Homocysteine Enhances Endothelial Apoptosis via Upregulation of Fas-Mediated Pathways

Toshimitsu Suhara, Keisuke Fukuo, Osamu Yasuda, Maki Tsubakimoto, Yukihiro Takemura, Hidenobu Kawamoto, Toyohiko Yokoi, Masaki Mogi, Taeko Kaimoto, Toshio Ogihara

Abstract—Hyperhomocysteinemia is an independent risk factor for the development of atherosclerosis. However, the underlying mechanism of endothelial cell injury in hyperhomocysteinemia has not been elucidated. In this study, we examined the effect of homocysteine (Hcy) on Fas-mediated apoptosis in endothelial cells. Hcy-induced upregulation of Fas in endothelial cells (ECs) in a dose-dependent manner. At the same time, Hcy increased intracellular peroxide in ECs. Hcy-induced Fas expression was inhibited by the treatment with catalase. Hcy increased NF-κB DNA binding activity, and adenovirus-mediated transfection of a IκB mutant (IκB mt) gene inhibited Hcy-induced Fas expression. ECs were sensitive to Fas-mediated apoptosis when exposed to Hcy. Under these condition, IκB mt protected ECs from Fas-mediated apoptosis. In addition, Hcy inhibited expression of the caspase-8 inhibitor FLICE-inhibitory protein (FLIP). Adenovirus-mediated transfection of constitutively active Akt gene abolished the Hcy-mediated downregulation of FLIP. These data suggest that upregulation of Fas expression and downregulation of FLIP is a mechanism through which Hcy induces EC apoptosis. (Hypertension. 2004;43:1208-1213.)

Key Words: endothelium • apoptosis • oxidative stress • protein kinases

Hyperhomocysteinemia is an independent risk factor for atherosclerosis and vascular disease. Elevated plasma homocysteine (Hcy) level is associated with 3-fold increase in the risk of acute myocardial infarction. Hcy is an amino acid derived from the metabolic demethylation of dietary methionine. Hyperhomocysteinemia is caused by homozygous deficiency of the gene encoding cystathionine β-synthetase or methionine. Hyperhomocysteinemia is caused by homozygous deficiency of vitamins B6, B12, and folic acid. Hcy increases coagulation, adhesion molecule, and oxidation of low-density lipoprotein in endothelial cells (ECs). Hcy decreases endothelial nitric oxide production and impairs endothelium-dependent vasodilation. Hcy also induces EC apoptosis. The mechanism of Hcy-induced cell death is not well understood.

Fas (also called APO-1 or CD95) is a type I membrane protein belonging to tumor necrosis factor receptor family that transmits a death signal in various cell types. Activation of this pathway requires the receptor cross-linking with Fas ligand (FasL) or anti-Fas antibodies. A growing body of evidence shows that atherogenic factors induce EC apoptosis, whereas anti-atherogenic factors inhibit EC apoptosis. Expression of Fas has been detected in normal and diseased vessel wall, and it has been proposed that Fas-mediated apoptosis is a feature of atherogenesis, atherosclerotic plaque vulnerability, and allograft arteriopathy.

In this study, we examined the pathological role of Hcy in Fas-mediated apoptosis in ECs. We found that Hcy-induced apoptosis resulted from the upregulation of Fas and the downregulation of FLICE-inhibitory protein (FLIP). In these conditions, ECs were sensitive to Fas-mediated apoptosis. These data suggest that Hcy is toxic to ECs by sensitizing these cells to the Fas death pathway.

Methods

Cell Culture and Reagents

Human umbilical vein endothelial cells (HUVECs) were isolated as described. HUVECs were maintained in endothelial growth medium (EGM-2; Clonetics, San Diego, Calif) containing 2% fetal bovine serum (FBS) on collagen-coated dishes (IWAKI, Japan).

Adenoviral Constructs

Replication-defective adenovirus vectors expressing constitutively active form of murine Akt (Adeno-myrAkt) from the cytomegalovirus (CMV) promoter were described previously. Adenovirus vector expressing mutant IκB (S32A/S36/A) driven by the CMV promoter was a kind gift from Dr Michio Tammatsu (Osaka University, Japan). All viral constructs were grown in 293 cells and purified by CsCl gradient ultracentrifugation. Viral titers were determined by plaque assay.

Protein Detection by Flow Cytometry

To analyze cell-surface expression of Fas, harvested cells were incubated with 10 μg/mL mouse antibody against Fas (UB2, MBL)
or mouse IgG for 1 hour at 4°C. Next, cells were incubated with 10 μg/mL FITC-conjugated rat anti-mouse IgG (Pharmingen) for 30 minutes at 4°C. Immunofluorescence staining on the cell surface was analyzed by flow cytometry on the FL-1 channel.

Analysis of Fas mRNA
Total RNA from ECs was extracted by a guanidine isothiocyanate/acid phenol method. Poly(A)^+RNA was prepared using Oligo(dT)-Latex (Takara Biomedicals, Japan). Northern blot analysis was performed as previously described.23 The probe DNA of Fas a 2.5-kbp XhoI fragment contained human Fas cDNA. The cDNA probe for human Fas and glyceraldehydes-3-phosphate dehydrogenase (G3PDH) were labeled with [³²P]dCTP (111 TBq/mmol) by using the multiprime DNA labeling kit (Amersham).

Western Immunoblot Analysis
Protein extract (20 μg) was fractionated on SDS-polyacrylamide electrophoresis gel and transferred to a polyvinylidine difluoride membrane (Immobilon-P, Millipore). The membrane incubated with primary antibody (anti-phospho-Akt [Cell Signaling], anti-Akt1 [Santa Cruz], anti-α-tubulin [Carbiochem]) overnight at 4°C. Mouse monoclonal antibody against human FLIP (NF6) was a gift from Dr Marcus E. Peter (The Ben May Institute for Cancer Research, University of Chicago, Ill). Then, the membrane was incubated with secondary antibody (anti-mouse, anti-rabbit, or anti-goat IgG horse-radish peroxidase conjugate [Promega]) for 1 hour. The immune complexes were detected by chemiluminescence methods (ECL, Amersham).

Measurement of Intracellular Peroxide
After various treatments, cells were incubated with 10 μL/10-cm dish of 2', 7'-dichlorofluorescin diacetate for 30 minutes in CO₂ incubator. Harvested cells were suspended in 500 μL PBS. Intracellular peroxide was analyzed by flow cytometry on FL-1 channel.

Cell Viability Assays
Attached and floating ECs were fixed in cold 90% ethanol for 20 minutes and then resuspended in staining buffer consisting of 1 mg/mL RNaseA, 20 μg/mL propidium iodide, and 0.01% NP40. DNA content was analyzed by flow cytometry on FL-2 channel and gating was set to exclude debris and cellular aggregates.

Statistical Analysis
Statistical analysis was performed by 1-way ANOVA. Results are expressed as mean±SEM. A value of P<0.05 was considered significant.

Results
Homocysteine Induces Upregulation of Fas Expression Through Enhancement of Peroxide Production in ECs
To define the molecular mechanism underlying endothelial injury by homocysteine, we first examined whether homocysteine modulates the levels of Fas, a death receptor, in ECs. As shown in Figure 1A, homocysteine induced a dose-dependent increase in the levels of cell surface Fas expression in ECs. Homocysteine also induced an upregulation of Fas mRNA expression. A maximum increased level of Fas mRNA expression was seen at 12 hours after stimulation with homocysteine (Figure 1B). However, coincubation with catalase, a scavenger of peroxide, inhibited this upregulation. Additionally, homocysteine induced a dose-dependent increase in the levels of intracellular peroxide, and this increase was suppressed by coincubation with catalase (Figure 1C). These results suggest that peroxide is involved in the mechanism by which homocysteine upregulates Fas expression.

Homocysteine Induces Upregulation of Fas Expression Through Activation of a Transcriptional Factor NF-κB
We next examined whether activation of NF-κB involves homocysteine-induced upregulation of Fas expression by using adenoviral vector encoding mutant IκB (mtκB) that contains serine-to-alanine mutations at amino acids 32 to 36.
Homocysteine inhibits phosphorylation and proteosome-mediated degradation of IκB. To demonstrate that expression of mt IκB effectively inhibits NF-κB binding activity in ECs, we performed electrophoretic mobility shift assays with nuclear extracts and a consensus NF-κB DNA binding site. As shown in Figure 2, infection of adenoviral vector encoding mt IκB suppressed NF-κB DNA binding activity in ECs treated with homocysteine or H2O2, whereas adenoviral vector expressing LacZ had no effect. Additionally, transfection of mt IκB inhibited upregulation of Fas protein and mRNA expression induced by homocysteine, whereas control vector had no effect (Figure 3A and 3B).

Figure 2. Homocysteine induces upregulation of NF-κB DNA binding activity in ECs. ECs were preinfected with Adeno-IκB mt for 48 hours at MOI of 50. Cells were then treated with Hcy (5 mmol/L) or H2O2 (0.5 mmol/L) for 1 hour, and nuclear protein was extracted from these cells. NF-κB DNA binding activity was assessed by electrophoretic mobility shift assay using 32P-labeled DNA probes as described in the text.

Homocysteine Sensitizes ECs to Fas-Mediated Apoptosis via NF-κB–Dependent Pathways

We next examined whether homocysteine-induced upregulation of Fas expression results in an increment of EC apoptosis. Incubation with an agonistic antibody CH11 significantly increased the levels of apoptosis in ECs pretreated with homocysteine (Figure 4). CH11, however, did not increase the levels of apoptosis without homocysteine pretreatment (data not shown). Consistent with the results in Figure 3A and B, transfection of mt IκB significantly inhibited the induction of apoptosis by CH11 in homocysteine-pretreated cells, whereas control vector had no effect (Figure 4). These results suggest that homocysteine sensitizes Fas-mediated apoptosis through activation of NFκB-mediated pathways.

Figure 3. Adenoviral vector expressing IκB mutant inhibited upregulation of Fas expression induced by homocysteine. ECs were preinfected with Adeno-IκB mt or Adeno-LacZ for 48 hours at MOI of 50, then cells were incubated for 24 hours with or without Hcy (5 mmol/L). Cell surface Fas expression (A) was analyzed by a flow cytometry with monoclonal antibody to human Fas. Fas mRNA expression (B) was analyzed by Northern blot analysis as described in the text.

Figure 4. Homocysteine sensitized EC to Fas-mediated apoptosis. A, ECs were preincubated with or without Hcy for 24 hours at the concentrations of 2 to 5 mmol/L. Alternatively, HUVECs were preinfected with Adeno-IκB mt or Adeno-LacZ for 48 hours at MOI of 50, then cells were preincubated with or without Hcy for 24 hours at the concentrations of 5 mmol/L. After preincubation, cells were treated with 1 μg/mL of anti-Fas antibody (CH11) for 24 hours, then cells were fixed with 70% ethanol and stained with propidium iodide. DNA content was analyzed by flow cytometry. B, Data are presented as mean±SD in 4 experiments.

Homocysteine Downregulates Cellular FLIP Expression and Sensitizes Fas-Mediated Apoptosis Through Inhibition of Akt Activity

NFκB activation has been shown to upregulate cellular FLIP (cFLIP), an endogenous caspase 8 inhibitor, resulting in increased resistance to Fas-mediated apoptosis. Thus, we examined whether homocysteine upregulates cFLIP expres-
sion in EC. Although homocysteine induces NF-κB activation as shown in Figure 2, it did not upregulate, but downregulated cFLIP expression in ECs (Figure 5A). Because we previously demonstrated that cFLIP expression is regulated by Akt-mediated pathways,46,47 we next examined whether homocysteine downregulates through modulation of Akt activity. As shown in Figure 5B, homocysteine induced suppression of Akt activity in ECs. Importantly, activation of Akt exogenously by infection of adenoviral construct expressing the constitutively active Akt (myrAkt) reversed the downregulation of cFLIP expression by homocysteine. Additionally, VEGF, an activator of endogenous Akt, also reversed this downregulation. Furthermore, infection of Ad-myrAkt reversed agonistic antibody against Fas (CH11)-induced apoptosis in ECs preincubated with homocysteine, whereas control vector had no effect (Figure 5C). These findings suggest that homocysteine sensitizes Fas-mediated apoptosis through suppression of Akt-mediated pathways as well.

Homocysteine Promotes EC Apoptosis via Fas/Fas Ligand-Mediated Pathway in Autocrine/Paracrine Manner

As shown in Figure 5C, Hcy directly induced EC apoptosis in the absence of an agonistic antibody against Fas (CH11). To examine the participation of Fas-mediated death pathway in Hcy-induced EC apoptosis, ECs were incubated with Hcy in the presence or absence of a neutralizing antibody against Fas (ZB4). The preincubation and coinoculation of ZB4 partially inhibited Hcy-induced EC apoptosis dose-dependently (Figure 6). The treatment of control IgG had no effect on Hcy-induced EC apoptosis. This result shows that Hcy-induced EC apoptosis occurs via Fas-mediated death signaling in autocrine/paracrine manner.

Discussion

In the present study, we demonstrated the following findings on the mechanism responsible for the endothelial damage by homocysteine. Homocysteine upregulates the expression of Fas, a death receptor, in ECs via NF-κB activation. Downregulation of NF-κB activity by expressing mutant IκBα prevents homocysteine-induced sensitization to Fas-mediated apoptosis in ECs. Homocysteine suppresses the expression of cFLIP, an endogenous inhibitor of the caspase 8, through the downregulation of Akt, a survival signal for EC. Upregulation of Akt by expressing the constitutively active form of Akt prevents homocysteine-induced EC apoptosis through the restoration of cFLIP expression.

Hyperhomocysteinemia has been recognized as an independent risk factor that predicts adverse cardiovascular
events in patients with ischemic heart disease and stroke. Conversely, homocysteine-lowering therapy significantly decreases the incidence of major adverse events in patients with hyperhomocystinemia. Although the underlying mechanisms of these unfavorable effects of homocysteine have not been elucidated, endothelial dysfunction may be related to the development of cardiovascular events in these patients. Several lines of evidence have shown that EC survival is critical in the maintenance of endothelial function as well as in the regulation of angiogenesis and vessel integrity. Notably, atherogenic factors including homocysteine induce EC apoptosis, whereas antiatherogenic factors such as estrogen inhibit EC apoptosis. Fas is expressed in almost all cells, whereas expression of its ligand (FasL) is restricted in certain cell types such as inflammatory cells. Although ECs express both Fas and FasL, these cells are normally resistant to Fas-mediated apoptosis. The present finding that ECs exposed to homocysteine are susceptible to Fas-mediated apoptosis suggests that Fas ligation in these sensitized cells by FasL-expressing T cells or macrophages could promote EC loss by apoptosis in the plaque. In this regard, homocysteine stimulates the expression of monocyte chemoattractant protein-1, vascular cell adhesion molecule-1, and E-selectin, leading to increased adhesion of monocytes to the aortic endothelium in vivo. Additionally, recent studies have shown that inflammatory FasL-expressing cells are much more abundant in the unstable plaque compared with the stable plaque. Our previous data also demonstrated that plasma levels of the soluble form of FasL are elevated in patients with acute myocardial infarction and unstable angina pectoris. These findings suggest an importance of Fas-mediated EC apoptosis in the pathogenesis of endothelial dysfunction and the subsequent cardiovascular events in patients with hyperhomocystinemia. Thus, inhibitors of Fas-mediated apoptosis could have potential as therapeutic agents.

A growing body of evidence suggests that atherosclerosis results from or accompanied by inflammatory processes, in which the activation of NF-κB plays a pivotal role. Many inflammatory genes whose products are putatively involved in the atherogenesis are regulated by NF-κB. The Fas gene contains NF-κB sites in its promoters and is upregulated when NF-κB is activated. In the present study, we demonstrated that inhibition of NF-κB activation by transduction of mt IκB prevented homocysteine-induced sensitization of ECs to Fas-mediated apoptosis. The serine/threonine protein kinase Akt/PKB promotes viability in various cell types including endothelial cells. In this study, we demonstrated that homocysteine induced downregulation of Akt and that overexpression of Akt gene protect EC against homocysteine-induced EC apoptosis. Our study showed that Akt regulates FLIP expression and promotes Fas-mediated apoptosis in EC. Additionally, our recent observation showed that eicosapentaenoic acid, which is clinically well known as an anti-atherogenic agent, increased FLIP expression via Akt signaling. Tschopp et al showed that Akt signaling decreased sensitivity to Fas-mediated apoptosis via downregulation of the expression of Fas in epithelial cells and in NIH 3T3 fibroblasts. Taken together, these findings suggest that downregulation of Akt may be one of the pathological mechanisms in homocysteine-induced EC injury and that Akt can be a potential therapeutic target in hyperhomocystinemia.

EC apoptosis represents the critical event for the initiation of atherosclerosis. The concept of an association between EC apoptosis and the development of atherosclerosis has been supported by the hypothesis that disturbed shear-stress on vessel wall or adhesive platelets participate in EC apoptosis. Recent direct evidence demonstrated that EC apoptosis increases in the downstream part of atherosclerotic plaque whereas blood flow-mediated shear stress is low. Also, shed membrane particles including apoptotic ECs are elevated in plasma of patients with unstable angina and acute myocardial infarction. These findings show that EC apoptosis is involved in the determination of the susceptibility to atherosclerotic lesion development. Thus, our observation in this study suggests a new mechanistic link between EC apoptosis and the susceptibility of atherosclerotic plaques in patients with hyperhomocystinemia.

In conclusion, these observations suggest a new mechanism by which homocysteine may exert its proatherogenic effects in patients with cardiovascular diseases.

**Perspectives**

Homocysteine induces endothelial apoptosis via upregulation of Fas and downregulation of FLIP, an endogenous inhibitor of caspase-8, which might provide new insight into the pathological mechanism in hyperhomocystinemia.

**Acknowledgments**

We thank Taeko Kaimoto for excellent technical and secretarial assistance.

**References**


Homocysteine Enhances Endothelial Apoptosis via Upregulation of Fas-Mediated Pathways

Toshimitsu Suhara, Keisuke Fukuo, Osamu Yasuda, Maki Tsubakimoto, Yukihiro Takemura, Hidenobu Kawamoto, Toyohiko Yokoi, Masaki Mogi, Taeko Kaimoto and Toshio Ogihara

Hypertension. 2004;43:1208-1213; originally published online April 26, 2004; doi: 10.1161/01.HYP.0000127914.94292.76

Hypertension is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2004 American Heart Association, Inc. All rights reserved.
Print ISSN: 0194-911X. Online ISSN: 1524-4563

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://hyper.ahajournals.org/content/43/6/1208

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Hypertension 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 Hypertension is online at:
http://hyper.ahajournals.org//subscriptions/