Proatherosclerotic Mechanisms Involving Protein Kinase C in Diabetes and Insulin Resistance

Christian Rask-Madsen, George L. King

Abstract—In diabetes and insulin resistance, activation of protein kinase C (PKC) in vascular cells may be a key link between elevated plasma and tissue concentrations of glucose and nonesterified fatty acids and abnormal vascular cell signaling. Initial studies of PKC activation in diabetes focused on microvascular complications, but increasing evidence supports that PKC plays a role in several mechanisms promoting atherosclerosis. This review explains how PKC is thought to be activated in diabetes and insulin resistance through de novo synthesis of diacylglycerol. Furthermore, the review summarizes studies that implicate PKC in promoting proatherogenic mechanisms or inhibiting antiatherogenic mechanisms, including studies of endothelial dysfunction; gene induction and activation of vascular NAD(P)H oxidase; endothelial nitric oxide synthase expression and function; endothelin-1 expression; growth, migration, and apoptosis of vascular smooth muscle cells; induction of adhesion molecules; and oxidized low-density lipoprotein uptake by monocyte-derived macrophages. (Arterioscler Thromb Vasc Biol. 2005;25:487-496.)

Key Words: pathophysiology ■ cell signaling/signal transduction ■ gene regulation ■ type 2 diabetes ■ mechanism of atherosclerosis/growth factors ■ type 1 diabetes ■ endothelium/vascular type/nitric oxide

Abnormal signaling in vascular cells in diabetes and nondiabetic insulin resistance causes functional abnormalities long before the development of morphological manifestations of atherosclerosis. Activation of protein kinase C (PKC) by high concentrations of glucose and nonesterified fatty acids may have a key role in transducing abnormal metabolism into altered vascular cell signaling. As a result of increased intracellular concentrations of the lipid diacylglycerol (DAG), an intermediary in glucose and fat metabolism, PKC is chronically activated in diabetes and nondiabetic insulin resistance. Initially, most studies of PKC activation in diabetes focused on its significance for microvascular complications. However, increasing evidence supports that PKC is involved in many mechanisms promoting atherosclerosis. Such evidence is discussed in this review and is summarized in the Table and shown in schematic form in Figure 1.

PKC is an enzyme that phosphorylates protein substrates on serine (Ser) or threonine (Thr) residues. Of 10 known mammalian PKC isoforms, 8 are activated by DAG. PKC activation occurs through ligand activation of G-protein–coupled receptors, resulting in hydrolysis of a membrane phospholipid, phosphatidylinositol 4,5-bisphosphate (PIP₂), by phospholipase C. The products of this reaction are DAG and the PIP₂ head group, inositol 1,4,5-triphosphate (IP₃). IP₃, contributes to PKC activation by a separate mechanism, through opening of IP₃-gated Ca²⁺ transport channels in the...
endoplasmic reticulum membrane, thereby increasing $[\text{Ca}^{2+}]$. This is the classical mechanism for PKC activation seen, for example, during $\alpha$-adrenergic stimulation, angiotensin II stimulation, and endothelin-1 (ET-1) stimulation. An alternative mechanism, producing a more sustained increase in DAG concentration, is through a pathway that begins with hydrolysis of phosphatidylcholine by phospholipase D. Much less is known about the chronic activation of PKC through synthesis of DAG from glucose or lipid metabolites in diabetes and insulin resistance (see next section).

PKC is ubiquitously expressed, but different tissues have specialized distribution of isoforms regulated by transcription of separate genes for each isoform. Similarities exist among protein kinase A, protein kinase B (Akt), and PKC, not only by their structural homology but also by resemblance in regulation of enzyme activity by phosphorylation. PKC can bind several activators; not all are described here. PKC isoforms are grouped according to whether they contain domains that bind Ca$^{2+}$ or DAG, both of which positively regulate kinase activity. Conventional PKC (isoforms $\alpha$, $\beta1$, $\beta2$, and $\gamma$) binds both activators, novel PKC ($\delta$, $\epsilon$, $\eta$, $\theta$) binds DAG, but not Ca$^{2+}$, and atypical PKC ($\zeta$, $\iota$) binds neither (the mouse and rat homologue of human PKC$\iota$ is named PKCA).

### Activation of PKC in Diabetes and High-Glucose Conditions

High-glucose concentrations or diabetes cause increased activity of membrane-associated PKC and is associated with increased intracellular DAG concentrations in several tissues and cell culture systems, for example, in renal glomeruli from diabetic animals and in cultured aortic endothelial cells and vascular smooth muscle cells (VSMCs). Radioactive labeling studies have established that increased DAG mass occurs in such conditions, not through hydrolysis of PI$P_2$, but partly by de novo synthesis from glucose, probably via glyceroldehyde 3-phosphate and phosphatidic acid or from nonesterified fatty acids. De novo synthesis of DAG and increased DAG mass are manifest 2 to 3 days after exposure of vascular cells to high-glucose concentrations. In the aorta of diabetic dogs, increased DAG levels are sustained for several years.

High-glucose concentrations can likely cause increased DAG concentrations by de novo synthesis through several different metabolic pathways. One proposed mechanism is that increased synthesis of DAG is caused by inhibition of the glycolytic enzyme GAPDH, perhaps through poly(ADP-ribo)sylation during high-glucose concentrations. This will cause build-up of the glycolytic intermediate dihydroxyacetone phosphate, which can be used for DAG synthesis after reduction to glycerol-3-phosphate.

### Overview of PKC Isoform-Specific Role in Proatherogenic Mechanisms in Arteries and Arterial Cells

<table>
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<tr>
<td>eNOS upregulation and dysfunction</td>
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<td>Unidentified</td>
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<td>eNOS downregulation</td>
<td>At basal, insulin, glucose, oleic acid</td>
<td>Erk, fos/jun, NF$\kappa$B</td>
<td>PKC$\beta$ &amp; $\delta$</td>
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<td>Proliferation of VSMC</td>
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<td>Macrophage growth</td>
<td>oxLDL, glycated albumin, oleic acid, ATII</td>
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</table>

$cPKC$ indicates conventional PKC; nPKC, novel PKC. Their involvement has been inferred by results from PKC downregulation after PMA stimulation or selectivity of PKC inhibitor used. ROS, reactive oxygen species.
PKC and Proatherosclerotic Mechanisms

Interpreting Studies of Isoform-Specific PKC Function

Isoform-specific characteristics of PKC are important for drawing conclusions from studies of PKC-mediated effects. Phorbol esters are DAG analogues that only activate conventional and novel PKC, not atypical PKC that lack a DAG binding domain. The most widely used phorbol ester is 12-myristate 13-acetate (PMA) (synonymous with 12-O-tetradecanoylphorbol 13-acetate or TPA). Prolonged activation (6 to 12 hours or longer) by phorbol ester leads to downregulation of the expression of conventional and novel PKC, albeit differently for individual isoforms and in different cell types.

Phosphorylation of PKC in its activation loop is critical for kinase activity but is not sufficient for activation. Generally, PKC translocation (detected as protein content or as activity) from the cytosol to the plasma membrane or to internal membranes is the only reliable measure of PKC activation.

Only few PKC inhibitors possess useful specificity toward a single isoform. Ruboxistaurin inhibits the 2 splice variants of PKCβ, β1 and β2, with an IC50 ~50-times lower than that for other PKC isoforms. Its general specificity, for PKC as opposed to other kinases, is favorable. Even though it was recently reported that ruboxistaurin inhibits 3-phosphoinositide-dependent kinase-1 (PDK1), it does so with an IC50 of 750 nM in kinase assays using purified enzyme, whereas PKC inhibition in vivo is observed at plasma concentrations of 19 nmol/L or lower. As another example, rottlerin inhibits PKCδ with an IC50 ~10-times lower than for PKCα and β in vitro. Other inhibitors mentioned repeatedly in this review are GF109203X and calphostin C, both of which show selectivity toward conventional and novel PKC.

In general, a more specific approach than pharmacological inhibitors is targeting an individual PKC isoform with dominant-negative techniques (eg, expression of kinase-dead mutants or treatment with oligonucleotides), RNA interference, or targeted gene deletion in animals; reports have been published of mice with deletion of the genes for PKCα, β, γ, and δ, and they are all viable. In addition, isoform-specific activation or inhibition of PKC translocation can be achieved by peptides representing domains in PKC adaptor proteins.

Endothelium-Dependent Vasomotor Function

In diabetes, endothelial vasodilator function is compromised because of changed production of vasodilator and vasoconstrictor substances, particularly nitric oxide (NO), prostacyclin, cyclooxygenase-dependent vasoconstrictors, and ET-1. Dysfunction of endothelium-dependent vasodilation in diabetes characterizes a proatherosclerotic state. It likely also plays a causal role in atherogenesis because the underlying changes in vascular intracellular signal transduction and in secretion of endothelium-derived vasomotive factors predispose to atherosclerosis. Through such mechanisms, PKC may mediate proatherosclerotic processes by causing increased production of reactive oxygen species (ROS), decreased NO production, or increased ET-1 production.

The role of PKC activation in endothelial dysfunction in diabetes has been demonstrated both in animal models and in humans in vivo. In one study of aorta isolated from rabbit, high-glucose concentrations decreased endothelium-dependent vasodilation. PMA produced a similar effect, whereas inhibitors of PKC prevented this phenomenon. In aorta of rats with streptozotocin-induced diabetes, PKC activity in the membrane fraction was increased because of upregulation of the PKCβ isoform. Endothelial dysfunction by hyperglycemia in healthy humans has been prevented by pretreatment with the PKCβ inhibitor ruboxistaurin.
Vascular NAD(P)H Oxidase Activation and Induction

PKC regulation of neutrophil NADPH oxidase was suggested 2 decades ago when it was shown to be stimulated by phorbol ester.\(^{30}\) It is possible that neutrophils or monocytes contribute to vascular oxidative stress. Thus, increased NADPH oxidase subunit expression in monocytes was demonstrated in diabetic patients and was partly normalized after lowering of plasma glucose.\(^{31}\) Vascular homologues of neutrophil NADPH oxidase are sources of a major part of ROS production in VSMC and endothelial cells during physiological and pathological conditions.\(^{29}\) However, this section focuses on regulation of vascular NAD(P)H oxidase.

In VSMC, angiotensin II stimulates vascular NAD(P)H oxidase.\(^{32}\) Angiotensin II is involved in the development of cardiovascular disease in people with and without diabetes, perhaps through mechanisms independent of hypertension.\(^{33}\) A very rapid angiotensin II-stimulated activation of NAD(P)H oxidase involving PKC may cause redox activation of c-Src, leading to a more sustained activation of NAD(P)H oxidase by mobilizing a PKC-independent pathway.\(^{34}\) Angiotensin II also increases NAD(P)H oxidase gene expression. Vascular cells express several catalytic subunit isoforms, including nox2 (synonymous with gp91\(^{phox}\), the catalytic subunit of neutrophil NADPH oxidase; the suffix stands for phagocyte oxidase).\(^{29}\) In rats, subcutaneous infusion of angiotensin II for 7 days increased PKC activity in aorta and increased ROS production from the aortic lamina media;\(^{35}\) gp91\(^{phox}\) and p22\(^{phox}\) were increased by 7-fold and 3-fold, respectively. Continuous infusion of the isoform-nonselective PKC inhibitor chelerythrine decreased superoxide production and prevented approximately half the increase in NAD(P)H oxidase subunit expression.\(^{35}\) Angiotensin II infusion caused hypertension in these animals,\(^{35}\) Even though increased intra-arterial pressure was shown to increase p47\(^{phox}\) Ser\(^{497}\) phosphorylation (which precedes p47\(^{phox}\) membrane translocation and NAD(P)H oxidase activation)\(^{29}\) and superoxide production in a PKC-dependent manner,\(^{36}\) the VSMC culture studies described suggest that angiotensin II may stimulate activation of NAD(P)H oxidase independent of increased blood pressure.

High concentrations of glucose and nonesterified fatty acids can also increase superoxide production from NAD(P)H oxidase in cultures of aortic endothelial cells and vascular smooth muscle cells.\(^{24}\) Rats with streptozotocin-induced diabetes were shown to have a 7-fold increase of gp91\(^{phox}\) mRNA expression and increased activity of NAD(P)H oxidase in the aorta.\(^{25}\) These abnormalities could be partly normalized, without changes in plasma glucose, after treatment of rats with the PKC inhibitor N-benzoyl-stau-rosporine (synonymous with CGP41251,\(^{18}\) a PKC inhibitor with selectivity toward conventional PKC isoforms).\(^{25}\) Induction of several NAD(P)H oxidase subunits have also been shown in endothelial cell culture exposed to constant or intermittent high-glucose concentrations, and such upregulation was inhibited by LY379196, a specific PKC\(^{\beta}\) inhibitor.\(^{37}\) Evidence for increased activity of vascular NAD(P)H oxidase in Otsuka Long-Evans Tokushima Fatty rats, a model of insulin resistance, has also been published.\(^{38}\) In mammary arteries and saphenous veins from diabetic patients undergoing coronary artery bypass surgery, superoxide production was doubled compared with vessels from nondiabetic controls, likely because of increased endothelial expression of NAD(P)H oxidase subunits.\(^{39}\)

Only limited information is available about which PKC isoform is involved in neutrophil NADPH oxidase activation. In isolated neutrophils, PKC\(^{\zeta}\) inhibition prevented oxidant production,\(^{40}\) and in monocytes superoxide production caused by incubation in high-glucose concentrations was dependent on PKC\(^{\alpha}.\)\(^{41}\) Activation of conventional or novel PKC as mediators of vascular NAD(P)H oxidase in endothelial and VSMC culture is suggested by the temporal association of increasing DAG concentrations and PKC activation as well as the fact that increased superoxide production can be recapitulated by stimulation with PMA.\(^{21}\) This is consistent with data from renal glomeruli from rats with streptozotocin-induced diabetes, in which ruboxistaurine treatment prevented increased membrane-associated p47\(^{phox}\) and p67\(^{phox}\) without changing total p47\(^{phox}\) or p67\(^{phox}\) mRNA or protein expression.\(^{42}\) In contrast, p47\(^{phox}\) membrane translocation stimulated by tumor necrosis factor-\(\alpha\) (TNF-\(\alpha\)) in cultured endothelial cells was inhibited by antisense oligonucleotides or kinase-dead mutants targeting PKC\(^{\zeta}\), but not by PKC\(^{\alpha}\), \(\theta\), or \(\epsilon\) oligonucleotides or prolonged PMA stimulation.\(^{43}\)

Endothelial Nitric Oxide Synthase Expression and Dysfunction

The abnormal metabolic milieu of diabetes and insulin resistance results in the PKC-dependent dysregulation of many endothelium-derived substances that are primarily known as vasodilators or vasoconstrictors. For example, in aortic endothelial cells, PKC activation may lead to increased expression of cyclooxygenase, decreased production of the vasodilator prostacyclin, and increased production of the vasoconstrictor thromboxane A\(_2.\)\(^{22}\) However, in the next 2 sections, the focus will be on regulation of NO and ET-1, for which extensive evidence exists for an implication of PKC. A schematic representation of endothelial NO synthase (eNOS) regulation by PKC is shown in Figure 2.
NO mediates endothelium-dependent vasodilation and inhibits many proatherogenic mechanisms. It has been reported that eNOS expression is decreased in aortic endothelial cells cultured during high-glucose concentrations.44 This is controversial, however. During very similar culture conditions, it was demonstrated that eNOS expression was upregulated, albeit insufficiently to compensate for decreased NO bioavailability because of increased production of superoxide, which breaks down NO.45 Decreased NO production during the latter conditions can be restored by calphostin C, an inhibitor of conventional and novel PKC.22 The relevance of this finding in cell culture was supported by studies of rats with streptozotocin-induced diabetes.25 These studies pointed to eNOS as a source of vascular superoxide production that was decreased by N\textsuperscript{\textgamma}-nitro-L-arginine (L-NNA), an inhibitor of eNOS.25 Treatment of the diabetic rats with a PKC inhibitor decreased eNOS-derived superoxide production, prevented eNOS induction, and restored endothelium-dependent vasorelaxation of aortic rings.25

There are several mechanisms that may explain why eNOS synthesizes superoxide rather than NO, a situation termed “uncoupling” of eNOS. First, PKC may cause phosphorylation of eNOS at Thr\textsuperscript{495} in the calmodulin-binding domain of the enzyme, perhaps by direct phosphorylation of this site.46,47 Dephosphorylation of Thr\textsuperscript{495} during eNOS activation may be important for coupling electron flux in eNOS to NO production, and a relative increase in Thr\textsuperscript{495} phosphorylation may uncouple oxygen reduction from L-arginine oxidation so that eNOS produces superoxide. Second, superoxide, from vascular NAD(P)H oxidase or other sources, may react with NO and form peroxynitrite, which potently oxidizes tetrahydrobiopterin, causing uncoupling of eNOS and further eNOS superoxide production.49,50 Third, peroxynitrite may release Zn\textsuperscript{2+} from the Zn\textsuperscript{2+}–thiolate complex, breaking the eNOS homodimer and uncoupling eNOS.51 Each mechanism is thus a positive feedback cycle, in which superoxide production causes even more superoxide production. Although PKC activation decreases NO production in cell culture, it remains to be directly demonstrated that this occurs by uncoupling eNOS.

The cause of induction of eNOS expression in streptozotocin-induced diabetes is unclear. In endothelial cells cultured in 5.5 mmol/L glucose, the PKC inhibitors staurosporine,53 cherythrine,53 and GF109203X44 increased eNOS expression. PMA treatment for 24 hours, expected to downregulate PKC, decreased eNOS expression in endothelial cell culture.53 In another study, the same effect was present after PMA treatment with durations between 6 and 20 hours,55 consistent with PKC downregulation (although PKC expression was not measured at these time points, except for PKC\alpha and \epsilon). Ruboxistaurine (LY335331)—used at a dose in which it specifically inhibits PKC\beta—also increased eNOS mRNA.54 Thus, it seems that PKC activation in itself likely tends to downregulate eNOS expression. However, PKC inhibition was found to prevent eNOS upregulation in aortic endothelial cells cultured in high-glucose concentrations.22 One possible explanation is that PKC activation during high-glucose conditions increases eNOS transcription and eNOS mRNA half-life through promotion of oxidative stress.56

To further complicate this issue, it is controversial how eNOS expression is changed in nondiabetic insulin resistance. In the Zucker fatty rat, a model of nondiabetic obesity-associated insulin resistance, eNOS mRNA was found to be decreased to 29% of control levels in microvessels isolated from fat.54 In contrast, eNOS protein was increased 1.7-fold in brain arteries in another study of nondiabetic Zucker fatty rats.55 Thus, it is possible that eNOS expression is regulated differently in large and small vessels or in different tissues. eNOS expression is unchanged in skin biopsy samples from patients with insulin resistance or diabetes,58 but we are not aware of any published data on endothelial eNOS expression in human conduit vessels from such patients.

**ET-1 Expression**

ET-1 is primarily produced by endothelial cells and is one of the most potent vasoconstrictors known.23 Plasma concentrations of ET-1 are increased in patients with type 2 diabetes complicated with atherosclerosis, compared with nondiabetic patients with atherosclerosis and compared with healthy control subjects.59 Infusion of an ET\textsubscript{A} receptor blocker increased forearm blood flow in patients with type 2 diabetes, but not in healthy control subjects, indicating that ET-1 has a basal vasoconstrictor effect only in diabetes.60

A likely causal role for ET-1 in the development of atherosclerosis was established with a study of apolipoprotein E (apoE) knockout mice treated with an ET\textsubscript{A} receptor antagonist for 30 weeks. This intervention did not change blood pressure or plasma lipids but reduced ET-1 protein expression, increased NO-dependent vasorelaxation, and decreased atherosclerotic lesion area in the aorta.61

In microvascular cells, induction of ET-1 caused by high-glucose concentration is associated with increased membrane-associated PKC\beta and \delta and can be blocked by GF109203X,62 as well as an inhibitor of the upstream activator of Erk. The nuclear factors downstream of Erk activation, fos and jun, are responsible for induction of ET-1.63 PKC also mediates other stimuli for ET-1 induction. Thus, in heart endothelial cells, PKC mediated angiotensin II-stimulated induction of ET-1 expression because this effect could be blocked by calphostin C.64 Furthermore, oleic acid increased ET-1 expression in human aortic endothelial cells, and this could be blocked by inhibition of PKC or nuclear factor \kappa B (NF\kappa B). Oleic acid also increased membrane-associated PKC\alpha and \beta 2 and increased NF\kappa B binding activity, and the latter was prevented by treatment with a PKC inhibitor.65 Finally, ET-1 increases its own expression through a PKC-dependent mechanism.66

**Vascular Insulin Resistance**

Insulin stimulates skeletal muscle blood flow in healthy, lean individuals,67 but this effect is blunted in people with obesity67 or type 2 diabetes.68 Insulin-stimulated vasodilation is dependent on NO.69–71 Systemic or extravascular effects may contribute to insulin-stimulated vasodilation,72 for example, through platelet release of vasodilatory factors mediated by platelet-derived NO.73 However, at least part of the vasodilatory effect of insulin is likely caused by stimulation of
endothelial-derived NO as it occurs in isolated vascular rings, and only when the endothelium is intact, and because insulin-stimulated NO production is dependent on insulin signaling in endothelial cell culture, including activation of the insulin receptor, insulin receptor substrate (IRS), 1-phosphatidylinositol 3-kinase (PI3K), PDK1, Akt, and ultimately eNOS Ser1177 phosphorylation. Insulin also induces eNOS gene expression through the PI3K signaling pathway. In mice with conditional deletion of the insulin receptor gene only in endothelial cells, eNOS expression in aorta is decreased by 62%. Thus, insulin-stimulated regulation of endothelium-derived NO may be a factor necessary for vascular homeostasis that is absent in insulin resistance.

Although Ser/Thr phosphorylation of the insulin receptor with ensuing inhibition of insulin receptor autophosphorylation can inhibit insulin signaling, attempts to explain diabetes-related inhibition of PI3K–Akt signaling have given most attention to IRS modification. In endothelial cell culture, PMA inhibits IRS-2–associated PI3K activity, and in VSMC, PMA or PKCα overexpression inhibits IRS-1 tyrosine phosphorylation, necessary for binding PI3K. Mutations of IRS-1 are sufficient to alter insulin-stimulated eNOS function, demonstrated by elegant experiments in human umbilical vein endothelial cells with a common single nucleotide polymorphism in IRS-1. Cultures with this polymorphism had decreased insulin-stimulated activation and gene expression of eNOS through IRS-1, PI3K, and Akt. However, studies of insulin signaling compromised by PKC-mediated IRS modification in vascular cells are sparse. Currently, the most definite evidence for PKC-mediated inhibition of IRS comes from studies of insulin action in skeletal muscle of PKCθ knockout mice and shows that PKCθ activation during hyperlipidemia is necessary for inhibition of skeletal muscle IRS-1 tyrosine phosphorylation and insulin-stimulated glucose uptake. Although PKCθ can directly phosphorylate IRS-1, it may also activate other kinases, and the mechanism may include downregulation of IRS-1 expression. However, the PKC isoform involved may well be dependent on species, because lipid infusion in humans activates skeletal muscle PKCβ1, β2, and δ, but not PKCe, θ, or ε.

In insulin-resistant states, impairment of vascular insulin signaling is selective for insulin-stimulated PI3K pathways, leaving insulin-stimulated mitogen-activated protein kinase (MAPK) signaling unaffected. It is possible that insulin-stimulated ET-1 expression is preserved in insulin resistance, because ET-1 expression is dependent on nuclear factors fos/jun downstream of MAPK signaling.

### Proliferation and Apoptosis of VSMCs

The MAPK Erk1/2 is a major regulator of growth and proliferation. In VSMCs, Erk1/2 activation and proliferation stimulation by oxidized low-density lipoprotein (oxLDL), glycated serum albumin, oleic acid, and angiotensin II is dependent on PKC. Angiotensin II and high-glucose concentrations may stimulate VSMC growth by PKC-dependent induction of transforming growth factor-β. Other MAPK pathways are activated in diabetes. In rats with streptozotocin-induced diabetes, p38 MAPK activation in aorta was increased compared with control rats. p38 activation was also found in VSMC cultured in 16.5 mmol/L glucose, in which overexpression of PKCδ, but not PKCβ1, increased p38 activation.

During cyclic stretch of VSMC cultures, apoptosis is mediated by PKC-dependent p38 activation. In fact, PKCδ has been shown to promote VSMC apoptosis and limit intimal neoplasia in a model of vascular remodeling in response to increased vascular pressure. Thus, allografting of aorta to the carotid artery in mice resulted in marked neointimal hyperplasia in the vein graft after 8 weeks. However, vein grafts from PKCδ knockout mice showed exaggerated neointimal hyperplasia and decreased apoptosis compared with vein grafts from wild-type mice. Whether these findings are relevant for diabetes is unclear because VSMCs grown in high-glucose concentrations show decreased apoptosis. This antiapoptotic effect was prevented by prolonged incubation with PMA or treatment with calphostin C, suggesting that conventional or novel PKC were involved. When cultured in 5.5 mmol/L glucose, apoptosis of VSMCs as a result of serum starvation was prevented by overexpression of PKCα or β2, but not PKCδ. Whether VSMC apoptosis is increased or decreased in diabetes remains to be resolved.

The contribution of VSMC apoptosis to clinical atherosclerosis is complex, because intimal neoplasia may promote early atherosclerosis but result in instability of advanced plaques. It is more readily accepted that endothelial apoptosis promotes atherosclerosis. In endothelial cell culture, high-glucose concentrations have been shown to increase apoptosis through activation of caspase-3 and p38.

### Induction of Adhesion Molecules

A critical early step in atherogenesis is adhesion of monocytes to endothelium, followed by migration of monocytes to the intima where they transdifferentiate into macrophages that take up lipids and become foam cells. This process is initiated by binding of monocyte integrins to endothelial adhesion molecules. Vascular cell adhesion molecule-1 (VCAM-1) was first associated with early atherogenesis as an inducible adhesion molecule in endothelium covering fatty streaks in hyperlipidemic rabbits. In rabbits, VCAM-1 and E-selectin expression in aortic endothelial is increased by diabetes and further upregulated by diet-induced hyperlipidemia. The clinical relevance of these observations is supported by many human studies. For example, in healthy men, the future risk of myocardial infarction is associated with plasma concentrations of soluble intercellular adhesion molecule-1 (ICAM-1). In patients with type 2 diabetes, soluble VCAM-1 concentrations are independently associated with cardiovascular mortality.

Cell culture studies have firmly established a role for PKC in mediating leukocyte–endothelial interaction. Adhesion of monocytes to the endothelium is dependent on PKC activation in monocytes and PKC is necessary for monocyte differentiation into macrophages. In endothelial cells cultured in high-glucose concentrations, neutrophil adherence and expression of ICAM-1, E-selectin, and P-selectin are...
increased, but this can be prevented by incubation with PKC inhibitors.\textsuperscript{105} High-glucose concentrations was shown to increase NFκB activation and VCAM-1 expression in endothelial cell culture, and these events were inhibited by a selective PKCβ2 inhibitor.\textsuperscript{106} However, VCAM-1 induction stimulated by thrombin has been shown to be mediated by PKCβ and PKCζ through binding of NFκB and GATA-2, respectively, to the VCAM-1 promoter.\textsuperscript{107} Both conventional and atypical PKC may be involved in regulation of ICAM-1 expression as well. In endothelial cells, ICAM-1 induction is induced by NFκB binding to the ICAM-1 promotor, which may be mediated by PKCζ after TNF-α stimulation \textsuperscript{108} or PKCδ after thrombin stimulation.\textsuperscript{109} The pathways regulating ICAM-1 transcription during high-glucose concentrations have not yet been described.

**Monocyte–Macrophage LDL Uptake and Foam Cell Formation**

The earliest lesion in atherosclerosis consists of lipid accumulation in the lamina intima and formation of foam cells through uptake of modified LDL, including oxLDL, by monocyte-derived macrophages, dependent on macrophage scavenger receptors.\textsuperscript{110} The oxLDL increase induction of ICAM-1 in isolated porcine coronary arteries and leukocyte adhesiveness to endothelium,\textsuperscript{111} as well as growth of cultured macrophages,\textsuperscript{112} ICAM-1 induction\textsuperscript{111} and macrophage growth\textsuperscript{112} can be partly prevented with calphostin C and other PKC inhibitors.

In cultured macrophages, oxLDL was shown to also increase expression of scavenger receptor CD36, and this could be prevented by calphostin C.\textsuperscript{113} High-glucose concentrations caused induction of another scavenger receptor, LOX-1, in cultures of monocyte-derived macrophages.\textsuperscript{114} This increase in LOX-1 expression was associated with increased membrane location of PKCβ2 and could be prevented by calphostin C or the PKCβ-specific inhibitor LY379196.\textsuperscript{114} The study pointed to ROS production as an upstream event of PKCβ2 activation and LOX-1 induction because both could be prevented by the antioxidant N-acetyl-l-cystine.\textsuperscript{114} Thus, PKC signaling may be involved in foam cell formation by mediating several different effects of oxLDL.

**Pharmacotherapy**

The PKCβ inhibitor ruboxistaurine is currently being tested in ongoing clinical trials with microvascular end points. In the future, clinical trials may determine whether PKC inhibition can prevent atherosclerosis. However, PKC activation may be modified by strategies other than with PKC inhibitors. For example, troglitazone\textsuperscript{115} and other PPARγ agonists\textsuperscript{116} inhibit high-glucose–induced PKC activation in VSMCs\textsuperscript{115} and endothelial cells,\textsuperscript{116} and this may be caused by activation of DAG kinase, resulting in decreased DAG concentrations.\textsuperscript{116}

**Conclusions**

A large body of literature supports that vascular DAG accumulation and ensuing PKC activation in diabetes lead to endothelial dysfunction by causing activation of vascular NAD(P)H oxidase, dysfunction of eNOS, induction of ET-1, or by other mechanisms (Figure 1). The information about eNOS expression and dysfunction in diabetes and high-glucose conditions is contradictory and more studies are clearly needed. Vascular remodeling by VSMC proliferation and apoptosis is regulated by PKC, either through activation of the DAG–PKC pathway or as intermediary signaling, eg, after angiotensin II stimulation. Lastly, leukocyte adhesion, monocyte transdifferentiation, and macrophage growth leading to intimal foam cell formation are critical events in early atherogenesis, and all may be partly regulated through PKC activation. With regard to most of these mechanisms, the characterization of which PKC isoforms are involved is only partial at best.

Earlier studies of the role of vascular PKC activation in diabetes were primarily focused on microvascular dysfunction.\textsuperscript{1} Preliminary data show that PKCβ/apolipoprotein E double knockout mice have decreased atherosclerosis in the aorta compared with apolipoprotein E knockout mice,\textsuperscript{117} confirming a role for PKCβ in atherogenesis, even in the nondiabetic condition of hypercholesterolemia. Before deciding whether the role of PKC deserves to be tested in clinical studies of atherosclerosis, animal models will help evolve this field from the current suggestive evidence concerning proatherosclerotic signaling to studies of actual atherothrombosis.

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Proatherosclerotic Mechanisms Involving Protein Kinase C in Diabetes and Insulin Resistance

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