Homocysteine Enhances Endothelial Apoptosis via Upregulation of Fas-Mediated Pathways

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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 Iκ-B mutant (Iκ-B mt) gene inhibited Hcy-induced Fas expression. ECs were sensitive to Fas-mediated apoptosis when exposed to Hcy. Under these conditions, Iκ-B 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.1 Elevated plasma homocysteine (Hcy) level is associated with 3-fold increase in the risk of acute myocardial infarction.2,3 Hcy is an amino acid derived from the metabolic demethylation of dietary methionine. Hyperhomocysteinemia is caused by homozygous deficiency of the gene encoding cystathionine b-synthetase or methionine. 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 Iκ-B mutant (Iκ-B mt) gene inhibited Hcy-induced Fas expression. ECs were sensitive to Fas-mediated apoptosis when exposed to Hcy. Under these conditions, Iκ-B 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.)

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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.20 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.21 Adenovirus vectors expressing mutant P32A/S36/A protein from the CMV promoter were described previously.22 Adenovirus vectors expressing mutant IκB (S32A/S36A) driven by the CMV promoter was a kind gift from Dr Michio Tamatani (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. The probe DNA of Fas a 2.5-kbp XhoI fragment contained human Fas cDNA. The cDNA probe for human Fas and glyceraldehyde-3-phosphate dehydrogenase (G3PDH) were labeled with [³²P]dCTP (111 TBq/mmol) by using the multiprime DNA labeling kit (Amersham).

**Electrophoretic Mobility Shift Assay of NF-κB**
Nuclear proteins were prepared from HUVECs, as described. Oligonucleotides containing NF-κB consensus binding site (5'-GGG GAC TTT CCC-3') were labeled using polynucleotide kinase and [γ³²P] ATP; 10 μg nuclear extracts were incubated with 1 μL labeled DNA probe for 20 minutes on ice. Samples were separated in 5% acrylamide gel.

**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 peroxide 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'-dichlorofluorescein 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 (mtIκB) that contains serine-to-alanine mutations at amino acids 32 to 36
(IkBα S32A/S36A) and inhibits phosphorylation and proteosome-mediated degradation of IkB. To demonstrate that expression of mt IkB effectively inhibits NF-κB binding activity in ECs, we performed eletrophoretic 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 IkB 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 IkB inhibited upregulation of Fas protein and mRNA expression induced by homocysteine, whereas control vector had no effect (Figure 3A and 3B).

**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 IkB 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.

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

NF-κB 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 vector expressing the constitutively active Akt (myrAkt) at a MOI of 50, then HUVECs were treated with Hcy (5 mmol/L) for 15 hours. After each treatment, 20 μg of lysates were prepared. Phospho-Akt (P-Akt), total Akt (Akt), and cFLIP was analyzed by Western immunoblotting. Tubulin expression shows uniformity of protein loading each line. C, HUVECs were preinfected with an adenovirus vector expressing the constitutively active Akt (myrAkt) or LacZ at a MOI of 50, then HUVECs were treated with Hcy (5 mmol/L) for 15 hours. After pretreatments, cells were treated with 1 μg/mL of anti-Fas antibody (CH11) for 24 hours, then cell were fixed with 70% ethanol and stained with propidium iodide. DNA content was analyzed by flow cytometry. Data are presented as mean±SD in 4 experiments.

Figure 5. Akt protected HUVECs against Hcy-induced apoptosis. A, HUVECs were treated with Hcy (1 to 5 mmol/L) for 6 hours. B, HUVECs were preincubated with VEGF (100 ng/mL) or preinfected with an adenovirus vector expressing the constitutively active Akt (myrAkt) at a MOI of 50, then HUVECs were treated with Hcy (5 mmol/L) for 15 hours. After each treatment, 20 μg of lysates were prepared. Phospho-Akt (P-Akt), total Akt (Akt), and cFLIP was analyzed by Western immunoblotting. Tubulin expression shows uniformity of protein loading each line. C, HUVECs were preinfected with an adenovirus vector expressing the constitutively active Akt (myrAkt) or LacZ at a MOI of 50, then HUVECs were treated with Hcy (5 mmol/L) for 15 hours. After pretreatments, cells were treated with 1 μg/mL of anti-Fas antibody (CH11) for 24 hours, then cell were fixed with 70% ethanol and stained with propidium iodide. DNA content was analyzed by flow cytometry. Data are presented as mean±SD in 4 experiments.

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.\textsuperscript{27,28} Conversely, homocysteine-lowering therapy significantly decreases the incidence of major adverse events in patients with hyperhomocystinemia.\textsuperscript{29} 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.\textsuperscript{30,31} 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.\textsuperscript{32,33} Fas is expressed in almost all cells, whereas expression of its ligand (FasL) is restricted in certain cell types such as inflammatory cells.\textsuperscript{34} Although ECs express both Fas and FasL, these cells are normally resistant to Fas-mediated apoptosis.\textsuperscript{35} 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.\textsuperscript{36} Additionally, recent studies have shown that inflammatory FasL-expressing cells are much more abundant in the unstable plaque compared with the stable plaque.\textsuperscript{37,38} 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.\textsuperscript{39} 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.\textsuperscript{40} Many inflammatory genes whose products are putatively involved in the atherogenesis are regulated by NF-κB.\textsuperscript{41} The Fas gene contains NF-κB sites in its promoters and is upregulated when NF-κB is activated.\textsuperscript{42–44} 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.\textsuperscript{45} 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.\textsuperscript{46,47} Additionally, our recent observation showed that eicosapentaenoic acid, which is clinically well known as an anti-atherogenic agent, increased FLIP expression via Akt signaling.\textsuperscript{48} Tschopp et al\textsuperscript{49} 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.\textsuperscript{50} 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.\textsuperscript{51} Also, shed membrane particles including apoptotic ECs are elevated in plasma of patients with unstable angina and acute myocardial infarction.\textsuperscript{52} 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 plaque 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.

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