Expression of mRNA for adenosine A$_1$, A$_{2a}$, A$_{2b}$, and A$_3$ receptors in HL-60 cells: dependence on cell cycle phases

Michal Hofer$^1$*, Ladislav Dušek$^2$, Zuzana Hoferová$^1$, Lenka Stíxová$^3$, Milan Pospíšil$^1$

$^1$Laboratory of Experimental Hematology, Department of Molecular Cytology and Cytometry, Institute of Biophysics, v.v.i., Academy of Sciences of the Czech Republic, Královopolská 135, CZ-61265 Brno, Czech Republic;

$^2$Institute of Biostatistics and Analyses, Masaryk University, Kamenice 126/3, CZ-62500 Brno, Czech Republic;

$^3$Laboratory of Structure and Function of the Cell Nucleus, Department of Molecular Cytology and Cytometry, Institute of Biophysics, v.v.i., Academy of Sciences of the Czech Republic, Brno, Czech Republic;

*Corresponding author: Michal Hofer, MD, PhD, Institute of Biophysics, v.v.i., Academy of Sciences of the Czech Republic, Brno, Czech Republic, Královopolská 135, CZ-61265 Brno, Czech Republic, telephone: +420 541517171, fax: +420 54121293, e-mail: hofer@ibp.cz

Short title: Adenosine receptors and cell cycle
Summary
The present studies investigated changes in expression of mRNA for adenosine A1, A2a, A2b, and A3 receptors in samples of HL-60 promyelocytic cells differing in the actual presence of cells in various phases of the cell cycle induced by the double thymidine block method. Real-time PCR technique was used for obtaining data on mRNA expression. Statistical analysis of the data revealed that the mRNA expression of adenosine A1, A2a, and A3 receptors is dependent on the cell cycle phase. G0/G1 and G2/M phases were characterized by a higher mRNA expression of adenosine A1 receptors and a lower one of adenosine A2a and A3 receptors whereas the opposite was true for the S phase. Interestingly, expression of mRNA of the adenosine A2b receptors was independent on the cell cycle phase. The results indicate the plasticity of mRNA expression of adenosine receptors in the investigated promyelocytic cells and its interaction with physiological mechanisms of the cell cycle.

Keywords: adenosine receptors, messenger RNA expression, cell cycle, HL-60 promyelocytic cells

Introduction
Adenosine, an ubiquitous purine nucleoside released into the extracellular environment from metabolically active or stressed cells, has been recognized to act as a paracrine regulator of many cellular functions including proliferation and differentiation (Abbracchio and Burnstock 1998, Poulsen and Quinn 1998, Schulte and Fredholm 2003). The regulatory function of extracellular adenosine is based on the activation of cell surface receptors, namely A1, A2a, A2b, and A3. Receptor activation can be achieved either non-selectively, by adenosine, or selectively, using various adenosine analogs (Jacobson 2002).

We have demonstrated that pharmacologically induced elevation of extracellular adenosine, i.e. non-selective activation of adenosine receptors, stimulates hematopoiesis in mice (for review, see Hofer and Pospišil 2006, Hofer et al. 2011). Furthermore, we have aimed our effort at direct determination of mRNA expression for adenosine A1, A2a, A2b, and A3 receptors in four mouse hematopoietic precursor cell lines, namely granulopoietic/monocytopoietic, erythropoietic, B-lymphopoietic, and T-lymphopoietic ones. Similar studies were carried out with mouse RAW 264.7 macrophages taken as a model object representing the hematopoietic microenvironment. We have demonstrated that mRNA for all the four adenosine receptors is expressed in all cell types tested with the exception of the A1 receptor in the RAW 264.7 macrophages (Štreitová et al. 2010 a, b). Thus, the ability
of important cells of the hematopoietic system to respond to activation by selective adenosine receptor agonists has been proven. Furthermore, we have used the model of hematopoietic suppression evoked by the cytotoxic drug 5-fluorouracil, killing predominantly cycling cells, and we have found that particularly administration of two tested selective adenosine receptor agonists, i.e. N^{6}-cyclopentyladenosine (CPA) and N^{6}- (3-iodobenzy)adenosine-5′-N- methyluronamide (IB-MECA), selective for A_{1} and A_{3} receptors, respectively, influences cycling of hematopoietic progenitor cells: activation of adenosine A_{1} receptors has been found to inhibit whereas activation of adenosine A_{3} receptors to stimulate proliferation in the compartments of both bone marrow progenitor and precursor cells (Pospíšil et al. 2004, 2005, Hofer et al. 2006, 2007, 2008).

Starting from the knowledge platform summarized above, we have addressed the problem of adenosine receptor expression and we have studied whether or not is the mRNA expression of individual adenosine receptors related to the varying functional state of the hematopoietic tissue induced by the variable presence of cells occurring in different phases of the cell cycle. HL-60 promyelocytic cells have been used as a model of the hematopoietic cell renewal system. The mRNA expression for individual adenosine receptors has been determined by the quantitative real-time PCR technique.

**Materials and methods**

**Cell System and Culture Conditions**

Human promyelocytic leukemic cell line HL-60 was obtained from the American Tissue Culture Collection (ATCC). The cells were cultivated in RPMI-1640 medium (Sebak, Aidenbach, Germany) supplemented with 10% inactivated fetal bovine serum (Pan Biotech GmbH, Aidenbach, Germany), 1 mM sodium pyruvate (ICN Biomedicals, Costa Mesa, CA, USA), 100 μg/ml streptomycin (Gibco, Paisley, UK), 100 IU/ml penicillin (Gibco), 0.1 mg/ml gentamicin (PAN Systems, Nürnberg, Germany), 8 mM L-glutamine (Gibco), 1% nonessential amino acids (ICN Biomedicals), 5mM HEPES (Serva, New York, NY, USA), and 50 μM 2-mercaptoethanol (Fluka, Seelz, Germany). The cells were kept at 37°C in a humidified atmosphere containing 95% air and 5% CO_{2}, transferred into a fresh medium twice a week and used for experiments during the exponential growth phase.
Double Thymidine Block of HL-60 Cells
To obtain populations with varying percentages of cells in individual cell cycle phases, HL-60 cells were exposed to the double thymidine block. Stock solution of 200 mM thymidine (Sigma, St.Louis, MO, USA) in PBS was prepared in and used at a 1/50 dilution to produce a 4 mM thymidine solution. The cells in the exponential growth phase (analysed as sample 1) (5 x 10^5) were blocked for 18 h with 4 mM thymidine, released by washing out the thymidine once in phosphate-buffered saline (PBS, pH 7.4), and cultivated in fresh RPMI medium for 9 h. Then the cells were blocked again with 4 mM thymidine for 17 h to arrest a significant percentage of the cells at the beginning of S-phase. The arrest was then released by washing out thymidine and the cells were cultivated in fresh medium for 72 h. Further analyses were carried out at hours 1 (sample 2), 2 (sample 3), 3 (sample 4), 6 (sample 5), 24 (sample 6), 48 (sample 7) and 72 (sample 8). Relative representation of the cells in G0/G1, S, and G2/M cell cycle phases in the cell samples is shown in Table 1.

Cell Cycle Studies
The sampled cells were collected by centrifugation, washed once in PBS and suspended for 12 hours in 70 % ethanol for cell fixation at the temperature of 4 °C. The fixed cells were again collected by centrifugation, ethanol was aspirated off and the cells were resuspended in a staining buffer containing 5mg/ml propidium iodide, 1M TRIS (Roth, Karlsruhe, Germany) (pH 8), 10mg/ml RNase (Sigma) and 10 % Triton X-100 (AppliChem, Darmstadt, Germany). After 30 min of incubation at 37 °C, samples were analyzed with a FACScan flow-cytometer (Becton-Dickinson, San Jose, CA, USA) equipped with an argon laser (excitation at 488 nm). To estimate the percentage of cells in each phase of cell cycle (G0/G1, S and G2/M), histogram analyses of relative DNA contents were carried out with Mod Fit LT 2,0 software (VERITY, Software House, Inc., Topsham, ME, USA).

Isolation of Total RNA
In all samples (1 to 8), isolation of total RNA of the cells was carried out using the High Pure Isolation Kit (Roche, Mannheim, Germany). RNA concentration and purity were measured on Nano-Drop ND1000 Spectrophotometer (Thermo Scientific, USA). The 260/280 ratio was not less than 1.8 for each RNA sample. Total RNA was stored at -80 °C prior to cDNA synthesis.
Reverse Transcription of total RNA to cDNA

The subsequent cDNA synthesis for a two-step real-time polymerase chain reaction (RT-PCR) was carried out with the Transcriptor First Strand cDNA Synthesis Kit (Roche Diagnostics, Mannheim, Germany). One μg of RNA template was used per each RNA-to-cDNA reaction. The templates were mixed with anchored-oligo(dT18) primers (2.5 μM) and random hexamer primers (60 μM). The samples were placed in DNA Engine Peltier thermal cycler (BioRad, USA) and incubated for 10 min at 25°C, followed by 30 min at 55°C, and at the end heated to 85°C for 5 min. Synthesized cDNA was stored at -20°C.

Quantitative Real-Time PCR (RT-PCR)

Using FastStart SYBR Green Master (Roche) in combination with appropriate PCR primers, RT-PCR detection and quantification of DNA sequences for A1, A2a, A2b, and A3 subtypes of adenosine receptors were performed. Sequences of primers (see Štreitová et al. 2010a) were taken over from Ashton et al. (2003) and Overbergh et al. (1999) and the primers were synthesized by Generi Biotech (Hradec Králové, Czech Republic). RT-PCR was done in duplicates for each adenosine receptor primer on Rotor-Gene 6000 (Corbett Research, Sydney, Australia). The final reaction volume (20 μl) included 10 μl of FastStart SYBR Green Master Mix, 2.5 μl of cDNA, and 300 nM concentration of each primer. The first reaction cycle was carried out at 95°C for 10 min and was followed by 40 cycles, each of which consisted in 15 s at 95°C, 30 s at 60°C and 30 s at 72°C. To calculate relative gene expression, the delta-delta Ct method based on the difference of threshold cycles (Ct) of the target gene and the β-actin sequence was used. A twofold increase in PCR products per cycle was assumed. Any receptor was taken for relative quantification if the threshold cycle number was less than 36. If the threshold cycle number was greater than 36, the receptor mRNA was considered to be present in minimal quantities and relative quantification was not performed. A gene was considered not to be expressed if no amplification was detected by cycle 40.

Statistical Analysis

Primary data were obtained on the basis of two repeated experiments. In each experiment, two determinations of the mRNA expression from each sample were performed. Arithmetic means were calculated from the two repeated determinations in each sample and then calculations of arithmetic means from both experiments were carried out. Thus, a single value representing the expression of a particular receptor in each sample was obtained. This aggregation of
primary data was carefully checked and it was proved not to reduce overall experimental variance.

Mutual association of examined parameters was evaluated on the basis of rank Spearman’s non-parametric correlation and its statistical significance. Variance associated with the estimated correlations was assessed and the statistical significance of mutual differences between correlation coefficients was evaluated by a standard test based on normally distributed test statistics Z (Borkowf 2000, Cornbleet and Shea 1978).

The value \( p \leq 0.05 \) was considered to be a boundary of statistical significance in all performed analyses. The analyses were carried out after removal of outliers (4.2 %) identified by Dixon’s test (Dean and Dixon 1951, Rorabacher 1991). All analyses were performed using the SPSS 18.0.3. software (IBM Corporation, 2010).

Results
The experimental protocol employing the promyelocytic HL-60 cell line was based on investigations of relationships between mRNA expression of individual adenosine receptors and the presence of cells occurring in individual phases of the cell cycle, i.e. G0/G1, S, and G2/M. These analyses were performed separately for each receptor type and each cell cycle phase. Because of the four analysed adenosine receptors and the three investigated cell cycle phases, twelve correlations in total have been computed. Spearman’s correlation coefficients \( r_s \) were used as a robust measure of association between given adenosine receptor mRNA expression and given cell cycle phase. Thus, a positive value of \( r_s \) indicates that the given phase of the cell cycle is linked with a higher production of the given receptor mRNA. On the contrary, a negative value of \( r_s \) indicates that the given cell cycle phase is linked with a lower level of the given receptor mRNA production. Results of the experiments are presented in Figs. 1 – 3 which characterize the tested functional dependences by regression lines and Spearman’s correlation coefficients \( (r_s) \) with corresponding statistical significances (p).

The first distinct phenomenon of the results is the evidence that the mRNA expression of the adenosine A2b receptors is inert to the structure of cell cycle phases in the individual samples: in all samples it reaches nearly the same level. The experimental variability associated with the mRNA expression of the adenosine A2b receptors is very low, at the level of random error of fluctuations and no significant correlation occurred. This is in contrast to the experimental variability observed when analysing the expression of mRNA of all other adenosine receptor subtypes (see Figs. 1-3).
Concerning the cells in the G₀/G₁ phase of the cell cycle (Fig. 1), the following observations are worth mentioning: There is a positive and significant correlation for the expression of adenosine A₁ receptor mRNA, a negative and significant correlation for the expression of adenosine A₂a receptor mRNA, as well as a negative correlation (p=0.052) for the adenosine A₃ receptor mRNA. These findings suggest a higher level of mRNA expression of the A₁ receptors and a lower one of the A₂a and A₃ receptors in cells occurring in the G₀/G₁ phase of the cell cycle.

Differently pronounced results have been found by calculations of association between the mRNA expression of individual adenosine receptors and the presence of the cells in the S phase of the cell cycle (Fig. 2). Here, the negative rₛ for adenosine A₁ receptor mRNA and positive rₛ for mRNA of adenosine A₂a and A₃ receptors occur, even if not attaining statistical significance. These findings seem to indicate that the manifestations of the mRNA expression of the adenosine A₁, A₂a, and A₃ receptors in the S phase of the cell cycle are opposite to those obtained in the G₀/G₁ phase in terms of negativity or positivity of rₛ. For confirmation of this phenomenon, correlation coefficients between the mRNA expression of the three adenosine receptors and the presence of the cells in the cell cycle phases G₀/G₁ and S have been compared and the results are presented in Table 2. It is apparent that the mRNA expression of adenosine A₁, A₂a, and A₃ receptors differs significantly between the G₀/G₁ and the S phases of the cell cycle. For the G₀/G₁ phase an increased mRNA expression of the adenosine A₁ receptor is typical whereas in the S phase an expression of the adenosine A₂a and A₃ receptors predominates.

Data given in Fig. 3 demonstrate the dependence of the mRNA expression of adenosine receptors on the presence of the cells in the G₂/M phase of the cell cycle. Here, a negative statistically significant rₛ for the mRNA expression of the A₂a receptor dominates. This situation is reflected also by the significant difference of correlation coefficients for the expression of mRNA for the adenosine A₂a receptor between the S and G₂/M phases, as shown in Table 2.

Additional statistical processing of the data consisted in computing correlation coefficients representing the mutual relations in mRNA expression in pairs of adenosine receptors (A₁ – A₂a, A₁ – A₃, A₂a – A₃) when using data from all cell cycle phases taken as a whole. The results are given in Table 3 and show a statistically significant positive correlation between the mRNA expression of adenosine A₂a and A₃ receptors. There is also a negative correlation in receptor mRNA expression between A₁ and A₂a receptors, as well as between that of A₁ and A₃ receptors, but without statistical significance.
Discussion

To our knowledge, the obtained data present the first study investigating the expression of mRNAs of adenosine receptors in different phases of the cell cycle. Even if the rate of mRNA expression needs not be fully reflected at the corresponding protein levels, the presented data suggest at least tendencies for the synthesis of functional adenosine receptors and allows to formulate certain general conclusions.

The experiments performed on HL-60 promyelocytic cells suggest a diversity of mRNA expression of individual adenosine receptors in different phases of the cell cycle. The preparatory G0/G1 phase, as well as the G2/M phase, are positively linked to the mRNA expression of the A1 receptors and negatively to that of the A2a and A3 adenosine receptors. On the contrary, the synthetic S phase is characterized by the decrease of the mRNA expression of the A1 adenosine receptors and the increase of that of the A2a and A3 adenosine receptors. These findings might be analogical to our earlier considerations ensuing from in vivo experiments. We have observed positive effects of an adenosine A3 receptor agonist on cycling of hematopoietic cells (Pospíšil et al. 2004, Hofer et al. 2006, 2007, 2008), as well as an inhibitory action of an agonist of adenosine A1 receptors on the proliferation of cells in the murine hematopoietic system in vivo (Pospíšil et al. 2004, 2005, Hofer et al. 2008). Of particular interest are our findings in mice whose hematopoiesis was suppressed by 5-fluorouracil (Hofer et al. 2008). In these mice, the proliferation-stimulating effects of the adenosine A3 receptor agonist were most pronounced in the phase of maximum cell depletion when maximum cell proliferation was to be expected. On the other hand, the proliferation-inhibiting action of the adenosine A1 receptor agonist was most pronounced in the phase of maximum cell regeneration when a feedback suppressing the overshooting cell proliferation was needed (Hofer et al. 2008). Taking into account these findings and considerations, the data presented here on expression of mRNA of adenosine A1 and A3 receptors, which varies between the G0/G1, S, and G2/M phases of the cell cycle, might be a further evidence of the regulatory and homeostatic role of these two adenosine receptors.

Although an analogical behavior of premyelocytic HL-60 cells with hematopoietic progenitor and precursor cells in vivo, as discussed in the previous paragraph, can be expected, it cannot be completely excluded that the very process of malignization of the HL-60 cells could influence the mRNA expression of adenosine receptors. Therefore, certain caution should accompany the interpretation of the results obtained.

The opposite role of the adenosine A1 and A3 receptors in the regulation of cell cycling might be surprising because both these receptors are known to inhibit adenylyl cyclase.
However, they differ in their coupling to different G proteins (Fredholm et al. 2000) and to phospholipases C and D (Parsons et al. 2000). Another example of opposite effects of the two adenosine receptors was shown in experiments of Lee and Emala (2000) demonstrating that adenosine A1 receptor activation reduces, while adenosine A3 receptor activation worsens renal ischemia-reperfusion injury.

An interesting phenomenon of the presented experiments is the behavior of the expression of mRNA for adenosine A2a receptors which significantly positively correlates with that for adenosine A3 receptors. Activation of adenosine A2a receptors inhibits inflammatory processes in neutrophils, platelets, macrophages, and T cells (Linden 2001). Our earlier experiments investigating effects of the agonist of these receptors exhibited no significant effects on the cycling of haematopoietic cells (Pospíšil et al. 2004). Thus, the role of the adenosine A2a receptors in hematopoiesis and the relationships between the adenosine A2a and A3 receptor mRNA expression deserve further attention.

Worth noting is also the evidence of the independence of the expression of mRNA of adenosine A2b receptors on the different phases of the cell cycle. The reason might be the low affinity of these receptors towards the endogenous agonist adenosine (Fredholm 2007) and thus operation of adenosine A2b receptors may be important only under pathophysiological conditions.

Acknowledgments
Suported by grants from Ministry of Defense of the Czech Republic (Project Receptor, No. 1001 8 5090), Grant Agency of the Czech Republic (No.s 305/08/0158 and P303/11/0128), and Academy of Sciences of the Czech Republic (No.s AV0Z50050507 and AV0Z50040702).

References


Legends to Figures

Fig. 1. Dependence of expression of mRNA for adenosine A₁, A₂a, A₂b, and A₃ receptors on the per cent proportion of HL-60 cells in the G₀/G₁ cell cycle phase, as presented in Table 1. $r_s$ – Spearman’s correlation coefficient; $p$ – statistical significance of $r_s$.

Fig. 2. Dependence of expression of mRNA for adenosine A₁, A₂a, A₂b, and A₃ receptors on the per cent proportion of HL-60 cells in the S cell cycle phase, as presented in Table 1. $r_s$ – Spearman’s correlation coefficient; $p$ – statistical significance of $r_s$.

Fig. 3. Dependence of expression of mRNA for adenosine A₁, A₂a, A₂b, and A₃ receptors on the per cent proportion of HL-60 cells in the G₂/M cell cycle phase, as presented in Table. $r_s$ – Spearman’s correlation coefficient; $p$ – statistical significance of $r_s$. 
Table 1. Per cent representation of G0/G1, S, and G2/M cell cycle phases in individual cell populations (samples described in the text)

<table>
<thead>
<tr>
<th>Sample</th>
<th>G0/G1 phase</th>
<th>S phase</th>
<th>G2/M phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>67.0</td>
<td>32.5</td>
<td>0.5</td>
</tr>
<tr>
<td>2</td>
<td>35.8</td>
<td>60.3</td>
<td>3.9</td>
</tr>
<tr>
<td>3</td>
<td>36.0</td>
<td>61.7</td>
<td>2.3</td>
</tr>
<tr>
<td>4</td>
<td>37.9</td>
<td>60.2</td>
<td>1.9</td>
</tr>
<tr>
<td>5</td>
<td>39.6</td>
<td>40.6</td>
<td>19.8</td>
</tr>
<tr>
<td>6</td>
<td>41.7</td>
<td>40.3</td>
<td>18.0</td>
</tr>
<tr>
<td>7</td>
<td>54.0</td>
<td>35.9</td>
<td>10.1</td>
</tr>
<tr>
<td>8</td>
<td>69.2</td>
<td>25.0</td>
<td>5.8</td>
</tr>
</tbody>
</table>
Table 2. Comparison of correlation coefficients r_s between cell cycle phases G_0/G_1 and S, and between cell cycle phases S and G_2/M, for mRNA expression of adenosine A_1, A_2a, and A_3 receptors

<table>
<thead>
<tr>
<th>Receptor type</th>
<th>G_0/G_1 phase (r_s)</th>
<th>S phase (r_s)</th>
<th>G_2/M phase (r_s)</th>
<th>Comparison of r_s (G_0/G_1 vs. S)</th>
<th>Comparison of r_s (S vs. G_2/M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A_1</td>
<td>0.714</td>
<td>-0.667</td>
<td>0.190</td>
<td>p=0.021</td>
<td>p=0.141</td>
</tr>
<tr>
<td>A_2a</td>
<td>-0.714</td>
<td>0.679</td>
<td>-0.857</td>
<td>p=0.027</td>
<td>p=0.014</td>
</tr>
<tr>
<td>A_3</td>
<td>-0.750</td>
<td>0.714</td>
<td>-0.238</td>
<td>p=0.025</td>
<td>p=0.118</td>
</tr>
</tbody>
</table>

p – value of statistical significance of comparison of correlation coefficients r_s between the compared cell cycle phases.
Table 3. Relations of mRNA expression indices between individual pairs of adenosine A₁, A₂a, and A₃ receptors

<table>
<thead>
<tr>
<th>Receptor type</th>
<th>A₁</th>
<th>A₂a</th>
<th>A₃</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>rs</td>
<td>p</td>
<td>rs</td>
</tr>
<tr>
<td>A₁</td>
<td>-</td>
<td>-</td>
<td>-0.143</td>
</tr>
<tr>
<td>A₂a</td>
<td>-0.143</td>
<td>0.760</td>
<td>-</td>
</tr>
<tr>
<td>A₃</td>
<td>-0.393</td>
<td>0.383</td>
<td>0.786</td>
</tr>
</tbody>
</table>

rs – correlation coefficients; p – values of statistical significance of the pertinent rs
a) A₁ receptor

$r_s: -0.667 (p=0.071)$

b) A₂a receptor

$r_s: 0.679 (p=0.094)$

c) A₂b receptor

$r_s: 0.381 (p=0.352)$

d) A₃ receptor

$r_s: 0.714 (p=0.071)$