LDL Increases Inactive Tissue Factor on Vascular Smooth Muscle Cell Surfaces

Hydrogen Peroxide Activates Latent Cell Surface Tissue Factor

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Background—Tissue factor, which is required for the initiation of the extrinsic coagulation cascade, is known to be upregulated in cells within atherosclerotic lesions, including smooth muscle cells. Tissue factor expression on the smooth muscle cell surface could be of pathological significance as a contributor to plaque growth, thrombus formation, and the acute coronary syndrome after plaque rupture.

Methods and Results—In this study, we show that LDL increased tissue factor mRNA and cell surface protein in smooth muscle cells without a marked increase in surface tissue factor activity. Hydrogen peroxide activated tissue factor on the cell surface but did not increase tissue factor mRNA or cell surface protein. Sequentially added LDL and hydrogen peroxide increased mRNA, cell surface protein, and activity; surface activity was greater than that observed with hydrogen peroxide alone. The action of hydrogen peroxide did not involve a regulatory mechanism associated with the cytoplasmic tail of tissue factor because a truncated tissue factor lacking the cytoplasmic tail was activated by hydrogen peroxide.

Conclusions—These results suggest a novel 2-step pathway for increased tissue factor activity on smooth muscle cell surfaces in which lipoproteins regulate synthesis of a latent tissue factor and oxidants activate the protein complex. (Circulation. 1999;99:1753-1759.)

Key Words: coronary disease ■ atherosclerosis ■ thrombosis ■ free radicals

Tissue factor binding to factor VII is the first step in the extrinsic pathway of blood coagulation. Interest in the role that tissue factor expressed by smooth muscle cells (SMC) may play in atherosclerotic lesion growth, restenosis after angioplasty, and acute coronary syndrome has been heightened by multiple observations. Wilcox et al1 showed that tissue factor is expressed by mesenchymal cells in the SMC-rich media of carotid endarterectomy specimens1 but not in the media of normal vessels. These observations have been supported in studies on the atherosclerotic plaques of cholesterol-fed rabbits2 and humans.3-5 In addition, SMC in arteries of normolipemic rats upregulate tissue factor expression within 2 to 6 hours after balloon injury.6 SMC expression of tissue factor may thus be important in disease complications. In acute coronary syndrome, increased thrombin could promote coagulation after plaque rupture; in restenosis or atherosclerosis, increased thrombin could stimulate SMC proliferation.7

Accumulation of LDL in focal arterial sites is a known precursor of atherosclerosis. It has been postulated that atherosclerotic lesion development is promoted in response to the accumulation of LDL in the vessel wall coupled with the presence of mediators of lipid and lipoprotein oxidation.8 Evidence for generation of oxidants in early lesions includes (a) that the cell types present, endothelial cells, SMC, and macrophages, have all been shown to be capable of oxidizing lipids and lipoproteins in vitro,9,10 (b) lipid hydroperoxide constituents of oxidized LDL and lesions can promote peroxidation of cellular lipids,11,12 and (c) inflammatory phagocytes known to produce hydrogen peroxide reside in lesions.13,14

Various agents, including serum, thrombin, angiotensin II, and platelet-derived growth factor have been shown to induce tissue factor activity in SMC in vitro;5 however, little is known about the effects of the lesion constituents, LDL, and reactive oxygen species on tissue factor expression in these cells. To understand further the regulation of tissue factor in SMC, we investigated the effects of LDL and hydrogen peroxide on the surface expression and activity of tissue factor.

Methods

Tissue Culture

SMC were prepared from explants of excised aortas of Sprague-Dawley rats and samples of human aorta as previously described.16 Cultures from passages 4 to 10 were used in these studies. Forty-
eight-well plates were seeded with ~25,000 cells per well in DMEM containing 10% fetal bovine serum (FBS). One day after seeding, the medium was changed to serum-free DMEM after being washed twice with PBS. All cells were in serum-free DMEM for 48 hours before the addition of the agonist of interest, as previously described. Lipoprotein Isolation

Human LDL was isolated from citrated plasma by differential ultracentrifugation between solvent density limits of 1.019 to 1.063 g/mL, as previously described. EDTA at 4°C until use to inhibit oxidation. Preparations were assayed for total cholesterol (Boehringer Mannheim Diagnostics kit #236691) and total protein. Native LDL preparations were stored in 0.5 mmol/L EDTA at 4°C until use to inhibit oxidation.

Cell surface tissue factor activity was assessed with a 2-step amidolytic assay as previously described. After each well was washed twice with PBS, a reaction mixture containing 0.125 mL of 2 mg/mL S-2222 (Pharmacia-ATPAR), and 20 μL containing 0.5 Factor VII units of Proplex T (Human Factor VII and Human Factor X. Baxter Biotech) was added to each well. Standards containing the same reaction mixture with varying amounts of rabbit brain thromboplastin (Sigma) were also prepared. One unit of tissue factor activity was defined as the amount of activity contained in 0.1 μL of resuspended rabbit brain thromboplastin. The reaction mixture remained on cell layers for ~20 minutes. Aliquots of the media were pipetted into 96-well plates and read, along with the standards, on a spectrophotometer at 405 nm. The tissue factor activity in each well was then calculated by use of the standard curve.

Total cellular RNA was extracted by the guanidine isothiocyanate-cesium chloride method. Samples of total RNA (10 μg) were separated on a 1% agarose/2.2 mol/L formaldehyde gel and subsequently blotted onto Magna nylon membrane with 20×SSC by capillary transfer according to previously published methods.

The RNA was cross-linked to the membrane with an ultraviolet cross-linker (Stratagene). The blots were prehybridized overnight to 6 hours at 42°C in 50% formamide, 1% SDS, 5× SSC, 1×Denhardt’s solution (0.02% Ficoll, 0.02% BSA, 0.02% polyvinylpyrrolidone), 0.25 mg/mL denatured salmon sperm, and 50 μg/mL sodium phosphate (pH 6.5) and then hybridized with 2×10^6 cpm/mL of (α-32P) dCTP radiolabeled cDNA plasmid probe for rat tissue factor (generous gift from Dr Mark Taubman, Mount Sinai School of Medicine, New York, NY) at 42°C for 16 to 24 hours. After hybridization, blots were washed with 0.1% SDS, 2×SSC for 30 minutes at 65°C, followed by 2 washes with 0.1% SDS, 0.1×SSC for 30 minutes at 65°C. The blots were then exposed to XAR-5 x-ray film with intensifying screens at ~70°C. Expression of glyceraldehyde 3-phosphate dehydrogenase mRNA was used as an internal control for the quantity of total mRNA on each lane of the gel, and this control was applied in all experiments. Mutant Tissue Factor Preparation and Transfection

For transfection of wild-type tissue factor cDNA, rat full-length cDNA in pBluescriptSK (Stratagene) was subcloned into PCDNA3 vector (Invitrogen). To obtain mutant tissue factor without the cytoplasmic tail, the coding for the cytoplasmic cysteine (residue 276) was mutated to a stop codon with the following oligonucleotides and polymerase chain reaction amplification of the full-length rat cDNA of tissue factor in pBlue-scriptSK: forward: 5′-GGG GAT CCA CCT TCA TCC CCA TGC GC-3′; reverse: 5′-GGG GAT CCT CAC AGA GAT ATG TGT AGC AG-3′. The polymerase chain reaction product was subcloned into the BamHI site of PCDNA3, and the orientation of the insert was determined by restriction analysis. The forward construct was in vitro translated to verify the product by translation into TnT-coupled reticulocyte lysate (Promega). The blots were then exposed to XAR-5 x-ray film with intensifying screens at ~70°C. Expression of glyceraldehyde 3-phosphate dehydrogenase mRNA was used as an internal control for the quantity of total mRNA on each lane of the gel, and this control was applied in all experiments.

After exposure of cells to a given condition, cell layers were washed twice with PBS; rabbit anti-human tissue factor polyclonal antibody (American Diagnostics, Greenwich, Conn) at 0.5 μg/mL in DMEM was added to cell layers at 4°C for 2 hours to bind only cell surface tissue factor. Total cellular protein was immunoprecipitated from 20 μg of total cellular protein (modified Lowry protocol) by incubating with 20 μL of protein A sepharose-linked beads (Sigma) for 2 hours at room temperature. Protein A sepharose beads were washed twice with RIPA buffer, then incubated with 2×lamelli buffer with β-mercaptoethanol and heated for 3 minutes at 80°C. Supernatants from the beads were analyzed by SDS-PAGE with 10% acrylamide gels. Gels were blotted to membranes. Membranes were blocked with 5% milk powder and 0.1% Tween for 30 minutes, followed by 45 minutes of primary antibody (0.5 μg/mL rabbit anti-human tissue factor. American Diagnostics) in PBS containing 5% milk powder and 0.1% Tween and then washed 3 times in PBS and 0.1% Tween for 10 minutes. A 1:4000 dilution of a peroxidase-labeled secondary antibody (goat anti-rabbit IgG, Boehringer Mannheim, Indianapolis, Ind) was then added for 45 minutes. The blot was washed an additional 3 times and the signal was developed on film after reacting with ECL (Amersham, Buckinghamshire, England) with exposure to film for 10 to 30 seconds.

Statistics

Data are presented as mean±SD. All comparisons were made with the use of ANOVA and the statistical package SPSS 8.0 (SPSS Inc).

Results

Effects of LDL and Hydrogen Peroxide on Surface Tissue Factor Activity

Quiescent rat aortic SMC were incubated with LDL (200 μg protein/mL), H2O2 (1 mmol/mL), or FBS (10%, used here as a positive control) for 4 hours with the use of a protocol previously used to examine tissue factor induced by serum and other growth factors. FBS and hydrogen peroxide significantly increased surface tissue factor activity, but LDL did not (Figure 1). LDL also did not markedly increase surface tissue factor activity after exposures of up to 24 hours (data not shown). Hydrogen peroxide caused a marked increase in surface tissue factor activity in a time- and concentration-
Hydrogen peroxide but not LDL significantly increases cell surface tissue factor activity (Figure 1). No grossly apparent morphological changes suggestive of cell injury were noted by light microscopy at H$_2$O$_2$ concentrations of $\leq 1$ mmol/L. The hydrogen peroxide–induced increase in surface tissue factor activity was maximal at 2 hours (Figure 2A). In contrast, tissue factor activity in response to FBS was maximal at 4 to 6 hours, consistent with previous reports by others. These distinct kinetics suggested that hydrogen peroxide and serum caused an increase in cell surface tissue factor activity by different mechanisms.

**Effects of LDL and H$_2$O$_2$ on Tissue Factor mRNA and Surface Protein Expression**

To understand further the mechanism of tissue factor induction by H$_2$O$_2$, Northern blot analysis of tissue factor mRNA was undertaken. FBS and LDL significantly increased steady-state tissue factor mRNA in rat aortic SMC at 90 minutes, but H$_2$O$_2$ did not (Figure 3), even at concentrations that markedly increased tissue factor activity. Furthermore, H$_2$O$_2$ did not increase tissue factor mRNA levels at 30 or 60 minutes (data not shown).

Antibody to rat tissue factor was not available. However, we were able to verify that human and rat SMC responded similarly in our system. H$_2$O$_2$ but not LDL enhanced cell surface activity in both species of SMC (data not shown). We therefore used human SMC to measure cell surface tissue factor protein by Western blot analysis after immunoprecipitation with anti-human tissue factor antibody (Figure 4). Tissue factor protein was found to be present on the surface of untreated SMC. Both FBS and LDL caused an increase in surface tissue factor protein expressed on SMC surface at 4 hours; H$_2$O$_2$ did not.

The above results suggested that LDL increased tissue factor gene expression, protein synthesis, and expression of inactive tissue factor protein on the cell surface. In contrast, H$_2$O$_2$ did not induce gene expression or increase tissue factor protein on the cell surface. Rather, H$_2$O$_2$ appeared to activate a latent form of surface tissue factor protein. To test this hypothesis, we treated cells with LDL for 4 hours to increase tissue factor surface protein and

**Figure 1.** Hydrogen peroxide but not LDL significantly increases cell surface tissue factor activity: Cell surface tissue factor activity in quiescent rat aortic SMC 4 hours after addition of LDL (200 µg protein/mL), FBS (10%), or hydrogen peroxide (1 mmol/L). Data represent mean±SD of 4 wells per treatment. *P<0.05 compared with no treatment (NT) or native LDL.

**Figure 2.** Hydrogen peroxide significantly increases surface tissue factor activity in a time- and concentration-dependent fashion. A, Quiescent cells were treated with hydrogen peroxide (0.5 mmol/L, ○) or FBS (10%, □) for the specified periods of time before assessment of cell surface tissue factor activity. *P<0.05 compared with 0 hours. B, Hydrogen peroxide was added at specified concentrations and tissue factor surface activity was assayed 2 hours later. Concentrations >1 mmol/L (not shown) resulted in morphological changes in SMC suggestive of cell injury at 2 hours. Data represent mean±SD of 4 wells per treatment.

**Figure 3.** LDL but not hydrogen peroxide significantly increases tissue factor mRNA levels at 90 minutes: Northern blot analysis of tissue factor mRNA 90 minutes after addition of FBS (10%), LDL (200 µg protein/mL), or H$_2$O$_2$ (0.5 mmol/L) or in the absence of these treatments. Duplicate blots were hybridized for GAPDH to verify equal mRNA loading.

**Figure 4.** LDL but not hydrogen peroxide significantly increases surface tissue factor protein at 4 hours: Western blot analysis of immunoprecipitated human SMC surface tissue factor protein 2 hours after addition of H$_2$O$_2$ (0.5 mmol/L) or 4 hours after addition of FBS (10%) or LDL (200 µg protein/mL) or in the absence of these treatments (NT). Rabbit brain thromboplastin (RBT) is shown as a standard.
added H$_2$O$_2$ for the final 2 hours in an attempt to “activate” the LDL-enhanced level of latent tissue factor protein. The cells that received combined treatment with LDL and H$_2$O$_2$ had significantly more surface tissue factor activity than those treated with H$_2$O$_2$ alone (Figure 5). As expected, LDL alone did not increase activity.

Role of Cytoplasmic Domain of Tissue Factor on H$_2$O$_2$ Activation

In an initial step to explore the molecular mechanism underlying H$_2$O$_2$ activation of surface tissue factor protein, we evaluated the role of the cytoplasmic tail of the tissue factor molecule. That the cytoplasmic tail would contain sites for H$_2$O$_2$ regulation was suggested by reports that the cytoplasmic tail contains a cysteine residue near the inner leaflet of the plasma membrane that is palmitoylated$^{24,25}$ In addition, the cytoplasmic tail has been shown to contain at least 3 phosphorylation sites,$^{26}$ the significance of which are unknown. We therefore tested whether hydrogen peroxide activation required regulatory elements in the cytoplasmic tail. We made and expressed in bovine aortic endothelial cells (BAEC) and bovine aortic SMC (BASMC) cDNA encoding wild-type human tissue factor and a mutant tissue factor TF(1-244), which lacked the cytoplasmic domain from cysteine 245 (residues 245 to 263). We chose bovine cells because it has previously been demonstrated that human factors VII and X, used in our activity assay, are poor substrates for bovine tissue factor.$^{27}$ We confirmed that BASMC and BAEC had minimal detectable basal and no detectable FBS-inducible or hydrogen peroxide–inducible surface tissue factor activity (Figure 6). BASMC transfected with cDNA for the wild-type or the mutant tissue factor yielded significant tissue factor activity (Figure 7). Cells transfected with cDNA for the mutant in the reverse orientation did not. Transfectants expressing either wild-type or the mutant cDNA lacking the cytoplasmic domain of the tissue factor molecule exhibited enhanced tissue factor activity with H$_2$O$_2$ treatment, demonstrating that activation does not require the cytoplasmic tail. Similar results were obtained in BAEC (Figure 7).

Discussion

Tissue factor is expressed on SMC and macrophages in human atherosclerotic lesions,$^{1,3-5}$ and it has been proposed that the resulting increase in local thrombin production could play a pivotal role in the development of thrombus in acute coronary syndrome$^5$ or promote smooth
muscle proliferation in atherosclerotic lesion growth or in restenosis after angioplasty. The goals of this study were to evaluate the effects of LDL and hydrogen peroxide on tissue factor gene expression and cell surface activity in aortic SMC. The concentration of LDL used to induce tissue factor mRNA and surface protein levels in our studies was well within a range that would be available in the interstitial fluid of an early lesion site in the arterial intima. Although the local vascular tissue concentration of hydrogen peroxide at the site of production by macrophages is unknown, the concentration range over which we observed tissue factor activation is similar to the range used by others to induce other biological functions in SMC, such as proliferation and alterations in calcium homeostasis.

Northern and Western blot analysis revealed that incubation of SMC with LDL increased the steady-state level of tissue factor mRNA and cell surface protein. Surprisingly, however, LDL did not markedly increase SMC surface tissue factor activity. In contrast, incubation of SMC with H2O2 increased surface tissue factor activity but caused no change in tissue factor mRNA or protein. It appears, therefore, that tissue factor may exist on the cell surface in an inactive state and that its activation may represent a separate, regulatable event. These findings have led us to propose a novel, 2-step pathway by which SMC tissue factor surface activity can be increased, a pathway that may have pathological consequences in early vascular lesion sites or vascular injury sites. The first step begins at the mRNA level, with LDL causing an increase in the accumulation of tissue factor mRNA leading to increased tissue factor protein synthesis and expression on the cell surface. The second step involves an H2O2-mediated posttranslational modification that activates the latent cell surface tissue factor. In this proposed pathway, tissue factor may exist on the cell surface in an inactive state and require activation before participation in the initiation of the extrinsic pathway.

The concept that tissue factor can exist in an inactive form has been proposed previously in a variety of contexts. Suggestions to explain the observations have included (a) that cellular pools of cryptic tissue factor exist, for example, in caveolae; (b) that activity is controlled by tissue factor interactions with tissue factor pathway inhibitor (TFPI); or (c) that activation of latent tissue factor can be regulated by changes in tissue factor quaternary structure. Several instances of cell perturbation, including mild trypsin treatment, sublytic detergent treatment, and apoptosis-related cell changes have been reported to enhance the activity of apparently latent tissue factor in various cell systems. Our results reveal that H2O2 also has the capacity to enhance activity of a preexisting inactive pool of cell surface tissue factor.

Oxidant effects on tissue factor have been previously reported; however, these are distinct from the sequence of events that we have observed. For example, Golino et al reported tissue factor induction by xanthine:xanthine oxidase in rabbit endothelial cells. However, their studies showed that reactive oxygen species induced synthesis of new tissue factor protein, distinguishing this from the oxidant pathway that we observed in SMC. In addition, copper treatment of human monocytes THP-1 cells yielded an antioxidant-inhibitable increase in tissue factor mRNA, protein, and activity. These studies, too, are distinct from the effects we have observed, in that in our SMC cultures the oxidant H2O2 did not increase mRNA over a wide range of time and concentration.

To begin to define a mechanism for the H2O2-mediated activation, we hypothesized that the increased activity was due to the oxidant influencing regulatory elements of the cytoplasmic tail, for example, one of the phosphorylation sites or the palmitoylated cysteine. Others have demonstrated that the cytoplasmic tail of tissue factor can be phosphorylated and that these sites are highly conserved among diverse species. The cysteine residue can be palmitoylated and is a potential site for regulating molecular interactions between tissue factor and the plasma membrane. Our results confirmed that the cytoplasmic tail is not required for tissue factor activity, but they further demonstrated that the cytoplasmic tail is not necessary for the hydrogen peroxide–mediated increase in surface tissue factor activity.

This negative finding is important because it confines H2O2 regulation of tissue factor activity to the transmembrane or, more likely, the extracellular domain. Hydrogen peroxide may act, for example, by altering the factor VII or factor X binding sites or by altering the local membrane milieu. The activity of tissue factor is known to be affected by the negative charge of the local phospholipid composition in the membrane. Phospholipids with a negative charge, such as phosphatidylycerine and phosphatidylethanolamine, are thought to increase the delivery of factor X to the tissue factor:factor VIIa complex. Certain oxysterols have been shown to increase tissue factor activity in monocytic THP-1 cells by increasing the amount of phosphatidylycerine in the outer leaflet. However, hydrogen peroxide treatment has been shown not to increase outer membrane phosphatidylycerine content in at least one cell system, the red blood cell, casting doubt on whether our observations are a result of such a membrane alteration.

TFPI is a glycoprotein known to bind to tissue factor and block its interaction with factors VII and X. It is possible that LDL, known to contain TFPI, could deliver TFPI to the SMC, blocking the activity of tissue factor, and that H2O2 may cause dissociation of surface tissue factor from TFPI. Oxidation of LDL in free solution has been reported to decrease TFPI activity. However, in our studies, H2O2 enhanced tissue factor surface activity even in the absence of added LDL (Figure 2), indicating that activation by H2O2 can occur in the absence of exogenously delivered TFPI. It is also possible that there is endogenous TFPI on the surface of SMC. TFPI has been reported on SMC surfaces and the kidney mesangial cell, a related mesenchymal cell, has been shown to produce TFPI. Further studies will be necessary to elucidate whether H2O2-mediated disruption of tissue factor–TFPI interactions on the SMC surface is responsible for our observations;
however, such an outcome would be consistent with our observations that activation is an extracellular event. We have made 2 novel observations in SMC related to the expression of tissue factor. We have shown that LDL increases tissue factor protein production and expression on the surfaces of both rat and human aortic SMC without an increase in tissue factor activity. We have also demonstrated for the first time that the extrinsic pathway of blood coagulation can be regulated at the cell surface by hydrogen peroxide. These findings may help to explain the observations that significant tissue factor expression is found in human atherosclerotic lesions, in which SMC, LDL, and \( \text{H}_2\text{O}_2 \)-producing macrophages are all present in abundance. Furthermore, the activation of latent tissue factor by reactive oxygen species may help to explain procoagulant events in reperfusion and coronary ischemia.

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