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 [Ca$^{2+}$]. This is the classical mechanism for PKC activation seen, for example, during α-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 Ca$^{2+}$-binding domains that bind Ca$^{2+}$ or DAG, both of which positively regulate kinase activity. Conventional PKC (isoforms α, β1, β2, and γ) binds both activators, novel PKC (δ, ε, η, θ) binds DAG, but not Ca$^{2+}$, and atypical PKC (ζ, η) binds neither (the mouse and rat homologue of human PKCζ 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 PIP$_2$, but partly by de novo synthesis from glucose, probably via glyceraldehyde 3-phosphate and phosphatidic acid 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.

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

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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.
The PKC isoforms activated by diabetes depend on the tissue or cell type. In the aorta, membrane-associated PKCβ2 was found to be increased in diabetic rats, whereas PKCβ2 and PKCδ activation has been demonstrated in aortic VSMCs grown in high-glucose concentrations, whereas other isoforms have been observed in the retina (PKCa, β1, β2, and ε) and renal glomeruli of diabetic rats (PKCa and B1). The introduction of ruboxistaurin (LY333531), a PKC inhibitor specific for the β isoforms, showed improvement of glomerular filtration rate, albumin excretion rate, and retinal circulation in diabetic rats, supporting that activation of PKCβ1 or β2 is important for vascular dysfunction in several organs in diabetes. Even though PKCβ isoforms are expressed at low levels in vascular cells, activation of PKCβ in diabetes leads to an increase in membrane-associated general PKC activity.

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 of PKC activity 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 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 of 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, isomorph-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 vasomotor 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 PKCβ2 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. 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. 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. However, this section focuses on regulation of vascular NAD(P)H oxidase.

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In VSMC, angiotensin II stimulates vascular NAD(P)H oxidase. Angiotensin II is involved in the development of pathological conditions. In contrast, p47phox mRNA or protein expression was doubled compared with vessels from nondiabetic controls, likely because of increased endothelial expression of NAD(P)H oxidase subunits.

Only limited information is available about which PKC isoform is involved in neutrophil NADPH oxidase activation. In isolated neutrophils, PKCζ inhibition prevented oxidant production, and in monocytes superoxide production caused by incubation in high-glucose concentrations was dependent on PKCζ. 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. This is consistent with data from renal glomeruli from rats with streptozotocin-induced diabetes, in which ruboxistaurine treatment prevented increased membrane-associated p47phox and p67phox without changing total p47phox or p67phox mRNA or protein expression. In contrast, p47phox membrane translocation stimulated by tumor necrosis factor-α (TNF-α) in cultured endothelial cells was inhibited by antisense oligonucleotides or kinase-dead mutants targeting PKCζ, but not by PKCα, θ, or ε oligonucleotides or prolonged PMA stimulation.

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 vasoconstrictor prostacyclin, and increased production of the vasoconstrictor thromboxane A2. 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. 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. Decreased NO production during the latter conditions can be restored by calphostin C, an inhibitor of conventional and novel PKC. The relevance of this finding in cell culture was supported by studies of rats with streptozotocin-induced diabetes. These studies pointed to eNOS as a source of vascular superoxide production that was decreased by N\textsuperscript{\textregistered} -nitro-L-arginine (L-NNA), an inhibitor of eNOS. 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.

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. Dethylation 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 peroxynitrite, which potently oxidizes tetrahydrobiopterin, causing uncoupling of eNOS and further eNOS superoxide production. Third, peroxynitrite may release Zn\textsuperscript{2+} from the Zn\textsuperscript{2+}-thiolate complex, breaking the eNOS homodimer and uncoupling eNOS. 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, chelerythrine, and GF109203X increased eNOS expression. PMA treatment for 24 hours, expected to downregulate PKC, decreased eNOS expression in endothelial cell culture. In another study, the same effect was present after PMA treatment with durations between 6 and 20 hours, consistent with PKC downregulation (although PKC expression was not measured at these time points, except for PKC\textalpha and \epsilon). Ruboxistaurine (LY333531)—used at a dose in which it specifically inhibits PKC\textbeta—also increased eNOS mRNA. 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.

One possible explanation is that PKC activation during high-glucose conditions increases eNOS transcription and eNOS mRNA half-life through promotion of oxidative stress.

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. In contrast, eNOS protein was increased 1.7-fold in brain arteries in another study of nondiabetic Zucker fatty rats. 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, 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. 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. Infusion of an ETA 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.

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 ETA 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.

In microvascular cells, induction of ET-1 caused by high-glucose concentration is associated with increased membrane-associated PKC\textbeta\textgamma and \delta and can be blocked by GF109203X 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. 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. 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\textalpha and \beta 2 and increased NF\kappa B binding activity, and the latter was prevented by treatment with a PKC inhibitor. Finally, ET-1 increases its own expression through a PKC-dependent mechanism.

**Vascular Insulin Resistance**

Insulin stimulates skeletal muscle blood flow in healthy, lean individuals, but this effect is blunted in people with obesity or type 2 diabetes. Insulin-stimulated vasodilation is dependent on NO. Systemic or extravascular effects may contribute to insulin-stimulated vasodilation, for example, through platelet release of vasodilatory factors mediated by platelet-derived NO. 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;90,74 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.75–77 Insulin also induces eNOS gene expression through the PI3K signaling pathway.54 In mice with conditional deletion of the insulin receptor gene only in endothelial cells, eNOS expression in aorta is decreased by 62%.78 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,82 and in VSMC, PMA or PKCα overexpression inhibits IRS-1 tyrosine phosphorylation,79 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.77 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 PKCε knockout mice, demonstrating 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.77 However, studies of insulin signaling compromised by PKC-mediated IRS modification in vascular cells are sparse.

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.97 In rabbits, VCAM-1 and E-selectin expression in aortic endothelium is increased by diabetes and further upregulated by diet-induced hyperlipidemia.98 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).99 and in patients with type 2 diabetes, soluble VCAM-1 concentrations are independently associated with cardiovascular mortality.100 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 monocytes100–103 and PKC is necessary for monocyte differentiation into macrophages.104 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.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.106 However, VCAM-1 induction stimulated by thrombin has been shown to be mediated by PKCα and PKCζ through binding of NFκB and GATA-2, respectively, to the VCAM-1 promoter.107 Both conventional and atypical PKC may be involved in regulation of ICAM-1 expression as well. In endothelial cells, ICAM-1 induction is expressed by NfκB binding to the ICAM-1 promotor, which may be mediated by PKCζ after TNF-α stimulation108 or PKCδ after thrombin stimulation.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.110 The oxLDL increase induction of ICAM-1 in isolated porcine coronary arteries and leukocyte adhesiveness to endothelium,111 as well as growth of cultured macrophages.112 ICAM-1 induction111 and macrophage growth112 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.113 High-glucose concentrations caused induction of another scavenger receptor, LOX-1, in cultures of monocyte-derived macrophages.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 LY379196.114 The study pointed to ROS production as an event, and these events were inhibited by a selective PKC inhibitor ruboxistaurine is currently being tested after thrombin stimulation114 or PKCδ after thrombin stimulation.109 The pathways regulating ICAM-1 transcription during high-glucose concentrations have not yet been described.

**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, troglitazone115 and other PPARγ agonists116 inhibit high-glucose–induced PKC activation in VSMCs115 and endothelial cells,116 and this may be caused by activation of DAG kinase, resulting in decreased DAG concentrations.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.1 Preliminary data show that PKCβ/apolipoprotein E double knockout mice have decreased atherosclerosis in the aorta compared with apolipoprotein E knockout mice,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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