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Research Article

Fluorinated Adenosine A<sub>2A</sub> Receptor Antagonists Inspired by Preladenant as Potential Cancer Immunotherapeutics

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Antagonism of the adenosine A<sub>2A</sub> receptor on T cells blocks the hypoxia-adenosinergic pathway to promote tumor rejection. Using an in vivo immunoassay based on the Concanavalin A mouse model, a series of A<sub>2A</sub> antagonists were studied and identified preladenant as a potent lead compound for development. Molecular modeling was employed to assist drug design and subsequent synthesis of analogs and those of tozadenant, including fluorinated polyethylene glycol PEGylated derivatives. The efficacy of the analogs was evaluated using two in vitro functional bioassays, and compound 29, a fluorinated triethylene glycol derivative of preladenant, was confirmed as a potential immunotherapeutic agent.

1. Introduction

The adenosine receptors belong to the G protein-coupled receptor (GPCR) family including A<sub>1</sub>, A<sub>2A</sub>, A<sub>2B</sub>, and A<sub>3</sub>, four subtypes based on their different subcellular localization, signal transduction pathways, activation profiles, ligand binding profiles, and G protein binding preferences [1, 2]. Adenosine receptor coupling and subsequent dissociation with G<sub>i</sub> and G<sub>s</sub> proteins serve to regulate the level of adenylylate cyclase activity, thus controlling levels of intracellular cAMP, a second messenger known to trigger a complex sequence of cellular events [1–3]. As a consequence, A<sub>2A</sub>R has become a drug discovery target of increased interest, implicated in diseases such as neurodegenerative disorders (e.g., Parkinson’s disease), cardiac ischemia, inflammation, and cancer [4–6]. After over a decade of effort applied to xanthine based A<sub>2A</sub>R antagonists, a derivative KW-6002 (istradefylline, 2) was developed and approved in 2013 as an anti-Parkinson drug in Japan under the brand name Nouriast®. The molecule preladenant (4) completed Phase II clinical trials for Parkinson’s disease but failed to show efficacy in subsequent Phase III trials. However, tozadenant (SYN115, 5a) entered Phase III trials in 2015 for the same indication (Figure 1) [7–9].

Given the surge in interest in A<sub>2A</sub>R antagonists, we have focused effort on the immunomodulatory capacity of agents. We have previously demonstrated antagonism of the hypoxia-adenosinergic pathway, wherein hypoxia-driven accumulation of extracellular adenosine triggered immune suppression via A<sub>2A</sub>R activation on the surface of immune cells [10–15]. Subsequent A<sub>2A</sub>R antagonism by YM241385 (1) led to delayed growth of CL8-1 melanoma in mice and increased levels of endogenous antitumor T cells [10–15]. Derivatization of xanthine 2 led to a PEG derivative (KW-PEG, 3), which showed enhanced properties, including cAMP suppression and cytokine IFN-gamma restoration [16]. Spurred by these findings we were motivated to employ molecular modeling methods to design optimized derivatives.
(PEG) of other classes of A$_2$A-R antagonists and to explore both their immunomodulatory capacity and potential to be converted to functional imaging agents.

2. Materials and Methods

To select lead compounds for immunotherapy application, an in vivo Concanavalin A (ConA)-induced liver damage assay was carried out in C57BL/6 mice through the pharmacological activation and deactivation of A$_2$A-Rs [17]. A variety of compounds were screened including 2, 3, and 4 [10, 18, 19]. As shown in Figure 2, compound 4 imparted the most severe immune induced liver damage and was selected as a core structure for analog design. Fluorinated analogs were envisioned to potentially serve as leads to ultimately be labeled at the distal position with fluorine-18 ($t_{1/2} = 109.8$ min), for diagnostic imaging with positron emission tomography (PET). A series of fluorinated PEG groups with increasing chain lengths were proposed for chemical modification to map the structure-activity relationship (SAR). Such modifications increase both hydrophilicity and molecular weight (MW), potentially to reduce blood-brain barrier (BBB) penetration as predicted by the central nervous system multiparameter optimization (MPO) score reported by Wager et al. [20].

To locate the ideal position for PEG attachment, molecular modeling was utilized based on our previously constructed homology model, which derived from the crystal structure of A$_2$A-R in complex with 1 (PDB ID 3EML) and includes a resolved EL2 cap [16, 21, 22]. This technique employed Glide (Schrödinger, version 10.4, LLC, New York, NY, 2015) extra precision (XP) docking to gain insights into the ligand-protein binding interactions [23–26]. As shown in Figure 3(a), 4 almost occupies the entire binding
pocket of A$_{2A}$R and shares similar key binding interactions as known ligand 1. Noteworthily, the methoxethyl ether group of 4 projects into the cytosolic solution and forms an additional H-bond with Pro266 at the solvent-exposed surface of the A$_{2A}$R, connecting with the cytosolic solution. Similarly, the current clinical candidate 5a also occupies a position near the edge of the A$_{2A}$R binding pocket, where the piperidine quaternary alkyl group forms hydrophobic interactions with Leu267 and His264 and the tertiary alcohol group forms a hydrogen bond with Glu169 (Figure 3(b)) [27, 28]. It was thus suggested that introduction of hydrophilic and fluorinated PEG groups at the phenolic position of 4 and the piperidine component of 5a would not impact key binding events of their core structures as the pendant groups would be capable of engaging in hydrogen bonds at the termini or in the case of their chains via hydrated networks. Accordingly, the octaethylene glycol monomethyl ether moiety, a tolerable substituent in prior studies on compound 2 [16] in conjunction with the phenyl-piperazine linker inherent in 4, was introduced to 5a and syntheses designed. In addition, synthesis of a demethylated version of the compound (5b) was planned, as such could be a useful intermediate for radiotracer synthesis (as either $[^{13}C]5a$ via a one-step $[^{13}C]$CH$_2$I methylation or a base-promoted coupling with an $^{18}$F-labeled short alkyl chain) at this locus.

Synthesis of reference compounds 2 and 3 was performed using refinements of reported methods which produced superior yields independent of scale [16]. For example, use of a mild (AIBN/NBS promoted) route to the 8-substituted xanthine scaffold resulted in an improvement in yield from 22% to 56% for this key step (see experimental section) [29]. Compounds 4 and 5a were synthesized based on modified literature methods (Scheme 1) [30–33], key intermediate 13 obtained from compound 7 via Vilsmeier-promoted halogenation and formylation, one-pot cascade condensation with 2-furoic acid hydrazine (9) and 2-hydroxyethyl hydrazine (11), Dimroth rearrangement to effect triazole formation, and finally bromination with POCl$_3$/ZnBr$_2$. The piperazine components were prepared starting from either commercially available fragment 14 or fluorination/activation of the known mono- or ditosylated PEG chains (15–19) and subsequent coupling reaction with 1-(4-(4-hydroxyphenyl)piperazin-1-yl)ethan-1-one (20) and then deacetylation prior to the final coupling reaction with intermediate 13 to furnish 4 and the desired analogs 27–31 [30, 34].

Synthesis of 5a is illustrated in Scheme 2. The bromide 32 was subjected to palladium-catalyzed coupling with morpholine (33), stannous nitro reduction, condensation with benzoyl isothiocyanate, bromine promoted formation of the benzothiazole ring, and installation of the piperidine ring through intermediate 38. Preparation of analog 40 was achieved via coupling of 26 and 38 [31]. Direct demethylation of 5a with BB$_3$ did not lead to the desired product 5b but instead led to decomposition and bromination of the tertiary alcohol [34]. Likewise, L-selectride promoted demethylation of 5a led to very poor yield of product 5b (5%) [35]. The sequence was finally realized when the phenyl carbamate protecting group of 38 was employed. With demethylation achieved, the phenyl carbamate protecting group (of 41) was replaced by 4-methylpiperidin-4-ol 39 to afford desmethyl tozadenant, 5b. Full details of all experimental procedures, bioassays, and molecular modeling are described in the Supplementary Material available online at https://doi.org/10.1155/2017/4852537.

3. Results and Discussion

Bioassay of compounds 27–31 and 40 and their parent compounds (4 and 5a) was conducted using two functional assays that evaluate A$_{2A}$R binding-dependent signaling through A$_{2A}$R on the surface of T cells [16]. The first assay screens
compounds on the basis of their extent of inhibition of A2A-R induced intracellular cAMP accumulation in A2A-R expressing lymphocytes [36, 37]. The A2A-R agonist, CGS21680 (CGS, 6), was used to activate A2A-R. As shown in Figure 4, all of the above compounds, except 40, were able to prevent CGS-mediated signaling. Stronger antagonism was observed for the preladenant-based analogs 27–29 versus the previously evaluated compounds 2 and 3. Further increments of the PEG chain length resulted in decreased antagonism (compounds 30 and 31). Surprisingly, 5a showed inferior antagonism to that of compounds 2 and 3, and its derivative 40 exhibited no suppression of intracellular cAMP accumulation.

An evaluation of the positive hits in the cAMP assay (27–29) was carried out in silico by Glide docking to study their binding orientation in A2A-R. The docking results confirmed the initial assumption for such analog design (Figure 5), the core structures of 27–29 anchoring in similar positions as 4, forming identical key binding interactions with Asn253, Glu169, and Phe168. The installed PEG chains interact with the residues at the edge of A2A-R via hydrophobic and H-bonding interactions.

The second immunoassay assesses secretion of the cytokine IFN-gamma, since it is considered to be sensitive to the A2A-R signaling pathway [16]. In these assays, during T cell receptor (TCR) activation by the CD3 ligand, C57BL/6 mice splenocytes T cells are incubated with A2A-R agonist CGS to inhibit IFN-gamma secretion resulting from A2A-R-induced immunosuppression via intracellular cAMP. Effective A2A-R antagonists block the A2A-R-activated signal, thus restoring secretion of the cytokine to potentiate and prolong the immune response. Compounds 29, 2, 3, and 4 were evaluated (Figure 6), and compound 29 showed similar capacity to that of 4, both of which resulted in superior restoration of IFN-gamma secretion compared to either 2 or 3.
Scheme 2: Synthesis of 5a, 5b, and PEGylated analog 40. Conditions: (a) morpholine (33), K$_3$PO$_4$, 2-biphenyl-dicyclohexylphosphine, Pd(OAc)$_2$, dimethoxyethane, 37%; (b) Sn powder, EtOH/con.HCl, 66%; (c) benzoyl isothiocyanate, acetone, 99%; (d) (i) NaOMe, MeOH; (ii) Br$_2$, CHCl$_3$, 73%; (e) phenyl carbonochloridate, pyridine, dichloromethane, 94%; (f) 4-methylpiperidin-4-ol hydrochloride (39), DIPEA, THF, CHCl$_3$, 53%; (g) 26, DIPEA, THF, CHCl$_3$, 28%; (h) BBr$_3$, dichloromethane, 52%; (i) (39), DIPEA, THF, CHCl$_3$, 62%.

Figure 4: Intracellular cAMP levels in lymphocytes after incubation with vehicle, 1µM CGS, and 1µM CGS plus 1µM of compounds 4 (preladenant), 27–31, 5a (tozadenant), 40, 2 (KW-6002), and 3 (KW-PEG) are shown. The intracellular cAMP levels were determined 15 min following stimulation using quantitative cAMP ELISA and are expressed as fmol/1×10$^6$ cells. Data shown represent mean ± SEM of triplicate samples.
Given the promising results in functional assays, the physicochemical properties of compound 29 and its homologs were determined, including its log $D_{7.4}$, aqueous solubility, human plasma protein binding (PPB), and metabolic stability [human liver microsome and rat hepatocyte clearance] as shown in Table 1. Broadly similar results were obtained, principle differences being enhanced aqueous solubility for 27, whereas intrinsic clearance was superior for 29 in the rodent derived line and for 28 in the human cell line. Reduced clearance for 27 in turn may bode well for use in biodistribution studies [38].

4. Conclusions

In summary, we have designed and synthesized a family of PEGylated analogs of 4 and 5a using molecular modeling techniques. Lead compound 29, a fluorinated triethylene glycol derivative of preladenant, was identified, which shows promising results in two functional immunoassays and physicochemical assays. Future work will focus on detailed mechanistic studies on the mode of action of 29 and investigation of its use as a potential cancer immunotherapeutic agent.
Conflicts of Interest

The authors report no conflicts of interest.

Acknowledgments

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