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## ORIGINAL ARTICLE

# Homocysteine concentration and adenosine A<sub>2A</sub> receptor production by peripheral blood mononuclear cells in coronary artery disease patients

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## Abstract

Hyperhomocysteinemia is associated with coronary artery disease (CAD). The mechanistic aspects of this relationship are unclear. In CAD patients, homocysteine (HCy) concentration correlates with plasma level of adenosine that controls the coronary circulation via the activation of adenosine A<sub>2A</sub> receptors (A<sub>2A</sub>R). We addressed in CAD patients the relationship between HCy and A<sub>2A</sub>R production, and in cellulo the effect of HCy on A<sub>2A</sub>R function. 46 patients with CAD and 20 control healthy subjects were included. We evaluated A<sub>2A</sub>R production by peripheral blood mononuclear cells using Western blotting. We studied in cellulo (CEM human T cells) the effect of HCy on A<sub>2A</sub>R production as well as on basal and stimulated cAMP production following A<sub>2A</sub>R activation by an agonist-like monoclonal antibody. HCy concentration was higher in CAD patients vs controls (median, range: 16.6 [7-45] vs 8 [5-12]  $\mu$ M,  $P < 0.001$ ). A<sub>2A</sub>R production was lower in patients vs controls (1.1[0.62-1.6] vs 1.53[0.7-1.9] arbitrary units,  $P < 0.001$ ). We observed a negative correlation between HCy concentration and A<sub>2A</sub>R production ( $r = -0.43$ ;  $P < 0.0001$ ), with decreased A<sub>2A</sub>R production above 25  $\mu$ M HCy. In cellulo, HCy inhibited A<sub>2A</sub>R production, as well as basal and stimulated cAMP production. In conclusion, HCy is negatively associated with A<sub>2A</sub>R production in CAD patients, as well as with A<sub>2A</sub>R and cAMP production in cellulo. The decrease in A<sub>2A</sub>R production and function, which is known to hamper coronary blood flow and promote inflammation, may support CAD pathogenesis.

## KEYWORDS

A<sub>2A</sub> receptor, adenosine, coronary artery disease, homocysteine

Pierre Deharo, Marion Marlinge, Clair Guiol, Emmanuel Fenouillet, Giovanna Mottola: Participating equally to the work.

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## 1 | INTRODUCTION

Homocysteine (HCy) is a thiol-containing amino acid intermediate the metabolism of which is linked to those of methionine, uric acid and adenosine. HCy and adenosine concentrations are correlated at least in coronary artery disease (CAD) patients.<sup>1</sup> Adenosine is an ATP derivative that is released by endothelial cells and myocytes during ischaemia, hypoxia or inflammation.<sup>2,3</sup> Adenosine impacts the cardiovascular system via the activation of its receptors namely  $A_1$  R,  $A_{2A}$  R,  $A_{2B}$  R or  $A_3$  R pending on their pharmacological properties.<sup>4</sup>  $A_{2A}$  R activation exerts artery vasodilation via cAMP production<sup>5</sup> and specially coronary vasodilation,<sup>6</sup> cAMP production and coronary vasodilation being correlated.<sup>7</sup>

Chronic ischaemia elicits coronary vasodilation in the myocardium.<sup>8</sup> This adaptive response is partly due to adenosine release that improves coronary blood flow via activation of  $A_{2A}$  R<sup>6,9,10</sup> and  $A_{2B}$  R.<sup>9,10</sup> Although acute release of adenosine leads to coronary vasodilation and may be consequently beneficial for the myocardium, chronic exposure to high adenosine level may have deleterious effects.<sup>11</sup>

Hyperhomocysteinemia (HHCy) is associated with cardiovascular disease<sup>12,13</sup> and independently associated with CAD<sup>14,15</sup> and myocardial infarction-induced death.<sup>16</sup> It was also found that HHCy is correlated with CAD severity<sup>1,17</sup> although the mechanistic aspects of this relationship are unclear. Finally, HHCy is associated with increased oxidative stress<sup>18</sup> and endothelial dysfunction.<sup>19</sup> However the precise mechanism by which HHCy participates into CAD progression remains controversial because homocysteine-lowering therapy does not affect the inflammatory status of CAD patients<sup>20</sup> and poorly influences cardiovascular risk.<sup>21</sup>

Peripheral blood mononuclear cells (PBMC) can be easily sampled and the behaviour of adenosine receptors produced on PBMC mirrors their counterparts in heart,<sup>22</sup> and in coronary arteries.<sup>23</sup> Therefore, PBMCs are useful to address  $A_{2A}$  R pharmacological properties in patients and to evaluate the influence of HCy on adenosine receptors of the vascular system. We previously observed a decrease in  $A_{2A}$  R production by PBMC of CAD patients<sup>24</sup> the cause of which not yet investigated.

Thus, we evaluated here the relationship between HCy concentration and  $A_{2A}$  R production in CAD patients. We also examined in cellulo the effect of HCy concentration on  $A_{2A}$  R and cAMP production in basal conditions and after agonist exposure.

## 2 | MATERIALS AND METHODS

### 2.1 | Patients

#### 2.1.1 | Panel size

A difference in APL or  $A_{2A}$  R expression >20%-25% was considered to have pathophysiological relevance; accordingly, a panel of

30-40 subjects was considered to be sufficient to provide statistical signification.

#### 2.1.2 | Study population

We recruited 46 patients (13 women and 33 men, mean age  $69.3 \pm 11.6$  years) admitted for coronary angiography in the department of Cardiology, University Hospital, Marseille, between January 2016 and January 2018. Clinical presentation could be an acute coronary syndrome or stable angina. The patients included presented with a significant CAD defined by an angiographic stenosis  $\geq 50\%$ . Exclusion criteria for the study were creatinine clearance  $<25$  mL/min and age  $<18$  or  $>80$  years. Twenty healthy subjects (7 women and 13 men, mean age  $63 \pm 7$ ) from the medical staff, matched for age and sex, were used as controls for the adenosinergic profile. They were without history of cardiovascular or inflammatory disease and not under any medical treatment. The ethic committee of our institution (CPP number: 17 05 45; protocol number: 2017-36) approved the study protocol, and patients and healthy subjects gave written informed consent for participation.

### 2.2 | Blood sample collection

Blood sample collection was performed before invasive coronary angiography (ICA). For adenosine measurement, blood (3 mL) was collected from a cubital vein using a syringe containing 2 mL of a cold stop solution to prevent uptake and degradation of adenosine by red blood cells.<sup>25,26</sup> The stop solution was composed of dipyridamole (0.2 mM), ethylene diamine tetracetic acid disodium (4 mM), erythro -9-(2-hydroxy-3-nonyl adenine (5  $\mu$ M) I, -methyleadenosine 5' diphosphate (79  $\mu$ M), coformycin 10  $\mu$ g/mL, and heparin sulphate 1 IU/mL (Sigma Aldrich, St Quentin Fallavier, France). After collection, samples were placed on ice then centrifuged (4°C, 1500 g).

### 2.3 | Adenosine concentration measurement

Adenosine plasma concentration (APC) as well as adenosine measurement in free cell culture supernatant were performed as previously described by liquid chromatography-tandem mass spectrometry after extraction<sup>26,27</sup> using a Shimadzu UFLC XR system (Shimadzu, Marne la Vallée, France).

Plasma extraction procedure: internal standard solution with 2-Chloro adenosine was prepared (300 nM in water). Plasma sample (100  $\mu$ L) was transferred into a microfuge tube. Each sample was spiked with internal standard solution (50  $\mu$ L) and methanol (300  $\mu$ L) and vortexed for 1 minute. Samples were then centrifuged (4°C, 10 minutes, 13 300 g). Supernatant was then evaporated to dryness at 60°C under nitrogen. Formic acid (0.1% in water; 150  $\mu$ L) was then added and quickly vortexed prior to transfer in

an HPLC auto-sampler vial. The intra-assay coefficient of variation (CV) was <10%.

## 2.4 | Hcy measurement

Blood was collected in a tube with EDTA and centrifuged (4°C, 10 minutes, 2000 g). Plasma was frozen and stored until assay. Total homocysteine was quantified with the LC-MS Clinmass® 'Homocysteine in plasma/serum' kit (Recipe, Germany). Supernatants were analysed using a Shimadzu UFLC XR system consisting of two LC-20ADXR binary pumps, a DGU20A5R vacuum degasser, a CT0-20AC thermostated column oven and a SIL-20ACXR cooled auto sampler (Shimadzu). The LC system was interfaced with an ABSciex 4500 triple quadrupole mass spectrometer (Les Ulis, France) operating with an electrospray ionization source (ESI) using nitrogen (purity: 99.99%). The intra- or inter-assay CV was <5%.

## 2.5 | PBMC A<sub>2A</sub>R production

The procedure has been described.<sup>28–30</sup> In brief, blood was collected in a tube containing sodium citrate, a polyester gel and a density gradient liquid (Vacutainer CPT, Beckton Dickinson) prior to centrifugation (20 minutes; 1700 g at room temperature). The PBMC layer was collected and washed twice using phosphate-buffered saline prior to treatment with lysis buffer and sonication. Samples ( $0.25 \times 10^6$  cells) were then submitted to standard 12% polyacrylamide gel electrophoresis under reducing conditions prior to transfer onto a PVDF membrane. The filter was then incubated with Adonis (1 µg/mL), a homemade IgM, kappa mouse monoclonal antibody directed against a linear epitope of A<sub>2A</sub>R (By et al 2009). Detection was performed using phosphatase alkaline-labelled anti-mouse antibodies and phosphatase alkaline substrate. The 45-kDa band corresponding to A<sub>2A</sub>R was submitted to densitometry analysis using the ImageJ 1.42q software (National Institutes of Health) and results were expressed as arbitrary units (AU) as previously described<sup>31,32</sup> (the ratio of pixels generated by the A<sub>2A</sub>R band to pixels generated by the background signal was calculated). In these conditions, the intra- or inter-assay CV was <10%.

## 2.6 | Cell culture experiments

Human lymphoblastoid T cells (CEM cells; ATCC CCL 119) that express A<sub>2A</sub>R were cultured in RPMI 1640 medium in the presence of bovine foetal serum (10%) and C02 (5%) at 37°C. CEM cells ( $5 \times 10^5$ /mL) were then seeded in flasks (75-cm<sup>2</sup>, 50 mL) and cultured for 48 hours in the presence of Hcy (50 and 200 µM). Hcy concentration was readjusted every 4 hours according to Hcy dosage (see

above). Duplicates were performed. Cell viability was addressed using the Trypan Blue dye exclusion method.

## 2.7 | Adenosine concentration measurement in cell culture medium

Cell-free supernatant was blotted on a Whatmann blot paper (6 mm diam.) prior to extraction using a mixture of methanol (400 µL) and internal standard (see above) for 90 minutes at 45°C. After extraction, an aliquot (350 µL) was evaporated to dryness at 60°C under nitrogen. Formic acid (0.1% in water; 150 µL) was added and vortexed prior to transfer into an HPLC auto-sampler vial. Dosage was then performed using LC-MS/MS as described above.

## 2.8 | Adenosine deaminase activity (ADA) measurement

Ado (28 mM; 750 µL) was mixed with cell culture medium (750 µL) in NaCl 0.9% (2 mL final volume). Aliquots were then incubated (40 minutes, 37°C). The reaction was started by adding the substrate and was stopped by cold immersion. COBAS 8000 apparatus (Roche®, Geneva, Switzerland) was used to quantify ammonia concentration. The intra- and inter-assay coefficients of variation ranged between 3% and 5%.

## 2.9 | cAMP dosage

The method has been previously described.<sup>25</sup> PBMC ( $2 \times 10^5$  per well) were incubated with increasing concentrations of Hcy during 48 hours. IBMX (1 mM; inhibitor of phosphodiesterase to prevent cAMP degradation) and Adonis (1 µM; used as an agonist) were then added for 90 minutes. Dodecyltrimethylammonium bromide acetate buffer was used to stop the incubation step. Dosage of cAMP was performed in duplicate using the Amersham Biotrak Kit (distributed by Sigma Aldrich, St Quentin Fallavier, France). The intra or inter-assay CV was <10%.

## 2.10 | Statistical analysis

Data were described by mean and standard deviation or median and interquartile range. Correlations between biological parameters were quantified and tested using Pearson's correlation coefficient. Comparisons of biological parameters between patients and controls were performed using a variance analysis (ANOVA two ways). All statistical tests were two-sided and *P* values less than 0.05 were considered statistically significant. Analysis were performed using the SPSS software (version 13.0 2004; SPSS Inc, Chicago, IL, USA).

**TABLE 1** Clinical characteristics

Characteristics	All patients (n = 46)
Female (n, %)	13 (28%)
Age (years; M $\pm$ SD)	69.3 $\pm$ 11.6
BMI (kg/m <sup>2</sup> ; M $\pm$ SD)	26.6 $\pm$ 4.3
Hypertension (n, %)	33 (72%)
Type II diabetes (n, %)	18 (39%)
Dyslipidaemia (n, %)	25 (54%)
Current smoker (n, %)	12 (26%)
Previous CAD (n, %)	9 (20%)
ACS (n, %)	14 (30%)
One-vessel disease (n, %)	19 (41%)
Two-vessel disease (n, %)	10 (22%)
Three-vessel disease (n, %)	17 (37%)
PCI (n, %)	34 (74%)
CRP (mg/L; M $\pm$ SD)	4.2 $\pm$ 2.5
Fibrinogen (g/L; M $\pm$ SD)	3.9 $\pm$ 1.0
Triglyceride (g/L; M $\pm$ SD)	1.9 $\pm$ 1.4
Cholesterol (g/L; M $\pm$ SD)	1.7 $\pm$ 0.5
HDL (g/L; M $\pm$ SD)	0.4 $\pm$ 0.1
LDL (g/L; M $\pm$ SD)	0.9 $\pm$ 0.4
Glycaemia (mmol/L; M $\pm$ SD)	7.1 $\pm$ 2.7
Creatinine ( $\mu$ mol/L; M $\pm$ SD)	94.3 $\pm$ 25.6
HbA1c (%; M $\pm$ SD)	6.8 $\pm$ 1.3
Haemoglobin (g/dL; M $\pm$ SD)	13.5 $\pm$ 1.8
Platelets (G/L; M $\pm$ SD)	256 $\pm$ 61
Lymphocytes (G/L; M $\pm$ SD)	1.989 $\pm$ 950*

Abbreviations: n: number; M: mean; SD: standard deviation; BMI: Body Mass Index; CAD: coronary artery disease; RAS: Renin Angiotensin System; ACS: Acute Coronary Syndrome; PCI: percutaneous coronary intervention; CRP: C-reactive protein; HDL: High density lipoprotein; LDL: low density lipoprotein; HbA1C: glycosylated haemoglobin.

\*Normal range 1.000-4.000.

### 3 | RESULTS

#### 3.1 | Patients

Clinical characteristics of the 46 patients are summarized in Table 1; treatments are reported in Table 2. Of note, 13 (28%) women had a mean age of 69.3  $\pm$  11.6 years and mean BMI of 26.6  $\pm$  4.3 kg/m<sup>2</sup> and 14 (30%) patients presented with ACS.

HCy and adenosine plasma concentrations (APC) were higher in patients vs controls (median, range: 16.6 [7-45] vs 8 [5-12]  $\mu$ M,  $P < 0.001$ , Figure 1A; 0.8 [0.45-1.4] vs 0.52 [0.4-0.8]  $\mu$ M,  $P < 0.01$ , Figure 1B, respectively). A<sub>2A</sub> R expression was lower in patients vs controls (1.1 [0.62-1.6] vs 1.53 [1.1-1.7] AU,  $P < 0.001$ , Figure 2). It is of note that overall the presence of diabetes, HTA, dyslipidaemia or ACS did not significantly modify HCy, A<sub>2A</sub> R production or APC (Table S1). No significant difference was found concerning gender

**TABLE 2** Treatment of CAD patients

Betablocker	n = 27 (59%)
Bisoprolol	12 (26)
Metoprolol	11 (24)
Propranolol	4 (9)
ACE inhibitors	5 (11)
Ramipril	5 (11)
RAS inhibitors	28 (61)
Valsartan	18 (39)
Irbesartan	6 (13)
Candesartan	4 (9)
Calcium blocker	6 (13)
Nicardipine	3 (7)
Amlodipine	1 (2)
Lercanidipine	1 (2)
Diltiazem	1 (2)
Fibrates	3 (6)
Fenofibrate	3 (6)
Statin	34 (73)
Atorvastatin	14 (30)
Pravastatin	8 (17)
Simvastatin	8 (17)
Rosuvastatin	4 (9)
Aspirin	36 (78)
P2Y12 inhibitor	18 (39)
Clopidogrel	18 (39)
Diuretics	6 (13)
Furosemide	6 (13)
Anti-diabetics	14 (30)
Metformin	10 (21)
Gliclazide	4 (9)

in patients (HCy: men vs women: 18.7  $\pm$  9.4 vs 16.9  $\pm$  5  $\mu$ M,  $P = 0.9$ ; APC: 0.78  $\pm$  0.22 vs 0.76  $\pm$  0.14  $\mu$ M,  $P = 0.9$ ; A<sub>2A</sub> R production: 1.08  $\pm$  0.25 vs 1.12  $\pm$  0.19 Arbitrary Units,  $P = .39$ ).

In patients, we observed a negative correlation between HCy concentration and A<sub>2A</sub> R production ( $r = -0.43$ ;  $P < 0.0001$ ; Figure 3A), with decreased A<sub>2A</sub> R production above 25  $\mu$ M HCy (Figure 3B). We did not find a correlation between C reactive protein and A<sub>2A</sub> R production ( $r = 0.16$ ,  $P = 0.41$ ) while a trend in correlation was found between HCy and C reactive protein concentrations ( $r = 0.33$ ,  $P = 0.06$ ).

#### 3.2 | In cellulo study

Using CEM cells, we observed that HCy inhibited in a concentration- and time-dependent manner (a) A<sub>2A</sub> R production ( $-39\%$  and  $-46\%$  at 50  $\mu$ M at 24 and 48 hours, respectively;  $-54\%$  and  $-69\%$  at

200  $\mu\text{M}$  at 24 and 48 hours, respectively; Figure S1) and (b) cAMP production (basal conditions: -24%, -55% and -69% at 25, 50 and 200  $\mu\text{M}$ , respectively; Figure S2A). We also observed that while Adonis (0.9  $\mu\text{M}$ ) increased cAMP production (+153% vs basal condition), Hcy inhibited the Adonis-induced cAMP production increase in a concentration dependent manner (-18%, -66% and -75% at 25, 50 and 200  $\mu\text{M}$ , respectively; Figure S2B). It is of note that (a) the adenosine concentration level was very weak in culture medium (<0.025  $\mu\text{M}$ ) irrespective of the experimental condition; (b) ADA per cell did not increase significantly as a function of time or Hcy concentration (Table S2); (c) Hcy (25-200  $\mu\text{M}$ ) did not influence cell proliferation.

#### 4 | DISCUSSION

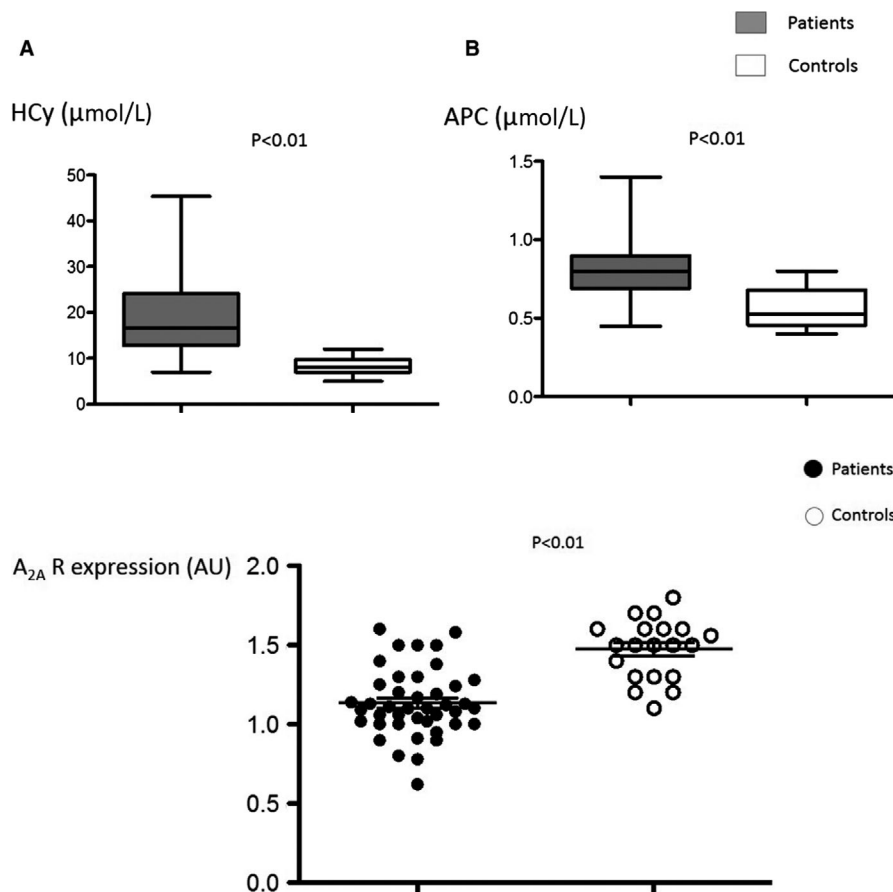
We report here a negative correlation between Hcy concentration and  $\text{A}_{2\text{A}}$  R production by PBMC in CAD patients. We also found that Hcy concentrations in the range of those measured in CAD patients decreased both  $\text{A}_{2\text{A}}$  R and cAMP production in CEM human T cells. In the latter conditions, it is likely that down regulation of  $\text{A}_{2\text{A}}$  R resulted from Hcy and not from changes in adenosine concentration or ADA.

These results support and expand our previous observation that took advantage of an in cellulo model of inflammation and hypoxia, which may be considered as reflecting CAD conditions. Using CEM

T cells, we previously showed that Hcy decreases  $\text{A}_{2\text{A}}$  R and cAMP production via  $\text{H}_2\text{S}$  and NF kappa B pathway.<sup>33,34</sup> In patients, low  $\text{A}_{2\text{A}}$  R and cAMP production may participate in CAD in three ways: (a) by altering the adaptive vasodilation of coronary arteries when oxygen supply is needed, an hypothesis that is supported by the correlation found between the CAD gravity score (Syntax score) and Hcy concentration<sup>1</sup>; (b) by inhibiting the adenosinergic T cell immunosuppression mechanism via  $\text{H}_2\text{S}$  production that, in turn, promotes inflammation<sup>33</sup>; and (c) by favouring platelet aggregation and activation through Hcy/ $\text{H}_2\text{S}$  pathway, thus contributing to atherothrombosis, stroke or myocardial infarction.<sup>35</sup>

It was reported that an increase in 5  $\mu\text{M}$  Hcy promotes the incidence of CAD<sup>36</sup> and that HHcy is associated with restenosis of CAD patients treated by percutaneous intervention<sup>37</sup> as well as with cardiovascular causes of death.<sup>38</sup> Furthermore, an association between CRP and Hcy concentrations was reported in patients with acute myocardial infarction.<sup>39</sup> The effects of Hcy in CAD may result from an increase in oxidative stress in the vascular endothelium.<sup>40</sup>

It was shown that Hcy promotes endothelial cell dysfunction via the up-regulation of p66shc expression following hypomethylation of the promoter.<sup>41</sup> Additionally, Hcy promotes vascular inflammation and atherosclerosis through hypermethylation of the *SMAD7* promoter.<sup>42</sup> A mild elevation of Hcy, associated with a specific polymorphism of the enzyme methyl tetrahydrofolates (MTHF) was also suggested to modify MTHF activity.<sup>43</sup> In addition, Hcy was shown to interfere with cell viability,<sup>44</sup> migration<sup>45,46</sup> and cytokine

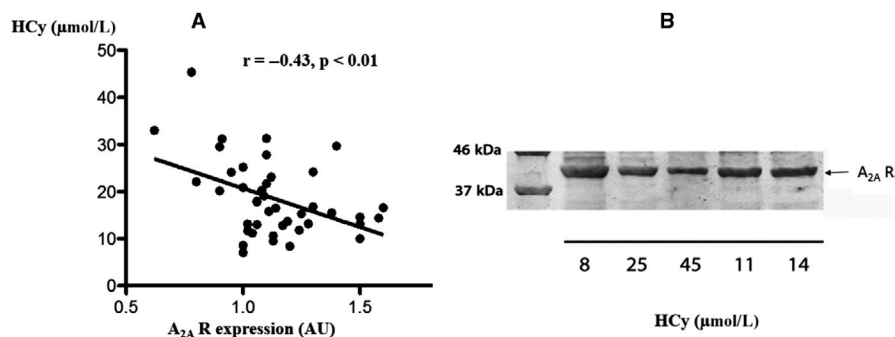


**FIGURE 1** Homocysteine concentrations (Hcy, A) and adenosine plasma concentrations (APC, B) in coronary artery disease patients ( $n = 46$ ) and healthy subjects (controls;  $n = 20$ )

**FIGURE 2** Adenosine  $\text{A}_{2\text{A}}$  receptor ( $\text{A}_{2\text{A}}$  R) production by peripheral blood mononuclear cells from coronary artery disease patients ( $n = 46$ ) and healthy subjects (controls,  $n = 20$ ).  $\text{A}_{2\text{A}}$  R production was evaluated by Western blotting and expressed as arbitrary units (AU)



**FIGURE 3** A, Correlation curve (Pearson) between plasma homocysteine concentration (HCy) and  $A_{2A}$  receptor ( $A_{2A}$  R) production by peripheral blood mononuclear cells in 46 coronary artery disease patients. B,  $A_{2A}$  R production (Western blot; apparent MW of the molecular species: 45 kDa) and HCy concentration found in selected patients



production<sup>45,47,48</sup> in various cell populations although these effects have been found for homocysteine concentrations that are only very rarely found in CAD patients (above 300  $\mu$ M).

With regard to the adenosinergic system, we observed high APC in patients vs controls. High APC has been previously described in CAD,<sup>1,23,24</sup> adenosine being released by endothelial and muscle cells to control inflammation,<sup>3,49</sup> ischaemia<sup>2,50</sup> and hypoxia.<sup>2,49</sup> However, part of adenosine production may be secondary to high HCy level inasmuch as HHCy induces a rapid metabolism of ATP, ADP and AMP into adenosine via macrophage ectonucleotidases.<sup>50</sup> Activation of  $A_{2A}$ R has anti-inflammatory effects.<sup>51,52</sup> Conversely, the decrease in  $A_{2A}$ R activation found in CAD patients probably promotes inflammation that in turn promotes atherosclerosis.<sup>53,54</sup>

In summary, we found that HCy concentrations measured in CAD patients are associated with low production of  $A_{2A}$ R in CAD patients as well as with low production of cAMP in cellulo. These data are consistent with the possibility that HCy participates in CAD pathophysiology by reducing coronary blood flow and by promoting inflammation and atherosclerosis.

#### 4.1 | Limitations

The possible influence of  $A_1$  and/or  $A_2B$  receptors on the effects of HCy on cAMP production was not addressed in this study.

## 5 | CONCLUSION

HCy is negatively correlated with  $A_{2A}$  R production in CAD patients, and negatively associated with  $A_{2A}$  R production and cAMP level in cellulo. The decrease in  $A_{2A}$  R production and cAMP level, which is known to hamper coronary blood flow and promote inflammation, may support CAD pathogenesis.

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#### CONFLICT OF INTEREST

The authors have nothing to disclose.

#### AUTHOR CONTRIBUTION

**Pierre Deharo:** Conceptualization (lead); Resources (equal); Software (equal). **Marion Marlinge:** Data curation (equal). **Clair Guiol:** Supervision (equal). **Donato Vairo:** Investigation (equal). **Julien Fromonot:** Software (equal). **Patrick Mace:** Investigation (equal). **Mohamed Chefrour:** Visualization (equal). **Marguerite Gastaldi:** Project administration (equal). **Laurie Bruzzese:** Validation (equal). **Melanie Gaubert:** Project administration (equal). **Marine Gaudry:** Investigation (equal). **Nathalie Kipson:** Resources (equal). **Christine Criado:** Formal analysis (equal). **Thomas Cuisset:** Resources (equal). **Franck Paganelli:** Data curation (equal). **Jean Ruf:** Writing-original draft (equal). **Regis Guieu:** Writing-review & editing (equal). **Emmanuel Fenouillet:** Validation (equal). **Giovanna Mottola:** Conceptualization (equal); Visualization (equal).

#### DATA AVAILABILITY STATEMENT

Non available.

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#### REFERENCES

- Fromonot J, Deharo P, Bruzzese L, et al. Adenosine plasma level correlates with homocysteine and uric acid concentrations in patients with coronary artery disease. *Can J Physiol Pharmacol*. 2016;94:272-277.
- Grenz A, Homann D, Eltzschig HK. Extracellular adenosine: a safety signal that dampens hypoxia-induced inflammation during ischemia. *Antioxid Redox Signal*. 2011;15:2221-2234.
- Eltzschig HK, Sitkovsky MV, Robson SC. Purinergic signaling during inflammation. *N Engl J Med*. 2012;367:2322-2333.
- Burnstock G. Purinergic signaling in the cardiovascular system. *Circ Res*. 2017;120:207-228.
- Iwamoto T, Umemura S, Toya Y, et al. Identification of adenosine  $A_2$  receptor-cAMP system in human aortic endothelial cells. *Biochem Biophys Res Commun*. 1994;199:905-910.
- Shryock JC, Snowdy S, Baraldi PG, et al.  $A_{2A}$ -adenosine receptor reserve for coronary vasodilation. *Circulation*. 1998;98:711-718.
- Cushing DJ, Brown GL, Sabouni MH, Mustafa SJ. Adenosine receptor-mediated coronary artery relaxation and cyclic nucleotide production. *Am J Physiol*. 1991;261:H343-H348.
- Banerjee A, Newman DR, Van den Bruel A, Heneghan C. Diagnostic accuracy of exercise stress testing for coronary artery disease: a systematic review and meta-analysis of prospective studies. *Int J Clin Pract*. 2012;66:477-492.

9. Berwick ZC, Payne GA, Lynch B, et al. Contribution of adenosine A(2A) and A(2B) receptors to ischemic coronary dilation: role of K(V) and K(ATP) channels. *Microcirculation*. 2010;17:600-607.
10. Sanjani MS, Teng B, Krahn T, et al. Contributions of A2A and A2B adenosine receptors in coronary flow responses in relation to the KATP channel using A2B and A2A/2B double-knockout mice. *Am J Physiol Heart Circ Physiol*. 2011;301:H2322-H2333.
11. Borea PA, Gessi S, Merighi S, et al. Pharmacology of adenosine receptors: the state of the art. *Physiol Rev*. 2018;98:1591-1625.
12. McCully KS. Vascular pathology of homocysteinemia: implications for the pathogenesis of arteriosclerosis. *Am J Pathol*. 1969;56:111-128.
13. Liu J, Quan J, Li Y, et al. Blood homocysteine levels could predict major adverse cardiac events in patients with acute coronary syndrome: ASTROBE-compliant observational study. *Medicine (Baltimore)*. 2018;97:e12626.
14. Schaffer A, Verdoia M, Casetti E, et al. Relationship between homocysteine and coronary artery disease. Results from a large prospective cohort study. *Thromb Res*. 2014;134:288-293.
15. Akyürek Ö, Akbal E, Güneş F. Increase in the risk of ST elevation myocardial infarction is associated with homocysteine level. *Arch Med Res*. 2014;45:501-506.
16. Zylberstein DE, Bengtsson C, Björkelund C, et al. Serum homocysteine in relation to mortality and morbidity from coronary heart disease: a 24-year follow-up of the population study of women in Gothenburg. *Circulation*. 2004;109:601-606.
17. Ma Y, Peng D, Liu C, et al. Serum high concentrations of homocysteine and low levels of folic acid and vitamin B(12) are significantly correlated with the categories of coronary artery diseases. *BMC Cardiovasc Disord*. 2017;17:37.
18. Tyagi N, Sedoris KC, Steed M, et al. Mechanisms of homocysteine-induced oxidative stress. *Am J Physiol Heart Circ Physiol*. 2005;289:H2649-H2656.
19. Pushpakumar S, Kundu S, Sen U. Endothelial dysfunction: the link between homocysteine and hydrogen sulfide. *Curr Med Chem*. 2014;21:3662-3672.
20. Bleie Ø, Semb AG, Grundt H, et al. Homocysteine-lowering therapy does not affect inflammatory markers of atherosclerosis in patients with stable coronary artery disease. *J Intern Med*. 2007;262:244-253.
21. Martí-Carvajal AJ, Solà I, Lathyris D, Dayer M. Homocysteine-lowering interventions for preventing cardiovascular events. *Cochrane Database Syst Rev*. 2017;8:CD006612.
22. Varani K, Laghi-Pasini F, Camurri A, et al. Changes of peripheral A2A adenosine receptors in chronic heart failure and cardiac transplantation. *FASEB J*. 2003;17:280-282.
23. Gariboldi V, Vairo D, Guieu R, et al. Expressions of adenosine A2A receptors in coronary arteries and peripheral blood mononuclear cells are correlated in coronary artery disease patients. *Int J Cardiol*. 2017;230:427-431.
24. Guieu R, Kipson N, Ruf J, et al. Low basal expression of A2A adenosine receptors and increase in adenosine plasma concentration are associated with positive exercise stress testing. *Int J Cardiol*. 2015;180:15-17.
25. Bonello L, Laine M, Kipson N, et al. Ticagrelor increases adenosine plasma concentration in patients with an acute coronary syndrome. *J Am Coll Cardiol*. 2014;63:872-877.
26. Gaubert M, Marlinge M, Kerbaul F, et al. Adenosine plasma level and A2A receptor expression in patients with cardiogenic shock. *Crit Care Med*. 2018;46:e874-e880.
27. Marlinge M, Vairo D, Marolda V, et al. Rapid measurement of adenosine concentration in human blood using fixed potential amperometry: comparison with mass spectrometry and high-performance liquid chromatography. *J Anal Bioanal Tech*. 2017;8:371.
28. By Y, Durand-Gorde J-M, Condo J, et al. Production of an agonist-like monoclonal antibody to the human A2A receptor of adenosine for clinical use. *Mol Immunol*. 2009;46:400-405.
29. Franceschi F, By Y, Peyrouse E, et al. A2A adenosine receptor function in patients with vasovagal syncope. *Europace*. 2013;15:1328-1332.
30. Jacquin L, Franceschi F, By Y, et al. Search for adenosine A2A spare receptors on peripheral lymphocytes. *FEBS Open Bio*. 2012;3:1-5.
31. Ruf J, Paganelli F, Bonello L, et al. Spare adenosine A2a receptors are associated with positive exercise stress test in coronary artery disease. *Mol Med*. 2016;22:530-536.
32. Paganelli F, Resseguier N, Marlinge M, et al. Specific pharmacological profile of A2A adenosine receptor predicts reduced fractional flow reserve in patients with suspected coronary artery disease. *J Am Heart Assoc*. 2018;7:e008290.
33. Bruzzese L, Fenouillet E, Fromont J, et al. High homocysteine levels prevent via H2 S the CoCl<sub>2</sub>-induced alteration of lymphocyte viability. *J Cell Mol Med*. 2016;20:1411-1419.
34. Bruzzese L, Fromont J, By Y, et al. NF-κB enhances hypoxia-driven T-cell immunosuppression via upregulation of adenosine A(2A) receptors. *Cell Signal*. 2014;26:1060-1067.
35. Di Villa BRE, Mitidieri E, Di Minno MND, et al. Hydrogen sulphide pathway contributes to the enhanced human platelet aggregation in hyperhomocystinemia. *Proc Natl Acad Sci (USA)*. 2013;39:15812-15818.
36. Humphrey LL, Fu R, Rogers K, et al. Homocysteine level and coronary heart disease incidence: a systematic review and meta-analysis. *Mayo Clin Proc*. 2008;83:1203-1212.
37. Ma YL, Li LI, Shang X-M, et al. Analysis of factors related to short-term prognosis in patients undergoing percutaneous coronary intervention for acute myocardial infarction. *Exp Ther Med*. 2013;5:1206-1210.
38. Fu Z, Hao X, Guo J, et al. Hyperhomocysteinemia is an independent predictor of long-term clinical outcomes in Chinese octogenarians with acute coronary syndrome. *Clin Interv Aging*. 2015;10:1467-1474.
39. Marković Boras M, Čaušević A, Brizić I, et al. A relation of serum homocysteine, uric acid and C-reactive protein level in patients with acute myocardial infarction. *Med Glas (Zenica)*. 2018;15:101-108.
40. Ganguly P, Alam SF. Role of homocysteine in the development of cardiovascular disease. *Nutr J*. 2015;14:6.
41. Kim C-S, Kim Y-R, Naqvi A, et al. Homocysteine promotes human endothelial cell dysfunction via site-specific epigenetic regulation of p66shc. *Cardiovasc Res*. 2011;92:466-475.
42. Wei L-H, Chao N-X, Gao SI, et al. Homocysteine induces vascular inflammatory response via SMAD7 hypermethylation in human umbilical vein smooth muscle cells. *Microvasc Res*. 2018;120:8-12.
43. Nash AJ, Mandaviya PR, Dib MJ, et al. Interaction between plasma homocysteine and the MTHFR c.677C > T polymorphism is associated with site-specific changes in DNA methylation in humans. *FASEB J*. 2019;33:833-843.
44. Dawson H, Collins G, Pyle R, et al. The immunoregulatory effects of homocysteine and its intermediates on T-lymphocyte function. *Mech Ageing Dev*. 2004;125:107-110.
45. Su S-J, Huang L-W, Pai L-S, et al. Homocysteine at pathophysiologic concentrations activates human monocyte and induces cytokine expression and inhibits macrophage migration inhibitory factor expression. *Nutrition*. 2005;21:994-1002.
46. Ma K, Lv S, Liu BO, et al. CTLA4-IgG ameliorates homocysteine-accelerated atherosclerosis by inhibiting T-cell overactivation in apoE(-/-) mice. *Cardiovasc Res*. 2013;97:349-359.
47. Dalal S, Parkin SM, Homer-Vanniasinkam S, Nicolaou A. Effect of homocysteine on cytokine production by human endothelial cells and monocytes. *Ann Clin Biochem*. 2003;40:534-541.
48. Wang N, Tang H, Wang X, et al. Homocysteine upregulates interleukin-17A expression via NSun2-mediated RNA methylation in T lymphocytes. *Biochem Biophys Res Commun*. 2017;493:94-99.



49. Eltzschig HK, Carmeliet P. Hypoxia and inflammation. *N Engl J Med*. 2011;364:656-665.
50. Zanin RF, Bergamin LS, Braganhol E, et al. Homocysteine modifies extracellular ATP availability in macrophages. *Toxicol In Vitro*. 2013;27:2273-2278.
51. Antonioli L, El-Tayeb A, Pellegrini C, et al. Anti-inflammatory effect of a novel locally acting A<sub>2A</sub> receptor agonist in a rat model of oxazolone-induced colitis. *Purinergic Signal*. 2018;14:27-36.
52. Kinsel JF, Sitkovsky MV. Possible targeting of G protein coupled receptors to manipulate inflammation in vivo using synthetic and natural ligands. *Ann Rheum Dis*. 2003;62:ii22-24.
53. Schwartz CJ, Valente AJ, Sprague EA, et al. Atherosclerosis as an inflammatory process. The roles of the monocyte-macrophage. *Ann N Y Acad Sci*. 1985;454:115-120.
54. Berliner JA, Navab M, Fogelman AM, et al. Atherosclerosis: basic mechanisms. Oxidation, inflammation, and genetics. *Circulation*. 1995;91:2488-2496.

## SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

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