Increased Expression of Thrombospondin-1 in Vessel Wall of Diabetic Zucker Rat

Olga I. Stenina, PhD; Irene Krukovets, MS; Kai Wang, MD, PhD; Zhongmin Zhou, MD; Farhad Forudi, BS; Marc S. Penn, MD, PhD; Eric J. Topol, MD; Edward F. Plow, PhD

Background—Thrombospondin-1 (TSP-1) expression in the vascular wall has been related to the development of atherosclerotic lesions and restenosis. TSP-1 promotes the development of neointima and has recently been associated with atherogenesis at a genetic level. Because TSP-1 expression is responsive to glucose stimulation in mesangial cells, we hypothesized that glucose may stimulate its production by vascular cells. Thus, TSP-1 expression in the blood vessel wall may increase, providing a molecular link between diabetes and accelerated vascular lesion development.

Methods and Results—To determine whether the expression level of TSP-1 in vessel wall is increased in diabetes, aorta and carotid arteries of Zucker rats were used for immunostaining, Western blotting, and in situ RNA hybridization. A significant increase in TSP-1 expression was found in the adventitia of blood vessels from diabetic rats. Consistent with the well-known antiangiogenic effect of TSP-1, the number of vasa vasorum was reduced in aortas from diabetic rats. In cultured endothelial cells, vascular smooth muscle cells, and fibroblasts, TSP-1 expression increased in response to glucose stimulation (>30-fold). After balloon catheter injury to carotid arteries, expression of TSP-1 protein and mRNA was higher at all time points in the vessels of diabetic rats.

Conclusions—Increased expression of TSP-1 in blood vessels in diabetes may represent a new link between diabetes, atherogenesis, and accelerated restenosis. This increase in TSP-1 production may be a direct response of vascular cells to glucose. (Circulation. 2003;107:3209-3215.)

Key Words: diabetes mellitus ■ aorta ■ cardiovascular diseases ■ glucose
24 hours, 48 hours, 10 days, and 21 days after balloon catheter injury; these time points were chosen on the basis of published information on TSP-1 expression and development of neointima in Zucker rats. After anesthesia, a midline abdominal incision was performed, and the distal abdominal aorta was exposed. An 18-gauge intravenous catheter introduced at the aortic bifurcation was used to flush the aorta with 50 mL of Ringer’s lactate solution at 120 mm Hg. Then, vessels were harvested and fixed in 5% Histochoice (Amresco). Once the perfusion-fixation was started, the animals were killed with an overdose of Pentothal through the tail vein.

Detection of TSP-1 Expression in Vessel Wall of Zucker Rats

TSP-1 Immunostaining

Tissues were embedded into paraffin, and sections were stained with monoclonal anti-TSP-1 antibody (NeoMarkers, clone A6.1). TSP-1 expression was visualized with diaminobenzidine (DAB) chromogenic substrate. For every section, a negative control without anti-TSP-1 antibody was processed simultaneously. Staining of matching sets of tissues from lean and diabetic rats was done simultaneously. Sections were counterstained with hematoxylin and eosin (except von Willebrand factor [vWF] staining). vWF was visualized with anti-vWF antibody (Accurate Chem).

RNA Isolation and In Situ RNA Hybridization

RNA isolation was performed with TriZol reagent (Invitrogen). Biotinylated RNA probe was synthesized in vitro with the Riboprobe System T7/SP6 (Promega). The 5’ terminal fragment of TSP-1 (600 base pairs of clone TS-33 from ATCC) was subcloned into pGEM-T vector (Promega) and used to synthesize antisense and sense riboprobes. One hundred fifty nanograms of mRNA per slide was used for hybridization. Sections were fixed in 2% 3-aminopropylthriethoxysilane in acetone, and the endogenous peroxidase activity was blocked. Then the sections were deproteinized with 40 μg/mL proteinase K, fixed in 4% paraformaldehyde, and dehydrated. Hybridization was performed for 3 hours at 55°C; slides were washed in 0.2× SSC overnight, blocked with BSA, and incubated with streptavidin-peroxidase (Sigma). Staining was developed with DAB (Sigma), and slides were mounted with Vectashield (Vector).

Morphometry

Morphometric analysis of the arterial segments was performed with computerized digital microscopic planimetry software (Image-Pro Plus 4.5.1, Media Cybernetics).

Extraction of TSP-1 From Vessel Tissue

Tissues collected from lean and diabetic rats were homogenized in buffer containing 0.6% SDS, 5% Triton X-100, and protease inhibitors and incubated for 2 hours at 4°C. After 15 minutes of centrifugation at 15 000×g, the supernatants were used for Western blotting.

Stimulation of Cultured Cells With Glucose

Confluent human umbilical vein ECs, human aortic SMCs, and human foreskin fibroblasts were preincubated in 5 mmol/L glucose for 24 hours, then stimulated with 30 mmol/L cell culture–tested endotoxin-free (D+)-glucose for 0.5 to 48 hours. After incubation, cells were lysed in hypotonic buffer with 0.66% NP-40 and centrifuged at 12 000×g for 15 minutes. The supernatants were used for Western blotting (50 μg of protein per sample). Anti-TSP-1 antibody (NeoMarkers, clone A6.1) was used for TSP-1 detection.

Statistical Analysis

Values are mean±SEM. Probability values, derived with a t test, of ≤0.05 were considered significant.
TSP-1 mRNA Expression in Aorta and Carotid Artery of Zucker Rats

TSP-1 within the vessel wall might be synthesized by vascular cells, in which case TSP-1 mRNA would be present in the vessel wall. Alternatively, TSP-1 in the vessel wall might be derived from platelets, which are highly activated in diabetes and are a rich source of TSP-1. We sought to detect TSP-1 mRNA by in situ hybridization in uninjured aortas and carotid arteries (Figure 2). There was no hybridization with sense TSP-1 RNA used as a negative specificity control (Figure 2C). Little staining was detected with anti-sense TSP-1 RNA in vessels of lean rats; however, in diabetic rats, mRNA expression was increased dramatically in the cells of both the adventitia and media (Figure 2B), and this was confirmed by quantification of the staining intensity (Figure 2D).

TSP-1 Expression in Vascular Cells Stimulated by Glucose

We used cultured vascular cells to consider whether glucose might directly stimulate TSP-1 expression. Three major cell types present in the vessel wall (ECs, SMCs, and fibroblasts) were stimulated with 30 mmol/L glucose for different times. All 3 cell types responded to glucose by increasing their expression of TSP-1 protein (Figure 3). The stimulation of TSP-1 production by glucose was consistent and significant; at 24 hours, in ECs, TSP-1 levels increased 12.9 ± 7.2-fold (P=0.05), and in SMCs, they increased 7.2 ± 3.8-fold (P=0.001) as quantified by densitometric scans of Western blots (Figure 3B). The most dramatic effect was seen with the fibroblasts; the 30.5 ± 13.6-fold (P=0.017) increase is consistent with the presence of TSP-1 in the adventitia of diabetic vessels, where these cells predominate. Glucose produced a more pronounced effect than sorbitol, which indicates that the increase was not simply due to a change in osmolarity. mRNA was isolated from cells stimulated with glucose and used for Northern blotting. mRNA levels increased after 6 hours in all 3 cell types in response to glucose stimulation, reaching a maximum by 24 hours (Figure 4A).

Even though glucose levels in the blood of diabetic patients may be regulated, they still fluctuate, as indicated by the presence of glycation products in vascular wall in diabetics. As shown in Figure 4B, even short-term (30 minutes to 3 hours) exposure of fibroblasts to high glucose is sufficient to stimulate TSP-1 mRNA levels 24 to 48 hours later.

Vasa Vasorum in the Aorta of Diabetic Zucker Rats

A well-established function of TSP-1 is its antiangiogenic activity (reviewed elsewhere), and its increased expression in the adventitia of diabetic rats may result in inhibited development of the vasa vasorum, capillaries within the walls of large blood vessel. A decreased blood supply could create ischemic conditions in the inner layers of large blood vessels that contribute to SMC proliferation and atherosclerotic lesion progression. To determine whether there is an inverse correlation between the number of capillaries in aortas of diabetic rats and the level of TSP-1 in adventitia, we visualized ECs with anti-vWF immunostaining. A marked difference in immunostaining for vWF in uninjured aortas from lean and diabetic rats was noted (Figure 5A) and was confirmed quantitatively (Figure 5B). The area of immunostaining in aortas (excluding luminal endothelium and intercostal arteries) was 3.1-fold less in diabetic than lean rats (P=0.028). The mean intensity of immunostaining, which reflects the amount of vWF produced per cell, was the same (169 ± 22.4 in aortas from lean rats and 168 ± 22.4 in aortas from diabetic rats), which suggests that vWF expression per cell did not change in diabetic animals.

TSP-1 mRNA and Protein Expression in Carotid Arteries of Lean and Diabetic Zucker Rats After Balloon Catheter Injury

To examine TSP-1 expression in diabetic vessels after injury, balloon catheterization was performed on lean and diabetic rats. Right (injured) and left (uninjured) carotid arteries were...
collected at various times, and in situ hybridization was performed to visualize TSP-1 mRNA (Figure 6). Injury of the carotid artery of lean rat resulted in an increase in TSP-1 mRNA levels 24 hours after injury, which was sustained for up to 10 days. In diabetic vessels, in which mRNA levels were increased before injury, a rapid and marked downregulation of mRNA occurred within 6 hours after injury (Figure 6D). However, mRNA levels then increased by 24 hours after injury and remained elevated compared with nondiabetic vessels thereafter (2.5-fold at 24 hours \([P = 0.034]\), 3-fold at 48 hours \([P = 0.0005]\), 2.2-fold at 10 days \([P = 0.01]\), and 4-fold at 21 days \([P = 0.0001]\); Figure 7).

Extracts from injured arteries were subjected to Western blotting to detect TSP-1 (Figure 8). The extracts from

---

**Figure 3.** Glucose stimulation of TSP-1 expression in cultured vascular cells. ECs, SMCs, and fibroblasts (F) were stimulated with 30 mmol/L glucose for different times, and TSP-1 in cell lysates was detected by Western blotting. Equal loading was controlled by staining of membrane with Coomassie (A). Evaluation of relative TSP-1 amounts was done by densitometry of at least 4 blots for each cell type with NIH Image program (B). F indicates fibroblasts.

**Figure 4.** Increased mRNA expression in cultured vascular cells after glucose stimulation. Cells were stimulated with glucose as described in Methods and Figure 3, and isolated RNA (15 μg/sample) was used for Northern blotting. Ethidium bromide staining of ribosomal RNA was used to control RNA loading in samples (A). After 3-hour stimulation with glucose, cells were washed 2 times, and new growth medium was added for 48 hours. mRNA was then isolated and used for Northern blotting (B). HFF indicates human foreskin fibroblasts; HASMC, human aortic SMCs; and HUVEC, human umbilical vein ECs.
noninjured arteries of lean rats did not contain detectable TSP-1. At 48 hours after injury, TSP-1 of the expected size was detected, and trace amounts remained for up to 21 days after injury. In diabetic rats, TSP-1 was present in noninjured arteries; its levels were higher than in vessels from lean rats at all time points after injury, and it was still clearly detectable 21 days after injury (Figure 8).

Discussion
There are several lines of published evidence that suggest a relationship between TSP-1, diabetes, and atherosclerosis. Surprisingly, there is no direct information on TSP-1 expression and distribution in the vessel wall in diabetes, and the goal of the present study was to provide these missing data. We used Zucker rat, a model of type II diabetes that is known to respond to mechanical injury with accelerated restenosis and to proatherogenic stimuli with changes characteristic of early atherogenic response.19,25–27 The detection of TSP-1 in the vessel wall by immunohistochemistry and Western blotting demonstrated that its level was increased markedly in diabetic compared with nondiabetic vessels, and the TSP-1 protein accumulated primarily in the adventitia.

The increased levels of TSP-1 mRNA in diabetic vessels suggest that TSP-1 is synthesized by vascular cells rather than being derived from activated platelets. The capacity of vascular cells to respond to glucose by increasing TSP-1 production was demonstrated with cultured ECs, SMCs, and fibroblasts. With each cell type, the expression of TSP-1 increased dramatically on glucose stimulation. These results are not only compatible with the in vivo observations but also suggest that glucose itself may be the stimulus of enhanced TSP-1 production. TSP-1 mRNA may be regulated by glucose at the transcriptional or mRNA stability levels; both types of regulation have been implicated in the regulation of gene expression by glucose. Remarkably, short-term stimulation with glucose resulted in prolonged production of TSP-1.
mRNA. This observation may be particularly pertinent to diabetic patients, who experience fluctuations in glucose levels.

The present data describing the increased expression of TSP-1 in large vessels in response to high glucose complement the information on the role of TSP-1 in diabetic complications. TSP-1 was suggested to influence diabetic nephropathy and diabetic retinal vasculopathy. Thus, TSP-1 may be centrally involved in regulating the development of vascular complications in diabetes. However, the relationship between high glucose and TSP-1 expression is complex; unlike in mesangial cells and large vessels, TSP-1 is downregulated in the diabetic eye and in microvascular ECs.

We examined levels of TSP-1 mRNA in the carotid artery before and after balloon injury in diabetic and control Zucker rats. TSP-1 mRNA expression in diabetic arteries was consistently more robust than in nondiabetic vessels. Multiple reports indicate that TSP-1 expression in vascular wall is significantly increased in human restenotic arteries and after experimental mechanical injury to vessels in animal models. TSP-1 stimulates SMC proliferation after injury, and the blockade of TSP-1 with a specific antibody reduces intimal hyperplasia. The combined effects of injury, hyperglycemia, and the pro-proliferative consequences of the increased TSP-1 expression may contribute to the more aggressive development of intimal hyperplasia in diabetics. This prediction is consistent with the genetic link between TSP-1 and atherosclerosis.

The dysfunction of ECs in diabetes is well established, and TSP-1 certainly could contribute to this dysfunction because of its antiproliferative and apoptotic effects on ECs. Although TSP-1 in diabetic vessels may affect the metabolism of luminal EC monolayer and SMCs, the large amounts present in adventitia must result ultimately in compromised growth and remodeling of vasa vasorum. Indeed, the present data showed that the number of vasa vasorum decreased in diabetic aorta, inversely correlating with the expression of TSP-1, a potent antiangiogenic agent. In large blood vessels, this may lead to ischemic conditions in the inner layers of the vessel wall. Such oxygen stress could stimulate SMC proliferation and initiation of atherosclerotic lesions. Thus, the increased expression of TSP-1, which directly influences key events in the development of atherosclerotic lesions, provides a molecular connection between diabetes, hyperglycemia, and accelerated atherosclerosis and restenosis.

Acknowledgments

This study was supported in part by NIDDK grant K01DK62128 to Dr Stenina and NHLBI grant R01HL54392 to Dr Plow. We thank Dr DiCorleto and Lori Mavrakis for ECs.

References


Increased Expression of Thrombospondin-1 in Vessel Wall of Diabetic Zucker Rat
Olga I. Stenina, Irene Krukovets, Kai Wang, Zhongmin Zhou, Farhad Forudi, Marc S. Penn,
Eric J. Topol and Edward F. Plow

Circulation. 2003;107:3209-3215; originally published online June 16, 2003;
doi: 10.1161/01.CIR.0000074223.56882.97
Circulation is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2003 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7322. Online ISSN: 1524-4539

The online version of this article, along with updated information and services, is located on the
World Wide Web at:
http://circ.ahajournals.org/content/107/25/3209

Permissions: Requests for permissions to reproduce figures, tables, or portions of articles originally published in Circulation can be obtained via RightsLink, a service of the Copyright Clearance Center, not the Editorial Office. Once the online version of the published article for which permission is being requested is located, click Request Permissions in the middle column of the Web page under Services. Further information about this process is available in the Permissions and Rights Question and Answer document.

Reprints: Information about reprints can be found online at:
http://www.lww.com/reprints

Subscriptions: Information about subscribing to Circulation is online at:
http://circ.ahajournals.org//subscriptions/