High-Density Lipoproteins Affect Endothelial BMP-Signaling by Modulating Expression of the Activin-Like Kinase Receptor 1 and 2

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Objective—High-density lipoproteins (HDL) have antiinflammatory effects on the vascular endothelium. Because bone morphogenetic proteins (BMPs) are known to be inflammatory mediators, we examined the effect of HDL on BMP signaling.

Methods and Results—Increasing concentrations of HDL progressively enhanced expression of the activin-like kinase receptor (ALK)1 and ALK2 in human aortic endothelial cells as determined by real-time polymerase chain reaction and immunoblotting. Induction of ALK1 was a result of enhanced ALK2 expression as determined by siRNA interference, and was associated with increased levels of vascular endothelial growth factor (VEGF) and matrix Gla protein (MGP). The HDL-induction of ALK2 was dependent on BMP-signaling, and affected coregulation of the ALK2 gene by the homeodomain proteins MSX2, DLX3, and DLX5, as determined by reporter gene assays, siRNA interference, and chromatin immunoprecipitation. Apolipoprotein A-I transgenic mice, known to have high HDL and inhibition of atherogenesis, exhibited similar changes in aortic gene expression as seen in endothelial cells treated with HDL in vitro.

Conclusions—We conclude that HDL benefits the arterial wall by allowing for enhanced ALK1 and ALK2 signaling, resulting in an increase of VEGF and MGP, essential for endothelial cell survival and prevention of vascular calcification, respectively. (Arterioscler Thromb Vasc Biol. 2008;28:2266-2274.)

Key Words: high-density lipoproteins ▪ bone morphogenetic proteins ▪ BMP-receptors ▪ endothelial cells ▪ homeodomain proteins

High-density lipoproteins (HDL) are well recognized to be antiatherogenic and to play a role in mediating cholesterol efflux from cells. In addition, HDL has multiple endothelial and antithrombotic actions that may add to its protective and antiinflammatory effects, such as stimulation of endothelial NO synthase, maintenance of the lipid environment in caveolae, activation of prostacyclin synthesis, and modulation of inflammatory cytokines.

Bone morphogenetic proteins (BMPs)-2, -4, and -6 have been detected in atherosclerotic plaques and may contribute to their formation. In endothelial cells (ECs), BMP-2 and -4 have been identified as genes mediating the response to inflammation and oscillatory shear stress. Noggin and matrix Gla protein (MGP), both able to inhibit BMPs, are also induced by oscillatory shear stress, suggesting that the balance of BMP signaling is essential in the vascular endothelium. BMP-2 and -4 may contribute to the progression of vascular calcification because of their osteoinductive properties. Indeed, BMP-2 has been shown to augment signaling through MSH homeodomain 2 (MSX2)-Wnt signaling in aortic myofibroblasts, thereby stimulating osteogenic differentiation and calcification. In osteoblastic cells, MSX2 and distal-less homeodomains 3 and 5 (DLX3 and DLX5) have been shown to coregulate genes that are essential in bone development, including the RUNX2 and the osteocalcin genes.

The BMPs belong to the transforming growth factor (TGF)-ß superfamily of growth factors. These growth factors elicit their responses via 2 types of serine/threonine receptors, termed type I and type II receptors. BMP binds to the type I receptor, and this complex then binds the type II receptor with increased affinity. The receptor complex phosphorylates specific receptor-regulated (R)-SMAD proteins, which associate with a common partner (Co)-SMAD4 and translocate into the nucleus, where they regulate target gene expression.

Activin-like kinase receptor (ALK)2, ALK3 and ALK6 are categorized as type I BMP receptors, which interact with the BMP type II receptor (BMPRII) to phosphorylate SMAD1/5/8. ALK1 is also a type I receptor, which resembles ALK2, but was initially reported to be a receptor for TGF-ß1 and -3. However, BMP-9 and -10 were recently identified as ligands, and ALK1 was shown to interact with BMPRII similar to...
other BMP receptors.\textsuperscript{13,14} We previously showed that ALK1 expression is dose-dependently regulated by BMP-2 and -4 in vascular cells,\textsuperscript{15,16} suggesting regulatory links between the BMP receptors. ALK1 also mediates stimulatory effects of BMP-4 on expression of the vascular endothelial growth factor (VEGF), essential for EC survival,\textsuperscript{17} and MGP, an inhibitor of vascular calcification.\textsuperscript{18} However, the relationship between the respective BMP receptors in atherogenesis is incompletely understood.

Although HDL has multiple endothelial effects, its effect on BMP signaling is not known. In this study, we demonstrate that HDL promotes expression of ALK2 in ECs, allowing for induction of ALK1, VEGF, and MGP. We show that HDL-induction of ALK2 is dependent on BMP-signaling, and affects coregulation of the ALK2 gene by MSX2, a repressive homeodomain protein, and DLX3 and DLX5, activating homeodomain proteins.\textsuperscript{11,19} The importance of our in vitro findings was confirmed in apolipoprotein (apo) A-I transgenic mice with high HDL levels and resistance to atherogenesis.\textsuperscript{20} These mice exhibited similar changes in aortic gene expression as seen in ECs in vitro. Thus, HDL benefits the arterial wall by enhancing a response system for BMPs that allows for increased VEGF, which is essential for EC survival,\textsuperscript{17} and MGP, which prevents excess BMP-activity and vascular calcification.\textsuperscript{18}

Methods

Cell Culture and Transfection Assays
Human aortic ECs (HAECs) and bovine aortic ECs (BAECs) were obtained and cultured as previously described.\textsuperscript{15} Recombinant human BMP-4 and Noggin (both from R&D Systems) were added as indicated in the results section. HDL was prepared as previously described,\textsuperscript{15} and treatment with HDL was performed in M199 medium supplemented with 2% fetal bovine serum as previously described.\textsuperscript{21} Transient transfections of HAECs with siRNA were performed as previously described.\textsuperscript{15} Gene-specific SiRNAs (Silencer Validated siRNA, Ambion) and scrambled siRNAs with no sequence homology to any known mammalian gene, see supplemental data. The MSX2 expression construct was generously provided by Dr. Dwight A. Towler (Washington University, Bar Harbor, Maine).

Transgenic Mice
Apolipoprotein (apo)-AI transgenic mice on C57BL/6 background\textsuperscript{20} (derived from founder line A2) were obtained from Jackson Laboratory, Bar Harbor, Maine.

Vector Constructions
For construction and mutagenesis of the pG2ALK2pro reporter gene, see supplemental data. The MSX2 expression construct was kindly provided by Dr. Dwight A. Towler (Washington University, St. Louis, Mo).

RNA Analysis
Real-time PCR assays were performed as previously described.\textsuperscript{15} The following primers and probes were used: human ALK1 (hALK1) forward (F) (5'-AGGCGAAACCAGCATTG-3'), hALK1 reverse (R) (5'-GATTGTGCTTTGACGGCAT-3'), hALK1 Taqman probe (FAM-CACCGGACTCTCAAGGCGC-TAMRA). Primers and probes for other human and mouse genes were obtained from Applied Biosystems.

Immunoblotting and Immunocytochemistry
Immunoblotting was performed as previously described.\textsuperscript{15} Blots were incubated with antibodies to ALK1, ALK2, ALK3, or ALK6 (all 0.4 μg/mL; Santa Cruz Biotechnology), BMPRII (2 μg/mL; R&D Systems), SMAD1 or SMAD2 (both 1 μg/mL; Upstate Biotechnology), MSX2 (0.2 μg/mL; Abcam), DLX3, or DLX5 (0.2 μg/mL; Santa Cruz Biotechnology). β-Actin (1:5000 dilution; Sigma) was used as loading control. Immunocytochemistry was performed as previously described,\textsuperscript{15} with goat polyclonal antibodies to ALK1 and ALK2 from Santa Cruz Biotechnology.

Chromatin Immunoprecipitation Assays
A commercially available kit (USB Corporation) was used to perform chromatin immunoprecipitation (ChiP) assays in HAECs. The assays were performed as per the manufacturer’s protocol. Immunoprecipitation was performed using the same antibodies used for immunoblotting. PCR was performed using the following primers from the ALK2 promoter (surrounding MSX1.2 site at −2206): (F) 5'-CATGAAAACAATCTCCCAAA-3' and (R) 5'-TTTCTGA TGACCTCAATG-3' (94°C denaturation, 55°C annealing, 72°C extension, 35 cycles, 253 bp product).

Statistics
Data were analyzed for statistical significance by ANOVA with posthoc Scheffe analysis, using StatView, version 4.51 (Abacus Concepts). Experiments were repeated a minimum of three times.

Results

HDL Induces Expression of ALK1, ALK2, VEGF, and MGP in ECs
To determine the effect of HDL on the expression of components of BMP signaling pathways, we treated HAECs with HDL (0 to 150 μg/mL) for 24 hours. We analyzed changes in expression of BMP ligands and receptors. Our results showed that expression of ALK1 and ALK2 was significantly enhanced as determined by real-time PCR, immunoblotting, and immunocytochemistry (Figure 1A through 1D). Treatment with bovine serum albumin or LDL had no effect on expression of ALK1 and ALK2 (supplemental Figure I, available online at http://atvb.ahajournals.org), suggesting that the effect was specific for HDL. However, HDL had no significant effect on the expression of ALK3, ALK6, BMPRII, or BMP-2, -4, -6, and -7 (data not shown). Because our previous studies showed that activated ALK1 induced expression of VEGF and MGP,\textsuperscript{15} we also determined the effect of HDL on VEGF and MGP. As expected, the results showed that HDL significantly increased both VEGF and MGP as determined by real-time PCR (Figure 1E), suggesting a beneficial effect on the vascular wall.

HDL-Induction of ALK1 Expression Requires the ALK2 Receptor
To determine whether the HDL-induction of ALK1 was dependent on ALK2 or vice versa, we transfected HAECs with either ALK1 or ALK2 siRNA, which reduced RNA and protein levels up to 95%\textsuperscript{15} (supplemental Figure II). The cells were treated with HDL (0 to 150 μg/mL) for 24 hours, and expression of ALK1 and ALK2 was determined. The results showed that depletion of ALK2 blocked HDL-induction of ALK1 (Figure 2A), whereas depletion of ALK1 did not affect HDL-induction of ALK2 (Figure 2B), suggesting that HDL-induction of ALK1 depends on ALK2. We also performed a time course where HAECs were treated with HDL (100 μg/mL) for up to 24 hours. The results showed that ALK2 expression increased after 1 hour, whereas ALK1 expression...
increased after 4 hours as determined by real-time PCR and immunoblotting (Figure 2C) supporting that ALK1 expression depends on ALK2.

We also determined whether BMP receptors other than ALK2 and SMAD signaling were involved in HDL-induction of ALK1 expression by using siRNA to ALK3, ALK6, BMPRII, and SMAD1 or SMAD2, which mediate BMP and TGF–β signaling, respectively. The results showed that BMPRII and SMAD1, but not ALK3, ALK6, or SMAD2, were necessary for HDL-induction of ALK1 (supplemental Figure III). We have previously shown that ALK1 is dose-dependently induced by BMP-2/4 in ECs. Experiments using the same siRNA showed that BMP-4-induction of ALK1 also requires ALK2, BMPRII, and SMAD1 (supplemental Figure IV), which suggests that HDL and BMP-4 may use the same pathway to induce ALK2.

HDL and BMP-4 Activate the ALK2 Promoter

To determine whether HDL affected the activity of the promoter of ALK2, a 4.6-kb genomic DNA fragment from the promoter region of the human ALK2 gene (nucleotides −1 to −4625) was subcloned into a luciferase reporter gene. Three deletions were made in the ALK2 promoter, generating reporter genes with promoter fragments of 3.6, 1.2, and 0.1 kb (Figure 3A). The resulting vectors were transfected into BAECs because HAECs transfected poorly with expression vectors, and the cells were treated with HDL (0 to 150 μg/mL). After 24 hours, the luciferase activity was determined. The results showed that the activity of the ALK2 promoter decreased progressively as the promoter was shortened (Figure 3B).

When analyzing the sequence of the ALK2 promoter, 4 MSX1.2 sites were detected within the 4.6-kb promoter fragment (Figure 3A). MSX1 and MSX2 are well-known transcription factors targeted by BMP/SMAD signaling. The 3.6- and the 1.2-kb promoter fragments contained 2 and 1 MSX1.2 sites, respectively (Figure 3A). The 0.1-kb fragment contained no MSX1.2 sites. We hypothesized that the MSX1.2 sites are essential for HDL induction of ALK2, and mutated the sites marked 1, 2, and 3 in Figure 4A. We transfected BAECs with the resultant 3 reporter genes, treated with HDL (0 to 150 μg/mL), and determined the luciferase activity 24 hours later. The results showed that mutagenesis of any of the 3 MSX1.2 sites, in particular the site at −2206, reduced luciferase activity (Figure 3C). For unclear reasons, we were unable to mutate and test the MSX1.2 site at −1099. Mutation of a DLX5 site at −1099 had no effect on luciferase activity after HDL treatment (supplemental Figure VA). Together, the results suggested that the MSX1.2 sites are essential for HDL induction of ALK2.

Because BMP targets MSX1.2 sites, we tested whether BMP-4 also induced ALK2 expression. HAECs were treated with BMP-4 (0 to 100 ng/mL) for 24 hours, and ALK2 expression was determined by real-time PCR and immuno-
blotting. The results showed that BMP-4 increased ALK2 expression up to 4- to 5-fold (Figure 3D). We also transfected BAEcs with the mutated promoter constructs and treated the cells for 24 hours with BMP-4 (0 to 100 ng/mL), before determining the luciferase activity. As expected, the activity was diminished after mutation of MSX1.2 sites (Figure 3E). BMP-4 concentrations above 100 ng/mL had no further stimulatory effect (supplemental Figure VB). Thus, both HDL and BMP-4 are dependent on MSX1.2 sites for efficient induction of ALK2 expression.

HDL and BMP-4 Affect Expression of MSX2, DLX3, and DLX5, Which Coregulate ALK2 Expression

MSX1 and MSX2 are classical repressor proteins that are expressed in endothelial cells. A regulatory mechanism involving MSX2, DLX3, and DLX5 has been reported in the bone-related Runx2 and osteocalcin promoters, where MSX2 has a repressive function and DLX3 and DLX5 have an activating function. To determine whether HDL and BMP-4 affected the levels of MSX2, DLX3, and DLX5 in HAEcs, we treated cells with HDL (0 to 150 μg/mL) or BMP-4 (0 to 100 ng/mL) for 24 hours and determined protein levels with immunoblotting. The results showed that both HDL and BMP-4 reduced MSX2 and increased DLX3 and DLX5 (Figure 4A). To confirm that MSX2 was a repressor of ALK2 promoter activity, we cotransfected BAEcs with the 4.6-kb ALK2 promoter reporter gene and an expression construct for MSX2 or control vector. The cells were treated with HDL (0 to 150 μg/mL) or BMP-4 (0 to 100 ng/mL) for 24 hours before luciferase activity was determined. The results showed that overexpression of MSX2 abolished the effect of HDL and BMP-4 on the ALK2 promoter (Figure 4B).

To determine the importance of the homeodomain proteins for ALK2 expression, we transfected HAEcs with siRNA to MSX2, DLX3, DLX5, or DLX3 and DLX5, which reduced RNA and protein levels up to 95% (supplemental Figure II). The cells were treated with HDL (0 to 150 μg/mL) or BMP-4 (0 to 100 ng/mL) for 24 hours before determining expression of ALK2 by real-time PCR (Figure 4C) and immunoblotting (supplemental Figure VI). Depletion of just one DLX did not inhibit ALK2 expression. We then performed ChIP assays using untreated HAEcs transfected with the respective siRNA and primers surrounding the MSX1.2 site at 2206. Loss of this site significantly reduced stimulatory effects of HDL (Figure 3C and 3E). The results

Figure 2. HDL-induction of ALK1 is dependent on ALK2, but ALK2 is not dependent on ALK1. HAECs were transfected with scrambled siRNA or siRNA to ALK2 (A) or ALK1 (B), and treated with HDL (0 to 150 μg/mL) for 24 hours starting the day after transfection. Expression of ALK1 and ALK2 was determined by real-time PCR and immunoblotting. C, To determine the time course for expression, HAECs were treated for up to 24 hours with HDL (100 μg/mL). Expression of ALK1 and ALK2 was determined by real-time PCR and immunoblotting. Asterisks indicate statistically significant differences compared to control (no HDL). *P<0.05; **P<0.01; ***P<0.001; Scheffe test.

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Figure 3. BMP-4 increased ALK2 expression up to 4- to 5-fold (Figure 3D). A, Scrambled siRNA or ALK2 siRNA were transfected into BAEcs, and treated with HDL (0 to 150 μg/mL) for 24 hours starting the day after transfection. Expression of ALK1 and ALK2 was determined by real-time PCR and immunoblotting. B, BMP-4 concentrations above 100 ng/mL had no further stimulatory effect (supplemental Figure VB). Thus, both HDL and BMP-4 are dependent on MSX1.2 sites for efficient induction of ALK2 expression.
showed that MSX2, DLX3, and DLX5 all bound to this site, but that the binding of DLX3 and DLX5 was dependent on MSX2 (Figure 4D, top). We then compared control- and HDL-treated HAECs. The results showed that HDL caused release of MSX2, allowing DLX3 and DLX5 to bind without MSX2 (Figure 4D, bottom). This suggests that the MSX1.2 site represents a DLX-binding cognate that is activated by DLX and suppressed by MSX2 in a similar fashion to what has been described in great detail for the Runx2 promoter when responding to BMP-2.11

The HDL Effect on ALK2 Expression Is BMP-Dependent and Is Affected by Changes in Cellular Cholesterol

Because the HDL effect on ALK2 is similar to that of BMP-4, we hypothesized that HDL may act through BMPs to induce ALK2. To test this, we treated HAECs with HDL (0 to 150 μg/mL) in the presence of absence of Noggin (300 ng/mL), a BMP-inhibitor. After 24 hours of treatment, expression of ALK2 was determined by real-time PCR and immunoblotting. The results showed that HDL-induced ALK2 expression was inhib-
HDIs by Noggin (Figure 5A), suggesting that HDL enhanced BMP-signaling. Because no exogenous BMP was added, the change in BMP signaling was presumably attributable to a change in the response to endogenously expressed BMP-2 or -4 (Figure 5B). No BMP was detected in HDL (Figure 5B). Because HDL has been shown to maintain the lipid environment in caveolae,1,2 we hypothesized the cholesterol balance might affect BMP signaling. To determine whether cellular cholesterol affected HDL induction of ALK2, HAECs were loaded with cholesterol (0 to 20 μg/mL) or treated with methyl-β-cyclodextrin (MCD, 0 to 30 mmol/L), a cholesterol binder, before HDL treatment. The cells were subsequently treated with HDL (0 to 150 μg/mL) for 24 hours before determination of ALK2 expression with real-time PCR and immunoblotting. The results showed that cholesterol loading significantly decreased ALK2 expression, and abolished induction of ALK2 when combined with HDL treatment (Figure 5C, real-time PCR, supplemental Figure VII, immunoblotting). However, MCD had the same effect (Figure 5C, 5D).

It is still possible that the effect of HDL is related to the removal of cellular cholesterol, if the manner in which HDL removes cholesterol is of importance. Alternatively, HDL affects ALK2 through a mechanism unrelated to cholesterol.

High HDL In Vivo Enhances Aortic Expression of ALK1, ALK2, VEGF, and MGP
To confirm the effect of HDL on gene expression in vivo, we prepared RNA and protein from aortas of apo A-I transgenic...
mice, known to have a 2-fold increase in HDL compared to control mice. The results showed a 2- to 3-fold increase in expression of ALK1, ALK2, VEGF, and MGP as determined by real-time PCR (Figure 6A). Immunoblotting confirmed the increased in ALK1 and ALK2, and also showed a decrease in MSX2 and an increase in DLX3 and DLX5 (Figure 6B). Together the results support that high HDL affects BMP-signaling in vivo and benefits the vascular wall.

**Discussion**

In this study, we demonstrate that HDL enhances the BMP-signaling system in ECs by promoting the expression of ALK2, which together with BMPRII, SMAD1, and endogenous BMP allows for induction of ALK1. The HDL-induction of ALK2 expression is dependent on BMP-signaling and intact MSX1.2 sites in the ALK2 promoter. We show that HDL and BMP-4 modulate the levels of MSX2, DLX3, and DLX5 in HAECs, and promote DLX-activation of the ALK2 gene similarly to the Runx2 gene responding to BMP-2. The increase in ALK1 is associated with enhanced expression of VEGF, essential for EC survival, and MGP, which effectively prevents excess BMP-activity and vascular calcification. The results were confirmed in vivo, and provide evidence for a novel role for HDL in benefiting the vascular wall (see Figure 6C for schematic working model).

Cellular cholesterol or lipid content has previously been implicated in BMP receptor function. For instance, Hartung et al showed that localization of BMP receptors in distinct membrane domains was a prerequisite for taking different endocytosis routes with specific signaling cascades. Although HDL did not affect TGF-β signaling through ALK5 in our experiments (data not shown), HDL and hypercholesterolemia have previously been shown to affect TGF-β and TGF-β signaling. HDL and hypercholesterolemia, respectively, induced endothelial expression of TGF-β2 and endoglin, a so-called TGF-β type III receptor, and cholesterol suppressed cellular TGF-β responsiveness by altering TGF-β binding to TGF-β receptors. Because our studies showed that both cholesterol loading and cholesterol depletion by MCD abolished the HDL effect, it is possible that the effect of HDL is specific for the manner in which cholesterol depletion occurs or is attributable to factors unrelated to cholesterol.

Al-Aly et al showed in their recent studies that BMP-2 and MSX2 were induced by tumor necrosis factor (TNF)- alpha, an inflammatory cytokine that is upregulated by high-fat diet in LDL-null mice, and that triggering of the BMP-2-MSX2 program led to increased vascular calcification. In osteoblastic cells, MSX2 is known to be part of a BMP-dependent molecular switch that regulates the osteocalcin and Runx2 genes, and also involves DLX3 and DLX5, MSX2 acts as a suppressor of gene expression, whereas DLX3 and DLX5 act as activating factors. Our results from ChIP assays support this model, in that HDL-activation of ALK2 expression releases MSX2 from the promoter allowing DLX3 and DLX5 to bind and drive transcription suggesting that the MSX1.2 sites are DLX-binding cognates. The
results prompt the question whether HDL and cholesterol levels have an effect on bone formation and osteoporosis. Although early studies suggested that so-called statins may exert an anabolic effect on bone, and conversely, that hypercholesterolemia may have an adverse effect on osteoporotic bone loss,\textsuperscript{27} recent clinical studies have not shown significant effects of statins on bone mineral density.\textsuperscript{28–30} Thus, the connections between lipid status and bone health remain unclear.

Although ALK2 upregulates ALK1, gene deletion produces different phenotypes and their respective target genes are presumably different. ALK1 deficiency is associated with hereditary hemorrhagic telangiectasia (HHT) and formation of arterio-venous malformations,\textsuperscript{13,14} whereas ALK2 affects the development of the cardiac outflow tract and aortic arch derivatives.\textsuperscript{31} Overall, the roles of the BMP-receptors are unclear in vascular inflammation and atherogenesis. ALK1 expression is induced in atherosclerotic lesions and may affect proliferation and aggregation of vascular cells.\textsuperscript{16} Based on our data, a high level of ALK2 relative to ALK3 and ALK6 may be beneficial and alter inflammatory effects of BMP-2/4 in the endothelium.\textsuperscript{6,7} However, further studies are needed to identify an optimal ratio between various BMP receptors in the endothelium.

Although HDL and BMP-4 are dependent on the same signaling pathway to induce expression of ALK1, the patterns of induction appear to be different. BMP-4-induction of ALK1 is dose-dependent with a narrow range of optimal concentrations\textsuperscript{15} (supplemental Figure IV), whereas HDL-induction...
increases with dose up to a plateau level (supplemental Figure III). Because BMP-4 and HDL affects the levels of MSX2, DLX3, and DIx5 similarly, we presume that other mechanisms or feedback loops are involved in determining the exact pattern of ALK1 expression.

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Disclosures

None.

References

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SUPPLEMENTAL DATA

METHODS

Vector constructions

To construct the pGL2ALK2pro reporter gene, a 4.6 kb fragment (nucleotides -1 to -4625) of the human ALK2 promoter region was obtained using the Elongase® amplification system (Invitrogen). The following primers were used: forward 5’- GGACCTTGTTACCCCTGAGAA -3’; reverse 5’- CAATGGTAGCTCGAGTGATGATTC -3’. Restriction sites for KpnI and XhoI were incorporated into the primers, and the fragment was subcloned into the pGL2 basic vector (Promega). The Genomatix Promoter Inspector software (URL: http://www.genomatix.de) was used to inspect the promoter sequence. Site-directed mutagenesis of the human ALK2 promoter was performed with the QuickSite mutagenesis kit (Stratagene) using the 4.6 kb pGL2ALK2pro construct as template.

FIGURE LEGENDS

Supplemental Figure I

LDL and bovine serum albumin (BSA) do not induce expression of ALK1 and ALK2.

HAEC were treated for 24 hours with LDL (0-150 µg/ml) or BSA (0-150 µg/ml). Expression of ALK1 and ALK2 was determined by real-time PCR.

Supplemental Figure II

Effect of siRNA on expression of BMP receptors and SMADs.

HAEC were transfected with scrambled siRNA or siRNA to ALK2, ALK3, ALK6, BMPRII, SMAD1, SMAD2, MSX2, DLX3 or DLX5. Expression of the respective protein was determined 24-48 hours later by real-time PCR and immunoblotting.

Asterisks indicate statistically significant differences compared to control (scrambled siRNA).

***, p < 0.001; Scheffe’s test.
Supplemental Figure III

HDL-induction of ALK1 expression is dependent on BMPRII and SMAD1.

HAEC were transfected with scrambled siRNA or siRNA to ALK3, ALK6, BMPRII, SMAD1 or SMAD2, which reduced RNA and protein levels up to 95% (supplemental Fig. II). The transfected cells were treated with HDL (0-150 µg/ml) for 24 hours starting the day after transfection. Expression of ALK1 was determined by real-time PCR and immunoblotting. Asterisks indicate statistically significant differences compared to control (no HDL). *, p<0.05; **, p<0.01; ***, p < 0.001; Scheffe's test.

Supplemental Figure IV

Induction of ALK1 expression by BMP-4 is dependent on ALK2 and BMPRII.

HAEC were transfected with scrambled siRNA or siRNA to ALK2, ALK3, ALK6 or BMPRII, which reduced RNA and protein levels up to 95% (supplemental Fig. II). The transfected cells were treated with BMP-4 (0-100 ng/ml) starting 24 hours after transfection. ALK1 expression was determined after 24 hours of treatment by real-time PCR and immunoblotting. SiRNA to ALK2 and BMPRII, but not ALK3 or ALK6 (data not shown), abolished the effect of BMP-4. This suggests that ALK2 and BMPRII are the receptors that mediate the BMP-4 induction of ALK1. Asterisks indicate statistically significant differences compared to control (no HDL). **, p<0.01; ***, p < 0.001; Scheffe's test.

Supplemental Figure V

(A) HDL-induction of ALK2 does not depend on the presence of an intact DLX5 site in the ALK2 promoter.

ALK2 promoter activity in response to HDL (0-150 µg/ml) using an ALK2 promoter construct with a mutated DLX5 site (at -1099) in the ALK2 promoter in comparison with an unmutated promoter construct, as determined by luciferase activity.

(B) Stimulation of ALK2 promoter activity by BMP-4 reaches a plateau at 100 ng/ml and above.
ALK2 promoter activity in response to BMP-4 (0-300 ng/ml) using ALK2 promoter constructs with mutated MSX1.2, site 1, 2 and 3, as determined by luciferase activity.

**Supplemental Figure VI**

*HDL and BMP-4 modulate expression of MSX2, DLX3 and DLX5.*

HAEC were transfected with scrambled siRNA or siRNA to MSX2, DLX3, DLX5, or DLX3 and DLX5, and treated with HDL (0-150 µg/ml) (left) or BMP-4 (0-100 ng/ml) (right) for 24 hours starting the day after transfection. Expression of ALK2 was determined by immunoblotting.

**Supplemental Figure VII**

*Changes in cellular cholesterol neutralize the effect of HDL on ALK2 expression.*

(Left) HAEC were treated with HDL (0-150 µg/ml), cholesterol (0-20 µg/ml), or HDL (0-150 µg/ml) with cholesterol (20 µg/ml). ALK2 expression was determined by immunoblotting.

(Right) HAEC were treated with HDL (0-150 µg/ml), methyl-β-cyclodextrin (MCD) (0-30 mM), or HDL (0-150 µg/ml) with MCD (0-30 mM). ALK2 expression was determined by immunoblotting.
Supplemental Figure V

A.

Norm Luciferase Activity (units)

HDL (µg/ml)

0 25 50 75 100 200

ALK2pro
Dlx5 mut

B.

Norm Luciferase Activity (units)

BMP-4 (ng/ml)

0 40 80 100 200 300

ALK2pro
Msx1.2 (1)
Msx1.2 (2)
Msx1.2 (3)
Supplemental Figure VII

[Image: Bar charts showing the effects of HDL and cholesterol on ALK2 levels with varying concentrations (0, 50, 100, 150 µg/ml or µM).]