Retina

Benzo(e)pyrene Inhibits Endothelium-Dependent NO-Mediated Dilation of Retinal Arterioles via Superoxide Production and Endoplasmic Reticulum Stress

Takayuki Kamiya, Taiji Nagaoka, Tsuneaki Omae, Shinji Ono, Shinichi Otani, and Akitoshi Yoshida

Department of Ophthalmology, Asahikawa Medical University, Asahikawa, Japan

PURPOSE. To investigate whether benzo(e)pyrene (B(e)P), a toxicant in cigarette smoke, affects the endothelium-dependent nitric oxide (NO)-induced vasodilation of the retinal arterioles, and whether oxidative stress, distinct protein kinase signaling pathways, and endoplasmic reticulum (ER) stress are associated with the B(e)P-induced effect on the retinal arterioles.

METHODS. In this in vitro study, porcine retinal arterioles were isolated, cannulated, and pressurized without flow. These vessels were treated with intraluminal administration of B(e)P or B(e)P plus blockers for 180 minutes. Diametric changes to agonists were recorded by videomicroscopy.

RESULTS. Intraluminal treatment with 100 μM B(e)P for 180 minutes significantly reduced the arteriolar vasodilation caused by the endothelium-dependent NO-mediated agonists bradykinin and A23187 but not that caused by endothelium-independent NO donor sodium nitroprusside. The adverse effects of B(e)P on the vasodilatory action of bradykinin were prevented by the superoxide scavenger 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPOL), the nicotinamide adenine dinucleotide phosphate-oxidase (NADPH oxidase) inhibitor apocynin, the c-Jun N-terminal kinase (JNK) inhibitor SP600125, the p38 mitogen-activated protein kinase inhibitor SB203580, genistein, resveratrol (RSV), and the ER stress inhibitor 4-phenylbutyrate (4-PBA). The xanthine oxidase inhibitor allopurinol did not alter the effect of B(e)P on the vasodilatory action induced by bradykinin.

CONCLUSIONS. B(e)P decreases the endothelium-dependent NO-induced vasodilation in the retinal arterioles through the production of superoxide from NADPH oxidase, which is linked to JNK and p38 kinase. The results suggested that ER stress is instrumental in B(e)P-induced endothelial dysfunction and that genistein and RSV might preserve endothelial function.

Keywords: benzo(e)pyrene, endothelial dysfunction, oxidative stress, endoplasmic reticulum (ER) stress

We reported significant decreases in the retinal blood flow in patients with type 2 diabetes who continued to smoke compared with those who had never smoked,[1] suggesting that smoking might impair the retinal microcirculation. Moreover, other studies have suggested that smoking might cause impaired endothelial function in the brachial arteries in healthy people[2] and in aortas isolated from normal rats via increased vascular oxidative stress.[3] Therefore, smoking could be involved in retinal vascular function and result in retinal microcirculatory abnormalities. However, the mechanism by which these abnormalities occur in the retinal circulation remains unclear.

With more than 4000 toxic components in cigarette smoke, benzo(e)pyrene (B(e)P), a polycyclic aromatic hydrocarbon (PAH), causes apoptosis and cellular death of human retinal pigment epithelial (ARPE-19) cells in vitro by generating reactive oxygen species (ROS),[4,5] resulting in oxidative stress. In addition, because oxidative stress is involved in endothelial dysfunction, which contributes to diabetic microvascular diseases,[6,7] intake of B(e)P might lead to development of vascular diseases. Endoplasmic reticulum (ER) stress, a new and

critical mediator related to retinal cellular damage and death in diabetic retinopathy (DR),[8–11] also causes vascular endothelial dysfunction.[12] Furthermore, several studies have reported that genistein and resveratrol (RSV) ameliorated oxidative stress in vivo and in vitro studies.[13,14]

In this study, using an isolated vessel preparation, we examined the effect of B(e)P on the endothelial of the retinal arterioles and determined whether oxidative stress and ER stress might be involved in the adverse effect of B(e)P. We also assessed the preservation effect of genistein and RSV on the adverse effect of B(e)P.

MATERIALS AND METHODS

Animal Preparation

The current study was conducted according to the ARVO Statement for the Use of Animals in Ophthalmic and Vision Research. The Animal Care Committee of Asahikawa Medical University approved all animal procedures. Pig eyes from animals of either sex (age, 16–24 weeks; weight, 15–25 kg)

were enucleated immediately after the animals were killed in a local abattoir. The eyes were transported in a moist chamber on ice to the laboratory. We previously reported the procedure used to harvest eyes.[15]

Microvessel Isolation and Cannulation

The techniques used to identify, isolate, cannulate, pressurize, and visualize the retinal microvessels were reported previously.[16] Using a pair of glass micropipettes, we cannulated and pressurized the isolated retinal arterioles (mean ± standard deviation [SD] of the mean [SDM], 97 ± 5 μm [range, 84–110 μm]) to an intraluminal pressure of 55 cmH$_2$O without flow using two independent pressure reservoir systems.[17] Video-microscopic observations were conducted continuously during the experiments to record the vasomotor activity of the isolated porcine retinal vessels.[18]

Experimental Protocols

In the control experiment, cannulated arterioles were bathed in physiologic saline solution (PSS) at a temperature between 36°C and 37°C for 30 to 40 minutes to facilitate the development of basal tone. After the basal tone developed, we evaluated the effect of B(e)P on the nitric oxide (NO)-mediated vasodilation. To accomplish this, the endothelium-dependent NO-mediated vasodilation in response to bradykinin (range, 1 pM–10 nM) was established before and after 180 minutes of intraluminal incubation with 100 μM B(e)P ($n = 6$). The vessels were exposed to each concentration of bradykinin for 2 to 3 minutes until a stable diameter was established. In a preliminary study, we found that the vasodilation that occurs with exposure to bradykinin was reproducible and sustained after repeated applications ($n = 6$). In another series of studies, to determine whether the effect of B(e)P is a selective response to endothelium-dependent NO-mediated vasodilation, the dose-dependent responses to the receptor-independent but endothelial NO-mediated vasodilator A23187 (range, 10 nM–3 μM; $n = 6$) and to endothelium-independent NO-donor sodium nitroprusside (SNP; range, 10 nM–100 μM; $n = 6$) were established before and after 180 minutes of intraluminal incubation of 100 μM of B(e)P. In each separate group of vessels, the roles of superoxide and oxidative enzymes xanthine oxidase and nicotinamide adenine dinucleotide phosphate (NADPH) oxidase in mediating the adverse effects of B(e)P were determined by evaluating bradykinin-induced vasodilation before and after treating the vessels with B(e)P (100 μM) combined with superoxide production pathway inhibitors, such as the cell-permeable superoxide scavenger, 4-hydroxy-2,2,6,6-tetramethylpiperidine-1-oxyl (TEMPOL; 1 mM; $n = 6$),[19] the xanthine oxidase inhibitor allopurinol (10 μM; $n = 6$),[20] or the NADPH oxidase inhibitor apocynin (100 μM; $n = 6$).[19] The roles of stress-activated protein kinase were examined by evaluating bradykinin-induced vasodilation before and after treating the vessels with B(e)P combined with the c-Jun N-terminal kinase (JNK) inhibitor SP600125 (5 μM; $n = 8$),[21] the p38 mitogen-activated protein kinase (MAPK) inhibitor SB203580 (0.1 μM; $n = 8$),[22] or coadministration of SP600125 and SB203580 ($n = 8$). To determine if genistein and RSV, which protect against oxidative stress, mitigated the action of B(e)P on the NO-mediated vasodilation, the arterioles were evaluated by bradykinin-induced vasodilation before and after treating the vessels with B(e)P (100 μM) combined with genistein (30 μM; $n = 8$) or RSV (1 μM; $n = 8$).

In addition, to investigate the involvement of ER stress, we evaluated the bradykinin-induced vasodilation before and after treating the vessels with B(e)P combined with the ER stress inhibitor 4-phenylbutyrate (4-PBA; 100 μM; $n = 6$).[23]

Chemicals

We purchased B(e)P from AccuStandard, Inc. (New Haven, CT), and the other drugs from Sigma-Aldrich Corp. (St. Louis, MO). We dissolved B(e)P, SP600125, SB203580, genistein, and RSV in dimethyl sulfoxide (DMSO), and the other drugs in PSS, which was used for all subsequent drug dilutions. The final DMSO concentration in the vessel bath was below 0.1%.[24] The final solvent concentrations did not affect the arteriolar function in the vehicle control studies.

Data Analysis

To obtain a maximal diameter at an intraluminal pressure of 55 cmH$_2$O, the arterioles were relaxed in ethylenediaminetetra-acetic acid (1 mM) calcium-free PSS after each experiment.[25] The diametric changes that occurred in response to the agonists were normalized to the maximal dilation. The changes were reported as percentages of the maximal vasodilation.[16,26] The data are expressed as the mean ± SEM; n represents the number of retinal arterioles. The changes that occurred in resting tone as a result of the inhibitors were compared by Student's t-test. To determine the significance of the difference between the control and the experimental interventions, we used 2-way ANOVA followed by the Bonferroni multiple-range test. $P < 0.05$ was considered significant. We performed power calculations to determine sample size on the basis of a two-sided alpha error of 5% and a power of 80%.

Results

Effect of B(e)P on NO-Mediated Vasodilation

The basal tone ranged from 40% to 60% (mean ± SEM, 55% ± 1%) of the maximal diameter in all 82 vessels. The mean resting and maximal vessel diameters were 54 ± 1 and 97 ± 1 μm, respectively. Bradykinin caused dose-dependent vasodilation of the retinal arterioles; incubation with 100 μM B(e)P significantly ($P < 0.001$) attenuated the bradykinin-evoked vasodilation (Fig. 1A). Increasing the dose of B(e)P (200 μM) did not decrease the bradykinin-evoked vasodilation further (data not shown). The 100-μM dose of B(e)P also significantly decreased the vasodilation induced by A23187 (Fig. 1C). However, B(e)P (100 μM) did not affect the vasodilation of the retinal arterioles caused by the endothelium-independent NO-donor, SNP (Fig. 1B). The resting vascular tone did not change in response to B(e)P (data not shown).

Roles of the Pathway of Superoxide Production and the Protective Effect of Genistein and RSV

TEMPOL prevented B(e)P (100 μM)-evoked inhibition of the vasodilatory response to bradykinin (Fig. 2A), which also was seen in arterioles treated with the NADPH oxidase inhibitor apocynin but not with allopurinol (Fig. 2B). Inhibition of JNK and p38 kinase by SP600125 and SB203580, respectively, partially but significantly prevented B(e)P (100 μM)-evoked inhibition of the vasodilatory response to bradykinin. Coadministration of SP600125 and SB203580 prevented B(e)P (100 μM)-evoked inhibition of the vasodilatory response to bradykinin (Fig. 3). Administration of B(e)P with genistein also prevented the B(e)P (100 μM)-evoked inhibition of the vasodilatory response to bradykinin (Fig. 4A), and administration of B(e)P with RSV partly prevented these adverse effects of B(e)P (Fig. 4B). These agents did not change the resting basal tone or bradykinin-induced vasodilation without B(e)P (data not shown).
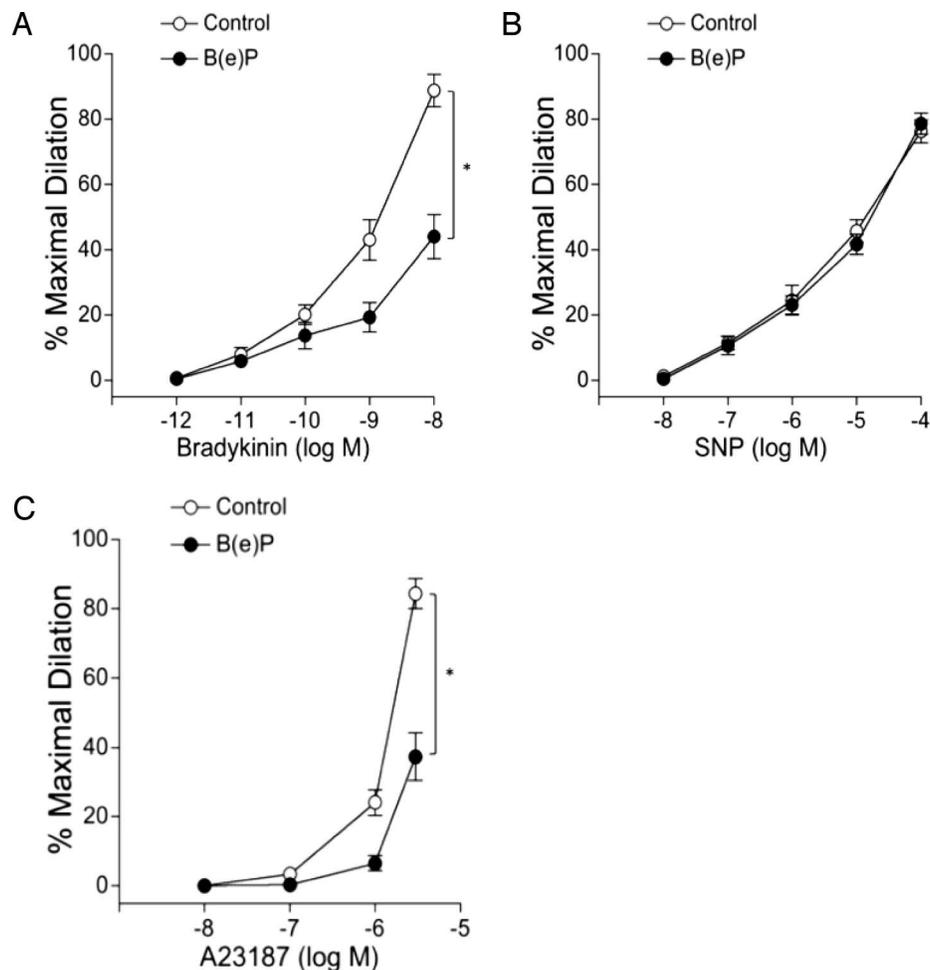
FIGURE 1. Effect of B(e)P on the retinal arterioles. (**A**) Dilation of isolated retinal arterioles to bradykinin was examined before (control, $n = 6$) and after intraluminal incubation with 100 μM of B(e)P ($n = 6$) for 3 hours. Retinal arteriolar dilation to SNP ([**B**], $n = 6$) and A23187 ([**C**], $n = 6$) before and after intraluminal incubation with 100 μM of B(e)P for 3 hours. *$P < 0.05$ versus the control.

Roles of ER Stress

The ER stress inhibitor 4-PBA also prevented B(e)P (100 μM)-evoked inhibition of the vasodilatory response to bradykinin (Fig. 5). This ER stress inhibitor did not change the resting basal tone or bradykinin-induced vasodilation without B(e)P (data not shown).

Response to SNP

The SNP-induced vasodilation of the retinal arterioles was not attenuated by administration of the drugs used in this study, indicating that the vascular smooth muscle function was unchanged by these experimental procedures.

DISCUSSION

We found that in porcine retinal arterioles the vasodilatory responses to bradykinin and A23187 but not that to SNP decreased significantly with exposure to B(e)P, a toxic compound in cigarette smoke (Fig. 1). This finding indicated that B(e)P might impair retinal endothelial function regarding the NO-mediated vasodilatory response. Among the PAHs, B(e)P causes cellular death through the involvement of some caspases in the ARPE-19 cells.[4] Significant loss of cellular viability resulted from exposure to the minimal B(e)P concentration of 200 μM.[4] A minimal concentration of 100-μM B(e)P activated the caspases.[4] Therefore, 100-μM B(e)P is considered to be the concentration that causes cellular damage. The current study showed that incubation with 100-μM B(e)P significantly ($P < 0.001$) attenuated the bradykinin-induced vasodilation (Fig. 1A). The current finding that B(e)P impaired the vascular endothelial function in the retinal arterioles agreed with these results. The 200-μM dose of B(e)P ($n = 6$) did not result in a further decrease in the bradykinin-induced vasodilation (data not shown). B(e)P also decreased the retinal vasodilatory response to the calcium ionophore A23187 (Fig. 1C), which activates endothelial NO synthase by elevating the intracellular Ca^{2+} level irrespective of receptor stimulation[27] and causes NO-dependent vasodilation in the retinal arterioles.[28] Considering these findings, we speculated that B(e)P might reduce the NO bioavailability in the endothelium of the retinal arterioles, which would impair the endothelium-dependent vasodilation.

A plausible explanation for the mechanism underlying the reduced NO bioavailability caused by B(e)P might involve elevated vascular oxidative stress. Indeed, cigarette smoke extracts evoked superoxide anion production in bovine pulmonary artery endothelial cells.[29] A study using human ARPE-19 cells found that ROS generation increased significantly in cells treated with 100 μM of B(e)P for 24 hours.[5] We also found that TEMPOL, the membrane-permeable superoxide scavenger, abrogated the inhibitory effect of B(e)P on
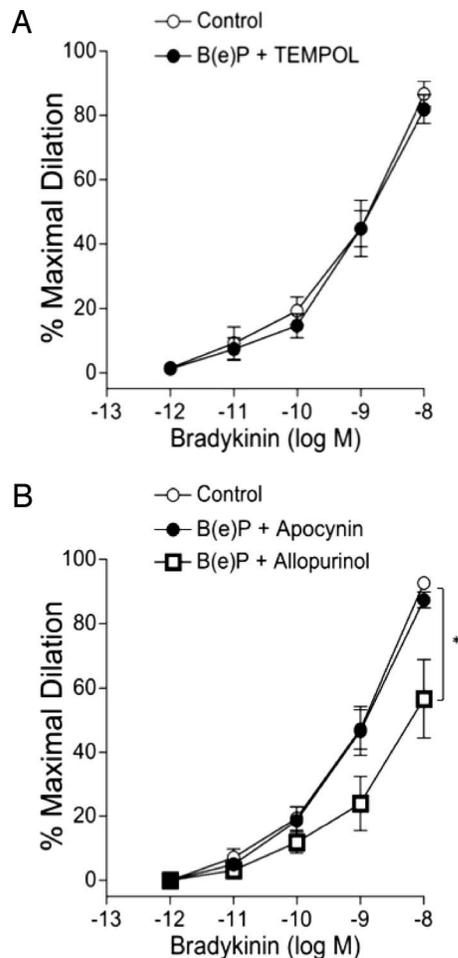
FIGURE 2. Blockade of superoxide production or NADPH oxidase activation. (A) Effect of bradykinin on the retinal arterioles before (control, $n = 6$) and after intraluminal incubation with 100 μM of B(e)P plus the superoxide scavenger TEMPOL (1 mM; $n = 6$). (B) Effect of bradykinin on the retinal arterioles before (control, $n = 12$) and after intraluminal incubation with 100 μM of B(e)P plus the xanthine oxidase inhibitor allopurinol (10 μM; $n = 6$) or the NADPH oxidase inhibitor apocynin (100 μM; $n = 6$). *$P < 0.05$ versus the control.
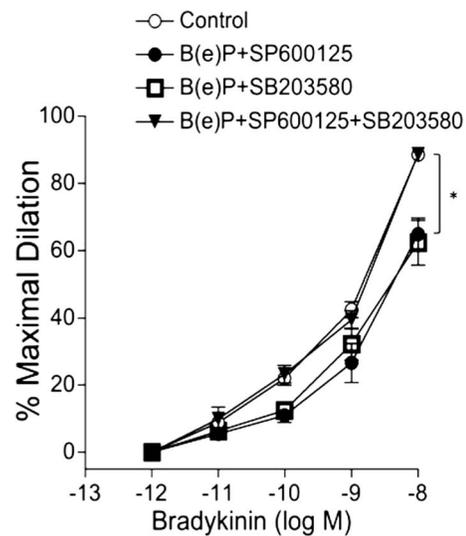

FIGURE 3. Blockade of JNK and p38 kinase activation. Effects of bradykinin on the retinal arterioles before (control, $n = 24$) and after intraluminal incubation with 100 μM of B(e)P plus the JNK inhibitor SP600125 (5 μM; $n = 8$), the p38 kinase inhibitor SB203580 (0.1 μM; $n = 8$), or coadministration of SP600125 and SB203580 ($n = 8$). *$P < 0.05$ versus the control.

endothelium-dependent vasodilation (Fig. 2A). Given these findings, our results suggested that oxidative stress might be related to the mechanism of the B(e)P-evoked endothelial dysfunction of the retinal arterioles.

The enzymes xanthine oxidase and NADPH oxidase in vascular cells can generate superoxide. In the current study, NADPH oxidase inhibitor apocynin[30] but not xanthine oxidase inhibitor allopurinol[31] prevented the inhibitory effect of B(e)P (Fig. 2B), suggesting that the adverse effects of B(e)P were caused by NADPH oxidase-evoked superoxide anions. Our results agreed with previous results indicating that NADPH oxidase is the primary source of vascular superoxide[32] and that substances in cigarette smoke activate endothelial NADPH oxidase in the pulmonary arterioles.[29] Taken together, B(e)P probably causes NADPH oxidase activation and results in ROS production in the retinal arteriolar endothelial cells.

The detail mechanisms underlying B(e)P-induced superoxide production by NADPH oxidase are not fully understood. JNK and p38 MAPK, which are referred to as stress-activated kinases, play a significant role in oxidative stress and inflammation,[33,34] however, benzopyrene activation of JNK and p38 MAPK remains controversial. Although PAH-induced

activation of JNK was generally thought to be related to oxidative stress[35] and associated with B(a)P, a derivative of B(e)P-induced hydrogen peroxide (H_2O_2) production,[36] B(a)P activated p38 MAPK but not JNK in HepG2 cells.[37] Another study showed that a B(a)P metabolic product, B(a)P-7,8-dihydrodiol-9,10-epoxide, activated JNK and p38 MAPK.[38] This is consistent with our results that showed that the JNK inhibitor SP600125 and the p38 MAPK inhibitor SB203580 reduced the adverse effect of B(e)P on the endothelium-dependent vasodilatory response in the retinal arterioles. Coadministration of SP600125 and SB203580 further blocked the adverse effect of B(e)P on the endothelium-dependent vasodilatory response of the retinal arterioles (Fig. 3). Therefore, we speculated that B(e)P might evoke ROS generation in both the JNK- and p38 MAPK-dependent pathways in the endothelial cells of the retinal arterioles through NADPH oxidase activation, resulting in impaired endothelial function of the retinal arterioles.

Genistein has various biochemical activities. It has been reported that genistein decreased the generation of free radicals and cellular oxidative stress by suppressing the cytochrome enzymes.[39] RSV, a polyphenolic substance present in foods such as grapes and wine, protects against oxidative injury.[40,41] RSV (10 μM, 20 minutes) also resulted in significant reduction of oxidative injury in human RPE R-50 cells and protected against B(a)P-induced DNA damage.[42] Moreover, the finding that genistein and RSV inhibited oxidant production caused by B(e)P[5] supports our result that genistein and RSV prevented the adverse effect of B(e)P on the bradykinin-evoked vasodilation (Figs. 4A, 4B). Although 30 μM of RSV prevented B(e)P-induced oxidative stress,[5] we previously found that 10 μM of RSV elicited dilation of approximately 20% of the isolated retinal arterioles.[43] Therefore, in the current study, we used the threshold concentration of RSV (1 μM), which previously did not cause porcine retinal arterioles to dilate.

Another hypothesis is that the underlying mechanism by which B(e)P reduces NO bioavailability in the retinal arterioles might be through increased vascular ER stress. Oxidative stress and ER stress reduce NO generation in murine aortic endothelial cells.[12] This was supported by the current result
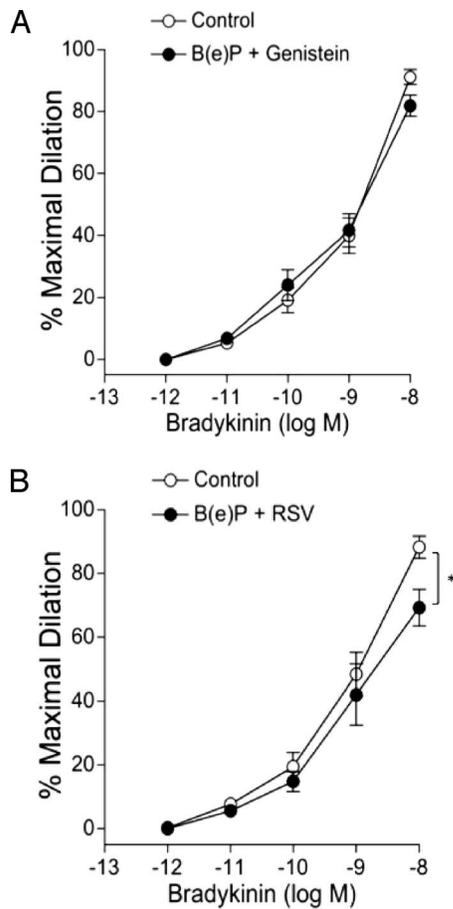
FIGURE 4. Genistein and RSV prevent B(e)P-induced reduction of retinal arteriolar dilation to bradykinin. Effect of bradykinin on the retinal arterioles before (control, $n = 8$) and after intraluminal incubation with (A) 100 μM of B(e)P plus genistein (30 μM; $n = 8$) and (B) 100 μM of B(e)P plus RSV (1 μM; $n = 8$). *$P < 0.05$ versus the control.

FIGURE 6. Schematic illustration of proposed signaling mechanisms involved in B(e)P-induced endothelial dysfunction of the retinal arterioles. Inhibition of these signaling pathways by their respective inhibitors is indicated by the *vertical lines* in reference to the direction of the *straight line*.
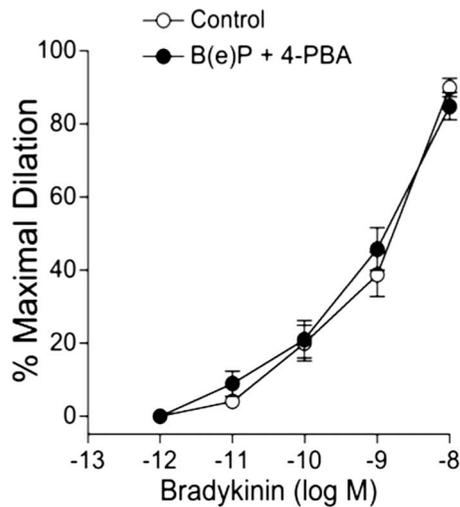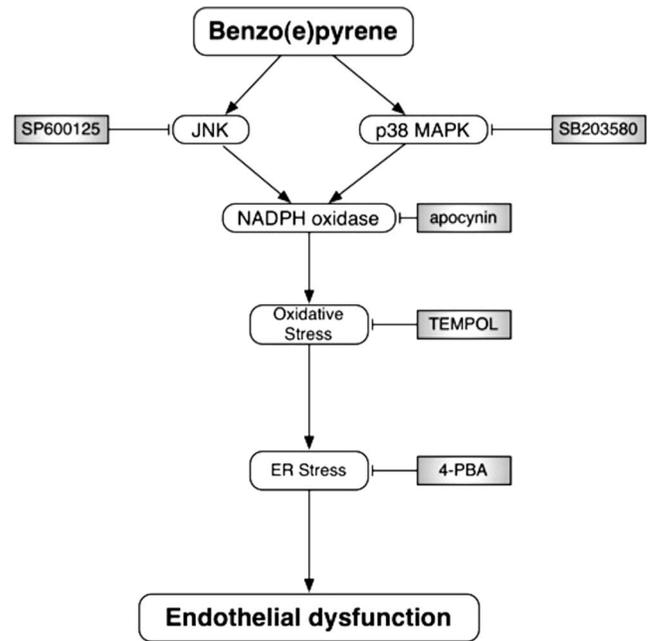

FIGURE 5. Blockade of ER stress. Effect of bradykinin on the retinal arterioles before (control, $n = 6$) and after intraluminal incubation with 100 μM of B(e)P plus the ER stress inhibitor 4-PBA (100 μM; $n = 6$). *$P < 0.05$ versus the control.

that the ER stress inhibitor 4-PBA prevented the inhibition of the endothelium-dependent vasodilation by B(e)P (Fig. 5). In our preliminary study, tunicamycin (1 mM, 180 minutes), an ER-stress inducer,[44,45] diminished bradykinin-evoked vasodilation, and 4-PBA (100 μM) inhibited the adverse effect of tunicamycin on bradykinin-evoked vasodilation (data not shown). The beneficial effect of 4-PBA was specific because this ER stress inhibitor did not change the resting basal tone or bradykinin-evoked vasodilation without B(e)P. No study has reported that B(e)P or B(a)P induced ER stress in the retina, but several in vitro studies have found that exposure to cigarette smoke induces ER stress in human umbilical vein endothelial cells and mouse lung epithelial cells.[46,47] Taken together, the current results showed that ER stress also might be related to the underlying mechanism in which B(e)P caused endothelial dysfunction of the retinal arterioles.

This study had some limitations. First, no previous study determined the plasma concentration of B(e)P from cigarette smoke in smokers. Here, we determined the B(e)P concentration based on in vitro studies.[4] Second, although the current study investigated only the acute effect of B(e)P on isolated porcine retinal arterioles, the chronic effects of B(e)P on the retinal circulation remain unclear. Therefore, further in vivo and clinical studies are required to determine these. Third, the relationship between oxidative stress and ER stress has not been clarified. In our preliminary study, the effect of 4-PBA equaled the effect of TEMPOL, and coadministration of TEMPOL and 4-PBA had no further preventative effect on the inhibition by B(e)P of the endothelium-dependent vasodilatory response of retinal arterioles (data not shown). Furthermore, TEMPOL did not reduce the inhibitory effect of the ER stress inducer, tunicamycin, on endothelium-dependent vasodilation (data not shown). It has been reported that oxidative stress-dependent ER stress is implicated in cigarette smoke-mediated apoptosis.[48] Taken together, we speculated that endothelial dysfunction induced by B(e)P in the retinal arterioles might result from ROS-dependent ER stress (Fig. 6).

In summary, we found that in isolated porcine retinal arterioles, B(e)P impaired the endothelium-dependent NO-initiated vasodilation. The mechanism of the adverse response to B(e)P is implicated in the generation of superoxide by vascular NADPH oxidase and ER stress. Moreover, it is likely that genistein and RSV protect against B(e)P-mediated endothelial dysfunction in the retinal arterioles, possibly by reducing oxidative stress. The current finding that B(e)P impaired the endothelial vasodilation of the retinal arterioles showed that B(e)P might be related to the mechanism of impaired retinal microcirculation in early-stage DR, especially in smokers.[1] The elucidation of the mechanisms of endothelial dysfunction of the retinal arterioles caused by B(e)P could provide a basis for developing strategies to prevent and treat smoking-induced retinal vascular disorders.

References

1. Omae T, Nagaoka T, Yoshida A. Effects of habitual cigarette smoking on retinal circulation in patients with type 2 diabetes. *Invest Ophthalmol Vis Sci*. 2016;57:1345–1351.

2. Celermajer DS, Adams MR, Clarkson P, et al. Passive smoking and impaired endothelium-dependent arterial dilatation in healthy young adults. *N Engl J Med*. 1996;334:150–154.

3. Shimosato T, Geddawy A, Tawa M, Imamura T, Okamura T. Chronic administration of nicotine-free cigarette smoke extract impaired endothelium-dependent vascular relaxation in rats via increased vascular oxidative stress. *Jpn Pharmacol Sci*. 2012;118:206–214.

4. Sharma A, Neekhra A, Gramajo AL, et al. Effects of Benzo(e)Pyrene, a toxic component of cigarette smoke, on human retinal pigment epithelial cells in vitro. *Invest Ophthalmol Vis Sci*. 2008;49:5111–5117.

5. Mansoor S, Gupta N, Patil AJ, et al. Inhibition of apoptosis in human retinal pigment epithelial cells treated with benzo(e)-pyrene, a toxic component of cigarette smoke. *Invest Ophthalmol Vis Sci*. 2010;51:2601–2607.

6. Khan ZA, Chakrabarti S. Cellular signaling and potential new treatment targets in diabetic retinopathy. *Exp Diabetes Res*. 2007;2007:31867.

7. Nacci C, Tarquinio M, Montagnani M. Molecular and clinical aspects of endothelial dysfunction in diabetes. *Intern Emerg Med*. 2009;4:107–116.

8. Oshitari T, Hata N, Yamamoto S. Endoplasmic reticulum stress and diabetic retinopathy. *Vasc Health Risk Manag*. 2008;4:115–122.

9. Li J, Wang JJ, Yu Q, Wang M, Zhang SX. Endoplasmic reticulum stress is implicated in retinal inflammation and diabetic retinopathy. *FEBS Lett*. 2009;583:1521–1527.

10. Li J, Wang JJ, Yu Q, Chen K, Mahadev K, Zhang SX. Inhibition of reactive oxygen species by Lovastatin downregulates vascular endothelial growth factor expression and ameliorates blood-retinal barrier breakdown in db/db mice: role of NADPH oxidase 4. *Diabetes*. 2010;59:1528–1538.

11. Jing G, Wang JJ, Zhang SX. ER stress and apoptosis: a new mechanism for retinal cell death. *Exp Diabetes Res*. 2012;2012:589589.

12. Cheang WS, Tian XY, Wong WT, et al. Metformin protects endothelial function in diet-induced obese mice by inhibition of endoplasmic reticulum stress through 5′ adenosine monophosphate-activated protein kinase-peroxisome proliferator-activated receptor delta pathway. *Arterioscler Thromb Vasc Biol*. 2014;34:830–836.

13. Gupta SK, Dongare S, Mathur R, et al. Genistein ameliorates cardiac inflammation and oxidative stress in streptozotocin-induced diabetic cardiomyopathy in rats. *Mol Cell Biochem*. 2015;408:63–72.

14. Liu Q, Ju WK, Crowston JG, et al. Oxidative stress is an early event in hydrostatic pressure induced retinal ganglion cell damage. *Invest Ophthalmol Vis Sci*. 2007;48:4580–4589.

15. Omae T, Nagaoka T, Tanano I, Yoshida A. Pioglitazone, a peroxisome proliferator-activated receptor-gamma agonist, induces dilation of isolated porcine retinal arterioles: role of nitric oxide and potassium channels. *Invest Ophthalmol Vis Sci*. 2011;52:6749–6756.

16. Hein TW, Ren Y, Yuan Z, et al. Functional and molecular characterization of the endothelin system in retinal arterioles. *Invest Ophthalmol Vis Sci*. 2009;50:3329–3336.

17. Kuo L, Davis MJ, Chilian WM. Endothelium-dependent, flow-induced dilation of isolated coronary arterioles. *Am J Physiol*. 1990;259:H1063–H1070.

18. Hein TW, Yuan Z, Rosa RH Jr, Kuo L. Requisite roles of A2A receptors, nitric oxide, and KATP channels in retinal arteriolar dilation in response to adenosine. *Invest Ophthalmol Vis Sci*. 2005;46:2113–2119.

19. Zhang C, Hein TW, Wang W, Kuo L. Divergent roles of angiotensin II AT1 and AT2 receptors in modulating coronary microvascular function. *Circ Res*. 2003;92:322–329.

20. Li L, Fink GD, Watts SW, et al. Endothelin-1 increases vascular superoxide via endothelin(A)-NADPH oxidase pathway in low-renin hypertension. *Circulation*. 2003;107:1053–1058.

21. Bennett BL, Sasaki DT, Murray BW, et al. SP600125, an anthrapyrazolone inhibitor of Jun N-terminal kinase. *Proc Natl Acad Sci U S A*. 2001;98:13681–13686.

22. Cirillo PF, Pargellis C, Regan J. The non-diaryl heterocycle classes of p38 MAP kinase inhibitors. *Curr Top Med Chem*. 2002;2:1021–1035.

23. Wu M, Yang S, Elliott MH, et al. Oxidative and endoplasmic reticulum stresses mediate apoptosis induced by modified LDL in human retinal Muller cells. *Invest Ophthalmol Vis Sci*. 2012;53:4595–4604.

24. Hein TW, Xu W, Kuo L. Dilation of retinal arterioles in response to lactate: role of nitric oxide, guanylyl cyclase, and ATP-sensitive potassium channels. *Invest Ophthalmol Vis Sci*. 2006;47:693–699.

25. Nagaoka T, Hein TW, Yoshida A, Kuo L. Simvastatin elicits dilation of isolated porcine retinal arterioles: role of nitric oxide and mevalonate-rho kinase pathways. *Invest Ophthalmol Vis Sci*. 2007;48:825–832.

26. Kamiya T, Nagaoka T, Omae T, et al. Role of Ca2+ -dependent and Ca2+ -sensitive mechanisms in sphingosine 1-phosphate-induced constriction of isolated porcine retinal arterioles in vitro. *Exp Eye Res*. 2014;121:94–101.

27. Huang A, Koller A. Both nitric oxide and prostaglandin-mediated responses are impaired in skeletal muscle arterioles of hypertensive rats. *J Hypertens*. 1996;14:887–895.

28. Nagaoka T, Kuo L, Ren Y, Yoshida A, Hein TW. C-reactive protein inhibits endothelium-dependent nitric oxide-mediated dilation of retinal arterioles via enhanced superoxide production. *Invest Ophthalmol Vis Sci*. 2008;49:2053–2060.

29. Jaimes EA, DeMaster EG, Tian RX, Raij L. Stable compounds of cigarette smoke induce endothelial superoxide anion production via NADPH oxidase activation. *Arterioscler Thromb Vasc Biol*. 2004;24:1031–1036.

30. Stolk J, Hiltermann TJ, Dijkman JH, Verhoeven AJ. Characteristics of the inhibition of NADPH oxidase activation in neutrophils by apocynin, a methoxy-substituted catechol. *Am J Respir Cell Mol Biol.* 1994;11:95–102.

31. Borges F, Fernandes E, Roleira F. Progress towards the discovery of xanthine oxidase inhibitors. *Curr Med Chem.* 2002;9:195–217.

32. Lassegue B, Clempus RE. Vascular NAD(P)H oxidases: specific features, expression, and regulation. *Am J Physiol Regul Integr Comp Physiol.* 2003;285:R277–R297.

33. Kumar S, Boehm J, Lee JC. p38 MAP kinases: key signalling molecules as therapeutic targets for inflammatory diseases. *Nat Rev Drug Discov.* 2003;2:717–726.

34. Manning AM, Davis RJ. Targeting JNK for therapeutic benefit: from junk to gold? *Nat Rev Drug Discov.* 2003;2:554–565.

35. Ng D, Kokot N, Hiura T, Faris M, Saxon A, Nel A. Macrophage activation by polycyclic aromatic hydrocarbons: evidence for the involvement of stress-activated protein kinases, activator protein-1, and antioxidant response elements. *J Immunol.* 1998;161:942–951.

36. Huc L, Tekpli X, Holme JA, et al. c-Jun NH2-terminal kinase-related Na+/H+ exchanger isoform 1 activation controls hexokinase II expression in benzo(a)pyrene-induced apoptosis. *Cancer Res.* 2007;67:1696–1705.

37. Lin T, Mak NK, Yang MS. MAPK regulate p53-dependent cell death induced by benzo[a]pyrene: involvement of p53 phosphorylation and acetylation. *Toxicology.* 2008;247:145–153.

38. Donauer J, Schreck I, Liebel U, Weiss C. Role and interaction of p53, BAX and the stress-activated protein kinases p38 and JNK in benzo(a)pyrene-diolepoxide induced apoptosis in human colon carcinoma cells. *Arch Toxicol.* 2012;86:329–337.

39. Leung HY, Yung LH, Poon CH, Shi G, Lu AL, Leung LK. Genistein protects against polycyclic aromatic hydrocarbon-induced oxidative DNA damage in non-cancerous breast cells MCF-10A. *Br J Nutr.* 2009;101:257–262.

40. de Almeida LM, Pineiro CC, Leite MC, et al. Resveratrol increases glutamate uptake, glutathione content, and S100B secretion in cortical astrocyte cultures. *Cell Mol Neurobiol.* 2007;27:661–668.

41. Chen CY, Jang JH, Li MH, Surh YJ. Resveratrol upregulates heme oxygenase-1 expression via activation of NF-E2-related factor 2 in PC12 cells. *Biochem Biophys Res Commun.* 2005;331:993–1000.

42. Revel A, Raanani H, Younglai E, et al. Resveratrol, a natural aryl hydrocarbon receptor antagonist, protects lung from DNA damage and apoptosis caused by benzo[a]pyrene. *J Appl Toxicol.* 2003;23:255–261.

43. Nagaoka T, Hein TW, Yoshida A, Kuo L. Resveratrol, a component of red wine, elicits dilation of isolated porcine retinal arterioles: role of nitric oxide and potassium channels. *Invest Ophthalmol Vis Sci.* 2007;48:4232–4239.

44. Sorensen S, Ranheim T, Bakken KS, Leren TP, Kulseth MA. Retention of mutant low density lipoprotein receptor in endoplasmic reticulum (ER) leads to ER Stress. *J Biol Chem.* 2005;281:468–476.

45. Li C, Wang L, Huang K, Zheng L. Endoplasmic reticulum stress in retinal vascular degeneration: protective role of resveratrol. *Invest Ophthalmol Vis Sci.* 2012;53:3241–3249.

46. Kenche H, Baty CJ, Vedagiri K, Shapiro SD, Blumental-Perry A. Cigarette smoking affects oxidative protein folding in endoplasmic reticulum by modifying protein disulfide isomerase. *FASEB J.* 2013;27:965–977.

47. Csordas A, Kreutmayer S, Ploner C, et al. Cigarette smoke extract induces prolonged endoplasmic reticulum stress and autophagic cell death in human umbilical vein endothelial cells. *Cardiovasc Res.* 2011;92:141–148.

48. Tagawa Y, Hiramatsu N, Kasai A, et al. Induction of apoptosis by cigarette smoke via ROS-dependent endoplasmic reticulum stress and CCAAT/enhancer-binding protein-homologous protein (CHOP). *Free Radic Biol Med.* 2008;45:50–59.