Advanced glycation end products potentiate the stimulatory effect of glucose on macrophage lipoprotein lipase expression

Marie-Claude Beauchamp, Sophie-Élise Michaud, Ling Li, Maryam Radimeh Sartippour, and Geneviève Renier

Centre Hospitalier de l’Université de Montréal Research Centre, Notre-Dame Hospital, Department of Nutrition, University of Montreal, Montreal, Quebec, Canada

Abstract Lipoprotein lipase (LPL) secreted by macrophages in the arterial wall promotes atherosclerosis. We have shown that macrophages of patients with type 2 diabetes overproduce LPL and that metabolic factors, including glucose, stimulate macrophage LPL secretion. In this study, we determined the effect of advanced glycation end products (AGEs) on LPL expression by macrophages cultured in a high-glucose environment and the molecular mechanisms underlying this effect. Our results demonstrate that AGEs potentiate the stimulatory effect of high glucose on murine and human macrophage LPL gene expression and secretion. Induction of macrophage LPL mRNA levels by AGEs was identical to that elicited by physiologically relevant modified albumin and was inhibited by anti-AGE receptor as well as by antioxidants. Treatment of macrophages with AGEs resulted in protein kinase C (PKC) and mitogen-activated protein kinase (MAPK) activation. Inhibition of these kinases abolished the effect of AGEs on LPL mRNA levels. Finally, exposure of macrophages to AGEs increased the binding of nuclear proteins to the activated protein-1 consensus sequence of the LPL promoter. This effect was inhibited by PKC and MAPK inhibitors. These results demonstrate for the first time that AGEs potentiate the stimulatory effect of high glucose on macrophage LPL expression. This effect appears to involve oxidative stress, PKC/MAPK activation, and activated protein-1 (AP-1) activation.

Supplementary key words oxidative stress • kinases • diabetes • atherosclerosis

Atherosclerosis is the leading cause of death in the Western world and the major complication of type 2 diabetes (1). Despite the well-documented association between diabetes and cardiovascular diseases, the reasons for the increased prevalence of atherosclerosis associated with type 2 diabetes are not well known.

Lipoprotein lipase (LPL) is a key enzyme in lipid metabolism that is secreted by macrophages and smooth muscle cells in the atherosclerotic lesion (2, 3). Evidence indicates that LPL secreted by macrophages in the arterial intima is proatherogenic. Indeed, LPL acts as an atherogenic ligand that associates with lipoproteins, thereby favoring their uptake by vascular cells as well as their retention to the subendothelial matrix (4–6). This enzyme also stimulates the production of the proinflammatory cytokine tumor necrosis factor-α (7, 8), increases monocyte adhesion to endothelial cells (9–11), and enhances the proliferation of vascular smooth muscle cells (12). Recently, several studies have demonstrated that macrophage LPL promotes foam cell formation and atherosclerosis in vivo (13–16).

We have previously shown that macrophages of type 2 diabetic patients overproduce LPL and that peripheral factors play a key role in this alteration (17). We have also recently proposed a role for glucose, fatty acids, and homocysteine as macrophage LPL-stimulatory factors in human diabetes (18–20). Besides these factors, advanced glycation end products (AGEs) may play a role in the induction of macrophage LPL in human diabetes. Indeed, AGEs accumulate in the plasma and tissues of type 2 diabetic patients (21) and exert proatherogenic effects (22, 23). In the present study, we sought to determine the effect of AGEs on glucose-induced macrophage LPL expression. Our study demonstrates that AGEs potentiate the stimulatory effect of glucose on macrophage LPL expression. This effect appears to involve oxidative stress, protein kinase C (PKC) and mitogen-activated protein kinase (MAPK)-dependent pathways, and activated protein-1 (AP-1) activation.

1 To whom correspondence should be addressed.

e-mail: genevieve.renier@umontreal.ca

Manuscript received 30 April 2004 and in revised form 4 June 2004.


DOI 10.1194/jlr.M400169-JLR200

Copyright © 2004 by the American Society for Biochemistry and Molecular Biology, Inc.

This article is available online at http://www.jlr.org

Journal of Lipid Research Volume 45, 2004 1749
Reagents

FBS was purchased from Wisent (St. Bruno, Quebec, Canada). RPMI 1640 medium, DMEM, and Trizol reagent were purchased from Life Technologies (Burlington, Ontario, Canada). Calpastatin G, N-acetyl-l-cysteine (NAC), GF109203X, U0126, and PD98059 were obtained from Calbiochem (La Jolla, CA). Affinity-purified polyclonal antibody against AGE receptor (RAGE) (M-20), CD56 (24), and extracellular signal-regulated protein kinase (ERK) 1/2 were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-scavenger receptor-A (SRA) (25) and anti-phospho-ERK1/2 antibodies were obtained from Serotec (Raleigh, NC) and Cell Signaling Technology (Pickering, Ontario, Canada), respectively. Irrelevant mouse IgG1 was purchased from R&D Systems (Minneapolis, MN). The anti-FCγII antibody II antibody was kindly provided by Dr. M. Sarfati (University of Montreal, Montreal, Quebec, Canada). Immunoglobulin and fatty acid-free BSA was obtained from Sigma (St. Louis, MO). LY379196 was kindly provided by Eli Lilly (Indianapolis, IN). U0126, LY379196, PD98059, and GF109203X were dissolved in 0.2% (v/v) penicillin-streptomycin and 2% (v/v) autologous serum. The cells were incubated for 8 days at 37°C in a humidified 5% CO2, 95% air atmosphere. The culture medium was changed at days 4 and 8.

Human macrophages

The J774 murine macrophage cell line was obtained from the American Type Culture Collection (ATCC; Rockville, MD). J774 cells were cultured in DMEM containing 10% FBS and 100 U/ml penicillin-streptomycin (Life Technologies).

Determination of human LPL immunoreactive mass and activity

One hour before the end of the incubation period, 50 U/ml heparin was added to the medium. The amount of LPL immunoreactive mass in the supernatants was measured by enzyme-linked immunosorbent assay using the Markit-F LPL kit (Dainippon Pharmaceutical, Osaka, Japan) (30). Extracellular LPL activity was determined using the Confuhi10 kit (Progen, American Research Products) (31). LPL mass and activity values were normalized to the levels of total cell proteins.

Electrophoretic mobility shift assay

The isolation of the nuclei and the DNA binding assay were performed as described previously (20). DNA probes

The cDNA probe for the detection of murine LPL was prepared by the PCR technique. cDNA was obtained from total RNA using a reverse transcription reaction. Two synthetic primers spanning bases 255–287 and 1117–1149 of the LPL cDNA were used to enzymatically amplify a 894 bp region of the LPL probe. The cDNA probe for murine S28 was purchased from the ATCC. A 20-mer double-stranded oligonucleotide (5′-GGGCACCTTGACTAGGCACAG-3′; 5′-TTGCTGGCGCTTGCATTGCAGG-3′) containing the consensus sequence for the AP-1-responsive element of the murine LPL gene promoter (32) was synthesized with the aid of an automated DNA synthesizer. After annealing, the double-stranded oligonucleotide was labeled with [γ-32P]ATP using the Boehringer Mannheim 5′ end-labeling kit (Indianapolis, IN).
Determination of total protein concentrations

Total protein content was measured according to the Bradford method (33) using a colorimetric assay (Bio-Rad, Mississauga, Ontario, Canada).

Statistical analysis

All values are expressed as means ± SEM. For single comparisons, data were analyzed by Student’s t-test. For multiple comparisons, data were analyzed by one-way ANOVA followed by the Student-Newman-Keuls test or Dunn’s method. $P < 0.05$ was considered significant.

RESULTS

Effect of AGEs on LPL mRNA levels and secretion by J774 macrophages

J774 murine macrophages were incubated for 24 or 72 h in culture medium containing low (5.6 mmol/l) or high (20 mmol/l) glucose concentrations in the presence or absence of BSA or AGEs. At the end of the incubation period, LPL mRNA levels and secretion were measured. Treatment of J774 macrophages for 24 h with BSA did not alter LPL mRNA levels regardless of the experimental conditions used (Fig. 1A). AGEs did not affect the levels of LPL mRNA in J774 macrophages cultured in a low-glucose medium, whereas both AGEs and GlyBSA (200 μg/ml) increased LPL mRNA levels in macrophages cultured in a high-glucose environment (Fig. 1A). The effect of AGEs on LPL mRNA levels was dose dependent, with maximal effect at a concentration of 200 μg/ml [LPL mRNA levels (% of control values): AGE (50 μg/ml), 108.6 ± 9.9; AGE (100 μg/ml), 137.5 ± 10.6 ($P < 0.05$); AGE (200 μg/ml), 162.1 ± 10.1 ($P < 0.01$)]. No modulation of LPL mRNA levels was observed when cells were treated with AGEs in the presence of 20 mmol/l D-mannitol (data not shown). Recovery of enhanced amounts of LPL immu-

![Fig. 1. Effect of advanced glycation end products (AGEs) on LPL mRNA levels and secretion in J774 macrophages. J774 cells were cultured for 24 h (LPL mRNA) or 72 h (LPL mass) in 5.6 or 20 mmol/l glucose in the presence of BSA, AGEs, or GlyBSA (200 μg/ml). At the end of these incubation periods, cells were lysed and total RNA was extracted and analyzed by Northern blot for LPL and S28 mRNA expression. A: LPL mRNA levels were normalized to the levels of S28 mRNA. *** $P < 0.001$ versus 5.6 mM medium (Med); ## $P < 0.01$ versus 20 mM medium. B: LPL mass was measured in supernatants and normalized to the levels of total cell proteins. ** $P < 0.01$, *** $P < 0.001$ versus 5.6 mM medium; ### $P < 0.001$ versus 20 mM medium.](https://www.jlr.org/article/jlr-00895/7/510)
noreactive mass in the supernatants of cells treated with AGEs for 72 h reflected the increase in macrophage LPL mRNA expression in response to AGEs (Fig. 1B). In contrast, no effect of AGEs on extracellular LPL activity was observed (data not shown).

**Effect of AGEs on LPL mRNA levels and secretion by human macrophages**

To assess the physiological relevance of our findings in J774 macrophages, we next determined the effect of AGEs on LPL gene expression and secretion by human macrophages cultured for 24 to 72 h in the presence of 5.6 or 20 mmol/l glucose. As documented in J774 macrophages, AGEs did not change LPL mRNA expression in human macrophages exposed for 24 h to a low-glucose environment (data not shown). In contrast, an increase in LPL mRNA expression was found when human macrophages were incubated for 24 h with AGEs or GlyBSA (200 μg/ml) in the presence of 20 mmol/l glucose (Fig. 2A). Although AGEs did not change LPL secretion by macrophages exposed for 24 or 48 h to a high-glucose environment (data not shown), a significant \( P = 0.03 \) stimulatory effect of AGEs on LPL immunoreactive mass was observed in human macrophages exposed to high glucose for 72 h (Fig. 2B). Levels of LPL activity secreted by AGE-treated macrophages remained unchanged regardless of the experimental conditions applied (data not shown).

**Role of RAGEs in AGE-induced macrophage LPL gene expression**

To determine the nature of the RAGEs mediating the stimulatory effect of AGEs on macrophage LPL expression, J774 cells cultured in a high-glucose medium were pretreated for 1 h with anti-RAGE, SR-A, or CD36 antibodies (1 μg/ml) before exposure to BSA or AGE (200 μg/ml). Immunoneutralization of RAGE totally abolished AGE-induced macrophage LPL gene expression (Fig. 3). In contrast, neither anti-SRA and anti-CD36, nor irrelevant IgG1 and anti-FC-γ receptor II antibodies, significantly reduced LPL gene expression (data not shown). A similar inhibitory effect of RAGE antibody was observed in human macrophages \[ \text{LPL mRNA levels (% of control values): AGEs, 174.9 \pm 24.4; RAGE + AGEs, 77.0 \pm 32.91} \] \( (P < 0.05 \text{ vs. AGEs}) \].

**Effect of antioxidants on AGE-induced macrophage LPL mRNA levels**

To assess the role of oxidative stress as a mediator of the stimulatory effect of AGEs on LPL mRNA levels, J774 cells were pretreated for 1 h with the antioxidant DMSO (0.5%) or NAC (10 mmol/l) and then exposed to AGEs

---

**Fig. 2.** Effect of AGEs on LPL mRNA levels and secretion in human monocyte-derived macrophages. Human monocyte-derived macrophages were cultured for 24 h (LPL mRNA) or 72 h (LPL mass) in 20 mmol/l glucose in the presence of BSA, AGEs, or GlyBSA (200 μg/ml). At the end of these incubation periods, cells were lysed and total RNA was extracted. LPL and GAPDH mRNA expression were analyzed by RT-PCR. A: LPL mRNA levels were normalized to the levels of GAPDH mRNA. B: LPL mass was measured in supernatants and normalized to the levels of total cell proteins. Results represent means ± SEM of three independent experiments. * \( P < 0.05 \), ** \( P < 0.01 \) versus medium.

**Fig. 3.** Role of AGE receptor (RAGE) on AGE-induced macrophage LPL mRNA expression. J774 cells were preincubated for 1 h with antibody against RAGE (1 μg/ml) and then incubated for 24 h in the presence of 20 mmol/l glucose with BSA or AGEs (200 μg/ml). At the end of these incubation periods, total cellular RNA was extracted and analyzed by Northern blot for LPL (A) and S28 (B) mRNA expression. C: LPL mRNA levels were normalized to the levels of S28 mRNA. Results represent means ± SEM of four independent experiments. * \( P < 0.05 \) versus BSA; * \( P < 0.05 \) versus AGEs.
Beauchamp et al. AGes induce macrophage LPL expression

Role of PKC and MAPK as intracellular signaling pathways mediating the stimulatory effect of AGes on macrophage LPL mRNA expression

To evaluate the role of PKC and MAPK in AGE-induced LPL gene expression, we first measured PKC and ERK1/2 phosphorylation in J774 macrophages treated for up to 30 min with AGes. As shown in Fig. 5A, treatment of J774 macrophages with AGes increased membrane PKC activity in these cells by 1.5-fold. This effect was totally reversed by preincubation of the cells with NAC (Fig. 5A). AGes also induced ERK1/2 activation as assessed by immunoblot analysis of phosphospecific ERK1/2 (Fig. 5B). The maximal effect of AGes on ERK1/2 activation was found at 30 min (data not shown). AGe-induced ERK1/2 activation was inhibited by calphostin C, LY379196, NAC, U0126, and PD98059 (Fig. 5B). In contrast, inhibitors alone or solvent controls did not affect basal or AGe-induced ERK1/2 activation, respectively (data not shown). To further investigate the involvement of PKC and MAPK in AGe-induced LPL gene expression, J774 and human macrophages were pretreated with the specific PKC and MAPK inhibitors calphostin C (0.1 µg/ml) and PD98059 (100 µmol/l), respectively. These compounds inhibited the induction of the LPL gene by AGes in both murine (Fig. 6) and human cells (human macrophage LPL mRNA levels (% of control values): AGes, 174.9 ± 24.4; calphostin C + AGes, 83.67 ± 13.04; PD98059 + AGes, 89.33 ± 14.68 (P < 0.05 vs. AGes)). A similar effect was noted when J774 macrophages were incubated with the classic PKC inhibitor GF109203X and the MAPK inhibitor U0126 (data not shown). To determine the role of PKC-β in the regulation of macrophage LPL gene expression by AGes, J774 cells were pretreated with the specific PKC-β inhibitor LY379196 (30 nmol/l) before exposure to AGes. As shown in Fig. 6, this compound totally inhibited AGe-induced LPL mRNA expression. None of these inhibitors affected basal LPL mRNA expression (data not shown).

Fig. 4. Effect of antioxidants on AGE-induced macrophage LPL mRNA expression. J774 cells were preincubated in the presence of 0.5% DMSO or 10 mmol/l N-acetyl-L-cysteine (NAC) for 1 h and then cultured for 24 h in 20 mmol/l glucose in the presence of BSA or AGes (200 µg/ml). At the end of these incubation periods, total cellular RNA was extracted and analyzed by Northern blot for LPL (A) and S28 (B) mRNA expression. C: LPL mRNA levels were normalized to the levels of S28 mRNA. Results represent means ± SEM of four independent experiments. *** P < 0.001 versus BSA; * P < 0.05, ** P < 0.01 versus AGes.

Fig. 5. Effect of AGes on protein kinase C (PKC) and mitogen-activated protein kinase (MAPK) activation in J774 macrophages. J774 cells were pretreated or not with NAC (10 mmol/l), calphostin C (cal C; 0.1 µg/ml), PD98059 (PD; 100 µmol/l), U0126 (U0; 20 µmol/l), or LY379196 (LY; 30 nmol/l) for 1 h and then incubated with 20 mmol/l glucose in the presence of BSA or AGes (200 µg/ml) for 30 min. A: PKC activity in cytosolic and particulate fractions was determined as described in Methods. Results represent means ± SEM of three independent experiments. * P < 0.05 versus BSA; * P < 0.05 versus AGes. B: Extracellular signal-regulated protein kinase (ERK) phosphorylation was assessed by Western blot using phospho-specific or specific ERK1/2 antibodies. Results represent means ± SEM of four independent experiments. One representative blot is shown. ** P < 0.01 versus BSA; * P < 0.05, *** P < 0.001 versus AGes.
We next determined whether incubation of J774 cells in the presence of AGEs might induce changes at the level of the LPL gene promoter binding proteins. We found that a 16 h exposure of J774 cells to AGEs led to an increase in the binding of nuclear proteins to the AP-1 consensus sequence of the LPL promoter (Fig. 7). This binding complex was specifically competed for in the presence of a 1,000-fold molar excess of the unlabeled AP-1 oligonucleotide. To assess the role of PKC and ERK1/2 in this effect, the effects of calphostin C, PD98059, and LY379196 on AGE-induced AP-1 activation were further evaluated. As shown in Fig. 7, these compounds inhibited the enhanced nuclear proteins binding to AP-1. These results suggest that AP-1 binding to the LPL promoter occurs downstream of PKC and MAPK activation in response to AGEs.

### DISCUSSION

Previous studies have demonstrated that the interaction of AGEs with RAGEs expressed on macrophages induces several biological events linked to the development of vascular lesions (34–36). Among these, increased monokine secretion has been documented in AGE-treated human monocytes and macrophages (34, 36). Interestingly, it has also been reported that these compounds act synergistically with high glucose to enhance human monocyte tumor necrosis factor-α and interleukin-6 production (36). In accordance with these data, our study demonstrates that AGEs, although ineffective per se, act synergistically with glucose to induce macrophage LPL secretion. These results further emphasize the critical role of AGEs as key regulators of macrophage function.

On the basis of our previous results showing that high glucose stimulates macrophage LPL at the transcriptional level, we evaluated whether the AGEs’ effect on macrophage LPL secretion may involve transcriptional events. Our findings that changes in LPL mRNA levels in AGE-treated macrophages correlate with changes in LPL secretion support this possibility. Among the signaling pathways initiated by the AGEs’ interaction with vascular cells, the induction of oxidative stress and the activation of kinases have captured considerable interest (37–39). Evidence that oxidant stress and PKC are involved in the regulation of macrophage LPL (40–42) suggests a role for these events in the induction of macrophage LPL in response to AGEs. Our results demonstrating that antioxidants inhibit AGE-induced macrophage LPL gene expression indicate that oxidative stress evoked by the AGEs-macrophage interaction is involved in this process.

Recent data have demonstrated that AGEs activate PKC and MAPK in mesangial cells and human monocytes, respectively (37, 39). In accordance with these results, we found that AGEs induce PKC activity in macrophages and that this event is required for the transcriptional effect of AGEs on macrophage LPL gene expression. Evidence that
the PKCβ isoform-specific inhibitor LY379196 inhibits AGE-induced LPL mRNA levels further supports a role for PKCβ in this effect. This finding, together with the previously documented effect of AGEs on PKCβ activation in vascular renal cells (37), emphasizes the critical role of this PKC isoform in diabetic vascular complications (43, 44). The requirement of high glucose levels to see increased LPL by AGEs may result from the differential kinetic pattern of PKC activation in response to glucose and AGEs. Indeed, in contrast to the rapid and transient activation of PKC that we reported in AGE-treated macrophages, we found that PKC activation in high-glucose-treated macrophages was evident only after several hours (unpublished observations). From these data, it is tempting to speculate that AGEs, although ineffective per se, may induce macrophage LPL by speeding up PKC activation in high-glucose-treated macrophages. Because oxidative stress induces PKC (45), activation of PKC in AGE-treated macrophages may result from the generation of reactive oxygen species. This possibility is supported by our results showing that NAC totally suppresses PKC activation in AGE-treated macrophages. Among the major downstream targets of PKC in human diabetes, MAPK is likely to constitute an important point of regulation of vascular cells. Indeed, it has been demonstrated that coactivation of PKC and MAPK occurs in cells maintained in high glucose (44, 46) and that PKC can activate MAPK (47, 48). Furthermore, evidence has been provided that AGEs activate ERK in human monocytes (39) and that MAPK isoforms constitute downstream effectors of AGE-induced PKC activation in smooth muscle cells (49). Our study clearly demonstrates that AGEs activate ERK1/2 in macrophages and suggests a role of this signaling pathway in AGE-induced macrophage LPL expression. Despite these observations, the use of pharmacologic inhibitors, particularly at high concentrations, can be misleading, and further studies are required to discern the precise role of PKC and ERK1/2 in this effect.

Recent studies have demonstrated that AGEs increase the activities of two major transcription factors involved in the regulation of the macrophage LPL gene, namely AP-1 (49, 50) and peroxisome proliferator-activated receptors (PPARs) (52). Evidence that AGEs activate PKC and MAPK in macrophages and that these kinases regulate the activities of AP-1 (52, 53) and PPARs (54) suggests a potential role of these transcription factors as mediators of the transcriptional effect of AGEs on macrophage LPL gene expression. Our results demonstrating that AGEs enhance the binding of nuclear proteins to the AP-1 sequence of the LPL gene and that this effect is abrogated by PKC and MAPK inhibitors support this hypothesis.

Binding and uptake of AGE proteins by macrophages is mediated by various receptors, including SR-A, CD36, and RAGE (55–57). Evidence that blockade of RAGE, but not of other AGE receptors, inhibits the stimulatory effect of AGEs on LPL indicates that AGEs operate via this receptor to induce macrophage LPL.

Although the potentiation of high-glucose effects by AGEs may be relevant for diabetic vascular complications, the significance of our observations to atherogenesis remains unclear. Given the very significant stimulation of LPL expression by high glucose alone that we previously documented at 96 and 120 h (18), the relatively modest effect of AGEs on glucose-induced LPL mass at 72 h may not have much physiological consequence. It remains to be determined whether AGEs isolated from diabetic sources at concentrations found in the arterial wall produce a similar effect. Finally, lack of an AGE effect on macrophage LPL activity may lessen the relevance of our data to atherogenesis. Although evidence that noncatalytically active LPL promotes atherogenesis partly addresses this issue (58), further studies are clearly needed to evaluate the physiological consequences of the AGE effect that we report here. In conclusion, this study demonstrates that AGEs potentiate the stimulatory effect of high glucose on macrophage LPL expression. This effect is mediated through oxidative stress and appears to require PKC and MAPK activation.

This work was supported by grants from the Canadian Institutes of Health Research, the Association Diabète Québec, and the Heart and Stroke Foundation of Canada. The authors thank Eli Lilly for providing LY379196.

REFERENCES


