Integrative Physiology

Endothelial Actions of ANP Enhance Myocardial Inflammatory Infiltration in the Early Phase After Acute Infarction

Wen Chen,* Annett Spitzl,* Denise Mathes,* Viacheslav O. Nikolaev, Franziska Werner, Johannes Weirather, Katarina Špiranec, Katharina Röck, Jens W. Fischer, Ulrike Kämmerer, David Stegner, Hideo A. Baba, Ulrich Hofmann, Stefan Frantz, Michaela Kuhn

Rationale: In patients after acute myocardial infarction (AMI), the initial extent of necrosis and inflammation determine clinical outcome. One early event in AMI is the increased cardiac expression of atrial natriuretic peptide (NP) and B-type NP, with their plasma levels correlating with severity of ischemia. It was shown that NPs, via their cGMP-forming guanylyl cyclase-A (GC-A) receptor and cGMP-dependent kinase I (cGKI), strengthen systemic endothelial barrier properties in acute inflammation.

Objective: We studied whether endothelial actions of local NPs modulate myocardial injury and early inflammation after AMI.

Methods and Results: Necrosis and inflammation after experimental AMI were compared between control mice and littermates with endothelial-restricted inactivation of GC-A (knockout mice with endothelial GC-A deletion) or cGKI (knockout mice with endothelial cGKI deletion). Unexpectedly, myocardial infarct size and neutrophil infiltration/activity 2 days after AMI were attenuated in knockout mice with endothelial GC-A deletion and unaltered in knockout mice with endothelial cGKI deletion. Molecular studies revealed that hypoxia and tumor necrosis factor-α, conditions accompanying AMI, reduce the endothelial expression of cGKI and enhance cGMP-stimulated phosphodiesterase 2A (PDE2A) levels. Real-time cAMP measurements in endothelial microdomains using a novel fluorescence resonance energy transfer biosensor revealed that PDE2 mediates NP/cGMP-driven decreases of submembrane cAMP levels. Finally, intravital microscopy studies of the mouse cremaster microcirculation showed that tumor necrosis factor-α–induced endothelial NP/GC-A/cGMP/PDE2 signaling impairs endothelial barrier functions.

Conclusions: Hypoxia and cytokines, such as tumor necrosis factor-α, modify the endothelial postreceptor signaling pathways of NPs, with downregulation of cGKI, induction of PDE2A, and altered cGMP/cAMP cross talk. Increased expression of PDE2 can mediate hyperpermeability effects of paracrine endothelial NP/GC-A/cGMP signaling and facilitate neutrophil extravasation during the early phase after MI. (Circ Res. 2016;119:237-248. DOI: 10.1161/CIRCRESAHA.115.307196.)

Key Words: anterior wall myocardial infarction ■ atrial natriuretic factor receptor A ■ cyclic GMP ■ cyclic nucleotide phosphodiesterases, type 2 ■ endothelial cells ■ guanylyl cyclase A

In patients after acute myocardial infarction (AMI), the extent of myocardial necrosis and the degree of adverse remodeling of the infarcted and surrounding myocardium determine long-term prognosis.1 The infiltration of the ischemic tissue by inflammatory cells affects initial injury and subsequent healing and remodeling processes.2 Hypoxia and cytokines released after AMI, such as tumor necrosis factor-α (TNF-α), provoke...
pathological coronary endothelial hyperpermeability and facilitate leukocyte extravasation. In the absence of reperfusion, polymorphonuclear granulocytes (neutrophils) are the first inflammatory cells recruited to the infarct area. Neutrophils initiate the acute inflammatory response to engulf dead cells and tissue debris and facilitate post-MI repair. However, excessive neutrophil infiltration exacerbates tissue injury by the release of inflammatory mediators and proteinases.

Another early event in AMI is the acute and marked increase of ventricular expression and release of atrial (ANP) and B-type natriuretic peptides (BNP). Hypoxia (via HIF-1α [hypoxia-induced factor 1 alpha]) and cytokines (TNF-α and interleukin-1β) stimulate myocyte BNP expression. In fact, the plasma level of BNP, released in the very early phase of AMI, might improve the endothelial barrier and attenuate the inflammatory infiltration of the myocardium, thereby limiting the area of necrosis.

To follow this hypothesis, we studied myocardial inflammation after experimentally induced AMI in control mice and littermates with conditional, endothelial-restricted inactivation of GC-A (knockout mice with endothelial GC-A deletion [EC GC-A KO]) or the downstream kinase cGKI (knockout mice with endothelial cGKI deletion [EC cGKI KO]). Our observations indicate that hypoxia and cytokines, that is, TNF-α, shift endothelial NP/GC-A/cGMP signaling toward activation of phosphodiesterase 2A (PDE2A). This diminishes subplasmalemmal cAMP levels and may contribute to disruption of the endothelial barrier and neutrophil activation and extravasation after AMI.

### Methods

Expanded Methods are available in the Online Data Supplement.

### Animals

The generation of mice with conditional, endothelial cell (EC)-restricted inactivation of either GC-A (Tie2-Cre<sup>+/0</sup>;GC-A<sup>floxflox</sup>; EC GC-A KO) or cGKI (Tie2-Cre<sup>+/0</sup>;cGKI<sup>floxflox</sup>; EC cGKI KO) and their control littermates (GC-A<sup>floxflox</sup>; cGKI<sup>floxflox</sup>), as well as of mice with green fluorescent granulocytes (LysM-eGFP<sup>+/0</sup> mice), has been described before. Two- to 3-month old mice were used for all experiments. The studies conformed to the regulations for animal experimentation and were approved by the local governments.

### Experimental AMI and Evaluation of the Ischemic Area at Risk and Infarct Size

After anesthesia with isoflurane (3%) and intubation, thoracotomy was performed and MI was induced by permanent ligation of the proximal part of the left coronary artery. Buprenorphine was administered for analgesia after surgery. For sham operation, thoracotomy was performed without arterial ligation. Two days after AMI, the area at risk (AAR) and infarct area were evaluated. After thoracotomy, Evans blue (Sigma, Deisenhofen, Germany) was injected from the cardiac apex to delineate the nonischemic tissue. The hearts were excised, washed with PBS, and cut into 5 transverse slices. The slices were stained with 2% 2,3,5-triphenyltetrazolium chloride (Sigma) to determine the infarct area, weighed, and photographed under a microscope (Olympus, Hamburg, Germany). LV area, AAR, and infarct area were determined by computerized planimetry. Mice with AAR <30% were excluded from subsequent evaluations.

### Analyses of Myocardial Inflammatory Infiltration

Myocardial slices were fixed in 4% paraformaldehyde and embedded in paraffin. Immunohistochemistry for neutrophils (clone 7/4; Linaris, Wertheim, Germany, #550274) and myeloperoxidase (antibody from Dako, Germany) was performed on 5-μm sections. In separate experiments, hearts were digested with collagenase and suspended inflammatory cells were analyzed by fluorescence-activated cell sorting. The specific antibodies are depicted in Online Table I.

### Determination of Myeloperoxidase Activity

Myeloperoxidase activity in homogenates prepared from the LV infarct area and from corresponding right ventricles was determined as described.

### Reverse Transcription Polymerase Chain Reaction Analyses

Extraction of mRNA from murine LV and reverse transcription were performed as described. mRNA expression levels of PDE2A, CXCL1 (keratinocyte-derived chemokine), and the adhesion proteins vascular cell adhesion protein 1, intercellular adhesion molecule 1 and E/P-selectins were analyzed by real-time quantitative reverse

<table>
<thead>
<tr>
<th>Nonstandard Abbreviations and Acronyms</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAR</td>
</tr>
<tr>
<td>AMI</td>
</tr>
<tr>
<td>ANP</td>
</tr>
<tr>
<td>BNP</td>
</tr>
<tr>
<td>cGKI</td>
</tr>
<tr>
<td>EC GC-A</td>
</tr>
<tr>
<td>EC cGKI</td>
</tr>
<tr>
<td>FITC</td>
</tr>
<tr>
<td>FRET</td>
</tr>
<tr>
<td>GC-A</td>
</tr>
<tr>
<td>HUVEC</td>
</tr>
<tr>
<td>LV</td>
</tr>
<tr>
<td>PDE2A</td>
</tr>
<tr>
<td>TNF-α</td>
</tr>
</tbody>
</table>
transcription polymerase chain reaction and normalized to glyceraldehyde-3-phosphate dehydrogenase.

**Detection of Coronary Endothelial Glycocalyx by Fluorescent Hyaluronic Acid Staining**

Hyaluronic acid, as one of the largest glycosaminoglycans (>1000 kDa), is an integral component of the endothelial glycocalyx. Fluorescent stainings were performed on cardiac cryosections (20 μm).16 Endothelial cells of myocardial arterioles and capillaries were visualized by confocal microscopy using CD31 and DAPI stainings. The glycocalyx was analyzed using ImageJ.42 Resulting integrated densities were normalized to the number of endothelial cells. From each heart, 2 sections were analyzed (3–6 vessels per section).

**Culture of Human Umbilical Vein Endothelial Cells, cGMP Determinations, and Immunoblotting**

All experiments were performed with confluent human umbilical vein endothelial cells (HUVECs) of passages 1 and 2. Cells were treated with human TNF-α (R&D Systems, Wiesbaden-Nordenstadt, Germany) or vehicle (PBS) during 24 hours under normoxic or hypoxic conditions (1% O2). Thereafter, the cells were stimulated with ANP (Bachem, Bubendorf, Switzerland) or with the nitric oxide donor S-nitroso-N-acetyl-L-penicillamine (Sigma) in the absence or presence of the specific PDE2 inhibitor Bay 60-7550 (local superfusion). Quantitative offline analysis in response to ANP or BNP were evaluated after intrascrotal injection of mouse TNF-α (R&D Systems, Wiesbaden-Nordenstadt, Germany) or vehicle (PBS) during 24 hours under normoxic or hypoxic conditions (1% O2). Thereafter, the cells were stimulated with ANP (Bachem, Bubendorf, Switzerland) or with the nitric oxide donor S-nitroso-N-acetyl-L-penicillamine (Sigma) in the absence or presence of the specific PDE2 inhibitor Bay 60-7550 (Alexis). Intracellular cGMP content was determined by radioimmunoassay.16 The expression levels of cGKI (antibody from Cell Signaling, Frankfurt, Germany), PDE2A (FabGenrix, Shreveport, LA), and PDE3A (antibody was a gift from Chen Yan, Rochester, NY) were determined by Western blotting.16 Levels were normalized to glyceraldehyde-3-phosphate dehydrogenase.

**Fluorescence Resonance Energy Transfer to Monitor Subsarcolemmal and Cytosolic cAMP Dynamics in Single Living HUVECs**

HUVECs were seeded onto 24-mm round glass coverslides, grown to 70% to 80% confluency and infected with adenoviral vectors encoding the membrane-targeted fluorescent cAMP sensor pmEpac2 camps or the (parental) cytosolic cAMP sensor Epac2 camps.21,22 A multiplicity of infection of 30 to 50 was used to infect HUVECs. Forty to 48 hours before live-cell fluorescence resonance energy transfer (FRET) measurements,23 Twenty-four hours before measurements, cells were incubated with TNF-α or vehicle and then subsequently with ANP, adenosine (Sigma), and isoprenaline (Sigma).

**Intravital Microscopy of the Mouse Cremaster Microcirculation**

As a measure of microcirculatory endothelial permeability, leakage of the macromolecule fluorescein isothiocyanate (FITC)–labeled dextran (70 kDa; Sigma) from postcapillary venules within the mouse cremaster muscle was analyzed by intravital fluorescence microscopy.16 EC GC-A KO, EC cGKI KO, and respective control mice were deeply anesthetized with intraperitoneal ketamine (100 mg/kg BW) and xylazine (10 mg/kg). After tail vein injection of FITC-dextran, microscopy was performed using a fluorescence filter for FITC for epifluorescence microscopy (Olympus). Topical application of ANP, BNP (mouse BNP; American Peptide Co, Sunnyvale, CA), or vehicle was always started 30 minutes after intravenous administration of FITC-dextran and continued for additional 40 minutes. In a second series of experiments, leukocyte extravasation was studied in transgenic LysM-eGFP reporter mice with green fluorescent granulocytes.21 FITC-dextran and leukocyte extravasation in response to ANP or BNP were evaluated after intracutal injection of mouse TNF-α22 or mouse TNF-α or vehicle (PBS) and for ANP in the absence or presence of Bay 60-7550 (local superfusion). Quantitative offline analysis of the microscopic images was performed with the computer-assisted image analysis system Cell-D (Olympus).16

**Statistics**

Results are presented as means±SEM. The number of experiments (n) is indicated in the figure legends. P values were determined by Student

---

**Results**

**Decreased Myocardial Infarct Size and Inflammatory Infiltration in Mice With Endothelial-Restricted Inactivation of the GC-A Receptor for ANP**

In the absence of reperfusion, neutrophil infiltration occurs within hours post MI and peaks at 1 to 3 days.2 To study whether endothelial effects of locally released ANP or BNP modulate acute inflammation post MI, we subjected EC GC-A KO mice and control littermates to 48 hours of permanent coronary artery ligation.18 In sham-operated control and EC GC-A KO littermates, there were no detectable areas of myocardium at risk of ischemia (AAR) or with infarctions. In mice with coronary ligation, the AAR was not different between genotypes, indicating that ligation site was the same in both groups (Figure 1A). However, the ratios of infarct-to-AAR were mildly but significantly smaller in EC GC-A KO mice (Figure 1A). In other words, the amount of healthy myocardial tissue was larger in the absence of endothelial GC-A.

By immunohistochemistry, the numbers of neutrophils per square millimeter were determined in the infarct area, the border zone, and the septum.18 As shown in Figure 1B, almost no neutrophils were detectable in the myocardium of sham-operated mice. In mice with AMI, neutrophil density was tremendously increased in the infarct zone and less in the border zone and septum. Notably, the number of neutrophils infiltrating the infarcted myocardium was significantly diminished in EC GC-A KO mice (Figure 1B). Fluorescence-activated cell sorting analyses24 further revealed a smaller portion of neutrophils within the CD11b+ myeloid cells infiltrating the LV myocardium of EC GC-A KO when compared with control littermates (Figure 1C). Such analyses also revealed that the infiltration by other inflammatory cells, such as T cells and monocytes/macrophages, was not different between genotypes (Online Table I). Accordingly, the number of myeloperoxidase-stained neutrophils and myeloperoxidase activity (a well known marker for neutrophil accumulation) were lower in the infarct area of EC GC-A KO mice (Figure 2A and 2B). Finally, we determined the LV mRNA levels of CXCL1/keratinocyte-derived chemokine, a chemokine that in the rodent postischemic myocardium is selectively expressed in infiltrating inflammatory cells.24 As shown in Figure 2C, LV CXCL1 levels were markedly lower in EC GC-A KO mice when compared with their control littermates.

To elucidate the mechanism(s) of diminished neutrophil activation in EC GC-A KO mice, the RNA levels of endothelial adhesion molecules were evaluated. Figure 2D to 2G illustrate that LV levels of intercellular adhesion molecule 1, vascular cell adhesion protein 1, and E/P-selectins were increased in control mice with AMI. These responses were drastically attenuated in EC GC-A KO littermates. Together, our observations demonstrate that inactivation of the endothelial GC-A receptor attenuates early inflammation after AMI. They indicate that GC-A/cGMP-mediated actions of endogenous local NPs contribute to the impairment of the barrier functions
of the coronary endothelium in the setting of myocardial isch-
emia, favoring the extravasation of neutrophils.

Unaltered Myocardial Infarct Size and Neutrophil Infiltration in EC cGKI KO Mice

Endothelial cells express at least 3 effector molecules for cGMP: cGKI, cGMP-inhibited PDE3A, and cGMP-stimulated PDE2A. To elucidate whether endothelial cGKI mediates the proinflammatory actions of NPs after AMI, we studied EC cGKI KO mice and respective control littermates. Figure 3A and 3B show that the myocardial infarct size, infarct-to-AAR ratio, and the number of neutrophils infiltrating the infarcted and surrounding myocardium were not different between genotypes. Therefore, cGKI does not mediate the proinflammatory effects of endothelial NP/GC-A/cGMP signaling.

Reduced Coronary Glycocalyx in Control and EC GC-A KO Mice After AMI

Studies in isolated perfused hearts showed that exogenous, synthetic NPs cause shedding of the coronary glycocalyx. Because disruption of the glycocalyx favors postischemic
controls EC GC-A KO

Figure 2. Diminished neutrophil activity and reduced expression of endothelial adhesion proteins in hearts from knockout mice with endothelial GC-A deletion (EC GC-A KO mice) with acute myocardial infarction (AMI). Myeloperoxidase (MPO) expression (A; immunohistochemistry) and activity (B; relative fluorescence units [RFUs]) in the infarct zone and right ventricle (RV) 2 days after induction of MI (n=5).

C-G. Left ventricular mRNA expression (by quantitative reverse transcription polymerase chain reaction) of the chemokine CXCL1 (right) confirms that treatment of HUVECs with TNF-α (10 ng/mL, 24 hours) induced PDE2A expression, whereas PDE3A protein levels were unaltered. Because PDE2A is a dual substrate esterase, higher PDE2 expression after TNF-α treatment should affect both the cGMP and cAMP responses of HUVECs to ANP. Indeed, the cGMP responses to ANP were significantly attenuated in TNF-α–treated HUVECs (Figure 5A, left). Specific inhibition of PDE2A with Bay 60-7550 (100 nmol/L, added 15 minutes before ANP) did not affect the baseline responses to ANP (not shown) but fully rescued the cGMP responses of TNF-α–treated HUVECs to ANP (Figure 5A).

Next, we studied the effect of ANP signaling on intracellular cAMP. Cyclic AMP signals within endothelial cells are highly compartmentalized, and Sayner et al suggested that cytosolic-produced cAMP decreases, whereas cAMP in submembrane compartments improves barrier functions. To analyze microdomain-specific cAMP dynamics, we transfected HUVECs either with pmEpac2 camps, a FRET cAMP sensor targeted to caveolae, or with the cytosolic sensor Epac2 camps. The cells were then treated with or without TNF-α during 24 hours before the acute FRET measurements. Single-cell cAMP responses to ANP (10 nmol/L) were compared with the responses to subsequent addition of adenosine (10 μmol/L) and isoprenaline (1 μmol/L). The effects of ANP and adenosine were calculated as percent of the effect of the β-adrenergic agonist isoprenaline (FRET in % maximum), which fully activates both sensors in HUVECs. Figure 5B and 5C depict original tracings recorded with the membrane-attached sensor. As shown in Figure 5B and 5D, in resting HUVECs, ANP clearly increased submembrane cAMP levels,
the effect being smaller than the effects of adenosine and isoproterenol. Figure 5C and 5D illustrate that TNF-α exposure and induction of PDE2A3 reversed the effect of ANP from an increase to a mild decrease of submembrane cAMP. The stimulatory cAMP effects of adenosine were significantly inhibited by TNF-α, whereas the effects of isoproterenol were not altered. Again the PDE2A inhibitor Bay 60-7550 (100 nmol/L, 10 minutes) did not alter the cAMP effects of ANP and adenosine in resting cells but fully rescued the stimulatory effects of ANP and adenosine in TNF-α–pretreated cells (Figure 5D, right bars). In other words, in TNF-α–pretreated cells, inhibition of PDE2A prevented the decrease of submembrane cAMP levels by ANP. Figure 5E shows that ANP and adenosine also enhanced the cytosolic cAMP levels of HUVECs, but these responses were not significantly altered by TNF-α. Together with published studies,28 these results indicate that TNF-α increases the endothelial expression and ANP/cGMP-stimulated activity of the membrane-anchored isoform PDE2A3. Ultimately, these changes can mediate a negative submembrane cross talk between cGMP and cAMP, which may weaken the endothelial barrier.

TNF-α Induces PDE2-Mediated Hyperpermeability Effects of ANP/GC-A in the Microcirculation

The extravasation of neutrophils primarily occurs in postcapillary venules, where hemodynamic shear forces are diminished and the vessel wall is thin.2 We hypothesized that ANP/PDE2 signaling may increase transendothelial neutrophil migration partly by enhancing paracellular permeability and studied this possibility with intravital microscopy analyses of macromolecular FITC-dextran leakage from postcapillary venules of the mouse cremaster muscle. Consistent with our previous studies,16 ANP or BNP (100 nmol/L, 40 minutes of local superfusion) had no direct effects on the permeability for FITC-dextran (Figure 6A and 6B). Pretreatment of the cremaster with a low dose of TNF-α (200 ng, intrascrotal injection)23 enhanced the mRNA expression levels of PDE2A (Figure 6C) but only mildly affected baseline-dextran permeability (Figure 6A and 6B). However, after TNF-α pretreatment, ANP and BNP significantly enhanced FITC-dextran extravasation, indicating augmented paracellular permeability (Figure 6A and 6B). Of note, this TNF-α–induced hyperpermeability effect of ANP was abolished in EC GC-A KO but preserved in EC cGKI KO mice (Figure 7A). Even more, in control mice pretreated with TNF-α, the hyperpermeability effect of ANP was fully prevented by inhibition of PDE2 with Bay 60-7550 (100 nmol/L, local superfusion of the cremaster during 15 minutes before addition of ANP; Figure 7B).

Finally, we studied mice with fluorescent leukocytes (LysM-eGFP)17 to visualize directly the effect of ANP on neutrophil extravasation. As shown in Figure 8, under basal conditions, ANP (100 nmol/L, 40 minutes of superfusion) did not change the number of perivascular leukocytes in the cremaster. TNF-α pretreatment (performed as above) significantly increased the number of interstitial leukocytes. In TNF-α–pretreated mice, ANP further enhanced leukocyte extravasation and this ANP effect was prevented by Bay 60-7550 (200 µm; Figure 8).

We conclude that in the presence of TNF-α, ANP attenuates microcirculatory endothelial barrier functions and stimulates leukocyte transmigration. This effect involves endothelial GC-A/cGMP signaling and PDE2A3 as an effector molecule.
Our functional and biochemical experiments in vitro together suggest that myocardial barrier dysfunction and thereby to inflammation after AMI. Concomitantly, the induction of endothelial adhesion molecules within the ischemic myocardium, may contribute to endothelial adhesion protein 1 by MI was markedly attenuated in these mice subjected to hypoxia or tumor necrosis factor-α (TNF-α), as well as in the myocardium of mice with acute myocardial infarction (AMI). A, HUVECs were incubated with TNF-α (10 ng/mL) or vehicle (PBS) under normoxic or hypoxic (1% O2) conditions for 24 h. Western blot analyses demonstrated that TNF-α, hypoxia, or a combination of both attenuate the expression of cGMP-dependent kinase I (cGK1) (right) and increase the expression of PDE2A (left). However, the combination of both stressors did not exert significant additional effects. Top, Representative Western blot. Bottom, Results from 3 independent experiments; *P<0.05 vs normoxia/PBS.

**Discussion**

**Principal Findings**

Our study shows that mice with endothelial deletion of GC-A, the cGMP-producing receptor shared by ANP and BNP, are significantly protected from myocardial neutrophil activation and infiltration, as well as from necrosis during the early phase after AMI. Attenuated neutrophil activation in the ischemic myocardium of EC GC-A KO mice is indicated by diminished myeloperoxidase activity and decreased mRNA levels of CXCL1 (keratinocyte-derived chemokine), a CXC chemokine that was previously shown to be induced in inflammatory cells but not in resident myocardial cells after experimental MI. Concomitantly, the induction of endothelial adhesion molecules (selectins, intercellular adhesion molecule 1, and vascular cell adhesion protein 1) by MI was markedly attenuated in these mice. We conclude that NPs, which are induced and released within the ischemic myocardium, may contribute to endothelial barrier dysfunction and thereby to inflammation after AMI. Our functional and biochemical experiments in vitro together with intravital microscopy studies of the cremaster muscle microcirculation in vivo demonstrate that hypoxia and cytokines, such as TNF-α, alter the immediate postreceptor signaling pathways of NP/cGMP in endothelial cells, decreasing cGKI and inducing PDE2A expression. This molecular remodeling may reverse the effects of ANP/BNP from endothelial barrier protection (via cGKI) to barrier disruption (via PDE2A; Online Figure II). It is well known that accentuation or prolongation of the inflammatory response in the early phase after AMI later on results in worse remodeling and dysfunction. Thus, our experimental studies may partly explain the clinical observations that sustained increases in ANP and, greater, BNP levels during the early phase of AMI correlate with progressive LV enlargement, decreased contractility, and increased stiffness.

Of note, EC GC-A KO mice have mild arterial hypertension and functionally well-compensated subclinical hypertrophy under baseline, resting conditions. Because LV hypertrophy is a powerful risk factor for cardiovascular disease, the protective effects of GC-A deletion need to be further explored in murine models with a more advanced hypertrophic state. In summary, this study suggests a potential role of GC-A in the maintenance of normal cardiac homeostasis in health and disease, and underscores the need for further exploration of the functional role of endothelial GC-A in cardiac dysfunction and remodeling.

**Figure 4.** Increased expression of phosphodiesterase 2A (PDE2A) in human umbilical vein endothelial cells (HUVECs) subjected to hypoxia or tumor necrosis factor-α (TNF-α) as well as in the myocardium of mice with acute myocardial infarction (AMI). A, HUVECs were incubated with TNF-α (10 ng/mL) or vehicle (PBS) under normoxic or hypoxic (1% O2) conditions for 24 h. Western blot analyses demonstrated that TNF-α, hypoxia, or a combination of both attenuate the expression of cGMP-dependent kinase I (cGK1) (right) and increase the expression of PDE2A (left). However, the combination of both stressors did not exert significant additional effects. Top, Representative Western blot. Bottom, Results from 3 independent experiments; *P<0.05 vs normoxia/PBS.

**Figure 5.** Tumor necrosis factor-α (TNF-α) alters atrial natriuretic peptide (ANP)-induced cGMP/cAMP cross talk in human umbilical vein endothelial cells (HUVECs). A, ANP-induced cGMP accumulation is reduced by TNF-α and rescued by Bay 60–7550. HUVECs were incubated with TNF-α (10 ng/mL) or vehicle for 24 h followed by ANP±Bay 60–7550. Results are shown for ANP and Ado as a % of maximal Iso response (10 ng/mL TNF-α) for 24 h. Increase of cyan fluorescent protein (CFP)/yellow fluorescent protein (YFP) ratio indicates an increase in cAMP levels. Cells were stimulated with 10 nmol/L ANP and subsequently with subsaturating concentrations of adenosine (Ado, 1 μmol/L) and isoproterenol (Iso, 1 μmol/L). B and C, Data are shown for ANP and Ado as a % of maximal iso response (*P<0.05; n=8–9 cells from 2 independent experiments). GDPH indicates glyceraldehyde 3-phosphate dehydrogenase.
disease, we expected that this intrinsic phenotype would exacerbate (not attenuate) ischemic myocardial necrosis of EC GC-A KO mice. This risk factor may explain why these mice exhibited only modest decreases in myocardial necrosis despite marked attenuation of inflammatory markers. In other words, the effect of the proinflammatory effects of NPs after MI might be underestimated in the experimental studies presented here.

Our observations of acute proinflammatory roles of ANP and BNP after AMI are in line with previous studies of permanent coronary occlusion or ischemia–reperfusion injury in mice with global, systemic inactivation (knockout) of ANP or GC-A or with transgenic overexpression of BNP in the liver.32–34 However, these former studies have the limitation that systemic arterial hypertension, increased systemic sympathetic and renin–angiotensin activities, and vascular abnormalities influence the cardiac responses of the global knockout mice to ischemia. In other words, the effect of the proinflammatory effects of NPs after MI might be underestimated in the experimental studies presented here.

Figure 6. Tumor necrosis factor-α (TNF-α) induces endothelial hyperpermeability effects of atrial natriuretic peptide (ANP) and B-type natriuretic peptide (BNP) in postcapillary venules of the m. cremaster. A and B, Time course of changes in net integrated optical intensity (an index of fluorescein isothiocyanate (FITC)–labeled dextran extravasation) during 40 min of local ANP, BNP (100 nmol/L), or vehicle superfusion after intrascrotal injection of vehicle (200 μmol/L PBS) or TNF-α (200 ng; n=6; *P<0.05 vs baseline at 10 min). C, Real-time reverse transcription polymerase chain reaction: pretreatment of the m. cremaster with TNF-α enhanced the mRNA expression levels of phosphodiesterase 2A (PDE2A).

Figure 7. Tumor necrosis factor-α (TNF-α)–induced hyperpermeability effect of atrial natriuretic peptide (ANP) in cremaster venules is mediated by endothelial cGMP-forming guanylyl cyclase-A (GC-A)/cGMP/phosphodiesterase 2A signaling and independent from cGMP-dependent kinase I (cGKI). Time course of changes in net integrated optical intensity during 40 min of continuous local ANP (100 nmol/L) superfusion 2 h after intrascrotal injection of TNF-α (200 ng): A, in mice with conditional, endothelial deletion of GC-A (EC GC-A KO mice) or cGKI (EC cGKI KO mice); B, in control mice after local superfusion with vehicle or with Bay 60–7550 (100 nmol/L; 15 min before addition of ANP). Endothelial GC-A inactivation (A) or pretreatment with Bay 60–7550 for 15 min (B) prevented TNF-α/ANP–induced hyperpermeability (n=6; *P<0.05 vs baseline at 10 min). A and B, Top, Representative original photographs.
the vessel wall is thin.\(^2\) This transendothelial migration takes place by transcellular and, mainly, by paracellular trafficking.\(^2\) Endothelial barrier properties have an important role, and a dysfunctional endothelium, with enhanced expression of neutrophil adhesion proteins and altered cell–cell contacts, is characteristic of many inflammatory diseases, including AMI. When a previously healthy, resting endothelium is involved in an acute allergic reaction mediated by mast cell histamine, the ANP/GC-A/cGMP pathway, via activation of cGKI, can attenuate pathological calcium entry and hyper-permeability.\(^16\) However, elegant in vitro studies in HUVECs showed that the effect of ANP/cGMP depends on the relative expression of different cGMP effector molecules.\(^25\) In particular, TNF-\(\alpha\), one of the main cytokines produced in AMI, induces the expression of PDE2A3, a membrane-anchored isofrom.\(^25,28\) In HUVECs with high PDE2A levels, ANP/cGMP enhanced endothelial permeability.\(^25\) Our observations extend these studies in HUVECs, showing that TNF-\(\alpha\) and also hypoxia enhance the expression and cGMP-hydrolyzing activities of PDE2A and, even more, attenuate cGKI levels. The later observation is consistent with published findings of diminished cGKI levels in hypoxic smooth muscle cells.\(^37\) However, whereas a loss of endothelial cGKI prevents the acute antihistaminergic action of ANP,\(^16\) this is not sufficient to reverse this protective effect into a proinflammatory action because EC cGKI KO mice did not show enhanced (but unaltered) myocardial inflammation after AMI.

In general, cAMP has been shown to stabilize the endothelial barrier. However, it is becoming increasingly apparent that cAMP signals within cells are compartmentalized.\(^25,38\) Studies suggest that elevation of cytosolic cAMP disrupts the endothelial barrier.\(^38,39\) In contrast, subplasmalemmal cAMP enhances the phosphorylation of effectors that promote junctional integrity, such as filamin A.\(^39\) In HUVECs, the NP/GC-A/cGMP pathway may have dual effects on cAMP, depending on the relative expression levels of the cAMP-degrading enzymes PDE3A (cGMP inhibited) and PDE2A (cGMP stimulated), mediating positive versus negative cGMP/cAMP cross talks.\(^25\) TNF-\(\alpha\) does not alter PDE3 but markedly enhances PDE2A3 expression as described in the present study and elsewhere.\(^25,28\) To analyze the effect on the regulation of submembrane versus cytosolic cAMP levels by ANP, we performed comparative FRET studies with a membrane-targeted and a cytosolic cAMP sensor. In resting HUVECs, ANP increased submembrane and cytosolic cAMP, indicating inhibition of PDE3A. In contrast, in cells pretreated with TNF-\(\alpha\), we observed an ANP/cGMP-driven, PDE2A-mediated mild but clear decrease of submembrane cAMP, whereas the effect of ANP on cytosolic cAMP was unchanged. The observation that this cAMP decrease is confined to the submembrane compartment supports the involvement of the membrane-anchored PDE2A3 isoform previously shown to be induced by TNF-\(\alpha\).\(^28\)

Of course, HUVECs just provide a more or less valid in vitro model system. Because we observed a significant induction of PDE2A expression in vivo, in hearts after AMI, our major goal was to study whether such molecular changes affect the microcirculatory actions of NPs. Limiting our studies, up-to-now it is technically impossible to measure dynamic cAMP changes in the microcirculatory endothelium in situ. Instead, we applied intravital microscopy to directly visualize the effects of synthetic ANP or BNP on the endothelial barrier of postcapillary venules within the cremaster muscle of monogenetic mouse models dissecting endothelial NP/GC-A signaling. By monitoring the extravasation of FITC-dextran and of fluorescent leukocytes as indices of endothelial barrier functions, we confirmed that NPs do not alter endothelial permeability under baseline, resting conditions.\(^16\) However, in cremaster preparations pretreated with TNF-\(\alpha\) to induce PDE2 expression, both ANP and BNP exerted striking proinflammatory effects, with macromolecule and leukocyte extravasation. A combination of specific genetic and pharmacological tools demonstrated that this effect was mediated by endothelial GC-A/cGMP/PDE2 signaling and was independent of cGKI.

**Downstream Pathways Contributing to Proinflammatory Endothelial NP/GC-A Signaling**

Decreases in endothelial submembrane cAMP might enhance the recruitment and transmigration of neutrophils by different mechanisms, such as endothelial production of reactive oxygen species, expression of adhesion molecules, and weakening of endothelial junctions.\(^25,40,41\) In particular, it was shown that
increased endothelial cAMP downregulates the expression of the cell surface adhesion proteins vascular cell adhesion protein 1, intercellular adhesion molecule 1, and E-selectin.40 Notably, the induction of these endothelial proinflammatory proteins by AMI was drastically downregulated in EC GC-A KO when compared with control littermates. This supports our concept that endothelial NP/GC-A signaling, possibly through PDE2-mediated cAMP decreases, contributes to the induction of the proinflammatory features of coronary endothelial cells during AMI.

Such adhesion molecules are normally harbored within the glycocalyx and are exposed after ischemia-induced shedding of larger constituents, particularly hyaluronan, which enhances leukocyte adhesion. Studies in isolated perfused hearts showed that intracoronary infusion of synthetic ANP or BNP caused shedding of the coronary glycocalyx, resulting in enhanced permeability.26 However, the pathophysiological significance in vivo was not investigated. Indeed, our fluorescent stainings of myocardial vessels revealed loss of hyaluronan from the apical surface of the endothelium 48 hours after AMI. However, we observed similar alterations in control and EC GC-A KO littermates, indicating that endogenous endothelial NP/GC-A signaling does not provoke this damage.

Summary and Conclusions

Our in vivo studies extend previous in vitro findings25 that the effect of the NP/GC-A/cGMP signaling pathway in endothelial cells is highly dependent on the molecular equipment of the cells, that is, the expression levels of the cGMP-modulated regulatory proteins cGKI and PDE2 versus PDE3. To our knowledge, this is the first study showing that cGMP/cAMP cross talk is compartmentalized in endothelial cells and that this dual NP/cGMP-dependent regulation of cAMP and microvascular endothelial cell permeability has pathophysiological relevance. When a previously healthy endothelium is involved in an acute allergic reaction, endothelial NP/GC-A/cGMP/cGKI signaling can counterbalance calcium-linked hyperpermeability16 (Online Figure II). However, when endothelial cells are exposed to hypoxia and cytokines, such as TNF-α, conditions which enhance PDE2A and impair cGKI expression, NP/GC-A/cGMP signaling may increase PDE2 activity, resulting in a decrease of submembrane cAMP with breakdown of endothelial barrier functions and enhanced expression of cell surface adhesion proteins. Such changes ultimately facilitate leukocyte activation and transmigration (Online Figure II). Our findings indicate that this pathway may contribute to inflammation in the early phase after MI and suggest that inhibition of endothelial PDE2A could have a beneficial effect in this setting.

Clinical Relevance

Our experimental studies unravel a novel endothelial signaling mechanism of NPs. Although previous25 and presented experiments here confirm this pathway in cultured human ECs, the relevance for the pathophysiology of MI in patients of course requires further investigations. In fact, clinical evaluation of intravenous infusions of synthetic ANP (carperitide) or BNP (nesiritide) indicate that NPs may be an effective adjunctive therapy for cardiac function protection in patients with AMI.12,42,45 Recent insights from the meta-analysis of 20 different trials showed that additional ANP or BNP treatment (low doses of carperitide or nesiritide infused during 2–7 days after AMI) was significantly superior to standard medical therapy. LV ejection fraction was improved by synthetic NPs both in the short-term (1 month) and long-term follow-ups, with a trend toward lower infarct sizes and reduced risk of major acute cardiovascular events.12 However, all of these studies only mentioned that the synthetic NPs were given at the acute phase after AMI, but the real interval between the onset of AMI and start of infusion remained unclear.12 Such protective long-term effects of short-term administered synthetic NPs likely involve their favorable systemic actions, including inhibition of the renin–angiotensin–aldosterone and vasodilation, as well as local cardiac antihypertrophic and antiinfectious actions,44 actions which obviously predominate over the unwarranted acute proinflammatory actions described here. In addition, 2 clinical aspects may counter regulate possible acute proinflammatory cardiac actions of local NPs: (1) AMI routine therapy includes anti-inflammatory drugs, such as aspirin and statins12; and (2) concurrent plasma concentrations of the endogenous NPs (measured with antibodies detecting the N-terminal parts of the prohormones BNP and ANP) fell with the introduction of nesiritide infusions and cardiac unloading, indicating diminished local, cardiac (endogenous) NP levels in the presence of enhanced systemic (exogenous) NP plasma levels.54 The presented experimental data here illustrate a novel pathway, which could be a target for therapies improving NP actions.

Sources of Funding

This study was supported by the Bundesministerium für Bildung und Forschung (BMBF 01 EO1004) and the Deutsche Forschungsgemeinschaft (SFB 688 to S. Frantz and M. Kuhn, DFG NI 1301/3-1 to V.O. Nikolaev, and SFB 1116 to J.W. Fischer).

Disclosures

None.

References


What Is Known?

- In acute myocardial infarction (AMI), the infiltration of the ischemic tissue by inflammatory cells affects initial injury and subsequent healing and remodeling processes.
- Another early event in AMI is the acute and marked increase of ventricular expression and release of the cardiac hormones atrial (ANP) and B-type natriuretic peptide (BNP), but the pathophysiological significance is unknown.

What New Information Does This Article Contribute?

- Normally, ANP and BNP, via their shared guanylyl cyclase A (GC-A) receptor and enhanced intracellular levels of the cyclic nucleotides cGMP and cAMP, exert protective endothelial actions improving vascular barrier functions.
- In AMI, tissue hypoxia and cytokines induce the expression of phosphodiesterase type 2A in endothelial cells, a cGMP-stimulated phosphodiesterase that degrades submembrane cAMP in response to natriuretic peptide/GC-A/cGMP signaling.
- In mice, genetic deletion of the endothelial GC-A receptor attenuates myocardial inflammation in the early phase of AMI, suggesting the presence of an ANP/BNP-mediated proinflammatory cross talk between cardiomyocytes and endothelial cells in this situation.

Plasma pro-BNP level after AMI is a clinical marker of the severity of ischemia and independently predicts cardiac function and 2-year survival. Of course, ANP and BNP are much more than diagnostic markers of cardiovascular diseases. Via their GC-A receptor, they exert cardioprotective functions as circulating hypotensive hormones and also as local factors moderating pathological cardiac remodeling. Therefore, synthetic ANP and BNP were considered promising adjunctive treatments in patients with AMI. In the early phase of AMI, endothelial dysfunction and myocardial inflammation are critical determinants of injury. To dissect the endothelial actions of NPs, we studied mice with endothelial-specific knockout of GC-A. To our surprise, we found that such mice exhibit less myocardial necrosis and inflammation after experimental AMI. Moreover, the induction of proinflammatory endothelial adhesion proteins was markedly attenuated. Molecular and intravital microscopy studies revealed that hypoxia and cytokines, such as tumor necrosis factor-α, induce the expression of the cGMP-stimulated phosphodiesterase type 2A in endothelial cells. NP/GC-A/cGMP signaling increases phosphodiesterase 2 activity, resulting in a decrease of submembrane cAMP with breakdown of endothelial barrier functions and enhanced leukocyte transmigration. This pathway may contribute to inflammation after MI, suggesting that inhibition of endothelial phosphodiesterase 2A could have a beneficial effect in this clinical setting.

Novelty and Significance
Endothelial Actions of ANP Enhance Myocardial Inflammatory Infiltration in the Early Phase After Acute Infarction

Wen Chen, Annett Spitzl, Denise Mathes, Viacheslav O. Nikolaev, Franziska Werner, Johannes Weirather, Katarina Spiranec, Katharina Röck, Jens W. Fischer, Ulrike Kämmerer, David Stegner, Hideo A. Baba, Ulrich Hofmann, Stefan Frantz and Michaela Kuhn

Circ Res. 2016;119:237-248; originally published online May 3, 2016; doi: 10.1161/CIRCRESAHA.115.307196

Circulation Research is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2016 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/119/2/237

Data Supplement (unedited) at:
http://circres.ahajournals.org/content/suppl/2016/05/03/CIRCRESAHA.115.307196.DC1

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation Research can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation Research is online at:
http://circres.ahajournals.org//subscriptions/
Supplemental Material

Materials and Methods

Genetic mouse models

Mice with conditional, endothelial (EC)-restricted inactivation of either GC-A (Tie-cre<sup>+/0</sup>;GC-A<sup>flox/flox</sup>, EC GC-A KO) or cGMP-dependent protein kinase I (Tie-cre<sup>+/0</sup>;cGKI<sup>flox/flox</sup>, EC cGKI KO) and their appropriate control littermates were generated by the Cre/loxP strategy as previously described (1). LysM-eGFPTG mice with green fluorescent leukocytes have also been described before (2). Male and female mice, 2 months old, were studied. Cre-Transgenic and nontransgenic littermates were compared for both floxed mouse lines within all experiments. The experiments complied with the Guide for the Care and Use of Laboratory Animals (NIH publication no. 85-23, revised 1996) and were approved by the animal care committee of the Universities of Würzburg and Düsseldorf.

Infarct model

Experimental acute myocardial infarction (AMI) was induced as described previously (3). In brief, mice were anesthetized with 2.5% isoflurane, intubated, and put on a mechanical small-animal ventilator. Adequacy of anesthesia was monitored from the disappearance of the pedal withdrawal reflex. After left-sided thoracotomy, MI was induced by ligating the proximal portion of the left coronary artery. Buprenorphine (0.05 - 0.1 mg/kg BW) was used for postoperative analgesia. In parallel subgroups, a thoracotomy was performed to expose the heart, but no suture was made to the coronary artery (sham operation) (3).

Evaluation of ischemic AAR and infarct size

Two days after AMI, the area at risk (AAR) and infarct area were evaluated (4). The thoracotomies were reopened, and 1 ml of 5% Evans blue (Sigma, Deisenhofen, Germany) was injected from the cardiac apex to delineate the nonischemic tissue. Thereafter the hearts were excised, washed with PBS, and cut into five transverse slices. The slices were stained with 2% 2,3,5-triphenyltetrazolium chloride (TTC; Sigma) solution to determine the infarct area, weighed, and photographed under a microscope (Olympus, Hamburg, Germany). Left ventricular (LV) area, AAR, and infarct were determined by computerized planimetry using a self-programmed automated-image analysis tool computing tissue volumes based on manual planimetry of digitalized images by the following formula: \[ (A_1 \times W_1) + (A_2 \times W_2) + (A_3 \times W_3) + (A_4 \times W_4) + (A_5 \times W_5) \], where \( A \) is the area of the slice denoted by the subscript and \( W \) is the weight of the respective section. Infarct area is expressed as a percentage of the AAR. Planimetry was performed independently by two observers blinded to the genotypes (4).

Immunohistochemical analysis of myocardial neutrophil infiltration

Left ventricular samples were fixed in 4% paraformaldehyde overnight and embedded in paraffin. 5-μm sections were stained immunohistochemically for neutrophils (clone 7/4, Linaris, Wertheim, Germany, # 550274 (3)) and for myeloperoxidase (MPO) using a rabbit anti-human MPO antibody (dilution: 1:750; #A0398, Dako, Germany). Antibody binding was detected with Zytomed polymer POLHRP-100 (Zytomed Systems, Germany) and visualized with diaminobenzidine (DAB 530, Zytomed Systems, Germany). Quantitative assessment of neutrophil density was performed by counting the number of neutrophils and the MPO-positive cells in the ischemic area using the computer-assisted image analysis system Cell-D (Olympus, Hamburg Germany), with the investigator blinded to the genotypes.
Fluorescence-Activated Cell Sorting (FACS) Analysis of myocardial inflammatory infiltration

Cell suspensions from individual hearts were prepared by digestion with collagenase type 2 and protease type XIV (Sigma), as described in detail (3). Staining protocols were as described (3). The specific antibodies are depicted in Online Table I.

MPO activity assay

Myocardial MPO activity was measured as described by Pulli et al. (5). From each heart, the macroscopic infarct area and right ventricle (RV, as control) were dissected, washed with ice-cold PBS and then incubated on ice for 2 hours in extraction buffer (0.32 M sucrose, 1 mM CaCl₂, 10 U/ml Heparin in Hanks Balanced Salt Solution). Samples were homogenized by a mechanical homogenizer in 500 µl CTAB buffer (50 mM cetyltrimethylammonium bromide, Sigma, in 50 mM potassium phosphate buffer at pH 6.0), sonicated, and centrifuged at 15,000 g for 15 min at 4°C. Supernatants were used for measuring protein content and intracellular MPO activity. Protein content was analyzed by BCA protein assay. To specifically capture MPO, samples were incubated in MPO ELISA dilution buffer (Hycult, Plymouth Meeting, PA) on anti-MPO antibody coated 96-well plates (Hycult) for 1 hour at room temperature (duplicates of each sample). Plates were then washed 4 times with washing buffer (PBS with 0.05% Tween 20), and once with PBS only. MPO activity of antibody-captured MPO was assessed with ADHP (10-acetyl-3,7-dihydroxyphenoxazine, Sigma). PBS (49 µl), 1 µl 0.03% hydrogen peroxide (H₂O₂) and 50 µl of 200 µM ADHP solution were added to each well and MPO activity was analyzed immediately with a Wallac Victor2 microplate reader (PerkinElmer, USA) using an excitation wavelength of 535 nm and an emission wavelength of 590 nm. Enzyme activity was defined as relative fluorescent units (RFU) normalized to the sample protein concentration (5).

Detection of endothelial glyocalyx by fluorescent hyaluronic acid (HA) stainings

Fluorescent HA stainings were performed on cardiac cryosections (20 µm) as described (6). Endothelial cells of myocardial arterioles and capillaries were visualized by simultaneous CD31 stainings. Sections were embedded in ProLong Gold antifade reagent containing DAPI (Invitrogen, Karlsruhe, Germany). Imaging of the sections was performed using a Zeiss Axio Observer Z1 microscope and a 63x objective. The glyocalyx was analyzed employing ImageJ 1.42. Resulting integrated densities were normalized to the number of endothelial cells as apparent by CD31 and DAPI staining. From each heart two sections were analyzed and the glyocalyx of 3-6 vessels per section was measured. These analyses were performed independently by two persons.

Culture of human umbilical vein endothelial cells (HUVECs) and cGMP determinations

HUVECs were isolated by collagen digestion and cultured in endothelial cell growth medium (PromoCell, Heidelberg, Germany). All experiments were performed with confluent HUVECs of passages 1 or 2 in mitogen-free, serum-reduced medium (0.5% fetal calf serum during 24 h prior to experimentation). In every experiment, HUVEC isolated from 3 different cords were combined. To study the effects of ANP on cyclic GMP content, cells seeded in 24-well plates were treated with human TNF-α (10 ng/ml; R&D Systems, Wiesbaden-Nordenstadt, Germany) or vehicle (PBS) during 24 h. Thereafter the cells were stimulated with ANP (Bachem, Bubendorf, Switzerland) for 10 min (with and without previous inhibition of PDE2A with 100 nM/L Bay 60-7550 (Alexis), added 15 minutes before ANP). The incubation medium was aspirated and intracellular cGMP was extracted with ice-cold 70% (v/v) ethanol. The samples were dried and reconstituted for determination of cGMP content by radioimmunoassay (1).

Western Blots with HUVECs

Cells were washed twice with PBS and then homogenized either in RIPA buffer (Figure 4A) or a buffer containing in mmol/L: 10 HEPES, 300 sucrose, 150 NaCl, 1 EGTA, 2 CaCl₂, and 1 % Triton-X (Figure 5A). Proteins were quantified using BCA Protein Assay (Pierce). Samples were boiled at
95°C for 5 minutes, and 30 μg of total protein per lane were subjected to 10% (Figure 4A) or 4-12% (Bis-AA gradient gels, Criterion, Bio-Rad) SDS-PAGE (Figure 5A) and to immunoblot analysis using anti-PDE2A antibody (Fabgennix, 1:750) and a monoclonal GAPDH antibody (HyTest, both overnight). The blots in Figure 4 were developed using the ECL detection system (Amersham-Pharmacia, Freiburg, Germany) and results were quantitated by densitometry (Image Quant). For Blots in Figure 5 detection was performed with ECL Prime detection reagent (Amersham) and FujiFilm Super RX films developed with automated Konica SRX 101A developer.

RT-PCR analyses

Extraction of mRNA from heart and m. cremaster and reverse-transcription (RT) were performed as described (1). Expression levels of CXCL1, ICAM-1, VCAM-1, E-selectin, P-selectin and PDE2A mRNA were analyzed by real time RT-PCR using LightCycler Technology (LC-96; Roche, Mannheim, Germany). The following primers and probes were used: for CXCL1, sense: 5’AGAAAGGGTGTGTGCGAAAA 3’; antisense: 5’ACTGACATCTTTTCAAGACATAACAA 3’; probe 75 (REF: 04688988001); for ICAM-1, sense: 5’ CGAAGCTTCTTTGCTCTGC 3’; antisense: 5’ GTCCAGCCAGAGACCTA 3’; probe 10 (REF: 04685091001); for VCAM-1, sense: 5’ TGTTGAATGGAATCTTTTCAAGACATAACAA 3’; antisense: 5’ CCCAGATGGGTGTTTCCTT 3’; probe 34 (REF: 0468761001); for E-selectin, sense: 5’ TCCTCTGAGAGTGGAGTG AG 3’; antisense: 5’ GTGGTGCTCAAAGCTCTCACC 3’; probe 19 (REF: 04686926001); for P-selectin, sense: 5’ CCGGAAGACTGTTTGCTTTC 3’; antisense: 5’ CTTGAGACTATGGCGCTTTC 3’; probe 47 (REF: 04688074001); for PDE2A: sense: 5’AAAGGATGAAGCCTCCTCACC 3’; antisense: 5’ TTGGTGTTATCCTACATGAGACC 3’; probe 83 (REF: 04689062001). Levels of GAPDH were used for normalization (GAPDH Gene Assay; REF: 05046211001, all Roche).

FRET to monitor subsarcolemmal and cytosolic cAMP dynamics in single living HUVECs

HUVECs were seeded onto 24 mm round glass coverslides, grown to 70-80% confluency and infected with pmEpac2-camps adenovirus or Epac2-camps adenovirus at multiplicity of infection (MOI) of 30-50. 40-48 h after infection, live-cell FRET measurements were performed exactly as described (7,8). Briefly, the cells were washed with FRET buffer (in mM: 144 NaCl, 5.4 KCl, 1 MgCl₂, 1 CaCl₂, 10 HEPES, pH 7.3), and 400 µL of the same buffer were added to the chamber. Measurements were performed using a Nikon Ti inverted fluorescent microscope equipped with 440 nm pE-1000 Cool LED, Dual View and ORCA 03-G camera. Images were acquired using ImageJ software. 24 h prior to measurements cells were incubated with human TNF-α (10 ng/ml; R&D systems) or vehicle, and thereafter the acute responses to consecutive additions of ANP, adenosine and isoprenaline were studied.

Intravital microscopy of the mouse cremaster microcirculation

As a measure of microcirculatory endothelial permeability, leakage of fluorescein isothiocyanate-labeled (FITC)-Dextran (70 kDa; Sigma) from postcapillary venules within the mouse cremaster muscle was analyzed by intravital fluorescence microscopy as described (1). Mice were deeply anesthetized by an intraperitoneal injection of ketamine (100 mg/kg BW) and xylazine (10 mg/kg). Body temperature was maintained at 37°C. The cremaster muscle was exteriorized and continuously superfused with bicarbonate-buffered saline, at a rate of 1.2 ml/min. At the end of the experiment the mice were sacrificed via intravenous ketamine injection.

After tail vein injection of FITC-Dextran, microscopy was performed using a fluorescence filter for FITC for epillumination (Olympus). Topical application of ANP, BNP (both 100 nM/L; BNP as mouse sequence; American Peptide Co., Sunnyvale, CA), or vehicle was always started 30 min after i.v. administration of FITC-Dextran and continued for additional 40 min. Permeability responses to NPs were evaluated after intrascrotal injection of mouse TNF-α (200 ng (9); R&D Systems) or vehicle (200 μL PBS), in the absence or presence of the PDE2 inhibitor Bay 60-7550 (local superfusion of 100 nM/L, started 15 minutes before ANP). Quantitative off-line analysis of the microscopic images was
performed with the computer-assisted image analysis system Cell-D (Olympus) (1). The observer was blinded to the treatment and genotype. Changes in microvascular permeability to FITC-Dextran were measured using integrated optical intensity (IOI) as an index. Six interstitial areas, immediately adjacent to postcapillary venules, and corresponding intravascular equal areas, were randomly selected for IOI analysis. The same preselected areas were observed every 10 min, as indicated in the results section and corresponding Figures.

The experiments with LysM-eGFP mice (2) were performed with the same chemicals and experimental conditions. The number of extravascular fluorescent leucocytes was quantified in 3 fields of view (160 × 240 µm) per animal at 3 time points: 0 (vehicle), 20 and 40 minutes (during superfusion of ANP, started at minute 1). The number of leukocytes per interstitial area (in square millimeters) was counted.

References


Legends for Online Figures I and II as well as for Online Table I

Online Figure I. Endothelial glycocalyx of myocardial arterioles and capillaries is reduced by experimental AMI. Control and EC GC-A KO mice were subjected to 2 days of coronary artery ligation or sham operation before analysis of the glycocalyx by fluorescent hyaluronic acid (HA) staining (green) by affinity histochemistry; arrows point toward the glycocalyx. Endothelial cells were identified by CD31 staining (orange) and nuclei were stained blue by DAPI. Representative images and quantitative analysis are presented. Fluorescent staining is expressed as integrated density per endothelial cell. (n=6-8 per group *P<0.05 vs sham).

Online Figure II. Proposed model of the dual effects of ANP and BNP on endothelial barrier functions. In a previously healthy endothelium, NP/GC-A/cGMP signaling stimulates cGKI and inhibits PDE3, leading to phosphorylation of cytoskeleton- and calcium-regulating proteins (RGS2, VASP, TRPC6, filamin). This attenuates the hyperpermeability actions of mast cells and histamine (16) or thrombin (25). In AMI, hypoxia and TNF-α impair cGKI and induce PDE2A3 expression (25,28 and present study). In this situation, the NPs/GC-A/cGMP pathway can activate PDE2A3, leading to decreased submembrane cAMP levels and thereby contributing to the impairment of endothelial barrier properties.

Online Table I. Fluorescence-Activated Cell Sorting (FACS) Analyses of myocardial inflammatory infiltration in hearts enzymatically digested two days after coronary artery ligation. (A) Antibodies used for FACS Analyses. (B) Cell populations infiltrating the myocardium of control (n=6) and EC GC-A KO littermates (n=7) after AMI (in %). *P < 0.05 vs controls.
Online Figure I

Sham

Control, AMI

EC GC-A KO, AMI

Coronary glycocalyx

fold of sham

0.0
0.2
0.4
0.6
0.8
1.0
1.2

sham
CTR
EC GC-A KO

AMI
ANP, BNP
↓
GC-A

Previously healthy endothelium

Endothelium exposed to hypoxia and TNF-α (e.g. in AMI)

↓
cGMP

cGKI, PDE3A

Phosphorylation of regulatory proteins (RGS2, TRPC6, VASP, Filamin)

↓
Attenuation of acute hyperpermeability effects of mast cells, histamine, thrombin

↓
cGKI, PDE3A

cAMP

↓
PDE2A3

↓
submembrane cAMP

↓
Impaired endothelial barrier (e.g. enhanced inflammation after MI)
**Online Table I**

<table>
<thead>
<tr>
<th>A. Antibodies</th>
<th>Specific clones</th>
<th>Company</th>
<th>Dilution</th>
</tr>
</thead>
<tbody>
<tr>
<td>FITC rat anti-mouse CD45</td>
<td>Clone: 30-F11</td>
<td>BD Pharmingen</td>
<td>1:100</td>
</tr>
<tr>
<td>PE rat anti-mouse CD11b</td>
<td>Clone: M1/70</td>
<td>BD Pharmingen</td>
<td>1:100</td>
</tr>
<tr>
<td>Alexa Fluor 647 anti-mouse Ly6G</td>
<td>Clone: 1A8</td>
<td>BioLegend</td>
<td>1:250</td>
</tr>
<tr>
<td>Anti-mouse CD3 PE-Cy5</td>
<td>Clone: 145-2C11</td>
<td>BD Biosciences</td>
<td>1:100</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>B. Infiltrating inflammatory cell populations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control mice</td>
</tr>
<tr>
<td>Neutrophils (CD45+ CD11b+ Ly6G+)/CD11b+</td>
</tr>
<tr>
<td>Monocytes/Macrophages (CD45+ CD11b+ Ly6G-)/CD11b+</td>
</tr>
<tr>
<td>Myeloid cells (neutrophils, monocytes, macrophages)/CD45+</td>
</tr>
<tr>
<td>T cells (CD45+ CD3+)/CD45</td>
</tr>
</tbody>
</table>