Cigarette smoke upregulates rat coronary artery endothelin receptors in vivo.

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Cigarette Smoke Upregulates Rat Coronary Artery Endothelin Receptors In Vivo

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Abstract

Background: Cigarette smoking is a strong cardiovascular risk factor and endothelin (ET) receptors are related to coronary artery diseases. The present study established an in vivo secondhand smoke (SHS) exposure model and investigated the hypothesis that cigarette smoke induces ET receptor upregulation in rat coronary arteries and its possible underlying mechanisms.

Methodology/Principal Findings: Rats were exposed to SHS for 200 min daily for 8 weeks. The coronary arteries were isolated and examined. The vasoconstriction was studied by a sensitive myograph. The expression of mRNA and protein for receptors was examined by real-time PCR, Western blot and immunofluorescence. Compared to fresh air exposure, SHS increased contractile responses mediated by endothelin type A (ETα) and type B (ETβ) receptors in coronary arteries. In parallel, the expression of mRNA and protein for ETα and ETβ receptors of smoke exposed rats were higher than that of animals exposed to fresh air, suggesting that SHS upregulates ETα and ETβ receptors in coronary arteries in vivo. Immunofluorescence staining showed that the enhanced receptor expression was localized to the smooth muscle cells of coronary arteries. The protein levels of phosphorylated (p)-Raf-1 and p-ERK1/2 in smoke exposed rats were significantly higher than in control rats, demonstrating that SHS induces the activation of the Raf/ERK/MAPK pathway. Treatment with Raf-1 inhibitor GW5074 suppressed SHS-induced enhanced contraction mediated by ETα receptors, and inhibited the elevated mRNA and protein levels of ETα and ETβ receptors caused by SHS. The results of correlation and regression analysis showed that phosphorylation of Raf and ERK1/2 were independent determinants to affect protein expression of ETβ and ETα receptors.

Conclusions/Significance: Cigarette smoke upregulates ETβ and ETα receptors in rat coronary artery, which is associated with the activation of the Raf/ERK/MAPK pathway.


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Introduction

Cigarette smoking is considered one of the most powerful risk factors for the development of cardiovascular disease (CVD), such as coronary artery disease (CAD), ischemic and congestive heart failure [1]. Increasing evidences demonstrate that passive smoke (secondhand smoke, SHS) contains relatively higher concentrations of toxic gaseous components than mainstream smoke [2]. Smoking is strongly associated with the pathogenesis of CAD which may be attributed to the promotion of atherosclerosis, the triggering of coronary thrombosis, coronary artery spasm and reduced capacity of the blood to deliver oxygen [3]. Although cigarette smoking is an established risk factor for atherosclerosis, the actual mediator of CAD associated with smoking is unknown.

The endothelin system plays an important role in CVD pathogenesis. Endothelin-1 (ET-1) is one of the important vasoactive peptide participating in the regulation of vascular functions, such as controlling the basal coronary artery tone [4]. To exert its effects, ET-1 binds to transmembrane endothelin type A (ETαA) and type B (ETβB) receptors to mediate vasomotor responses [5] which can alter the diameter of the vessel lumen as well as blood flow in the vasculature [6]. The ETαA and ETβB receptors in the vascular smooth muscle cells (VSMC) are involved in the atherosclerotic process by enhancing proliferation and migration of the VSMC [7]. In addition, there are many observations of ETβB receptor upregulation in patients [8] and experimental models [9] of atherosclerosis and ischemic heart disease [10].

The ET receptor system has been shown to be involved in the pathophysiological events that are associated with cigarette smoking [11]. By using an in vitro model, we have shown that dimethylsulfoxide-soluble smoke particles induce upregulation of ET receptors in rat cerebral [12] and mesenteric [13] arteries. Recently, a novel aspect of the vascular pathophysiology has been revealed, namely the upregulation of vasoconstrictor receptors in the smooth muscle of arteries [14]. There are differences in
receptor expression depending on different arteries, which may occur as a result in various diseases. As we know, receptor changes in cerebral arteries are related to ischemic stroke [14]. Receptor expression alterations in coronary arteries are associated with CAD and/or atherosclerosis [8,10]. Likewise, the coronary artery also possesses ET receptors [15]. Therefore, we hypothesize that cigarette smoking or SHS upregulates coronary artery ET receptors, which may be of considerable relevance to the understanding of SHS-associated CAD and/or atherosclerosis.

The mitogen-activated protein kinases (MAPKs) are serine/threonine-specific protein kinases that respond to extracellular stimuli and regulate various cellular activities [16]. MAPKs consist of three main signaling pathways: extracellular signal-regulated protein kinase 1 and 2 (ERK1/2), c-Jun N-terminal kinase (JNK) and p38 [17]. Raf-1 is the initial protein kinase in MAPK signal transduction and takes turns to phosphorylate the subsequent MAP kinase/ERK (MEK) 1/2 and ERK1/2 [18]. The MAPKs consist of three main signaling pathways: extracellular signal-regulated kinase 1 and 2 (ERK1/2), c-Jun N-terminal kinase (JNK), and p38 [17]. Raf-1 is the initial protein kinase in MAPK signal transduction and takes turns to phosphorylate the subsequent MAP kinase/ERK (MEK) 1/2 and ERK1/2 [18]. The MAPKs consist of three main signaling pathways: extracellular signal-regulated kinase 1 and 2 (ERK1/2), c-Jun N-terminal kinase (JNK), and p38 [17]. Raf-1 is the initial protein kinase in MAPK signal transduction and takes turns to phosphorylate the subsequent MAP kinase/ERK (MEK) 1/2 and ERK1/2 [18].

Smoke Upregulates Coronary Endothelin Receptors

The mRNA content of ETB and ETA receptors in coronary arteries was examined by real-time PCR. Results showed that following smoke exposure the mRNA level of coronary artery ETB receptor relative to GADPH was increased to 152.9% (n = 5) of fresh air group (P<0.01, Fig. 2A). Similarly, ETA receptor mRNA level was found significantly enhanced in coronary arteries from smoke exposed rats (132±8%, n = 5) as compared to the fresh air exposed ones (P<0.01, Fig. 2B). This is in concert with the findings on isometric contraction.

In order to demonstrate the intracellular pathway involved, we studied the inhibitory effects of Raf-1 inhibitor GW5074 on smoke exposure. Results showed that GW5074 suppressed the increased mRNA expression of both ETB and ETA receptors induced by smoke exposure (Fig. 2A, B). The mRNA level declined to 118±8% (ETB receptor, n = 5, P<0.05) and 110±5% (ETA receptor, n = 5, P<0.05), respectively, in comparison with the group exposed to smoke only.

Table 1. Contractile response property of coronary arteries induced by K+6c and ET-1.

<table>
<thead>
<tr>
<th>Group</th>
<th>K+ (mN)</th>
<th>6c maximum (% of K+)</th>
<th>6c pEC50</th>
<th>ET-1 maximum (% of K+)</th>
<th>ET-1 pEC50</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fresh air</td>
<td>10</td>
<td>3.5±0.22</td>
<td>9.3±1.1</td>
<td>9.11±0.11</td>
<td>153±4</td>
</tr>
<tr>
<td>Smoke</td>
<td>9</td>
<td>3.8±0.34</td>
<td>24.4±3.1</td>
<td>8.90±0.22</td>
<td>167±9</td>
</tr>
<tr>
<td>Smoke+GW5074</td>
<td>8</td>
<td>4.1±0.39</td>
<td>18.1±3.0</td>
<td>9.10±0.17</td>
<td>162±9</td>
</tr>
</tbody>
</table>

The coronary arteries were isolated from rats exposed to fresh air, cigarette smoke and cigarette smoke plus GW5074 (0.5 mg/kg). Emax represents maximal contraction, pEC50 represents the negative logarithm of the agonist concentration that produces 50% of the maximal contractile effect. Coronary artery contractile responses were induced by K+6c and ET-1. K+-induced responses were expressed as absolute values of contraction (mN), and 6c and ET-1-elicted responses were expressed as percentage of K+-induced contraction. Statistical analysis was performed with unpaired student’s t-test with Welch’s correction.

*P<0.01 vs. fresh air group; **P<0.001 vs. fresh air group; ***P<0.05 vs. smoke group.

There was no significant difference of the Emax values between the smoke and treatment groups (table 1).
Smoke Upregulates Coronary Endothelin Receptors

Western blotting was also performed in the smoke group treated with Raf-1 inhibitor GW5074. There was a significant decline in the protein level of the ETB receptor (0.16 ± 0.02, n = 5, P < 0.05) in coronary arteries from rats exposed to SHS plus GW5074 treatment (Fig. 3A), compared to SHS exposure alone. However, the protein level in treatment group remained elevated from the fresh air group (P < 0.05). For the ETA receptor, the protein level was significantly decreased after inhibition of the Raf/ERK/MAPK pathway (Fig. 3B). The protein level of ETA receptor relative to β-actin was 0.29 ± 0.10 (n = 5) following treatment with GW5074, compared to 0.66 ± 0.11 (n = 5, P < 0.05) in the smoke group. The Raf-1 blocker GW5074 inhibited the increased receptor expression caused by smoke exposure, which supports that Raf/ERK/MAPK pathway is activated by cigarette smoke exposure.

The ETB and ETA receptor protein levels were visualized by a fluorescence immunohistology method. There was a significant increase in both ETB and ETA receptor protein levels in the VSMC layer of SHS exposed rat coronary arteries, compared to the arteries from fresh air groups (Fig. 4A, B). Treatment with Raf-1 inhibitor GW5074 prevented the increase in expression of ETB and ETA receptors in the VSMCs of coronary arteries (P < 0.05, Fig. 4A, B).

MAPK Signal Pathway Studies

The proteins of phosphorylated [p]-Raf-1, p-ERK1/2, p-p38 and p-JNK, and their total protein expressions were examined by Western blotting in coronary arteries from rats exposed to fresh air and cigarette smoke. The results showed that the total Raf-1 and ERK1/2 proteins were at the same level in fresh air and smoke group. However, the levels of p-Raf-1 and p-ERK1/2 proteins relative to their own total protein in smoke exposed animals were 0.53 ± 0.10 [p-Raf-1] and 0.35 ± 0.07 [p-ERK1/2], respectively, which were both higher than that found in the fresh air group of
ERK1/2; 

plus GW5074. ETB (A) and ETA (B) receptor protein was shown relative to 
from rats exposed to fresh air, cigarette smoke and cigarette smoke 
rat coronary arteries. 

one-way ANOVA with Dunnett’s post-test.**

Figure 3. The protein expression of ETB and ETA receptors in 
rat coronary arteries. The coronary arterial segments were isolated 
from rats exposed to fresh air, cigarette smoke and cigarette smoke 
plus GW5074. ETB (A) and ETA (B) receptor protein was shown relative to 
\(|\beta\text{-actin}\) by Western blot (\(n=5\)). Statistical analysis was performed using 
one-way ANOVA with Dunnett’s post-test. \(^\ddagger\) \(P<0.01\) vs. fresh air group, 
\(^\ddagger\) \(P<0.05\) vs. smoke group, \(^\ddagger\) \(P<0.05\) vs. fresh air group. 
doi:10.1371/journal.pone.0033008.g003

Relation of the receptor expression with Raf/ERK1/2 
phosphorylation

Pearson’s correlation analysis showed that ETB/ETA receptor 
protein expression measured by Western blot positively correlated 
with Raf phosphorylation and ERK1/2 phosphorylation levels in 
rat coronary artery in vivo. Moreover, the receptor immunofluo-

rescence intensity in SMC of coronary arteries was found to 
positively correlate with phosphorylation of Raf and ERK1/2. 
There were statistical significances in correlation coefficient (\(r\)) 
values (\(P<0.05\) or \(P<0.01\)) (table 2). Stepwise multiple regression 
analysis was performed with receptor protein expression by 
Western blot and fluorescence intensity as dependent variables, 
and Raf phosphorylation and ERK1/2 phosphorylation as 
independent variables. The regression coefficient, \(\beta\) showed 
significant differences (\(P<0.05\) or \(P<0.01\)) (table 2), indicating 
that phosphorylation of Raf and ERK1/2 were independent 
determinants that affected protein expression and immunofluo-

rescence staining of ETB and ETA receptors.

Discussion

Smoking is a significant independent risk factor for CVD and is 
a leading cause of structural and functional alterations of the 
cardiovascular system [23]. It has been demonstrated that 
cigarette smoking is associated with vascular impairment which 
includes injury to the vascular endothelium, producing superoxide 
and nitrogen, reducing production and bioavailability of nitric oxide, 
increasing production and release of endothelin, causing endothel-
lial dysfunction, atherosclerosis, which are all hallmarks of CAD 
[23]. The present study has for the first time demonstrated that 
SHS in vivo induces ET receptor upregulation in rat coronary 
arteries, and this upregulation is involved in the activation of the 
Raf/ERK MAPK pathway. This may be a partial explanation of 
mechanisms involved in cigarette smoke-associated CAD.

Increased arterial blood pressure, heart rate and ET-1 levels 
were observed in smokers [24]. A previous study has already 
reported a significant increase in plasma ET-1 in chronic cigarette 
smoke exposed rats compared with non-smoking ones [11], 
indicating that ET-1 is associated with cigarette smoking. If an 
elevated ET-1 level is combined with increased number of ET 
receptors, then the vasoconstrictor effect in the cardiovascular 
system is magnified. If only the ET-1 level is increased but the 
receptor number not changed, there would be less possibility to see 
enhanced contractile responses in coronary arteries. If the receptor 
amount is increased, there would be a stronger contraction 
induced by ET-1. In other words, it is more crucial to examine the 
receptor number change when we study the vascular contractile 
property. A recent study showed that ETA and ETB receptor 
antagonists attenuated vascular hyperreactivity in aortas and 
carotid arteries of cigarette smoke exposed rats [11]. Tanus-Santos 
et al. also found that blockade of the ETA receptor attenuated the 
pressor effects of nicotine inhaled in cigarette exposed rats [25], 
suggesting that ET receptor activation is associated with smoke-
induced vascular hyperreactivity and hence involved in the 
pathological process of CVD. The coronary artery constriction/tone 
with increased resistance is more prominent in chronic 
smokers [26], which may contribute to the cardiovascular 
consequences of cigarette smoking or SHS. In the present study, 
we imitated the manner of SHS exposure in rats. The results 
showed that the smoke exposure increased contractile responses 
mediated by ETA and ETB receptors in coronary artery, but there 
was a need to expose the animals for 8 weeks. The choice of the 
time-point 8 weeks was based on a preceding study which revealed 
that there was no significant alteration in receptor expression at 2
or 4 weeks (data not shown). Since the contractile response reflects respective receptor expression, the receptor-mediated vasoconstriction should be in accordance with the receptor level. Interestingly, we found parallel results of mRNA and protein expressions of ETA and ETB receptors which are in agreement with this view. The expression of mRNA and protein for both ETA and ETB receptors in smoke exposed rats were higher than that in animals exposed to fresh air. The results also demonstrate that the increased ETA and ETB receptor expressions were primarily localized to VSMC. Accordingly, our study reveals for the first time that cigarette smoke upregulates contractile ETA and ETB receptors of coronary artery in vivo.

ET receptor activation induces strong VSMC contraction and is associated with aggravation of the progression of vessel wall hypertrophy [20]. It is known that patients with atherosclerosis have increased plasma levels of ET-1 [27]. Several studies have revealed increased number of ETB receptors and stronger contractile ETB receptor-mediated responses in coronary arteries in atherosclerotic lesions [8], congestive heart failure [28] and during organ culture of arteries [29]. There is a progressive increase in ETB receptors in patients with suspected acute coronary syndrome and with ischemic heart disease [30,31]. In addition, both ETA and ETB receptor mRNA levels have in a previous study been found to be significantly higher in coronary arteries from patients with ischemic heart disease as compared to healthy controls [10]. Collectively, this suggests that ETA and/or ETB receptor upregulation occurs during CAD pathogenesis. Therefore, blockage of ET receptors may offer a novel approach for the treatment and may turn out to be beneficial in vascular complications [32]. Many studies have reported that ETA and ETB receptor antagonists effectively reduced cardiovascular hypertrophy and decreased blood pressure in experimental hypertension [33,34,35]. Taken together, upregulation of ET receptors may be a key event in the development of CVD such as CAD, ischemic heart disease and atherosclerosis.

We examined the histology of coronary arteries by hematoxylin and eosin staining. The results demonstrate that there was no difference in structure between the fresh air and the smoke groups (data not shown). This suggests that our animal model of SHS exposure did not affect coronary artery structure. Nevertheless, we

Figure 4. Immunofluorescence staining of ETB and ETA receptors in rat coronary arteries. (A) ETB and ETA receptor immunofluorescence in coronary arteries isolated from rat exposed to fresh air, cigarette smoke and cigarette smoke plus GW5074. (B) Bar graphs showing fluorescence intensity for ETB and ETA receptors. There was clear increase in ETB and ETA receptor protein levels in the smooth muscle cell layer of coronary arteries from smoke exposed rats, as compared to the fresh ones. Treatment with GW5074 significantly suppressed the increased receptor expression. The results were in arbitrary units of fluorescence intensity (%), a.u. Images were taken with a 40× objective (n = 5). Statistical analysis was performed using one-way ANOVA with Dunnett’s post-test. *P<0.05, **P<0.01 vs. fresh air group, #P<0.05 vs. smoke group.
doi:10.1371/journal.pone.0033008.g004
Figure 5. The effects of cigarette smoke on phosphorylation of Raf-1 and ERK1/2 in rat coronary arteries. The coronary arterial segments were isolated from rats exposed to fresh air and cigarette smoke. The phosphorylated (p)-Raf-1 (A) and p-ERK1/2 (B) protein was shown relative to total Raf-1 or ERK1/2 level using Western blot (n = 6). Statistical analysis was performed using one-way ANOVA with Dunnett’s post-test. *P < 0.05 vs. fresh air group. (C) Immunofluorescence staining for phosphorylation of Raf-1 and ERK1/2. There was an increase in p-Raf-1 and p-ERK1/2 expression in the smooth muscle cell layer of coronary arteries from smoke exposed rats. Images were taken with a 40× objective. doi:10.1371/journal.pone.0033008.g005

Table 2. The r values of correlation analysis and β values of regression analysis between dependent variables, ET receptor protein expression by Western blot and immunofluorescence staining and independent variables, the phosphorylated (p)-Raf-1, p-ERK1/2 in rat coronary arteries.

<table>
<thead>
<tr>
<th>Dependent variables</th>
<th>r values in correlation test</th>
<th>β values in regression test</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>p-Raf</td>
<td>p-ERK1/2</td>
</tr>
<tr>
<td>ETβ receptor protein by Western blot</td>
<td>0.802**</td>
<td>0.774***</td>
</tr>
<tr>
<td>ETβ receptor immunofluorescence</td>
<td>0.854**</td>
<td>0.763***</td>
</tr>
<tr>
<td>ETA receptor protein by Western blot</td>
<td>0.894**</td>
<td>0.767***</td>
</tr>
<tr>
<td>ETA receptor immunofluorescence</td>
<td>0.860**</td>
<td>0.721**</td>
</tr>
</tbody>
</table>

Correlation analysis was performed with Pearson’s correlation test and regression analysis was performed with a multiple regression test. The r value represents correlation coefficient in correlation analysis (n = 10) and β value represents regression coefficient in regression analysis (n = 10).

*P < 0.05,
**P < 0.01.
doi:10.1371/journal.pone.0033008.t002
found contractile receptor upregulation in coronary arteries of SHS-exposed rats. The upregulated contractile receptors can lead to enhanced coronary artery vasoconstriction to ET-1, which further narrows the coronary artery lumen and reduces the blood flow. This may aggravate and facilitate the pathological process of SHS-induced coronary heart diseases. Therefore, we hypothesize that there is a close relationship between ET receptors and SHS-associated CVD.

The MAPK signal pathways are involved in a variety of cellular programs including transcription of receptors. Activation of MAPKs results in activation of transcription factors which transcribe specific receptor genes in the nucleus, which are then translated in the cytoplasm and exported to the cell membrane [36]. In previous studies we have shown that the MEK/ERK pathway is involved in the receptor upregulation, in particular related to stroke [37]. Recently, we have revealed that cigarette smoke extracts in vitro promote VSMC proliferation and enhance contractile responses in vasculature via activation of ERK1/2 signaling [6]. In the present study, SHS exposure increased the proportion of p-Raf-1 and p-ERK1/2 protein in coronary arteries, indicating that the Raf/ERK/MAPK pathway may be involved in the process of the ET receptor upregulation, but not the p38 or the JNK pathways. Furthermore, our data of correlation analysis in the present study showed significant positive correlations between receptor (ETB and ETA) protein expression levels and Raf/ERK1/2 phosphorylation. On the other hand, regression analysis showed that phosphorylation of Raf and ERK1/2 were independent factors to impact protein expression level and immunofluorescence intensity of ETB and ETA receptors. These results suggest that the activation of the Raf/ERK/MAPK pathway is closely linked to the receptor expression in coronary arteries in vivo.

Raf-1 is a MAP kinase kinase kinase, which functions downstream of the Ras family of protein kinases [18]. Activated Raf-1 can phosphorylate MEK1 and MEK2, which in turn activate ERK1 and ERK2. Downstream of Raf-1, activated ERK1/2 plays an important role in the control of gene expression. In the present study a Raf-1 inhibitor GW5074 was chosen to further prove the involvement of Raf/ERK/MAPK pathway in the upregulation. The specificity and efficacy of GW5074 for inhibiting Raf-1 in vivo has been established in previous studies [38]. The present results showed that GW5074 attenuated the SHS-induced elevated coronary contraction mediated by ETA receptors and the receptor mRNA and protein levels. In addition, GW5074 decreased the smoke exposure-induced increase in mRNA and protein levels of ETB receptors. This strongly suggests that the SHS-induced upregulation of ETA and ETB receptors in coronary artery is associated with the activation of the Raf/ERK/MAPK signaling.

To conclude, cigarette smoke exposure upregulates ETA and ETB receptors of rat coronary arteries, which is related to the activation of the Raf/MEK/ERK pathway. This may provide a new prospective on possible mechanisms involved in SHS-associated CAD.

Materials and Methods

Animals
Experiments were performed on male Sprague-Dawley rats (200-250 g) supplied by the Animal Center of Xi’an Jiaotong University College of Medicine (Xi’an, China). Animals were allowed free access to fresh food and water. All experimental protocols were endorsed by the Animal Ethics Committee of Xi’an Jiaotong University.

Cigarette Smoke Exposure Model
Thirty rats were randomly divided into 3 groups, 10 rats in each group: (1) fresh air exposure; (2) smoke exposure; (3) smoke exposure and treatment with GW5074 0.5 mg/kg. GW5074 was a gift from professor Yu-hai Tang (Science College of Xi’an Jiaotong University, China) and its specificity has previously been studied [38]. The rats were exposed to cigarette smoke from commercially-available filter cigarettes (Marlboro, 1.0 mg of nicotine and 12 mg of tar content) in a plastic chamber (115×50×65 cm; 0.37 m³). Ten rats were put in the chamber and each cigarette was lit from the cigarette end and freely burning for 15 min, then let the cigarette smoke diffuse in the whole chamber for another 25 min. Fresh air inhalation was performed for at least 10 min after every 40 min of SHS exposure [39]. For each smoke exposure, 2 cigarettes were lit simultaneously. The rats were repeatedly exposed to the smoke for total 10 cigarettes every day for up to 8 weeks. Total time of smoke exposure was 5×10 min = 200 min/day. Gas chromatography was used to determine the CO₂ concentration inside the chamber. It was 774±85 ppm at the time point of burning for 15 min and 611±89 ppm when the smoke diffusing for another 25 min, respectively. The rest of time animals were exposed to fresh air. In fresh air group, rats were placed in similar chambers and exposed to room air. For the treatment group, GW5074 was administrated intraperitoneally to the animals once every day for 8 weeks in addition to the same condition of smoke exposure.

Coronary Artery Harvest
The rats were anesthetized with CO₂ and decapitated to prepare artery samples 24 h after the final exposure. The heart was immediately removed and immersed into cold bicarbonate solution. A furosemide solution was used to determine the CO₂ concentration inside the chamber. It was 774±85 ppm at the time point of burning for 15 min and 611±89 ppm when the smoke diffusing for another 25 min, respectively. The rest of time animals were exposed to fresh air. In fresh air group, rats were placed in similar chambers and exposed to room air. For the treatment group, GW5074 was administrated intraperitoneally to the animals once every day for 8 weeks in addition to the same condition of smoke exposure.

Coronary Artery Contractile Studies
The in vitro contractility experiments were performed in the Xi’an Jiaotong University, while the other experiments were done in the Lund University. In the present study, wire myograph (Danish Myo Technology A/S, Aarhus, Denmark) was used for recording the vessels contractile properties. The LAD arteries were cut into segments of approximately 1–2 mm in length and then mounted on two thin wires (40 µm in diameter). The set-up has been detailed described before [29]. The rings were allowed to equilibrate for at least 1.5 h with an optimal resting tension of 1.0 mN. Thereafter, the viability of the arterial segments was determined by exposure to 63.5 mM K⁺ buffer solution.

Concentration-contraction responses were obtained by cumulative administration of contractile receptor agonists S6c (Merck, Darmstadt, Germany), and ET-1 (NeoMPS, Strasbourg, France). The ETB receptor-mediated contractile response was obtained by using the ETB receptor selective agonist S6c. When the contraction reached the maximum, i.e. desensitization of ETB receptor, ET-1 (both ETA and ETB receptor agonist) was then administrated to induce a contraction response that was only mediated by ETA receptors [40].
Real-time PCR

Total RNA was extracted from the collected coronary arteries using RNAeasy Mini kit (Qiagen, Valencia, CA) with the instruction of the supplier. The RNA concentration was measured and recorded with an Eppendorf Biophotometer (Hamburg, Germany). Reverse transcription of total RNA to cDNA was performed using the TaqMan Reverse Transcription Reagents (Applied Biosystems, Branchburg, USA) in a Perkin Elmer 2400 GeneAmp PCR system (Perkin Elmer, MA, USA). Real-time PCR was carried out using the GeneAmp SYBR® Green kit (Applied Biosystems) in a GeneAmp 7500 Sequence Detection System (Applied Biosystems). The system automatically monitors the binding of a fluorescent dye SYBR® Green to double-stranded DNA during each cycle of PCR amplification. The real-time PCR was prepared in 25 μl reaction volume and started at a temperature of 50°C for 2 min; 95°C for 10 min and the following 40 thermal cycles with 95°C for 15s and 60°C for 1 min. The dissociation curves were ran after the real-time PCR to identify the specific PCR products. A blank without template was included in all the experiments as negative controls. Specific primers for the receptors were designed as follows: ET_A receptor, forward: 5’-GTC GAG AGG TGG CAA AGA CC-3’, ET_A receptor, reverse: 5’-ACA GGG CCA AGA TGA CCA CC-3’; ET_B receptor, forward: 5’-GAT ACG ACA ACT TCC GCT CCA-3’, ET_B receptor, reverse: 5’-GTC CAC GAT GAG GAC AAT GAG-3’. As an endogenous standard, the primers of glyceraldehyde-3-phosphate dehydrogenase (GAPDH) were designed as follows: GAPDH, forward: 5’-GAT CAC GAT GAG GAC AAT GAG-3’, GAPDH, reverse: 5’-GGG CAT GTC AGA TCC ACA AC-3’. The comparative cycle threshold (Ct) method was used for the mRNA content analysis [41,42].

Western Blot

The coronary arteries were harvested as mentioned above, snap frozen in liquid nitrogen. The arteries were homogenized in cell extract denaturing buffer (BioSource, USA) with addition of a phosphatase inhibitor cocktail and protease inhibitor cocktail (Sigma, St. Louis, USA). The mixtures were then centrifuged at 12,000×g at 4°C for 10 min and the supernatants were collected as protein samples. Protein concentrations were measured using a protein assay reagent (Bio-Rad Laboratories, Hercules, CA) and a Tecan Infinite M200 microplate reader. For western blotting, protein samples were mixed with Laemmli Sample Buffer (Bio-Rad Laboratories) and boiled for 5 min. Equal amount of protein (40 μg) were loaded onto a 4–15% Ready Gel Precast Gels (Bio-Rad Laboratories). A molecular weight marker was loaded onto each gel for protein band identification. After gel electrophoresis the proteins were transferred to a nitrocellulose membrane (Bio-Rad Laboratories). The membrane was then blocked in 5% non-fat milk and incubated with the primary antibodies at appropriate dilution at 4°C overnight. The antibodies used were shown as follows: 1:200 rabbit anti-ET_A receptor (sc-33535, Santa Cruz Biotechnology, CA, USA), 1:500 rabbit anti-ET_B receptor (ab65972, Abcam, Cambridge, UK), 1:1000 rabbit anti-phospho-e-Raf (Ser338) (#9427, Cell Signaling Technology, Beverly, CA), 1:2000 rabbit anti-phospho-ERK1/2 (#4370, Cell Signaling Technology), 1:1000 rabbit anti-phospho-SAPK/JNK (#4668, Cell Signaling Technology), 1:1000 rabbit anti-phospho-p38 (#4631, Cell Signaling Technology), 1:1000 mouse anti-f-actin (#4970, Cell Signaling Technology) or 1:2000 mouse anti-ERK1/2 (#4696, Cell Signaling Technology). Then, membranes were incubated with 1:2000 horseradish peroxidase-conjugated anti-rabbit (#7074, Cell Signaling Technology) or anti-mouse (#7076, Cell Signaling Technology) secondary antibodies for 1 h at room temperature. Finally, membranes were developed and visualized using a Fujifilm LAS-1000 Luminescent Image Analyzer (Fujifilm, Stamford, USA) and the band intensity was quantified using ImageJ software.

Immunofluorescence

The paraformaldehyde-fixed arteries were embedded in paraffin and cut into 4-μm sections. After deparaffinization, the sections were treated with 10 mM sodium citrate buffer, pH 6.0, in a microwave oven for 10 min for antigen retrieval. Immunostaining with rabbit polyclonal antibody ET_A receptor (sc-33535, Santa Cruz Biotechnology) and ET_B receptor (sc-33538, Santa Cruz Biotechnology) diluted 1:100, rabbit monoclonal phospho-Raf-1 (Ser338) antibody (#9427, Cell Signaling Technology) and phospho-ERK1/2 antibody (#4370, Cell Signaling Technology) diluted 1:100 were performed. Goat anti-rabbit IgG conjugated to fluorescence isothiocyanate (FITC, #10006588, Cayman Chemical, Michigan, USA) diluted 1:100 was used as secondary antibody. Then the slides were sealed with anti-fading mounting medium. To identify the smooth muscle layer of the artery segments, immunostaining with the primary antibody against rat smooth muscle actin (sc-50315, Santa Cruz Biotechnology) diluted in 1:200, and the secondary antibody donkey anti-mouse IgG (H+L) conjugated to Texas Red (#715-076-150, Jackson ImmunoResearch) diluted in 1:200 were also performed. In the control experiments, either the primary antibody or the secondary antibody was omitted. Immunoreactivity was visualized with an epifluorescence microscope (Nikon 80i, Tokyo, Japan) and photographed using a digital camera (Nikon DS-2Mv).

Calculations and Statistics

All data are expressed as means ± S.E.M. and n refers to the number of rats. Contractile responses to agonists in each segment were expressed as percentage of the K+ induced contraction. Emax values represent maximal contractile response elicited by agonists and pEC50 values represent the negative logarithm of the agonist concentration that produces 50% of the maximal contractile effect. Unpaired Student’s t-test was applied to compare the data sets. One-way analysis of variance (ANOVA) with Bonferroni’s post-test was used for multiple comparisons. Two-way ANOVA with Dunnett’s post-test was performed to compare the two corresponding data points at each concentration of the two curves. Pearson’s correlation analysis was used to determine the relationship between receptor protein expression and Raf/ERK1/2 phosphorylation. Stepwise multiple regression analysis was performed to define the factors of influencing the receptor protein expression and fluorescence intensity in SMC of coronary arteries. All calculations and statistical analysis were carried out using Graph-Pad Prism 5.0 (GraphPad Software, La Jolla, USA). Statistical significance was accepted when P<0.05.

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Author Contributions

Conceived and designed the experiments: CBX YXC LE. Performed the experiments: LC. Analyzed the data: LC. Contributed reagents/materials/analysis tools: CBX LE YXC. Wrote the paper: LC YZ YXC LE CBX.
References


