Statin-Induced Expression of Decay-Accelerating Factor Protects Vascular Endothelium Against Complement-Mediated Injury

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Abstract—Complement-mediated vascular injury is important in the pathophysiology of atherosclerosis and myocardial infarction. Because recent evidence shows that statins have beneficial effects on endothelial cell (EC) function independent of lipid lowering, we explored the hypothesis that statins modulate vascular EC resistance to complement through the upregulation of complement-inhibitory proteins. Human umbilical vein and aortic ECs were treated with atorvastatin or simvastatin, and decay-accelerating factor (DAF), membrane cofactor protein, and CD59 expression was measured by flow cytometry. A dose-dependent increase in DAF expression of up to 4-fold was seen 24 to 48 hours after treatment. Statin-induced upregulation of DAF required increased steady-state mRNA and de novo protein synthesis. L-Mevalonate and geranylgeranyl pyrophosphate reversed the effect, confirming the role of 3-hydroxy-3-methylglutaryl coenzyme A reductase inhibition and suggesting that constitutive DAF expression is negatively regulated by geranylgeranylation. Neither farnesyl pyrophosphate nor squalene inhibited statin-induced DAF expression, suggesting that the effect is independent of cholesterol lowering. Statin-induced DAF upregulation was mediated by the activation of protein kinase C and inhibition of RhoA and was independent of phosphatidylinositol-3 kinase and NO activity. The increased DAF expression was functionally effective, resulting in significant reduction of C3 deposition and complement-mediated lysis of antibody-coated ECs. These observations provide evidence for a novel cytoprotective action of statins on vascular endothelium that is independent of the effect on lipids and results in enhanced protection against complement-mediated injury. Modulation of complement regulatory protein expression may contribute to the early beneficial effects of statins in reducing the morbidity and mortality associated with atherosclerosis. (Circ Res. 2002;91:696-703.)

Key Words: atorvastatin • complement • cytoprotection • atherosclerosis • endothelium

The statins reduce cholesterol synthesis through inhibition of 3-hydroxy-3-methylglutaryl coenzyme A (HMG-CoA) reductase and are widely prescribed to hyperlipidemic patients to reduce their risk of atherosclerotic complications. The efficacy of this group of drugs in reducing coronary morbidity and mortality has been demonstrated in large intervention trials. However, statins have additional benefits on vascular function above and beyond their lipid-lowering effects. Analysis of clinical trial data has shown that the benefits occur early, extend to patients within the normal LDL cholesterol range for Western populations, and exceed those of other lipid-lowering drugs, despite comparable falls in total cholesterol. Through the inhibition of mevalonate synthesis, statins also prevent the synthesis of isoprenoid intermediates, including farnesyl pyrophosphate (FPP) and geranylgeranyl pyrophosphate (GGPP). Isoprenylation is important in the posttranslational modification of a variety of proteins, including the small GTPases (Rho, Rac, and Ras), and hence plays an integral role in cellular signaling. Moreover, interference with isoprenylation underlies many of the beneficial actions of the statins on vascular endothelium, which include increased endothelial NO synthase (eNOS) expression, proangiogenic effects, increased fibrinolytic activity, reduced secretion of proinflammatory cytokines, and reduced leukocyte adhesion and transmigration.

It is recognized that chronic inflammation is central to the progressive development of atherosclerotic plaques. Complement activation has been proposed as an important component of this response, and this is supported by the presence of C1q through C9 in atherosclerotic lesions, with evidence of complement activation in the form of C3d, C4d, and C5b-9. The generation of sublytic C5b-9 may result in cellular activation, adhesion molecule upregulation, secretion...
of chemokines and growth factors, and proliferation of vascular smooth muscle and endothelial cells (ECs).15

Innate mechanisms for the control of complement activation on the cell surface include the membrane-bound regulatory proteins: decay-accelerating factor (DAF, CD55), membrane cofactor protein (MCP, CD46), and CD59.16 DAF prevents the formation and accelerates the decay of C3 and C5 convertases,17 whereas MCP binds C3b and C4b and facilitates their degradation by factor I, and CD59 acts distally, inhibiting the incorporation of C9 into the C5b-9 membrane attack complex (MAC).16 In previous work, we have demonstrated that DAF, but not MCP or CD59, is inducible on the EC surface after stimulation with a variety of physiological agonists. We have identified distinct signaling pathways for DAF induction with tumor necrosis factor (TNF)-α, interferon-γ, basic fibroblast growth factor, and the C5b-9 MAC using a protein kinase C (PKC)-independent pathway, whereas thrombin and vascular endothelial growth factor–induced DAF is PKC dependent.18–21 DAF induction by these mediators protects ECs against complement-mediated cell lysis, leading us to propose that DAF may be important for maintaining vascular integrity during subacute and chronic inflammatory responses involving complement activation.21 This cytoprotective role during inflammation is further supported by studies in DAF-deficient mice, which demonstrate increased susceptibility to glomerular injury in models of glomerulonephritis.22,23

The importance of DAF in cellular cytoprotection and the demonstration that its expression is regulated on the vascular EC surface through distinct signaling pathways led us to propose that these pathways may be activated pharmacologically. In the present study, we show that statins stimulate DAF expression on the EC surface, leading to enhanced protection against complement-mediated EC injury. The data raise the possibility that in addition to their lipid-lowering effect, statins may exert a powerful inhibitory effect on the progression of atherosclerosis through the control of complement activation.

Materials and Methods
Anti-DAF monoclonal antibody (mAb) 1H4 and anti-MCP mAb TRA-2-10 were kind gifts from Drs D. Lublin and J. Atkinson (Washington University School of Medicine, St Louis, Mo), mAbs A35 (anti-CD59) and RMAC8 (anti-endoglin) were kind gifts from Prof B.P. Morgan (University of Wales College of Medicine, Cardiff, UK) and Dr A. d’Apice (St Vincent’s Hospital, Victoria, Australia), respectively. DETA NONOate was from Cayman Chemical; G6976, GF109303X, GGTI-286, atorvastatin, and simvastatin were from BIOMOL. Myristoylated PKC peptide inhibitor (myr-PKC) was from Promega. Other products were from Sigma Chemical Co.

EC Isolation and Culture
Human umbilical vein ECs (HUVECs), the human dermal EC line HMEC-1, and human aortic ECs (HAECs), purchased from Promocell, were cultured as described previously.18,24

Flow Cytometry
Flow cytometry was performed as previously described.18 Pharmacological antagonists were added 60 minutes before the addition of statins. In some experiments, the results are expressed as the relative fluorescence intensity (RFI), representing mean fluorescence intensity (MFI) with test mAb divided by the MFI using an isotype-matched irrelevant mAb. Cell viability was assessed by examination of EC monolayers using phase-contrast microscopy, cell counting, and estimation of trypan blue exclusion.

Northern Blotting
Northern analysis was performed as previously described.18 Northern blots were quantified by an Appligene Image Analysis System, and densitometry was performed using Image program 1.52 software (National Institutes of Health). Values were corrected with respect to ethidium bromide–stained RNA loading patterns, and an arbitrary value of 1 was assigned to unstimulated ECs.

Western Blotting
Western blot analysis was performed as described previously.24 The anti-PKcé antibody (C-20) was from Santa Cruz Biotechnology, and anti–phospho-PKcé was from Upstate Biotechnology. Changes in phospho-PKcé were quantified by the Appligene Image Analysis System, and values were corrected with respect to the PKcé bands.

C3 Binding and Cell Lysis Assays
The methods used for detection of cell surface C3 and cell lysis were as described previously.20 ECs cultured in the presence and absence of atorvastatin for 24 hours were opsonized with mAb RAMC8 and incubated with 5% to 20% normal human serum (NHS) for 3 hours at 37°C before analysis by flow cytometry. In the inhibition studies, blocking mAbs were added at a final concentration of 25 μg/mL. To estimate complement-mediated cell lysis, ECs pretreated with atorvastatin or plain medium alone for 24 hours were loaded with calcein AM (Molecular Probes), opsonized, and incubated with 5% to 20% baby rabbit serum (Serotec) for 30 minutes at 37°C. Percent specific lysis in triplicate wells was calculated as follows: (complement-mediated calcein release−spontaneous release)/maximal release−spontaneous release)×100%, where maximal release is complement-mediated release+detergent-mediated release.

Statistical Analysis
Differences between the results of experimental treatments were evaluated by the Mann-Whitney U test. Differences were considered significant at values of P<0.05.

Results
Statins Upregulate DAF Expression on Human ECs
As seen in Figure 1A, 24-hour exposure of HUVECs to atorvastatin led to a significant unimodal increase in DAF expression. In 10 separate experiments, atorvastatin increased DAF expression by 3- to 4-fold above the baseline on unstimulated HUVECs (mean±SEM RFI was 50.8±11.3 for unstimulated HUVECs and 222.4±38.4 for atorvastatin-stimulated HUVECs, P<0.01). Dose-response studies showed an increase in DAF expression after treatment with 0.05 to 0.1 μmol/L atorvastatin, with maximal upregulation at 1 to 2.5 μmol/L (Figure 1B). To determine the kinetics of DAF induction, HUVECs were cultured in the presence of atorvastatin for up to 48 hours. An increase in DAF was first
detectable 12 to 18 hours after treatment and was maximal at
24 to 48 hours (Figure 1C). In contrast, atorvastatin had no
effect on the surface expression of MCP, and although an
increase in CD59 expression was seen, this did not reach
significance (Figure 1D). Significant upregulation of DAF
was also seen after treatment with 0.0625 to 0.125
\(\mu\)mol/L simvastatin, with a maximal response at 1.25
\(\mu\)mol/L (Figure 2A). Experiments performed on HAECs (to represent a
vascular bed affected by atherosclerosis) and on the human
dermal microvascular EC line HMEC-1 confirmed that they
behaved in the same way as HUVECs in terms of DAF
upregulation in response to atorvastatin and simvastatin
(Figure 2B). Therefore, further experiments were performed
with HUVECs.

Statin-Induced DAF Expression Requires
Increased Steady-State mRNA and De Novo
Protein Synthesis
To determine whether the increase in DAF after statin
treatment was dependent on gene transcription, HUVECs
were pretreated with actinomycin D before the addition of
atorvastatin. The presence of actinomycin D completely
inhibited atorvastatin-induced DAF expression (Figure 3A).
Northern analysis was performed using mRNA extracted
from unstimulated HUVECs and cells stimulated with ator-
vastatin for up to 24 hours. Two DAF mRNA transcripts (2.4
and 1.8 kb) were detected at low levels in unstimulated ECs
(lane 1, Figure 3B). In three experiments, atorvastatin treat-
ment led to an increase in DAF mRNA that was first
detectable at 6 to 9 hours and was persistent at 24 hours after
stimulation. Quantification of mRNA levels using densito-
metric scanning of the 2.4-kb band demonstrated a 3-fold
increase above baseline at 24 hours after stimulation.
To investigate whether the effect of atorvastatin on DAF
gene transcription was direct or required synthesis of a
transactivating factor, ECs were preincubated for 30 minutes
with cycloheximide before the addition of atorvastatin. As
previously described,\textsuperscript{2} incubation with cycloheximide
alone led to a superinduction of steady-state DAF mRNA by
up to 60%, as quantified by densitometry (lane 6, Figure 3B).
Incubation with atorvastatin and cycloheximide led to a rise
in steady-state DAF mRNA similar to that seen with cyclo-
heximide alone (lanes 7 and 8, Figure 3B). This was in
contrast to thrombin, which induced an increase in DAF
mRNA in the presence of cycloheximide (not shown).\textsuperscript{1}
The failure of atorvastatin to enhance the cycloheximide-induced
rise in steady-state DAF mRNA suggests that the changes in
DAF gene transcription observed are indirect and dependent
on the synthesis of \(\approx\)1 intermediary protein.
To determine whether the increase in cell surface DAF was
dependent on de novo protein synthesis, HUVECs were

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**Figure 1.** Analysis of DAF, MCP, and CD59 expression on
HUVECs after stimulation by atorvastatin (AT). DAF expression
was assessed by flow cytometry using mAb 1H4. A, DAF
expression on HUVECs is shown in the absence of AT (MFI 45,
open histogram with dotted line) and after 24-hour stimulation
with 2.5 \(\mu\)mol/L AT (MFI 152, open histogram with solid line).
Background fluorescence (irrelevant antibody and FITC-labeled
rabbit anti-mouse immunoglobulin) is shown by the shaded his-
togram. B, ECs were stimulated for 24 hours with AT at varying
concentrations before analysis for DAF expression. C, Time
course for AT-induced DAF expression on HUVECs is shown.
D, Studies involved unstimulated (US) ECs and ECs stimulated
for 24 hours with AT (2.5 \(\mu\)mol/L). Expression of CD59 and MCP
was detected by flow cytometry using mAbs A35 and TRA2-10,
respectively. Bars represent mean \(\pm\) SD RFI (n=3), derived by
dividing the MFI with test mAb by the MFI with the use of
isotype-matched irrelevant mAb. *P<0.05, **P<0.01. Data are
representative of 4 replicate experiments.

**Figure 2.** A, HUVECs were incubated for 24 hours with simva-
statin (SIM) at the concentrations shown and analyzed by flow
cytometry for DAF expression with the use of mAb 1H4. Values
are mean \(\pm\) SD RFI (n=3). B, Studies involved US HAECs and
HMECs and also HAECs and HMECs treated with AT or SIM
(both 1 \(\mu\)mol/L) or plain medium alone for 24 hours. DAF
expression was analyzed by flow cytometry as described above.
Values are mean \(\pm\) SD RFI (n=3). *P<0.05, **P<0.01. Data are
representative of 3 replicate experiments.
pretreated with cycloheximide before the addition of atorvastatin. This led to a complete abrogation of atorvastatin-induced DAF (Figure 3C). Taken together, these observations suggest that upregulation of DAF expression by statins is associated with gene transcription, an increase in steady-state DAF mRNA, and de novo protein synthesis.

**Effect of Mevalonate and Isoprenoid Intermediates**

Because HMG-CoA reductase catalyzes the conversion of HMG-CoA to mevalonate, we tested the capacity of l-mevalonate to override the effect of statins on DAF expression. l-Mevalonate inhibited DAF upregulation by atorvastatin (Figure 4A), simvastatin, and mevastatin (not shown) in a dose-dependent manner, suggesting that statin-induced DAF expression involves inhibition of HMG-CoA reductase. After this, a series of experiments was performed to further investigate the molecular signal transduction pathway by which the statins modulate EC DAF expression. Pretreatment of ECs with the isoprenoid intermediates GGPP or GGOH led to a dose-dependent inhibition of atorvastatin-induced DAF upregulation (Figure 4B). On the other hand, preincubation of ECs with FPP or squalene, downstream metabolites in the cholesterol synthesis pathway, did not influence statin-induced DAF expression (Figure 4C). These data suggest that geranylgeranylated proteins negatively regulate constitutive endothelial DAF expression.

**Role of Rho-GTPases**

Because geranylgeranylation is known to activate Rho-GTPases, we tested the effect of the geranylgeranyl trans-
ferase inhibitor GGTI-286 and C3 exoenzyme, an inhibitor of Rho-GTPases. Treatment of ECs for 24 hours with GGTI-286 or C3 exoenzyme resulted in a significant increase in DAF expression (Figure 5A). These data indicate that statin-induced DAF expression is mediated, at least in part, by inhibition of the geranylgeranylation of small G proteins.

Effect of PI-3 Kinase, NO, and PKC Pathways on Statin-Induced DAF Expression

Treatment of HUVECs with statins results in the phosphorylation of Akt by a mechanism involving phosphatidylinositol-3 kinase (PI-3 kinase). To investigate the role of PI-3 kinase in statin-induced DAF upregulation, we preincubated HUVECs with LY290042 before the addition of atorvastatin for 24 hours. As shown in Figure 6A, the presence of LY290042 paradoxically enhanced DAF expression alone and in the presence of atorvastatin.

Statins have also been shown to stabilize eNOS mRNA and increase local synthesis of NO. To investigate the role of NO in statin-induced DAF upregulation, we preincubated HUVECs with LY290042 before the addition of atorvastatin for 24 hours. As shown in Figure 6A, the presence of LY290042 paradoxically enhanced DAF expression alone and in the presence of atorvastatin.

We have previously identified distinct PKC-dependent and -independent pathways for the regulation of DAF in ECs. To examine whether PKC was implicated in statin-induced DAF expression, we initially used a pharmacological inhibitor of the classic and novel PKC isoenzyme GF109203X. As seen in Figure 7A, pretreatment with GF109203X significantly inhibited atorvastatin-induced DAF upregulation. Subsequent experiments used G6976, a specific antagonist for the classic PKC isozymes PKCα and PKCβ. Although G6976 inhibited simvastatin-induced DAF expression, LY379196, a selective PKC inhibitor, had no effect (Figure 7B). This suggested that PKCα was the principle isoenzyme involved in statin-induced DAF expression, and this was further supported by use of the cell-permeable peptide myr-γ/δPKC, specific for PKCα and PKCβ, which abrogated atorvastatin-induced DAF expression (Figure 7B). Furthermore, Western blotting with an antibody specific for the phosphorylated form of PKCα demonstrated a 3-fold increase in PKCα phosphorylation after 30 minutes of exposure to atorvastatin (Figure 7C), as quantified by densitometry.

Statin-Induced DAF Expression Enhances EC Resistance to Complement-Mediated Injury

To address the functional significance of DAF upregulation by statins, the effects of atorvastatin on complement factor C3 deposition on the EC surface were measured. Unstimulated and atorvastatin-treated HUVECs were opsonized with RMAC8, an IgG2a anti-endoglin mAb. Endoglin is highly expressed on the EC surface and was not influenced by incubation of HUVECs with atorvastatin for 24 hours. Opsonized HUVECs were incubated with 20% NHS for 3 hours, and C3 binding to the cell surface was quantified by flow cytometry for DAF expression with the use of mAb 1H4. Results are expressed as mean ± SD RFI (n=3). *P<0.05. Data are representative of 3 replicate experiments.
cytometry. Compared with no treatment, atorvastatin reduced C3 deposition on the EC surface by 60% (Figure 8A). The inhibitory anti-DAF mAb 1H4 was used to confirm the role of DAF in the reduction of C3 binding observed. In addition, the inhibitory mAb (A35) against CD59 and a control antibody (EN4), which would not be expected to inhibit C3 binding, were studied. As seen in Figure 8B, the addition of 1H4 markedly increased the binding of C3 to unstimulated opsonized ECs exposed to 20% NHS. Moreover, the reduction in C3 binding seen in response to atorvastatin treatment was reversed by 1H4, with levels of C3 deposited on the cell surface becoming equivalent to those observed on unstimulated ECs in the presence of 1H4 (Figure 7B). In contrast, neither A35 nor EN4 had any effect on the level of C3 binding observed (not shown).

To assess the physiological relevance of this reduction in C3 binding, HUVECs were loaded with calcein AM, opsonized with mAb RMAC8, and exposed to baby rabbit serum. Endothelial lysis was subsequently measured by estimation of calcein release. As seen in Figure 8C, pretreatment of ECs with atorvastatin for 24 hours was cytoprotective, significantly reducing cell lysis after exposure to 5% to 10% rabbit serum. However, at serum concentrations of ≥20%, the cytoprotective effect of atorvastatin was overcome. These observations suggest that the increased levels of cell surface DAF seen in response to the treatment of ECs with statins provide additional protection against complement-mediated injury.

Discussion

The effects of statins in the reduction of cardiovascular morbidity and mortality can be detected remarkably early, before significant angiographic changes. Furthermore, statins benefit patients with normal-range LDL cholesterol, raising the possibility that they have beneficial effects beyond cholesterol lowering. The data presented in the present study demonstrate a novel potentially atheroprotective action of statins, namely, the regulation of complement activation.

Treatment of ECs with three different statins (atorvastatin, simvastatin, and mevastatin) resulted in an upregulation of DAF expression at least equivalent to that previously ob-
In vascular ECs, Ras translocation is dependent on farnesylation, whereas geranylgeranylation has been implicated in Rho translocation. Thus, the upregulation of DAF by GGTI-286 and the inhibition of statin-induced DAF by GGPP and GGOH suggest that inhibition of Rho might be important in DAF upregulation. This was confirmed by the observation that C3 exoenzyme, an inhibitor of Rho-GTPase, induced a significant rise in DAF cell surface expression. However, the upregulation of DAF after treatment with C3 exoenzyme or GGTI-286 was always less than that seen with atorvastatin, an observation also made for lovastatin-induced responses, suggesting that statins influence additional downstream signaling pathways in ECs beyond the inhibition of Rho.

Recent studies have revealed a role for the PI-3 kinase/Akt pathway in statin-induced angiogenesis, In addition, statins stabilize eNOS mRNA, resulting in increased local concentrations of NO. Notwithstanding this, statin-induced DAF expression was independent of both PI-3K activation and NO generation. Paradoxically, exposure of ECs to the PI-3K inhibitors LY290042 and wortmannin enhanced both basal DAF and statin-induced DAF expression. This implies that DAF expression is under tight regulation and is downregulated by the activation of PI-3K/Akt and upregulated by a distinct parallel pathway.

We have previously described PKC-dependent pathways of DAF upregulation in ECs. Inhibition of the classic and novel isozymes of PKC with GF109203X abrogated statin-induced DAF upregulation. Furthermore, experiments with Gø6976, LY379196, and particularly the specific inhibitory peptide myr-PKCö suggest that PKCo is the predominant isozyme involved in this response. This conclusion was supported by the demonstration that atorvastatin induced phosphorylation of PKCo in HUVECs. The mechanism by which the statins activate PKC and confirmation of a link between changes in the activation state of PKCo and Rho in the upregulation of DAF remain to be determined. Evidence to date suggests that protein-protein interactions between PKC isozymes, (including PKCo) and Rho-GTPases do occur. Although the outcome varies between cell types and assay systems, the data suggest that significant cross talk occurs between these two pathways. Indeed, a recent study has demonstrated that phosphor ester–induced PKC activation results in a significant decrease in Rho activity in aortic smooth muscle cells.

Complement activation has an established role in the pathogenesis of inflammatory cardiovascular diseases, including atherosclerosis, myocardial infarction, and the accelerated atherosclerosis of transplantation. Analysis of atherosclerotic plaques has revealed the presence of activation products, including C3d, C4d, and the C5b-9 membrane attack complex. Complement may be activated in the arterial wall by deposition of immune complexes, such as those generated by autoantibodies against oxidized lipoproteins, and by cholesterol crystals, modified LDL, and C-reactive protein. Although DAF and other complement inhibitory proteins have been identified in atherosclerotic lesions, their expression, regulation, and function are poorly understood. However, a recent study demonstrated that although expression of DAF, MCP, and CD59 is evident in normal arteries, there is no increase in their expression in the face of complement activation in atherosclerotic lesions. This led to the proposal that inhibition of complement activation
may be required to control disease progression.41 According to our observations, it is possible that the ability of the statins to prevent coronary events in patients with relatively low lipid levels is due, at least in part, to a reduction in complement activation within the atherosclerotic vessel wall through the upregulation of DAF expression on ECs and perhaps also other cells in the vessel wall.

In conclusion, we have demonstrated a novel cytoprotective action of the statins that involves increased expression of the complement regulatory protein DAF. This may represent a means by which endothelium can be therapeutically conditioned for the prevention and treatment of atherosclerosis and other vascular inflammatory diseases involving complement activation.

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References

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