Augmentation of Synthesis of Plasminogen Activator Inhibitor Type-1 in Arterial Endothelial Cells by Glucose and Its Implications for Local Fibrinolysis

Thomas K. Nordt, Kevin J. Klassen, David J. Schneider, Burton E. Sobel

Because of the frequent occurrence of premature cardiovascular disease in patients with non-insulin-dependent, type II diabetes mellitus (NIDDM), the attenuated fibrinolytic activity of plasma from type II diabetic patients with increased concentrations of plasminogen activator inhibitor type-1 (PAI-1), and the fact that insulin stimulates synthesis of PAI-1 by human hepatic cells in vitro, we and others have hypothesized that accelerated vascular disease in type II diabetes may result in part from impaired fibrinolysis secondary to excessive elaboration of PAI-1 stimulated by insulin. Alternatively, the hyperglycemia associated with type II diabetes could influence the synthesis and secretion of PAI-1 directly. The present study was performed to determine whether PAI-1 secretion is or is not sensitive to the prevailing concentration of glucose in the conditioned medium of endothelial and liver cells, which are thought to be the major sources of circulating PAI-1 in vivo. Confluent cells were exposed to 0, 2.8, 5.6, 11.1, or 22.2 mmol/L (0, 50, 100, 200, or 400 mg/dL) glucose in medium without serum and subsequently to media with or without insulin (7.3 nmol/L). Secretion of PAI-1 by highly differentiated human hepatoma (Hep G2) cells did not increase as a function of increasing concentrations of glucose, whether or not insulin was present. In contrast, with pig aortic endothelial cells, the secretion of PAI-1 increased significantly with extracellular glucose with or without insulin. The increases in PAI-1 were specific (as shown by metabolic labeling experiments) and not attributable to osmotic effects (as shown by replacement of glucose by sorbitol). Furthermore, the changes were paralleled by a specific, significant increase in the concentration of PAI-1 mRNA. These results indicate that increases in PAI-1 activity in type II diabetic patients are likely to be attributable to direct effects of glucose on the synthesis of PAI-1 by arterial endothelial cells, in addition to the effects of insulin on the synthesis of PAI-1 by liver cells. The effects of glucose on endothelial cells may contribute to reduced local fibrinolysis, thereby exacerbating atherogenesis. (Arterioscler Thromb. 1993;13:1822-1828.)

Key Words • hyperglycemia • fibrinolysis • atherogenesis • atherosclerosis • cardiovascular disease • type II diabetes • non-insulin-dependent diabetes mellitus

Accelerated atherosclerosis is associated with diverse conditions in which insulin resistance and hyperinsulinemia are prominent, including type II, non-insulin-dependent diabetes mellitus (NIDDM).1 Because the activity of plasminogen activator inhibitor type-1 (PAI-1), the primary physiological inhibitor of tissue-type plasminogen activator (TPA) in plasma, is increased in NIDDM2-3 and because pathological concentrations of insulin stimulate PAI-1 synthesis in human hepatic cells (although not in human endothelial cells4-5), we and others have hypothesized that the accelerated atherosclerosis may be secondary, in part, to an unfavorable shift in the balance between thrombosis and fibrinolysis.5,7 Under conditions of such an imbalance, cells lining the vessel walls may be exposed inordinately to clot-associated mitogens that can potentiate the migration and proliferation of vascular smooth muscle cells,9 chemotaxis and activation of macrophages,9 and, accordingly, atherogenesis. Complex atherosclerotic plaques frequently contain components of thrombi,10 a phenomenon consistent with this mechanism.

If impaired fibrinolysis is a contributor to accelerated atherosclerosis in patients with NIDDM and other conditions characterized by insulin resistance, then elucidation of the mechanisms responsible should facilitate the development of effective strategies for retarding the otherwise accelerated atherosclerosis. Unfortunately, however, it is not clear whether the increases in activity of PAI-1 and its concentration in plasma are a consequence of augmentation of PAI-1 synthesis by factors other than hyperinsulinemia per se.11-16

We and others have shown that insulin increases PAI-1 synthesis directly in Hep G2 cells in vitro in concentrations that are seen in the plasma in patients...
with NIDDM. The present study was performed to determine whether or not increases in the concentration of glucose consistent with the hyperglycemia seen in NIDDM can influence PAI-1 synthesis directly. Because arterial and venous, fetal and adult endothelial cells may differ, we used adult aortic endothelial cells to simulate human arterial endothelial cells that are thought to be pivotal determinants of atherosclerosis.

Methods

Cell Cultures

Hep G2 cells were acquired from the American Type Culture Collection (Rockville, Md) and grown to confluence in minimum essential medium with Earle’s salts and L-glutamine (Life Technologies, Grand Island, NY) supplemented with 10% NuSerum (Collaborative Biomedical, Bedford, Mass), 30 U/mL penicillin, and 30 μg/mL streptomycin (Life Technologies). Monolayers of confluent cells were serum starved in Dulbecco’s modified Eagle’s medium with Ham’s nutrient mixture F-12 and N-2-hydroxyethylpiperazine-N’-2-ethanesulfonic acid (DME, Washington University Medical School Tissue Culture Support Center, St Louis, Mo) for 16 hours to permit PAI-1 synthesis to decline to basal levels. Cells were exposed to selected concentrations of glucose in glucose-free DME supplemented with cell culture-grade d-glucose (Sigma Chemical, St Louis, Mo). After serum starvation of the cells was complete, the medium was changed so that cells could be exposed to medium constituted with cell culture-grade bovine insulin (Sigma) first dissolved in distilled water with 1% glacial acetic acid (at 10 mg/mL insulin, according to the manufacturer’s recommendation) and then further diluted in DME with 10% fetal bovine serum (FBS, Life Technologies). The FBS was used to minimize the adherence of insulin to the storage and transfer devices. Its final concentration was 0.1%. Control experiments were performed with vehicle alone. All solutions and components were verified to be endotoxin free with the Limulus amebocyte assay (Pyrotell assay, Associates of Cape Cod, Woods Hole, Mass). Palmitic acid (Sigma) was dissolved in distilled water, suspended in 10% bovine albumin (final concentration), and used as an alternative energy source for the cells.

Aortic endothelial cells were harvested from aortas of farm pigs (30 to 60 kg) with the use of collagenase type 2 (Worthington Biochemicals, Freehold, NJ) according to a protocol approved by the Washington University Animal Studies Committee. They were grown to confluence in medium 199 (Life Technologies) with 20% FBS, 30 U/mL penicillin, 30 μg/mL streptomycin, and 50 μg/mL endothelial cell growth supplement (ECGS, Collaborative Biomedical) in positively charged cell-culture dishes (Polystyrene Plastek C, Tekmat, Ashland, Mass). Confluent cell monolayers were exposed to serum-free medium (DME with 50 μg/mL ECGS) for 48 hours to permit PAI-1 synthesis to decline to basal levels.

In conditioned media of both Hep G2 and pig endothelial cells, the concentrations of glucose were verified spectrophotometrically in assays with hexokinase and glucose-6-phosphate dehydrogenase (SVR Glucose Test, Behring Diagnostics, Somerville, NJ) and the use of a glucose autoanalyzer (Gemini, Electro-Nucleonics, Fairfield, NJ). The concentrations of glucose in cell-culture medium decreased slightly (by 0.9 to 1.3 mmol/L, or 17 to 23 mg/dL) over the 24 hours of incubation of endothelial cells. In conditioned media of Hep G2 cells, it declined by an average of 3.3 mmol/L (60 mg/dL) over 24 hours.

Experiments with pig endothelial cells were performed with cells in primary culture from one animal and repeated with primary cell cultures from different animals. Each type of experiment was performed in triplicate (ie, n=3 for each condition).

Quantification of PAI-1

Conditioned media from Hep G2 and endothelial cells were supplemented with Tween 80 (final concentration, 0.01%). Cellular debris was removed by centrifugation at 4°C. Samples of conditioned media were stored at −20°C until assay.

The concentration of PAI-1 antigen in conditioned medium from Hep G2 cells (active, latent, and TPA-complexed PAI-1) was measured by enzyme-linked immunosorbent assay (ELISA) (TintElize PAI-1, Biopool, Umeå, Sweden). Pig aortic endothelial cell PAI-1 antigen is not detected well with the ELISA used for the Hep G2 cell experiments. Because a suitable antibody for assay of porcine PAI-1 was not available, results with pig endothelial cells were obtained by spectrophotometric assay of PAI-1 activity with a chromogenic substrate, S-2251 (KabiVitrum, Stockholm, Sweden), plasminogen (Kabi, Mölndal, Sweden), and TPA (KabiVitrum).

Quantification of PAI-1 mRNA

After serum starvation for 2 days and subsequent incubation of the endothelial cells in fresh culture medium for an additional 24 hours, total cellular RNA was extracted with RNAzol B (Tel-Test, Friendswood, Tex) and chloroform (Fisher, Fair Lawn, NJ). RNA was precipitated by isopropanol (Fisher), washed with ethanol (Quantum, Tuscola, Ill), and fractionated by size on 1.5% formaldehyde agarose gels (5 μg). Northern blots were performed by prehybridization at 42°C for 6 hours and hybridization at 42°C for 20 to 24 hours. The 0.9-kb cDNA probe used for PAI-1 (EcoRI and Sal I digestion) and the 1.1-kb cDNA probe used for 18S ribosomal RNA (18S rRNA) (EcoRI and BamHI digestion) were random-prime labeled with [α-32P]dCTP (Amersham, Arlington Heights, Ill, and Boehringer Mannheim, Indianapolis, Ind). To ensure equal loading and transfer of RNA, staining with ethidium bromide was performed. The radioactivity of hybridized bands was quantified by radioisotopic scanning (AMBIS, Radioanalytic Imaging System, San Diego, Calif). Results were confirmed by autoradiography. To strip the probes, membranes were boiled in 10 mmol/L tris(hydroxy-methyl)aminomethane (Tris), pH 8.0; 1 mmol/L EDTA, pH 8.0; and 1% sodium dodecyl sulfate (SDS) for 10 minutes.

Quantification of Cellular DNA

After serum starvation for 2 days and incubation for an additional 24 hours, the endothelial cells were trypsinized, washed in ice-cold phosphate-buffered saline, and resuspended in digestion buffer (100 mmol/L NaCl; 10 mmol/L Tris-Cl, pH 8.0; 25 mmol/L EDTA,
Accumulation of PAI-1 by Hep G2 Cells Exposed to Selected Concentrations of Glucose

The concentrations of glucose were selected to be in the range between mild hypoglycemia (2.8 mmol/L) and severe hyperglycemia (22.2 mmol/L) in NIDDM. It was recognized prospectively that medium devoid of glucose might compromise PAI-1 synthesis nonspecifically because of deprivation of a substrate needed for energy for cell metabolism. Accordingly, our analysis of the potential response of PAI-1 synthesis to augmentation of the concentration of glucose focused on the changes elicited by concentrations >2.8 mmol/L (50 mg/dL).

Monolayers of confluent Hep G2 cells were exposed to 0, 2.8, 5.6, 11.1, 16.7, or 22.2 mmol/L (0, 50, 100, 200, 300, or 400 mg/dL) glucose in conditioned medium devoid of serum for 16 hours and in fresh media with or without insulin during subsequent incubations for 24 hours. PAI-1 synthesis was assayed after exposure of the cells either to 7.3 mmol/L (1000 μU/mL) insulin, a concentration to which hepatocytes are likely to be exposed in vivo by portal venous blood draining directly from the pancreas into the liver, or to vehicle alone. PAI-1 was assayed in conditioned medium to define the magnitude of increases induced by glucose or insulin.

The concentration of PAI-1 protein in conditioned medium did not increase when the concentration of glucose was increased from 2.8 to 22.2 mmol/L (Fig 1).
PAI-1 Activity in Conditioned Medium of Endothelial Cells

To determine whether endothelial cells behaved similarly to Hep G2 cells, pig aortic endothelial cells were exposed to 0, 2.8, 5.6, 11.1, and 22.2 mmol/L (0, 50, 100, 200, and 400 mg/dL) glucose while being serum starved for 2 days and subsequently while exposed to insulin for 24 hours. When glucose was present in concentrations of at least 2.8 mmol/L (50 mg/dL), the concentrations of glucose decreased slightly over the 24 hours of incubation. The decreases in concentrations of glucose observed (decreases of 1.3 mmol/L with 2.8 and 5.6 mmol/L glucose, 1.2 mmol/L with 11.1 mmol/L, and 0.9 mmol/L with 22.2 mmol/L) were similar to those seen by others.22

As shown in Fig 2, PAI-1 activity was 12.0 ± 2.4 arbitrary units (AU)/mL under basal conditions when glucose was absent from the conditioned medium. With 2.8 mmol/L glucose, PAI-1 activity increased to 16.6 ± 0.8 AU/mL, presumably because of the greater availability of energy for protein biosynthesis. Increases in the concentration of glucose to 5.6, 11.1, and 22.2 mmol/L led to further increases in PAI-1 activity in comparison with PAI-1 activity with 2.8 mmol/L glucose (23.0 ± 1.7 [P = .014], 26.4 ± 0.8 [P < .001], and 28.6 ± 2.0 AU/mL [P = .001], respectively). Insulin concentrations of 0.01, 0.1, and 1 mmol/L did not elicit additional increases of PAI-1 activity in conditioned medium. Even 7.3 mmol/L insulin (1000 μU/mL), a supraphysiological concentration, did not increase PAI-1 activity.

When sorbitol was substituted for glucose to simulate its osmotic effects (Fig 3), PAI-1 activity ranged from 11.9 ± 2.5 (with 5.6 mmol/L total concentration of glucose plus sorbitol) to 18.0 ± 0.9 AU/mL (with 11.1 mmol/L). With the highest amounts of glucose plus sorbitol, PAI-1 activity increased, but not significantly so (P = .081 with 22.2 mmol/L compared with PAI-1 with 2.8 mmol/L). Thus, sorbitol exerted no marked stimulation of PAI-1 synthesis. Accordingly, osmotic effects of glucose per se are not likely to substantially influence PAI-1 synthesis.

Effects of Glucose on the Concentration of PAI-1 mRNA in Endothelial Cells

Aortic endothelial cells were incubated with 2.8, 5.6, 11.1, or 22.2 mmol/L glucose (50, 100, 200, or 400 mg/dL) while being serum starved for 2 days and were subsequently exposed to fresh medium for 24 hours. Subsequently, RNA was extracted and assayed. Two species of PAI-1 mRNA (3.2 and 2.2 kb) were detected in cell lysates. The 3.2-kb form constituted approximately 95% of total PAI-1 mRNA.

As shown in Fig 4 and the Table, the concentration of total PAI-1 mRNA increased significantly when cells were exposed to increasing concentrations of glucose. The radioactivity detected increased from 159 ± 10 to 280 ± 12 counts per minute. In regular DME (with a concentration of 10 mmol/L glucose), 7.3 mmol/L insulin did not increase PAI-1 mRNA compared with that seen with DME without insulin over 24 hours, confirming the lack of an effect of insulin on PAI-1 activity.

To confirm the conclusion that increases in PAI-1 mRNA were not simply a result of an increased number of cells, we performed additional parallel experiments...
in which DNA was measured. The results are shown in the Table, with those of PAI-1 mRNA values normalized for DNA. The total amount of DNA per culture flask remained virtually constant regardless of the concentration of glucose. This observation is consistent with the results by Kaiser et al., who exposed confluent calf aortic endothelial cells to selected concentrations of glucose for 24 to 48 hours and saw no change in cell number. A decrease in cell number and thymidine incorporation was seen by Maiello et al., in human umbilical vein endothelial cells exposed to high concentrations of glucose. This decrease may have occurred because of the long incubations in medium (13±4 days for primary cultures).

To verify the consistency of loading and transfer of RNA to the membranes, additional experiments were performed in which 18S rRNA was quantified. The membranes with the size-fractionated RNA used for PAI-1 mRNA assay were stripped first because the 18S rRNA bands (at 1.9 kb) would have interfered with the 2.2-kb PAI-1 bands. Thus, after stripping, the membranes were rehybridized with a CDNA probe for 18S rRNA. No significant glucose-dependent changes in 18S rRNA concentrations were evident (Table). In fact, the PAI-1 mRNA to 18S rRNA ratio increased with increasing concentrations of glucose, indicative of a relatively specific effect of glucose on the concentration of PAI-1 mRNA.

**Effects of Glucose on Overall Protein Synthesis in Endothelial Cells**

Metabolic labeling of all newly synthesized protein was performed to identify potentially nonspecific effects of glucose on the synthesis of protein. Metabolic labeling was preferred to chemical quantification of total protein content in conditioned medium because of the possible interference by the protein in FBS in the conditioned medium that was used to avoid unspecific binding. Confluent pig aortic endothelial cells were serum starved for 2 days and stimulated with 7.3 mmol/L insulin or vehicle alone for the subsequent 23 hours in media with 2.8, 5.6, 11.1, or 22.2 mmol/L (50, 100, 200, or 400 mg/dL) glucose, 0.5 hour in methionine-free medium, and 1 hour in the same medium spiked with labeled methionine. These concentrations of glucose were maintained throughout the incubations with methionine-free medium and with the medium containing labeled methionine. At the midpoint of the incubation with labeled methionine, the duration of exposure of the cells to medium corresponded to that preceding harvesting of conditioned medium for assay of PAI-1 and harvesting of RNA in the experiments described above. Assay of cell lysates 1 hour and of conditioned media 24 hours after the addition of labeled methionine did not indicate any influence of changes in the concentration of glucose on protein biosynthesis. Exposure of the cells to insulin elicited a modest, nonsignificant increase in overall protein biosynthesis.

**Discussion**

The present study was performed to identify the potential contribution of hyperglycemia, as opposed to hyperinsulinemia, to the increases in PAI-1 in plasma seen in hyperinsulinemic, type II diabetic patients. Because the liver and endothelium are considered to be the primary sources of plasma PAI-1, we studied Hep G2 cells and pig aortic endothelial cells as model systems. The Hep G2 cell line is an "immortal," well-differentiated human hepatoma cell line that responds similarly to human hepatocytes in primary culture in terms of induction of PAI-1 synthesis by insulin. The pig aortic endothelial cells were used in primary culture only because secretion of PAI-1 by endothelial cells is consti-

### Table: Plasminogen Activator Inhibitor Type-1 mRNA in Endothelial Cells

<table>
<thead>
<tr>
<th>Glucose, mmol/L</th>
<th>PAI-1 mRNA, cpm</th>
<th>DNA, µg</th>
<th>PAI-1 mRNA to DNA Ratio, cpm</th>
<th>18S rRNA, cpm</th>
<th>PAI-1 mRNA to 18S rRNA Ratio, cpm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.8</td>
<td>159±10</td>
<td>19±2</td>
<td>159±10</td>
<td>548±130</td>
<td>159±10</td>
</tr>
<tr>
<td>5.6</td>
<td>232±3</td>
<td>20±2</td>
<td>220±3</td>
<td>525±21</td>
<td>242±3</td>
</tr>
<tr>
<td>11.1</td>
<td>260±8</td>
<td>20±2</td>
<td>247±8</td>
<td>571±64</td>
<td>250±8</td>
</tr>
<tr>
<td>22.2</td>
<td>280±12</td>
<td>22±3</td>
<td>241±10</td>
<td>525±117</td>
<td>292±11</td>
</tr>
</tbody>
</table>

*Plasminogen activator inhibitor type-1 (PAI-1) mRNA in pig aortic endothelial cells was exposed to 2.8, 5.6, 11.1, or 22.2 mmol/L (50, 100, 200, or 400 mg/dL) glucose during serum starvation for 48 hours followed by 24-hour incubations. Results are means±SE. PAI-1 mRNA values that are normalized for DNA contents and concentrations of 18S rRNA are shown in columns 4 and 6.*
tutively greater after initial passage.17 Differences in the regulation of TPA and PAI-1 in fetal compared with adult vascular endothelium and in arterial compared with venous cells17 led us to avoid using umbilical vein endothelial cells. Pig endothelial cells, rather than those from another species, were used because of the similarity of complex atherosclerotic plaques in pigs and humans.26 Human aortic endothelial cells could not be harvested in a sufficient number and quality for routine use.

PAI-1 secreted by the endothelial cells was measured as PAI-1 activity because of the lack of a suitable antibody detection system for the pig PAI-1 protein. We have previously shown with the use of Western blots that the changes in PAI-1 activity in conditioned medium of pig aortic endothelial cells induced by lipopolysaccharide as a strong agonist parallel the changes in PAI-1 protein (K.J. Klassen, unpublished data). With the use of Northern blots, we have demonstrated parallel changes in PAI-1 mRNA as in the present study. Thus, the changes in PAI-1 activity induced by glucose appear to reflect increased elaboration of PAI-1 rather than simply preservation of PAI-1 activity in conditioned medium. Possible species differences in the hybridization of the (human) PAI-1 cDNA probe to human and pig mRNA species cannot be excluded. However, such differences cannot account for the increase in PAI-1 mRNA seen in the pig aortic endothelial cells exposed to increasing concentrations of glucose.

Increases in the concentration of glucose in Hep G2 cells did not result in increases in secretion of PAI-1 into conditioned medium. In contrast, insulin in concentrations seen in portal venous blood in patients with hyperinsulinemic type II diabetes did increase secretion of PAI-1 at all concentrations of glucose above 0. Thus, it is unlikely that hyperglycemia in patients with type II diabetes contributes to the increased plasma levels of PAI-1, which appears to be derived from the liver.

When glucose was present in concentrations of at least 2.8 mmol/L (50 mg/dL) in the conditioned medium of pig aortic endothelial cells, the concentrations of glucose did not change appreciably over the 24 hours of incubation, in accord with the excess of substrate available for energy supply to the cultured cells. Increases in the concentration of glucose in the conditioned medium elicited an increase in PAI-1 activity. The effects observed with glucose were not attributable to changes in osmolarity, as judged from our results with sorbitol. The increase in PAI-1 activity was paralleled by an increase in PAI-1 mRNA even after normalization with respect to DNA or 18S rRNA, consistent with a specific effect of glucose that is mediated at the transcriptional level. These results are consistent with changes observed previously by others who have used higher concentrations of glucose (30 mmol/L, or 540 mg/dL) in human umbilical vein endothelial cells.23,27

Results of the present study show that glucose, in concentrations typically seen in diabetic patients (up to 22.2 mmol/L, or 400 mg/mL), induces striking effects. Furthermore, although venous endothelial cells may contribute to increased levels of plasma PAI-1 in NIDDM, the response we observed in arterial endothelial cells may exacerbate atherogenesis by locally reducing fibrinolysis.

Results of some but not all epidemiological studies have implicated hyperglycemia in NIDDM as a risk factor for atherosclerotic vascular disease. In 1979, the International Collaborative Group concluded that asymptomatic hyperglycemia should not be considered an independent risk factor for coronary artery disease or other major types of adult cardiovascular disease.28 Subsequently, increased mortality attributable to coronary artery disease has been attributed to hyperglycemia (Tecumseh Study29). Some have reported that both fasting4 and postprandial13 hyperglycemia are independent risk factors. Elevated HbA1c, an index of hyperglycemia over time, appears to be associated with an increased risk of coronary disease in women but not men in the Framingham Heart Study.16

Microvascular complications of diabetes such as retinopathy16 are associated with hyperglycemia. However, the pathophysiological link between NIDDM and macrovascular manifestations such as coronary artery disease remains obscure. We and others have considered the possibility that the hyperinsulinemia typical of NIDDM may be a significant contributor to macrovascular complications. Because insulin can increase expression of PAI-1 in cells of hepatic origin, even at high concentrations of glucose as shown in the present study, hyperinsulinemic subjects may be prone to excessive deposition or persistence of microthrombi secondary to attenuated fibrinolysis. This in turn may exacerbate atherosclerosis. In addition, as shown in the present study, glucose can increase the expression of PAI-1 in arterial endothelial cells. Thus, hyperglycemic diabetic patients may be at additional risk for accelerated atherosclerosis as a consequence of impaired fibrinolysis at the interface between the blood and the arterial wall. Accordingly, our results suggest that normalization of endogenous fibrinolysis may be possible by interdiction of potentially deleterious effects of both hyperinsulinemia and hyperglycemia on the fibrinolytic system.

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References


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