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Search for adenosine A_{2A} spare receptors on peripheral human lymphocytes

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ABSTRACT

Some ligand–receptor couples involve spare receptors, which are apparent when a maximal response is achieved with only a small fraction of the receptor population occupied. This situation favours cross-reactions with low-affinity ligands, which may be detrimental for cell signaling. In the case of the adenosine A_{2A} receptors (A_{2A}R), which have an immunosuppressive effect on lymphocytes through cAMP production, the presence of spare A_{2A}R remains to be established. We examined the situation using patients over-expressing lymphocyte A_{2A}R and an agonist-like mAb to A_{2A}R. We found that maximal mAb binding and functional response varied among the patients whereas the dissociation constant and half-maximal effective concentration had similar mean values (0.19 and 0.18 μM, respectively). Lymphocyte A_{2A}R expression was correlated to plasma adenosine level and A_{2A}R occupation but not to A_{2A}R response. These results are consistent with a lack of a reserve of functional A_{2A}R on human lymphocytes as a general rule and suggest that the amount and functional state of the expressed A_{2A}R determine the maximal level of the lymphocyte response to adenosine.

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1. Introduction

Adenosine, an endogenous purine nucleoside, acts through four classes of G protein-coupled receptors (A₁R, A_{2A}R, A_{2B}R and A₄R) to exert various physiologic effects [1]. Most of these actions affect cardiovascular, neuronal and immune cells [2–7]. In lymphocytes, adenosine regulates multiple physiologic processes including inflammation [8–14] and congenital defect of adenosine deaminase – an enzyme that degrades the nucleoside and hence regulates its plasma level – associated with aberrant signaling through adenosine receptors contributes to the severe combined immunodeficiency syndrome [15]. CD4⁺ and CD8⁺ T-cells express A_{2A}R, A_{2B}R, and A₃R [16–21]. Numerous *in vivo* and *in vitro* studies suggest that A_{2A}R selectively inhibit T-cell receptors of activated T-cells, thereby inhibiting lymphocyte inflammatory activity [18,22–25]. Activation of the A_{2A}R on CD4⁺ T-cells prevents myocardial ischemia–reperfusion injury by inhibiting the lymphocyte accumulation and activation in the reperfused heart [26]. A_{2A}R can also prevent Th1/Th2 development [27] as well as T-cell apoptosis [28]. Finally, it was reported that adenosine produced by regulatory T-cells mediates immune suppression activity through

A_{2A}R [29,30]. Thus, the study of the expression and function of A_{2A}R on lymphocytes appears to be of pivotal importance to evaluate their immuno-regulatory role.

Various ligand–receptor models are available in pharmacology and may be applicable to agonist–A_{2A}R interactions in order to study the role of A_{2A}R in lymphocyte regulation. Among them, the spare receptor theory [31] postulates that a given ligand can exert maximum biological effect while occupying only a small amount of the available receptors. Such a reserve of receptors may allow for a response to low, transient ligand concentrations and low-affinity interactions which are compatible with several T-cells properties, hence supporting the presence of spare receptors for T-cell receptor activation [32]. From a pharmacological point of view, the presence of spare receptors is evidenced if the maximal ligand response (E_{max}) is obtained at less than the maximal occupation of the receptors (B_{max}). This pattern is usually determined by comparing the half-maximal effective concentration (EC₅₀) that refers to the ligand concentration necessary to reach 50% of the maximal effect with the dissociation constant (K_D) that refers to the ligand concentration necessary to reach 50% of the maximal binding. If the EC₅₀ is less than the K_D , spare receptors are existing.

Spare A_{2A}R were reported in cardiac tissue of guinea pig using an irreversible A_{2A}R antagonist to block receptor response to various agonists [33]. In other study on mouse T-cells, using gene targeting to generate mice lacking one or two alleles of A_{2A}R, the authors showed that the decrease in the number of A_{2A}R in thymocytes from A_{2A}R^{+/-} and A_{2A}R^{-/-} mice versus the A_{2A}R^{+/+} control mice resulted

Abbreviations: A_{2A}R, adenosine A_{2A} receptors; E_{max} , maximal ligand response; B_{max} , maximal occupation of the receptors; EC₅₀, half-maximal effective concentration; K_D , dissociation constant; NMS, neurally-mediated syncope; APC, adenosine plasma concentration; PBMC, peripheral blood mononuclear cells; AU, arbitrary units

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in proportional decrease in the adenosine-induced cAMP and apoptotic responses of their respective T-cells [34]. No investigations were conducted on human lymphocyte $A_{2A}R$ expression, occupation and function because of some experimental constraints, mainly low $A_{2A}R$ expression in normal individuals and lack of efficient ligand to stably bind to the receptor. Here, we took advantage of Adonis, an agonist-like mAb which steadily binds to an extra-cellular part of the $A_{2A}R$ [35], to investigate the presence of a reserve of $A_{2A}R$ in peripheral lymphocytes of patients with neurally-mediated syncope (NMS) who generally display high adenosine plasma concentrations (APC) and increased lymphocyte $A_{2A}R$ expressions [36–38].

2. Materials and methods

2.1. Selection of patients

Ten patients with clinical symptoms of NMS [38] were enrolled. NMS patients were chosen because they frequently exhibit high APC [36,39] associated with high expression levels of $A_{2A}R$ on peripheral lymphocytes [37], which was found to mirror the increase in $A_{2A}R$ expression on disease target organs [40]. This study was conducted in compliance with the principles of the Declaration of Helsinki and approved by the Ethics Committee for Human Research of our university hospital. All patients provided written informed consent to participate.

2.2. Adenosine assay

Blood sampling was processed as described using laboratory-prepared tubes containing 3 ml of cold-stop solution composed of inhibitors of degradation and red blood cell uptake of adenosine [36,39,41]. Samples were then maintained on ice until centrifugation. After deproteinization, adenosine was quantified by HPLC (Chrom-Systems, Munich, Germany), adenosine being identified by its elution time and spectrum [39]. Measurement was made by comparison of peak areas with those obtained using standards. The intra-assay and inter-assay coefficients of variation ranged from 1% to 3%.

2.3. Incubation of Adonis with lymphocytes

Blood samples were collected from brachial vein into 8 ml tubes containing sodium citrate/Ficoll (BD Vacutainer CPT, Beckton Dickinson, Franklin lakes, NJ). Peripheral blood mononuclear cells (PBMC) were prepared according to the manufacturer's instructions. Viable cell recovery was consistently over 98% with more than 95% of lymphocytes and less than 3% granulocytes. 0.25×10^6 cells were mixed with Adonis (0–1.2 μM in 1 ml culture medium), an IgM mAb directed against a linear part of the second external loop of $A_{2A}R$ [35]. After 90 min incubation at room temperature under shaking, PBMC were either washed twice with phosphate-buffered saline, pH 7.3 for binding and $A_{2A}R$ expression tests or only centrifuged without washing for functional test. Cell pellets were kept at -20°C until use.

2.4. Western blotting

To quantify both Adonis binding to lymphocytes and the lymphocyte $A_{2A}R$ expression, we used the Western blotting procedure previously described [42]. PBMC pellets previously incubated with or without Adonis were lysed by a 3 min sonication treatment at 47 kHz with the SDS–PAGE loading buffer containing 5% mercaptoethanol. Samples were then submitted to 12% SDS–PAGE analysis followed by transfer onto a PVDF membrane. Filters were incubated 20 min with Adonis and then with horseradish peroxidase-labeled anti-mouse IgG Fab specific antibodies prior to chemiluminescent staining with SuperSignal West Femto (Pierce Biotechnology, Rockford, IL).

In SDS–PAGE analysis in reducing condition, Adonis resolved in heavy (65 kDa) and light (25 kDa) IgM chains bands. Quantification of Adonis bound to $A_{2A}R$ was based on the detection of the light chain of the IgM because it is readily detected by the labeled second antibody directed partly to the light chain of Fab portion of mouse IgG shared by mouse IgM. Densitometry analysis used ImageJ 1.42q (National Institutes of Health, USA) and results from duplicates were expressed as arbitrary units (AU) defined as pixels of the light chain band versus blot background.

The lymphocyte $A_{2A}R$ expression was similarly quantified except that AU were defined as pixels of the canonical $A_{2A}R$ band versus blot background. $A_{2A}R$ from PBMC not previously incubated with Adonis migrated at 45 kDa and the corresponding band was detected by Adonis binding during the Western blot procedure.

Adonis binding curves were established using six concentrations of Adonis and non linear regression analysis were performed with a one site specific binding equation $Y = B_{\text{max}} \times X / (K_D + X)$ using Prism 5 (GraphPad Software, Inc La Jolla, CA). B_{max} expressed using the same units as Y values and K_D expressed using the same units as X values were estimated for Adonis binding to each PBMC preparation.

2.5. cAMP test

The agonist properties of Adonis allow its use as a specific effector for cAMP production [35]. Briefly, cellular cAMP measurement was achieved on PBMC pellets incubated with Adonis by ELISA using the Amersham Biotrak Kit (GE healthcare Bio-Sciences, Upsala, Sweden). Stimulation was stopped by adding dodecyltrimethylammonium bromide acetate buffer. Results of duplicates were expressed as AU defined as cAMP production generated in the presence versus in the absence of Adonis. We examined the results obtained using six concentrations of Adonis with Prism 5 (GraphPad Software) and the sigmoidal dose–response curve: $Y = \text{Bottom} + (\text{Top} - \text{Bottom}) / (1 + 10^{[(\text{Log EC}_{50} - X) \times \text{Hill Slope}]})$. Top (E_{max} here) and Bottom are plateau values in the units of Y and EC_{50} is the concentration of Adonis that gives a response half way between Top and Bottom values. Hill slope describes the steepness of the family of curves.

2.6. Statistical analysis

Quantitative variables were expressed using means \pm SEM. Paired t-test was used to compare K_D and EC_{50} values and correlation tests were made between adenosine, B_{max} and E_{max} values. All the tests were two-tailed and P-values less than 0.05 were considered as statistically significant. Analyses were performed with Prism 5 (GraphPad Software).

3. Results

3.1. Adenosine levels

The patients listed in Table 1 (7 women and 3 men; mean age: 52 years) were selected on the basis of NMS clinical symptoms. They had APC ranging from 0.29 to 2.91 μM with a mean value \pm SEM of $1.29 \pm 0.27 \mu\text{M}$. As expected from the literature on NMS, most patients (7 out of 10) had higher APC than control subjects (0.20 to 0.70 μM ; data from the Biochemistry Laboratory of the Timone Hospital, Marseille, France).

3.2. Saturation curves and dose–response curves

Adonis binding to PBMC from patients was assessed by Western blotting visualizing the light chain of bound Adonis (Fig. 1(A)). After densitometry analysis of the bands, the resulting Adonis binding curves exhibited various plateau values ranging from 3.05 to 68.13 AU (pixels of the light chain band versus blot background) with a mean

Table 1

List of patients with results.

Patients	Sex	Age	APC (μM)	B_{max} (AU)	K_{D} (μM)	E_{max} (AU)	EC_{50} (μM)	$A_{2A}R$ (AU)
1	Female	62	1.55	63.14	0.12	22.57	0.48	19.56
2	Female	18	0.99	26.66	0.15	32	0.1	19.53
3	Female	39	2.37	68.13	0.09	16.5	0.08	32.02
4	Female	49	1.82	59.16	0.08	28.29	0.11	12.12
5	Female	74	0.77	27.33	0.33	34.62	0.36	6.41
6	Male	38	2.91	61.49	0.26	41.73	0.23	17.97
7	Male	62	0.29	12.39	0.42	49.89	0.09	8.69
8	Female	49	0.66	8.92	0.23	21.56	0.17	7.29
9	Female	52	1.01	3.05	0.08	31.57	0.11	9.24
10	Male	71	0.5	12.37	0.13	36	0.06	8.61
	Mean	51.7	1.29	34.26	0.19	31.47	0.18	14.14
	\pm SEM	5.43	0.27	8.18	0.04	3.14	0.04	2.56

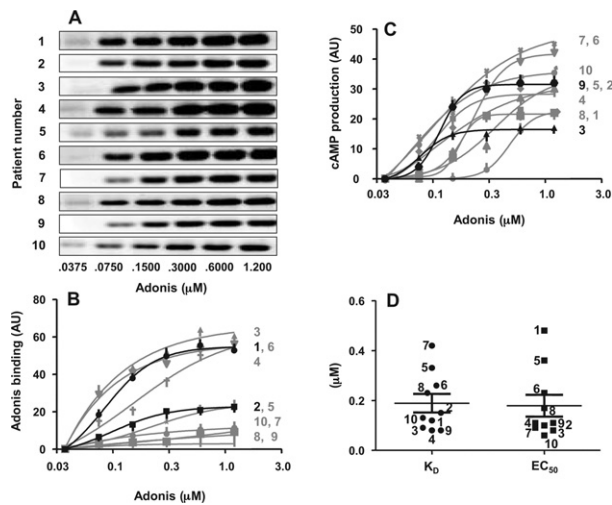


Fig. 1. (A) Western blots of Adonis (25 kDa light chain) binding to PBMC from the 10 patients. For each patient, 6 doses of Adonis were tested in duplicate on separate gels and one representative set of blots is shown. (B) Binding curves giving B_{max} and K_{D} values. Curves derived from the pixel analysis of the Adonis light chain blots. (C) Dose-response curves giving E_{max} and EC_{50} values for the 10 patients. For each set of curves, 2 representative curves are in black, the 8 other ones are in gray. Patient numbers are at right of the curves. Results expressed in arbitrary units (AU) as defined in Materials and methods are means \pm SD of duplicates. (D) Comparison of K_{D} (black circles) and EC_{50} (black squares) values interpolated from complete binding and dose-response curves with Adonis. Results are expressed in μM . Each symbol with the corresponding patient number represents individual mean value. Horizontal bars are means \pm SEM for the 10 patients.

value \pm SEM of 34.26 ± 8.18 AU (Fig. 1(B) and Table 1). Representative curves from Patients 1 and 2 were highlighted in black in Fig. 1 (B). Binding reached a plateau value at 63.14 AU of Adonis binding for Patient 1 and at 26.66 AU for Patient 2, both patients exhibiting similar K_{D} value (0.12 and 0.15 μM , respectively; Table 1).

Adonis response curves for cAMP production also exhibited various plateau values ranging from 16.50 to 49.89 AU (cAMP production generated by Adonis versus basal cAMP level in the absence of Adonis) with a mean value \pm SEM of 31.47 ± 3.14 AU (Fig. 1(C) and Table 1). Representative curves from Patients 9 and 3 were highlighted in black in Fig. 1 (C). A maximal effect at 31.57 AU of cAMP production was obtained for Patient 9 whereas only 16.5 AU were obtained for Patient 3, both patients exhibiting similar EC_{50} values (0.11 and 0.08 μM , respectively; Table 1).

Fig. 1(D) shows that, taken as a whole, the distribution of K_{D} and EC_{50} values extrapolated from the above curves was not statistically different: K_{D} values ranged from 0.08 to 0.42 μM with a mean value \pm SEM of 0.19 ± 0.04 μM and EC_{50} values ranged from 0.06 to 0.48 μM with a mean value \pm SEM of 0.18 ± 0.04 μM . We noticed 2

exceptions, Patient 7 displaying the highest K_{D} (0.42 μM) had a 5-fold lower EC_{50} (0.09 μM) and, conversely, Patient 1 displaying the highest EC_{50} (0.48 μM) had a 4-fold lower K_{D} (0.12 μM) (Fig. 1(D) and Table 1).

3.3. Expression of $A_{2A}R$

We found various lymphocyte $A_{2A}R$ expression levels with values ranging from 6.41 to 32.02 AU (pixels of the $A_{2A}R$ band versus blot background) with a mean value \pm SEM of 14.14 ± 2.56 AU. Correlation studies were performed to compare lymphocyte $A_{2A}R$ expressions to APC, B_{max} and E_{max} . Lymphocyte $A_{2A}R$ expressions were found to be correlated with APC (Fig. 2(A)) and B_{max} (Fig. 2(B)) but not E_{max} (Fig. 2(C)) values. Once more, we noticed 2 exceptions: Patient 7 displaying the highest E_{max} (49.89 AU) had low $A_{2A}R$ level (8.69 AU) while Patient 3 displaying the lowest E_{max} (16.5 AU) expressed the highest $A_{2A}R$ level (32.02 AU).

4. Discussion

We found that B_{max} of Adonis to $A_{2A}R$ varied from subject to subject whereas K_{D} values were similar. Various E_{max} were also found whereas the EC_{50} values were similar. More importantly, the K_{D} values were found to be statistically not different from the EC_{50} values, suggesting a lack of a reserve of receptors according to the criteria previously defined. In 8 out of the 10 patients tested, the highest cAMP production occurred when all the receptors were occupied by Adonis. Results from 2 patients, however, illustrate opposite situations: Patient 7 exhibited a K_{D} which was 5-fold higher than EC_{50} , consistent with the situation where a few occupied receptors produce a maximal effect (presence of spare receptors), and Patient 1 exhibited a K_{D} which was 4-fold lower than EC_{50} , indicating a situation where a low effect is obtained while all receptors are occupied. The latter case suggests that many $A_{2A}R$ of this subject are not functional.

We also performed experiments to address the lymphocyte $A_{2A}R$ expression using Western blotting. As previously reported in patients with intradialytic hypotension during hemodialysis [43] and spontaneous and head-up-tilt-induced syncope [37,38], we found an overexpression of lymphocyte $A_{2A}R$ which correlated with the increase in APC and therefore with the maximal level of Adonis binding. This suggests that adenosine and $A_{2A}R$ are upregulated concomitantly and/or interdependently. More intriguingly, lymphocyte $A_{2A}R$ expression was generally not correlated with E_{max} suggesting a non linear relation between the amount of receptors and their overall efficiency. Therefore, adenosine appeared necessary but not sufficient to modulate its immunosuppressive effect via the $A_{2A}R$. Two patients illustrate opposite situations regarding E_{max} : Patient 7, previously suspected with spare receptors, who expressed a few but highly efficient receptors and, conversely, Patient 3 who expressed high level of receptors exhibiting low overall efficiency. The former, displaying a K_{D} higher

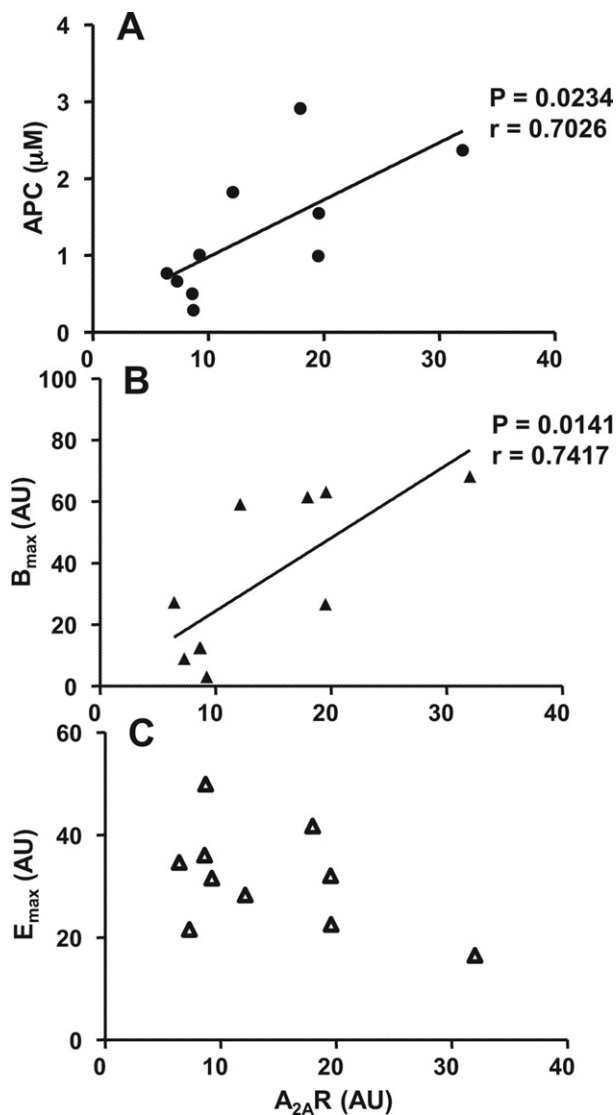


Fig. 2. Correlation study between lymphocyte $A_{2A}R$ expression levels and (A) APC, (B) B_{max} and (C) E_{max} . Results are expressed in μM for adenosine plasma levels and arbitrary units (AU) as defined in Materials and methods for $A_{2A}R$ expression, B_{max} and E_{max} levels. $A_{2A}R$ expressions were measured using Western blotting. Each symbol represents individual mean value. Significant correlation ($P < 0.05$) for the 10 patients is indicated at right.

than EC_{50} , had probably some receptors engaged in an hyper-active state with an efficient coupling to the effector (Gs for cAMP production) whereas the latter, displaying a K_D similar to EC_{50} , likely expressed mostly inactive receptors, unmounted to cell-surface and constituting a putative reserve of intra-cellular standby receptors.

T-cells possess a T-cell receptor reserve to increase the flexibility of cell response to ligands of weaker potency [44]. Accordingly, we suggest that a reserve of $A_{2A}R$ would promote cross-reactions with low affinity ligands such as weak and partial agonists/antagonists. Consequently, stimulating or blocking ligands other than adenosine would impede the fine tuning of adenosine-induced immune regulation by occupying more receptors to respond. However, absence of spare receptors does not systematically mean that the amount of expressed $A_{2A}R$ on lymphocytes is the limiting factor to determine the extent of the effector response. Regarding the NMS situation, $A_{2A}R$ are frequently over-expressed in peripheral lymphocytes and some

patients having a specific $A_{2A}R$ gene polymorphism express more receptors [45]. However, the resulting efficiency of the $A_{2A}R$ response can also depend on the functional state of the receptors. The multimerization process of G protein-coupled receptors [46] modulates agonist efficiency when occupancy of a single receptor is needed to obtain a full agonist action. For a recent example, TSH receptor signals via activation of Gs to stimulate cAMP production when TSH binds to one protomer of the TSH receptor homodimer [47]. Therefore, the presence of spare receptors may also refer to the functional state of the multimerized receptors.

Together, these data are consistent with a lack of spare $A_{2A}R$ on lymphocytes as a general rule and their putative presence in some patients appeared to be dependent on the functional state of the targeted receptors. Therefore, the adenosinergic signaling efficiency in lymphocytes likely involves many but not a few $A_{2A}R$ expressed on lymphocytes and this is the amount and functional state of these expressed receptors that determine the maximal level of the lymphocyte response to adenosine.

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