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Fluorinated Adenosine A_2A Receptor Antagonists Inspired by Preladenant as Potential Cancer Immunotherapeutics

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Antagonism of the adenosine A_2A 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_2A 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_1, A_2A, A_2B, and A_3, 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_i and G_s 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_2A 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_2A 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_2A 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_2A R activation on the surface of immune cells [10–15]. Subsequent A_2A R antagonism by ZM241385 (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
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$_{2A}$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$_{2A}$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
Figure 3: Glide XP docking results of 4 and 5a. The interacting residues of A<sub>2A</sub>R are colored grey and the H-bond is represented as a dotted line. (a) 4 and (b) 5a renderings from YASARA [39].

The phenyl-piperazine linker inherent in 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 networks. Accordingly, the octaethylene glycol monomethyl ether moiety, a tolerable substituent in prior studies on networks. Accordingly, the octaethylene glycol monomethyl ether moiety, a tolerable substituent in prior studies on networks.

The interacting residues of A<sub>2A</sub>R are colored grey and the H-bond is represented as a dotted line. (a) 4 and (b) 5a renderings from YASARA [39].

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 POCI<sub>3</sub>/ZnBr<sub>2</sub>. 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].

The sequence was finally realized when the bromide 32 was subjected to palladium-catalyzed coupling with morpholine (33), stannous nitro reduction, condensation with benzyl 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<sub>3</sub> 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<sub>2A</sub>R binding-dependent signaling through A<sub>2A</sub>R on the surface of T cells [16]. The first assay screens
compounds on the basis of their extent of inhibition of A$_{2A}$R-induced intracellular cAMP accumulation in A$_{2A}$R expressing lymphocytes [36, 37]. The A$_{2A}$R agonist, CGS21680 (CGS, 6), was used to activate A$_{2A}$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 A$_{2A}$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 A$_{2A}$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 A$_{2A}$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 A$_{2A}$R agonist CGS to inhibit IFN-gamma secretion resulting from A$_{2A}$R-induced immunosuppression via intracellular cAMP. Effective A$_{2A}$R antagonists block the A$_{2A}$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, 1 μM CGS, and 1 μM CGS plus 1 μM 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/10$^6$ cells. Data shown represent mean ± SEM of triplicate samples.
Figure 5: Docking results of 27–29 via Glide XP method. The interacting residues of A2A.R are colored grey and the H-bond is represented as cyan dotted line. (a) Compound 27. (b) Compound 28. (c) Compound 29. Rendered from YASARA [39].

Table 1: Physicochemical properties and docking results of compounds 27–29.

<table>
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<th>Compound</th>
<th>Glide score</th>
<th>log D$_{7,4}$</th>
<th>Aqueous solubility (μM)</th>
<th>Human PPB (%)</th>
<th>HLM CLint (μL/min/mg)</th>
<th>Rat hepatocyte CLint (μL/min/10$^6$)</th>
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<td>27</td>
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<td>2.3</td>
<td>10</td>
<td>98.3</td>
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<td>72.9</td>
</tr>
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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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References


