (Figure 3B). Therefore, we modified the three-concentration–dependent assay into a one-concentration–based method. From Table 1, it follows that this simplified method is enough to quantify the binding kinetics, which eventually enables testing in a faster medium-throughput format, yet without loss of accuracy. As we used an antagonistic radioligand, [^{3}H]-ZM241385, we checked the GTP effect on the equilibrium affinity and the binding kinetics of one representative A_{2A} receptor agonist, namely NECA. In our system, the hA_{2A} receptor was insensitive to GTP (Table 2) and only one single binding site was observed (Figure 3A). Hence, we did not continue to apply GTP in our assays. Subsequent quantification of the binding kinetics of 10 A_{2A} receptor agonists in the simplified model generated comparable 'kinetic K_D' with their K_i values (Table 3). This excellent correlation (Figure 7B, $r^2 = 0.99$, $P < 0.0001$) proved the accuracy and efficiency of the one-concentration based competition association assay for the determination of a ligand's association and dissociation rates at the hA_{2A} receptor.

To guarantee an accurate kinetic determination, experiments were carried out at 5°C. Firstly, increasing the experimental temperature resulted in very fast kinetics of the radioligand, which is less practical to quantify the ligand-receptor binding kinetics. Secondly, it is reasonable to speculate that differences in receptor residence times will be more pronounced at 5°C than at higher temperatures, which would allow an easier identification of compounds

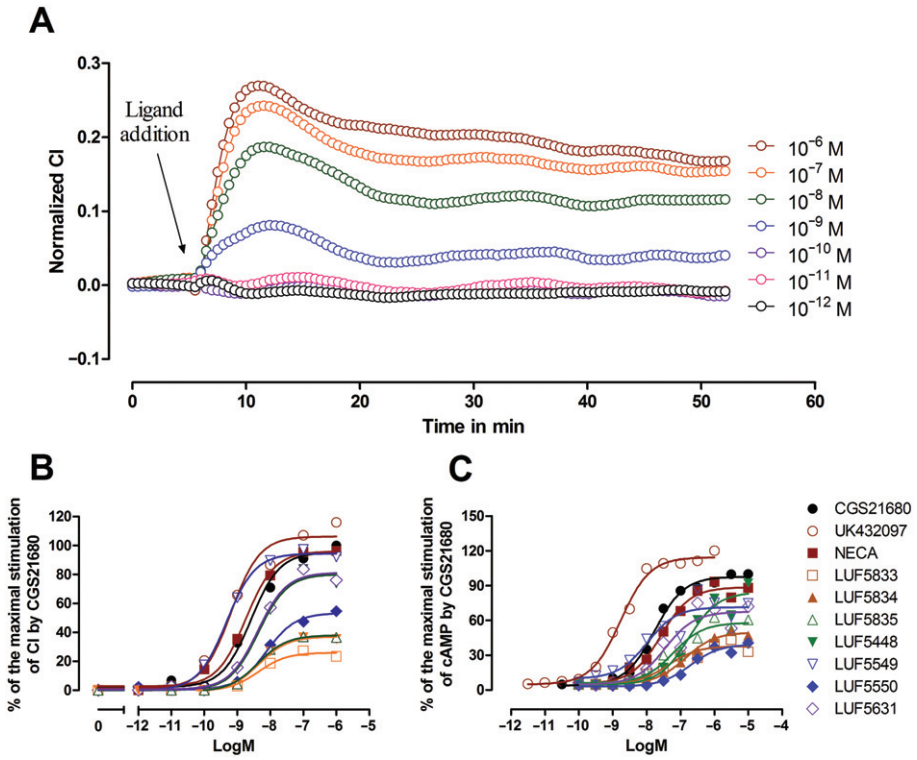

Figure 8

(A) Representative graph of normalized cell-electrode impedance (expressed as CI) after the addition of different concentrations of CGS21680 in a label-free impedance-based assay: agonist stimulation of HEK293hA_{2A}R cells results in an increased CI. The change in CI was normalized over time against the vehicle control. (B) Concentration–response curves for difference A_{2A} receptor agonists at HEK293hA_{2A}R derived from peak-analysis of CI changes in the xCELLigence RTCA system. The cellular response was normalized and shown as % of the maximal CI by 1 μM CGS21680. (C) Concentration–response curves of cAMP stimulation by ten A_{2A} receptor agonists in a cAMP assay. Data were normalized and shown as % of the maximal cAMP production by 10 μM CGS21680 in HEK293hA_{2A}R cells (=100%). Representative graphs from one experiment performed in duplicate.

Table 4

Agonist potency and efficacy derived from both cAMP and label-free whole-cell assays

Agonist	Label-free whole-cell assay[a] Potency (EC_{50}, nM)	Efficacy (E_{max}, %)	Relative efficacy (τ)[b]	cAMP assay Potency (EC_{50}, nM)	Efficacy (E_{max}, %)	Relative efficacy (τ)[b]
CGS21680	3.8 ± 0.4	100 ± 1	13 ± 5	19 ± 0.6	100 ± 2	4 ± 0.40
NECA	2.5 ± 0.1	90 ± 4	4 ± 0.8	27 ± 0.9	88 ± 3	3 ± 0.30
UK432,097	0.47 ± 0.01	114 ± 4	51 ± 5	1.7 ± 0.1	115 ± 2	14 ± 5
LUF5448	2.4 ± 1	83 ± 5	2 ± 0.4	172 ± 15	84 ± 3	2 ± 0.40
LUF5549	1.0 ± 0.4	92 ± 4	6 ± 0.8	10 ± 3	71 ± 6	1 ± 0.20
LUF5550	5.8 ± 1	63 ± 6	0.7 ± 0.1	195 ± 12	39 ± 1	0.5 ± 0.04
LUF5631	4.3 ± 1	91 ± 8	2 ± 0.3	36 ± 23	67 ± 5	1 ± 0.20
LUF5833	3.9 ± 0.6	54 ± 9	1 ± 0.3	44 ± 2	38 ± 2	0.5 ± 0.04
LUF5834	3.6 ± 0.7	47 ± 6	0.8 ± 0.2	21 ± 1	50 ± 1	0.7 ± 0.06
LUF5835	5.7 ± 2	54 ± 8	0.8 ± 0.1	17 ± 1	58 ± 2	0.9 ± 0.09

Data are shown as mean ± SEM of three separate experiments each performed in duplicate.
[a]Agonist potency (EC_{50})and efficacy (E_{max}) were calculated from concentration-response curves derived from peak-analysis of CI changes.
[b]The relative efficacy (τ) was analysed by the operational model of Black and Leff (1983) using global fitting.

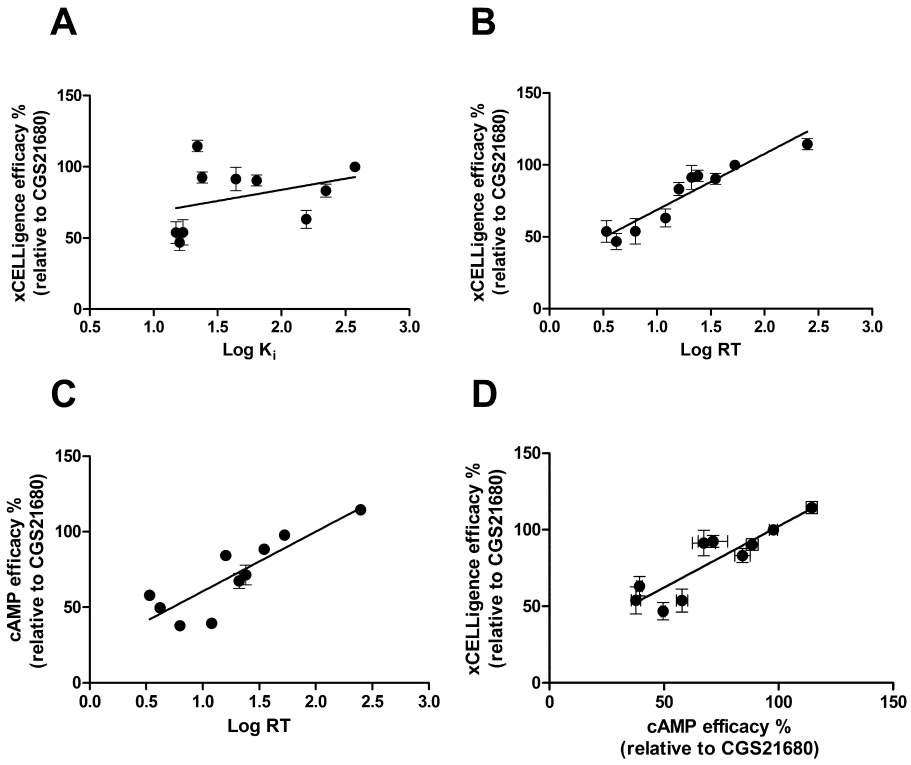

Figure 9

Correlation of the functional efficacy (E_{max}) derived from label-free whole-cell assay against (A) Log K_i ($r^2 = 0.13$, $P = 0.32$) and (B) Log RT (residence time) ($r^2 = 0.90$, $P < 0.0001$). (C) Correlation of the functional efficacy derived from cAMP assay against Log RT ($r^2 = 0.74$, $P < 0.001$). (D) Correlation of the functional efficacy derived from label-free whole-cell assay against the functional efficacy derived from cAMP assay ($r^2 = 0.79$, $P < 0.001$). Data used in these plots are detailed in Tables 3 and 4. Data are expressed as mean ± SEM from at least three independent experiments.

with longer residence times in future screening campaigns. It might be argued that such a low temperature cannot be representative for residence times observed *in vivo*. However, it was reported in a guinea pig bronchoconstriction model that UK432,097 (the agonist with the longest residence time in our studies) had a duration of action that lasted over 8 h, whereas the effect of the reference agonist CGS21680 quickly returned to baseline within 60 min (Mantell *et al.*, 2008; 2009). Admittedly, the long-lasting effect is likely to be influenced by a number of other factors such as dissolution rate, system pharmacokinetics or tissue residence/rebinding (Vauquelin and van Liefde, 2006; Vauquelin and Charlton, 2010). Even so, it is noteworthy that a kinetic difference determined by this protocol (i.e. at 5°C) is still inextricably linked to the *in vivo* efficacy of a drug candidate.

In the present study, we observed a broad range of ligand-receptor residence times from 3.4 ± 0.3 min for LUF5835 to 250 ± 0.8 min for UK432,097. From Table 3, it follows that a non-ribose agonist (LUF5833, LUF5834 and LUF5835) associates to the receptor 10- to100-fold faster, but remained at the receptor for a much shorter time than a ribose-containing agonist (for structures see Figure 1). This observation supports the integral role of a ribose moiety in the binding kinetics upon agonist receptor activation. To activate the A_{2A} receptor, common requirements include the destabilization of H-bond networks at W246$^{6.48}$ and H278$^{7.43}$ (superscripts refer to Ballesteros and Weinstein numbering, 1995) and, for example, the displacement of several structural water molecules (Kim *et al.*, 2003; Jaakola *et al.*, 2008). One can imagine that such 'obstacles' in the binding cavity will prevent the co-ordination of the ribose group and, as a result, slow down the agonist association process (Figure 10A). The lower on-rates of ribose-containing agonists that were observed compared with those of non-ribose agonists fit this hypothesis. It has been shown that upon receptor activation (Figure 10B), the ribose moiety inserts deeply into the binding cavity, as illustrated in the agonist-bound A_{2A} receptor crystal structures (Lebon *et al.*, 2011; Xu *et al.*, 2011), and is stabilized by key residues like S277$^{7.42}$ and H278$^{7.43}$. These residues, together with V84$^{3.32}$, L249$^{6.51}$, are in close contact with the agonist ribose ring, and form essential H-bonds or non-polar interactions with the ribose moiety for agonist binding. Moreover, displacement of the structural water molecules from the hydrophobic pocket favours entropic energy (Borea *et al.*, 1996), which further stabilizes the molecule in its interactions and allows it to stay longer. For the co-crystallized UK432,097 in particular it was shown that it has an extensive ligand-receptor interaction network, which includes 11 hydrogen bonds, one aromatic stacking and a number of van der Waals interactions, in the A_{2A} receptor/UK432,097 complex (Xu *et al.*,

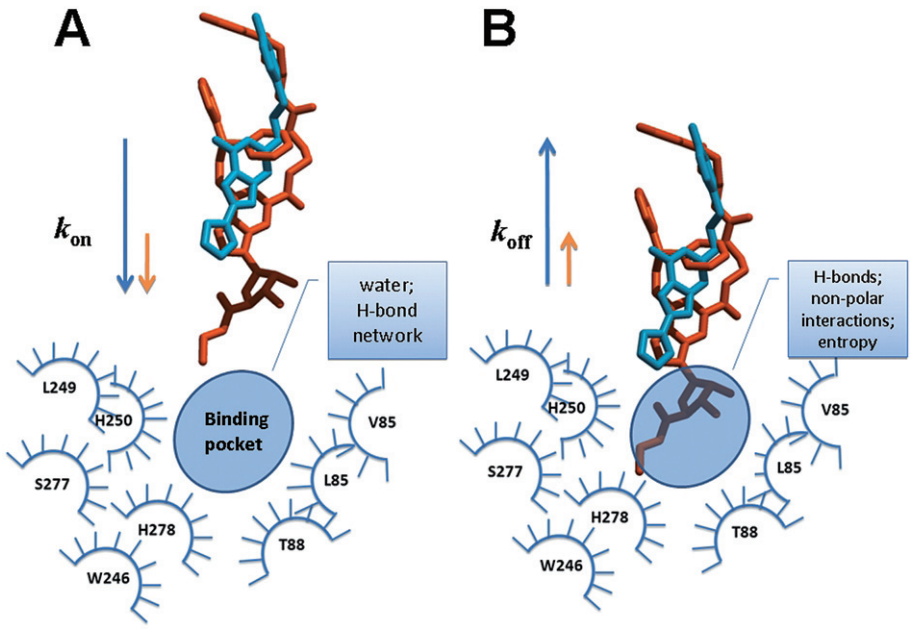

Figure 10

Proposed schematic representation of (A) obstacles at the bottom of the binding pocket and (B) the stabilization effects of the ribose moiety after agonist binding to the receptor. Molecule in blue is ZM241385; molecule in orange is UK432,097. The length of arrows in blue (ZM241385) and orange (UK432,097) indicates the speed of ligand association and dissociation. The relative position of these two molecules is co-ordinated according to the surrounding amino acids based on the crystal structures reported by Jaakola *et al.* (2008; PDB code: 3EML) and Xu *et al.* (2011; PDB code: 3QAK). In comparison to ZM241385 (non-ribose compound), UK432,097 (ribose-containing compound), binds deeper in the main binding pocket, hence before receptor activation obstacles such as water molecules or structural H-bond networks slow down the association of UK432,097 (A). After ligand binding to the receptor, the ribose part of UK432,097 is stabilized by H-bonds and non-polar interactions and stays in an entropy favourable state after the displacement of explicit water molecules (as present in the ZM241385 crystal structure). This would represent a molecular mechanism accounting for the slower dissociation of ribose-containing agonists compared to antagonists (B).

2011). This further corroborates our finding that UK432,097 has the longest residence time in the hA_{2A} receptor.

In the present study, the A_{2A} receptor-mediated activation was determined in two different functional assays, namely, in a novel label-free impedance-based assay (xCELLigence RTCA system), which was compared with a classic cAMP assay. Recently, label-free impedance-based technologies have been shown to have promising applications in assaying functional activity of GPCRs (McGuinness, 2007; Peters and Scott, 2009). In particular, this assay does not require any labelling or recombinant expression of receptor or reporter proteins because it is based on detection of cell morphological changes induced by an agonist. Using this impedance-based technology, we were able to discriminate full from partial agonists at the hA_{2A} receptor (Figure 8B and Table 4). Their efficacies were similar to those obtained in a traditional cAMP assay (Figure 8C and Table 4), which indicates that the novel label-free technology is a useful tool to study A_{2A} receptor-mediated activation. Notably, we observed a similar correlation between the residence time of an agonist and its functional efficacy in both assays: compared to the equilibrium affinity, the receptor residence time of an A_{2A} receptor agonist has a much better correlation to its intrinsic efficacy (Figure 9). This correlation was found in other studies as well. For instance, in the case of the α_2-adrenoceptors, the full agonist UK14,304 had a 12-fold longer residence time than the partial agonist clonidine (Hoeren *et al.*, 2008). In another study, Sykes *et al.* (2009) tested seven agonists with a broad range of efficacies at the muscarinic M_3 receptor. Similarly, they found that a slowly dissociating M_3 agonist appeared to cause a higher efficacy in functional assays. Taken together with these observations, our results suggest that receptor residence time and functional efficacies are positively correlated, which may lead us to further understand the molecular basis of agonist functional efficacy at the hA_{2A} receptor.

In the label-free impedance based assay, we observed that the potencies (EC_{50}) of the A_{2A} receptor agonists were generally higher than the respective binding affinities (compare Table 4 with Table 3). A similar observation was reported in a study by Dionisotti *et al.* (1997), for the functional potency and binding affinity of NECA and CGS21680. Firstly, this discrepancy could be related to the effect of receptor reserve. Occupation of a fraction of the receptor is sufficient to obtain maximal activation in the signal transduction cascade (Dionisotti *et al.*, 1997), which is supported by the relatively low values of the relative efficacies (Table 4). Secondly, we used an antagonist radioligand, [^{3}H]-ZM241385, to determine agonist affinity, which generally yields lower affinity values than when an agonist radioligand is used (Bruns *et al.*, 1987; Nonaka *et al.*, 1994; Zocchi *et al.*, 1996). It has been shown that the use of an agonistic radioligand, such as [^{3}H]-NECA or [^{3}H]-CGS21680 at the A_{2A} receptor, results in agonist affinities close to their functional potencies (Jarvis *et al.*, 1989; Müller *et al.*, 2000). In the present study, we decided to use an

antagonistic radioligand because it recognizes the whole receptor population (G protein-coupled and – uncoupled), which as a result provided a robust condition for kinetic measurements. Moreover, it should be mentioned that the results from the label-free impedance-based assay represent the integration of several signalling pathways, which might explain the difference in agonist potencies obtained in the impedance-based and the cAMP assay. To elaborate this phenomenon, several lines of research indeed indicate that the A_{2A} receptor can interact with several 'less traditional' scaffold proteins, such as β-arrestin and α-actinin (Burgueno *et al.*, 2003; Keuerleber *et al.*, 2010; Verzijl and IJzerman, 2011). This may further engage cell morphological changes next to effects induced via the classical G_s pathway, and as a result cause an increased, or at least different, potency in a whole-cell impedance-based assay. We also explored the relative efficacy, τ, of agonists in the operational model of Black and Leff (1983). Critically, we observed a correlation between the receptor residence time and the relative efficacy in the xCELLigence assay ($r^2 = 0.60$, $P < 0.01$), but it was less significant than the correlation found in the cAMP assay ($r^2 = 0.80$, $P < 0.001$). This might also be due to the fact that the label-free impedance-based assay combines cell morphological changes induced via several signalling pathways, as stated above.

In summary, we set up and validated a simplified competition association assay at the hA_{2A} receptor, which allowed an accurate and fast measurement of a ligand's binding kinetics. Agonist efficacy at the hA_{2A} receptor was determined in a cAMP assay and, for the first time, in a novel label-free impedance-based system. In both functional assays, our data provide evidence that the receptor residence time is correlated to the functional efficacy at the hA_{2A} receptor rather than the 'traditional' equilibrium affinity of a compound. This finding may lead to a further understanding of the fundamental basis of agonist efficacy at the hA_{2A} receptor.

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Conflict of interest

None.

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