Regulatory Effects of HDL on Smooth Muscle Cell Prostacyclin Release

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Abstract—One mechanism by which high density lipoproteins (HDLs) exert their protective effect against coronary artery disease could be related to the induction of prostacyclin (PGI₂) release in the vessel wall. We have recently shown that HDL increases PGI₂ production in rabbit smooth muscle cells (RSMCs) and that this increase is dependent on cyclooxygenase-2 (Cox-2). Here we analyze the mechanism by which rabbit HDL induces PGI₂ release in RSMCs. Our results show that although HDL₂ and HDL₃ share a similar capacity to induce Cox-2 protein levels, HDL₃ stimulates a higher PGI₂ release than does HDL₂, probably because of their relative arachidonate contents. Acetylsalicylic acid pretreatment (300 μmol/L, 30 minutes) significantly reduced the HDL-induced PGI₂ release, suggesting that both preexisting and induced Cox-2 activities were involved in the HDL effect. Ca²⁺-dependent cytosolic phospholipase A₂ (cPLA₂) and Cox-1 protein levels were not altered by HDL. Dexamethasone (2 μmol/L), which also inhibited the HDL-induced PGI₂ release, reduced significantly both Cox-2 mRNA and protein levels without affecting cPLA₂ and Cox-1 protein levels. In addition, methylarachidonyl fluorophosphonate, a potent inhibitor of cPLA₂, did not produce any effect on HDL-induced PGI₂ release. In the presence of cycloheximide, Cox-2 mRNA levels were induced by HDL and inhibited by dexamethasone, suggesting that HDL and dexamethasone work in the absence of de novo protein synthesis. These results indicate an early effect of HDL on PGI₂ biosynthesis, specifically increasing Cox-2. PD98059, an inhibitor of mitogen-activated protein kinase kinase, completely inhibited HDL-induced PGI₂ release, whereas GF109203X, a protein kinase C inhibitor, had no effect. Thus, HDL induces PGI₂ synthesis by a mechanism dependent on the mitogen-activated protein kinase pathway but independent of protein kinase C. (Arterioscler Thromb Vasc Biol. 1999;19:2405-2411.)

Key Words: lipoproteins ▪ cyclooxygenase-1 ▪ cyclooxygenase-2 ▪ cytosolic phospholipase A₂ ▪ mitogen-activated protein kinases

Several epidemiological and experimental studies have shown that HDLs have a protective effect against coronary artery disease. ¹-⁵ The most widely accepted mechanism for this protective effect is through an enhanced reverse cholesterol transport. ⁶-⁷ However, other mechanisms such as induction of prostacyclin (PGI₂) synthesis in the vessel wall have been postulated. The stimulatory effect of HDL on PGI₂ production by both endothelial and smooth muscle cells (SMCs) has been widely demonstrated. ⁸-¹² In contrast, the effect of low density lipoprotein (LDL) on the biosynthesis of prostanooids is unclear: they can stimulate, inhibit, or have no effect on prostanooid synthesis. ¹¹-¹⁵ This variable effect of LDL has been related to its degree of oxidation. ¹⁶,¹⁷

PGI₂ is a vasodilator prostaglandin that is synthesized by blood vessels and contributes to the maintenance of vascular tone. ¹⁸,¹⁹ Other actions of PGI₂ include inhibition of platelet aggregation and adhesion, inhibition of SMC growth, inhibition of leukocyte activation and adhesion, and reduction of cholesterol ester accumulation in vessel wall cells. These biological actions of PGI₂ suggest that it is an endogenous antiatherogenic molecule. ²⁰

The rate-limiting step in the conversion of arachidonic acid to prostaglandins and other eicosanoids is at the level of cyclooxygenase (Cox; prostaglandin G/H synthase; E.C. 1.14.99.1). Two isoforms of Cox have been described: Cox-1 and Cox-2. Cox-1 is present in several cells and tissues in relatively stable levels, ²¹ although small increases in enzyme content can occur after stimulation with hormones or growth factors. ²²,²³ Cox-2 is usually absent in resting cells, and its expression is increased by serum, cytokines, mitogens, and different growth factors. ²¹,²⁴-²⁶

We have recently shown that HDL increases eicosanoid production in SMCs by a Cox-2–dependent mechanism. ²⁷ In the present study, we analyzed the involvement in this process of both preexisting and induced Cox-2 activities, as well as the role of other enzymes implicated in the formation of prostaglandins and leukotrienes, such as cytosolic phospholipase A₂ (cPLA₂). ²⁸ In addition, we investigated the intracellular signaling mechanisms by which HDL exerts this effect. Our results indicate that HDL induces PGI₂ biosynthesis by both preexisting and induced enzyme, specifically...
increasing Cox-2 mRNA and protein levels, and that HDL induces PG12 synthesis by a mechanism dependent on the mitogen-activated protein kinase (MAPK) pathway but independent of protein kinase C (PKC).

Methods

Materials

Cell culture medium and reagents were purchased from Gibco Laboratories. 3H]dCTP (3000 Ci/mmol), nylon membranes (Hybond-N), and the ECL chemiluminescent detection system were from Amersham. The 6-keto-PGF1α, enzyme immunoassay (EIA) kit and methylarachidonyl fluorophosphonate (MAFP) were from Cayman Chemical Co. Actinomycin D, cycloheximide, dexamethasone, and aspirin (acetylsalicylic acid; ASA) were from Sigma Chemical Laboratories. PD98059 and GF109203X were from Alexis Corp. 

Lipoprotein Isolation

Lipoproteins were obtained by sequential ultracentrifugation of normolipemic rabbit plasma in a Beckman 50.2 Ti rotor at densities 1.052 and 1.063 g/mL (LDL), 1.125 and 1.210 g/mL (HDL), and 1.063 and 1.210 g/mL (HDL). Lipoproteins were recentrifuged, dialyzed, and assayed for protein and lipid contents. 

RNA Blot Analysis

RSMCs were cultured as previously described. After lipoprotein incubations, stimulation was halted by the addition of ice-cold RNA isolation reagent Ultraspec RNA (1 mL/21-cm2 dish). RNA samples were fractionated in 1.1% agarose gels containing formaldehyde. RNA was transferred by capillarity to Hybond membranes and UV–cross-linked. Filters were prehybridized and hybridized at 42°C in 50% formamide, 1 mol/L NaCl, 50 mmol/L NaH2PO4 (pH 6.3), and 7.5× Denhardt’s solution. 1% SDS, 10% dextran sulfate, and 20 μg/mL denatured salmon sperm DNA were fractionated in 1.1% agarose gels containing formaldehyde. RNA was transferred by capillarity to Hybond membranes and UV–cross-linked. Filters were prehybridized and hybridized at 42°C in 50% formamide, 1 mol/L NaCl, 50 mmol/L NaH2PO4 (pH 6.3), and 7.5× Denhardt’s solution. 1% SDS, 10% dextran sulfate, and 20 μg/mL denatured salmon sperm DNA were hybridized with 32P–labeled sequences. Filters were then washed and exposed to X-ray film. 

Assay of cPLA2 Enzymatic Activity

RSMCs were cultured as indicated above and incubated with HDL (150 μg cholesterol per mL) for 1 hour. cPLA2 activity was assayed by using the cPLA2 kit from Cayman Chemical Co according to the manufacturer’s instructions. In brief, the cytosolic fraction from RSMC cultures was incubated with the substrate arachidonylthio phosphatidylcholine (ATPC). Enzymatic hydrolysis of ATPC re-
leaves free thiol, which is then converted into 5-thiol-2-nitrobenzoic acid by Ellman’s reagent \([5,5'\text{-dithiobis(2-nitrobenzoic acid)}]\). 5-Thiol-2-nitrobenzoic acid formation is determined by spectrophotometric analysis at 414 nm.

**Statistical Analysis**
Data are presented as mean±SEM. Means were compared by using ANOVA. Differences were considered significant at \(P<0.05\).

**Results**

**Effect of HDL\(_2\) and HDL\(_3\) Subfraction on PGI\(_2\) Release and Cox-2 Protein Levels**
RSMCs were incubated with HDL\(_2\), HDL\(_3\), or the complete HDL fraction (150 \(\mu\)g cholesterol per mL) for 24 hours, and PGI\(_2\) release was measured. Results showed that HDL\(_3\) induced a significantly higher release than did HDL\(_2\) (4.18±0.49 and 2.14±0.26 ng/mL, respectively; \(P<0.0001\); Figure 1A). In contrast, all of the fractions induced similar Cox-2 protein levels with respect to control cells (Figure 1B). Thus, subsequent studies were performed with the total HDL fraction.

**Effect of ASA Pretreatment, Cycloheximide, and Actinomycin D on PGI\(_2\) Release Induced by HDL**
HDL (150 \(\mu\)g cholesterol per mL) induced a time-dependent increase in PGI\(_2\) production in RSMCs. ASA pretreatment (300 \(\mu\)mol/L, 30 minutes) significantly reduced HDL-induced PGI\(_2\) release (Figure 2A). The ASA-produced inhibition was lost in a time-dependent fashion; it was highest at 2 hours (74.8±1.2%) and decreased after 8 (43.2±9.3%) and 24 (21.4±9.1%) hours of incubation. The effect of ASA pretreatment on control cells was maintained over time.

Both cycloheximide (2 \(\mu\)g/mL), a protein synthesis inhibitor, and actinomycin D (1 \(\mu\)g/mL), an inhibitor of transcription, abolished PGI\(_2\) release induced by HDL (the Table). Taken together, these results suggest that both basal and de novo synthesized Cox activities are involved in PGI\(_2\) production induced by HDL.

**Effect of Dexamethasone on PGI\(_2\) Release Induced by HDL**
In ASA-pretreated cells, dexamethasone (2 \(\mu\)mol/L), a Cox-2 inhibitor by transcriptional and posttranslational mechanisms,\(^{34,35}\) significantly reduced the HDL-induced PGI\(_2\) release. However, PGI\(_2\) values in the presence of dexamethasone did not reach baseline levels (31.1±7.5% at 2 hours, 40.9±8.6% at 8 hours, and 49.4±12.4% at 24 hours of incubation; Figure 2B). Furthermore, in ASA-pretreated SMCs maintained under ASA treatment for a prolonged incubation time (2, 8, or 24 hours), PGI\(_2\) synthesis induced by HDL was partially inhibited (HDL 3.14±0.69 ng/mL versus HDL plus ASA 0.45±0.09 ng/mL at 24 hours of incubation; Figure 2B). In contrast, ASA completely inhibited PGI\(_2\) release promoted by FCS (FCS 68.6±13.0 ng/mL versus FCS plus ASA 0.45±0.08 ng/mL).\(^{27}\) Thus, ASA abolishes the
high PGI₂ levels induced by FCS (99% inhibition at 24 hours) but only partially inhibits those induced by HDL (61% inhibition at 24 hours).

Role of Cox-2, Cox-1, and cPLA₂ on PGI₂ Release Induced by HDL

HDL treatment (150 μg cholesterol per mL, 6 hours) significantly stimulated Cox-2 protein levels but did not produce any effect on those of Cox-1 or cPLA₂. LDL (150 μg cholesterol per mL) did not affect Cox-1, Cox-2, or cPLA₂ protein levels (Figure 3). Dexamethasone treatment (2 μmol/L), which inhibited HDL-induced PGI₂ release, blocked Cox-2 protein levels but not those of Cox-1 and cPLA₂ (Figure 3). PGI₂ release induced by HDL was not abolished by high concentrations (1 mmol/L) of MAFP, a potent inhibitor of cPLA₂.³⁶,³⁷ (Figure 4). In addition, cPLA₂ activity levels from RSMCs activated by HDL were similar to those from controls (10.1±3.1 and 8.9±2.4 pmol·min⁻¹·mg⁻¹ protein, respectively).

Effect of Cycloheximide and Dexamethasone on Cox-2 mRNA Levels Induced by HDL

Cycloheximide (2 μg/mL, 3 hours), which inhibited PGI₂ release induced by HDL (the Table), produced a superinduction of Cox-2 mRNA, which was more significant in HDL than in control cells (saline or LDL-treated cells) (Figure 5A). In the presence of cycloheximide, dexamethasone efficiently inhibited superinduced Cox-2 mRNA levels in both control and HDL-treated cells (Figure 5B). These results indicate that de novo protein synthesis is not a requirement for the modulation of Cox-2 mRNA levels by HDL and dexamethasone. In contrast, cycloheximide prevented the inhibition by dexamethasone of Cox-2 mRNA levels induced by FCS.

Effect of an MAPK Kinase and PKC Inhibitors on PGI₂ Release Induced by HDL

PD98059 (30 μmol/L), a specific inhibitor of the activation of MAPK kinase,³⁸,³⁹ completely inhibited PGI₂ release induced by HDL in SMCs (Figure 6). In contrast, GF109203X (20 μmol/L), a protein kinase C (PKC) inhibitor,⁴⁰ had no effect on PGI₂ release induced by HDL. However, the effect of PD98059 and GF109203X on HDL-induced Cox-2 mRNA levels was negligible (data not shown).

Discussion

Previous reports have indicated that the levels of PGI₂ release by cells treated with HDL depend, at least in part, on HDL

Figure 3. Effect of dexamethasone (Dex) on Cox-2, Cox-1, and cPLA₂ protein levels. RSMCs were pretreated with ASA (300 μmol/L) and then incubated with medium alone or with HDL (150 μg cholesterol per mL) in the presence or absence of dexamethasone (2 μmol/L) for 6 hours. LDL (150 μg cholesterol per mL) was used as a control. Cox-1, Cox-2, and cPLA₂ protein levels were analyzed by Western blot as described in Methods. Results are representative of 3 experiments. The migration of molecular-weight markers used to estimate size is indicated on the left.

Figure 4. Effect of MAFP on PGI₂ release in response to HDL stimulation. RSMCs were treated with ASA (300 μmol/L) for 30 minutes and then preincubated with MAFP (1 mmol/L) for 30 minutes before addition of medium alone or with HDL (300 μg cholesterol per mL). After 3 hours of stimulation, the levels of 6-keto-PGF₁α in the supernatants were measured by EIA. Results are expressed as ng/mL 6-keto-PGF₁α and are shown as mean±SEM.

Figure 5. A, Effect of HDL on Cox-2 mRNA levels in the presence or absence of cycloheximide. ASA-pretreated cells were incubated with lipoproteins (150 μg cholesterol per mL) in the presence or absence of cycloheximide (2 μg/mL). FCS (20%) was used as a positive control. After 3 hours of incubation, total RNA was isolated and analyzed by Northern blotting. Membranes were sequentially hybridized with Cox-2 and 28S ribosomal RNA (rRNA) DNA probes. B, Effect of dexamethasone (Dex) on Cox-2 mRNA levels. ASA-pretreated cells were incubated with HDL in the presence of cycloheximide (Chx., 2 μg/mL) and in the presence or absence of dexamethasone (2 μmol/L). FCS (20%) was used as a positive control. After 3 hours of incubation, total RNA was isolated and analyzed by Northern blotting. Membranes were sequentially hybridized with Cox-2 and 28S ribosomal RNA (rRNA) DNA probes.
cholesteryl arachidonate content. We have recently shown that HDL increases eicosanoid production in RSMCs by a Cox-2–dependent mechanism. We now report that in RSMCs, rabbit HDL promotes PGI₂ release through both preexisting and induced Cox activity. HDL₁ is more effective than HDL₂ in inducing PGI₂ release, although both HDL fractions induce similar levels of Cox-2 protein. HDL₁ has a higher cholesteryl arachidonate content than does HDL₂ and thus, the former may provide a larger supply of substrate for Cox enzymatic activity. On the other hand, ASA pretreatment significantly reduced PGI₂ release induced by HDL. Thus, HDL may promote SMC PGI₂ synthesis acting as a substrate donor and as an inducer of Cox-2.

The prominent role of Cox-2 over Cox-1 in HDL-induced PGI₂ release has been suggested by the effectiveness of NS-398, a selective Cox-2 inhibitor; in addition, inhibition of both Cox isoforms with ASA only slightly augmented the effect produced by NS-398 or dexamethasone. However, a coordinate induction of Cox-2 and cPLA₂ has been reported in many cell types and it appears that glucocorticoids can inhibit Cox-2 only but also Cox-1 and cPLA₂ activities. cPLA₂ is an arachidonoyl-selective PLA₂ involved in PGI₂ synthesis induced by cytokines and growth factors in several cell types. A possible involvement of Cox-1 and cPLA₂ could therefore not be ruled out. In this article, we show that Cox-2 protein levels but not those of Cox-1 or cPLA₂ were induced by HDL. HDL did not increase cPLA₂ activity in RSMCs, and high concentrations of MAFP, a potent inhibitor of cPLA₂, did not inhibit PGI₂ release induced by HDL. Moreover, dexamethasone reduced the PGI₂ release induced by HDL basically through the inhibition of Cox-2 mRNA and protein levels without affecting cPLA₂ and Cox-1 protein levels. Thus, cPLA₂ does not seem to be a rate-limiting enzyme in the HDL effect on PGI₂ release.

Figure 6. Effect of PD98059 and GF109203X on PGI₂ release in response to HDL stimulation. RSMCs were treated with ASA (300 μg/mL) for 30 minutes and then preincubated with PD98059 (30 and 50 μg/mL) or GF109203X (0.5 and 20 μg/mL) for 30 minutes before addition of medium alone or with HDL (150 μg cholesterol per mL). After 3 hours of stimulation, the levels of 6-keto-PGF₁α in the supernatants were measured by EIA. Results are expressed as ng/mL 6-keto-PGF₁α, and are shown as mean ± SEM. (Deviations <3% of the mean do not appear in the computer-originated graphs.)

fact, the slow and progressive time course of HDL-induced PGI₂ synthesis differs markedly from the rapid effects of the phospholipase activators. To further characterize the mechanism by which HDL upregulates Cox-2 mRNA levels, we analyzed whether de novo protein synthesis was a requirement. Cycloheximide, a protein synthesis inhibitor, did not block HDL induction of Cox-2 mRNA levels, suggesting a mechanism independent of de novo protein synthesis. In contrast, cycloheximide potentiated the HDL upregulation of Cox-2 mRNA levels. The superinduction of Cox-2 mRNA levels and other early genes by cycloheximide has been previously shown. Several mechanisms have been proposed to explain the superinduction by cycloheximide of inducible mRNAs, including inhibition of the mRNA degradation machinery. Dexamethasone can block Cox-2 by transcriptional and posttranslational mechanisms. Our results show that dexamethasone did not inhibit Cox-2 mRNA levels induced by FCS in the presence of a protein synthesis inhibitor (cycloheximide). It has been shown that RNA and protein synthesis inhibitors reverse the effect of dexamethasone, suggesting that dexamethasone inhibition is mediated by 1 or more newly synthesized proteins. However, in the presence of cycloheximide, dexamethasone efficiently inhibited Cox-2 mRNA levels induced by HDL. Thus, dexamethasone could inhibit HDL-induced Cox-2 mRNA levels by acting mainly at the transcriptional level. Indeed, a potential glucocorticoid response element has been described in the Cox-2 gene. HDL activates a number of signaling pathways whose role in its cellular effects (intracellular cholesterol efflux, PGI₂ release, cell proliferation, etc) is not completely understood. We show that the MAPK pathway is involved in the HDL-induced PGI₂ release. Our present results with GF109203X and previous data with calphostin C, 2 specific inhibitors of PKC, suggest that HDL-induced PGI₂ release is signaled through MAPK activation, independent of PKC. Although PKC and MAPK activations are interrelated, some Cox-2 inducers work by a PKC-independent mechanism. Recently, several authors have shown data linking the MAPK pathway, but not that of PKC, to PGI₂ production induced by different molecules. In contrast, PKC seems to play a key role in HDL-induced cholesterol efflux. However, neither GF109203X nor PD98059, a specific inhibitor of MAPK kinase, was able to block the early upregulation of Cox-2 mRNA levels by HDL; thus, alternative signaling could be involved in the process. Taking into consideration that the MAPK pathway is usually linked to different cellular processes triggered by receptors and that purified apo A-I reproduces the binding parameters of HDL, partially mimics the HDL effect on PGI₂ synthesis, this HDL effect could be receptor mediated.

Eicosanoids are a widespread lipid-mediator system for intracellular signaling and hence, have multiple cellular actions such as regulation/modulation of vessel tone, platelet and neutrophil function, and fibrinolysis. Thus, it is not surprising that numerous events in the pathogenesis of atherosclerosis are associated with an altered formation of eicosanoids. HDL could exert its protective effect against coronary artery disease, at least in part, through the upregulation of PGI₂ biosynthesis. HDL would act through a multiple mechanism: providing substrate to the preexisting
and/or de novo Cox enzyme, inducing de novo synthesis of Cox-2 protein, and stabilizing the induced PGI$_2$. Plasma HDLs can contact directly with vascular SMCs when an atherosclerotic plaque or a healthy vessel suffers endothelial denudation. Cox-2 induction may thus contribute to the cardiovascular protection exerted by HDL as part of a defense mechanism triggered to limit the deleterious effect of minimal damage to the vessel wall. Supporting this hypothesis, previous reports have demonstrated that augmenting PGI$_2$ synthesis in angioplasty-injured carotid arteries resulted in inhibition of thrombosis. Although further studies are needed to understand the contribution of the different HDL effects to its protective cardiovascular properties, the present analysis provides new light on the mechanism by which HDL increases PGI$_2$ production in vessel wall cells.

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