Statins Use a Novel Nijmegen Breakage Syndrome-1–Dependent Pathway to Accelerate DNA Repair in Vascular Smooth Muscle Cells

Melli Mahmoudi, Isabelle Gorenne, John Mercer, Nicola Figg, Trevor Littlewood, Martin Bennett

Abstract—Although the hydroxymethylglutaryl-coenzyme A reductase inhibitors (statins) are widely used in atherosclerosis to reduce serum cholesterol, statins have multiple other effects, including direct effects on cells of the vessel wall. Recently, DNA damage, including telomere shortening, has been identified in vascular smooth muscle cells (VSMCs) in human atherosclerosis. Although statins reduce DNA damage in vitro, the mechanisms by which they might protect DNA integrity in VSMCs are unknown. We show that human atherosclerotic plaque VSMCs exhibit increased levels of double-stranded DNA breaks and basal activation of DNA repair pathways involving ataxia telangiectasia–mutated (ATM) and the histone H2AX in vivo and in vitro. Oxidant stress induced DNA damage and activated DNA repair pathways in VSMCs. Statin treatment did not reduce oxidant stress or DNA damage but markedly accelerated DNA repair. Accelerated DNA repair required both the Nijmegen breakage syndrome (NBS)-1 protein and the human double minute protein Hdm2, accompanied by phosphorylation of Hdm2, dissociation of NBS-1 and Hdm2, inhibition of NBS-1 degradation, and accelerated phosphorylation of ATM. Statin treatment reduced VSMC senescence and telomere attrition in culture, accelerated DNA repair and reduced apoptosis in vivo after irradiation, and reduced ATM/ATR (ATM and Rad3-related) activity in atherosclerosis. We conclude that statins activate a novel mechanism of accelerating DNA repair, dependent on NBS-1 stabilization and Hdm2. Statin treatment may delay cell senescence and promote DNA repair in atherosclerosis. (Circ Res. 2008;103:717–725.)

Key Words: atherosclerosis ■ vascular smooth muscle ■ aging ■ oxidant stress

Human atherosclerotic plaques demonstrate evidence of DNA damage, including expression of oxidized guanosine residues, DNA strand breaks, and activation of DNA repair enzymes.1,2 Although DNA damage is seen in both vascular smooth muscle cells (VSMCs) and macrophages, the mechanisms underlying DNA damage and its biological consequences are unknown. For example, DNA damage can promote apoptosis and premature cell senescence (reviewed elsewhere), both of which are prominent in VSMCs in human atherosclerosis.2,4 Conversely, accelerating DNA repair may prevent or reduce accumulated DNA damage, preventing apoptosis or cell senescence.

DNA damage induces a cascade of activated proteins that act as sensors and effectors of the damage response, to stall the cell cycle allowing repair to occur, to promote repair, or to induce apoptosis if damage is severe. DNA damage activates Nijmegen breakage syndrome (NBS)-1, a ubiquitously expressed 754-aa protein and key regulator of the MRE11/RAD-50/NBS-1 (MRN) complex.5,6 MRN promotes early processing of double-strand breaks (DSBs) via DNA binding and nuclease activities, functions as a DSB sensor, and also recruits the ataxia telangiectasia–mutated (ATM) protein to DSBs, followed by ATM activation.7–9 ATM is normally present as inactive dimers, but DSB exposure induces autophosphorylation at Ser1981, dimer dissociation, and kinase activation. ATM has multiple downstream substrates that mediate cell senescence, growth arrest and apoptosis, including histone (H)2AX. ATM accumulates at DSBs, as marked by nuclear foci of phosphorylated ATM and Ser139 phosphorylation of H2AX flanking the site of DNA damage.10 Phosphorylated H2AX (γ-H2AX) facilitates the local assembly of checkpoint and DNA repair factors and is a robust marker of DSBs.11

The hydroxymethylglutaryl-coenzyme A (HMG-CoA) reductase inhibitors (statins) are widely used in atherosclerosis to reduce serum cholesterol. More recently, statins have been reported to reduce DNA damage in vitro and also in vivo, after a variety of insults. There are multiple mechanisms by which statins might reduce DNA damage, including reduction of oxidative stress,12–15 inhibition of prenylation of proteins involved in inducing DNA damage,16 and inhibition of downstream signaling from damaged DNA.17,18 We, therefore, examined the effect of statin treatment on DNA damage and repair pathways in human VSMCs. We identify a novel
mechanism by which statins accelerate DNA repair involving NBS-1 and Hdm2. Importantly, statins can inhibit cell senescence, accelerate DNA repair, and reduce DNA damage in atherosclerosis in vivo.

Materials and Methods

Cell culture, preparation of nuclear extracts, immunoprecipitation, protein electrophoresis, Western blotting, and immunohistochemistry were as previously described. See the expanded Material and Methods section in the online data supplement, available at http://circres.ahajournals.org.

Small Interfering RNA

VSMCs were transfected with small interference (si)RNA using an Amaxa Nucleofector II (Amaxa, Ge) using the following sequences for Hdm2: sense, r(CUG UCU UAA AUG AGA AGU) AdTdT; and antisense, r(UAC UUC UUU AAG ACA G)dAdG.

Comet Assay

For analysis of DNA strand breaks, 30 000 cells per condition were centrifuged, suspended in 80 μL of low melting point agar, transferred to a slide coated with normal melting point agar, covered, and incubated for 10 minutes at 4°C. Cells were then lysed in alkaline buffer (2.5 mol/L NaOH, 100 mmol/L EDTA, 10 mmol/L Tris, pH 10), electrophoresed for 30 minutes in 0.3 mol/L NaOH, 1 mmol/L EDTA at 24 V and 0.29 A, neutralized in 0.4 mol/L Tris buffer, pH 7.5, and then stained with ethidium bromide. For each slide, 5 random pictures were taken using an Olympus BX51 microscope at ×10 magnification, and the comet length of 50 cells was counted using NIH Image analysis software.

Mouse DNA Repair

Mouse experiments were approved by the local Animal Ethics Committee and subject to United Kingdom Home Office licensing. C57BI-6 mice underwent sublthal body irradiation in a sealed chamber, using caesium gamma irradiation, at a dose of 7.5 Gy for 20 minutes. Mice were euthanized at differing times from 0 to 48 hours, and tissues were processed for histology.

Atherosclerosis in Rabbits

The study protocol was approved by the Internal Review Board of the Mount Sinai School of Medicine. Aortic atherosclerosis was induced in male New Zealand White rabbits (age, 3 months; weight, 3.5±0.2 kg) by a combination of a 9-month high-fat diet, enriched with 0.2% cholesterol (Research Diets Inc, New Brunswick, New Jersey), and aortic double-balloon denudation injury, as described previously. At 9 months, rabbits were randomized to high-fat diet, or low-fat diet, or low-fat diet/3.5 kg, by a combination of a 9-month high-fat diet, enriched with 0.2% cholesterol (Research Diets Inc, New Brunswick, New Jersey), and aortic double-balloon denudation injury, as described previously. At 9 months, rabbits were randomized to high-fat diet, or low-fat diet, or low-fat diet. The changes seen on Western blotting (Figure 2D).

Results

Human Atherosclerotic Plaque VSMCs Show DNA Damage and Chronic Activation of DNA Repair Pathways

We first examined human atherosclerotic plaques with a range of disease severity (American Heart Association Grade I to IV) for activation of DNA repair pathways and DNA damage, using immunohistochemistry for phosphorylation of ATM/ATR (ATM and Rad3-related) substrates (a measure of enzyme activity) and the phosphorylated site (Ser139 of H2AX, colabeled with α-smooth muscle actin to identify VSMCs). Phosphorylation of ATM/ATR substrates and H2AX in VSMCs increased with disease severity in vivo (Figure 1A), reaching 70% to 90% of intimal VSMCs in advanced disease. Normal aorta showed minimal expression in medial VSMCs. VSMCs cultured from plaques for several passages retained increased basal ATM and H2AX phosphorylation and increased nuclear foci of these proteins (Figure 1B and 1C), indicating their recruitment to sites of DNA damage and increased DNA strand breaks compared with normal VSMCs (Figure 1D), as assessed by alkaline electrophoresis (comet assay). These results in cultured cells suggest that DNA breaks and associated induction of DNA repair systems are intrinsic to plaque VSMCs and not just in response to the local plaque environment.

Atorvastatin Accelerates DNA Repair in Human VSMCs

To examine whether statin treatment reduces VSMC DNA damage, we administered the potent statin atorvastatin and studied oxidant stress and DNA damage and repair after treatment with the free radical–generating agent tert-butyl hydroperoxide (t-BHP). t-BHP induces DNA breaks in many cell types20 and can induce both “stress-induced premature senescence,” and accelerate telomere shortening of human VSMCs. t-BHP increased oxidant stress, DNA breaks and P-ATM and γ-H2AX expression in normal VSMCs to levels seen in plaque VSMCs, suggesting that plaque VSMCs might be subject to chronic oxidant stress (data not shown). Indeed, we have previously shown that plaque VSMCs generate higher levels of reactive oxygen species (ROS) than normal VSMCs in culture. Importantly, atorvastatin did not reduce oxidant stress over 6 hours over a range of concentrations (online data supplement, Figure I). DNA repair was assessed after 1 hour of incubation followed by removal of t-BHP and monitoring strand breaks over time. t-BHP-induced DNA breaks were repaired by 6 hours, as indicated by the normalization of comet tails (Figure 2A). Atorvastatin did not reduce DNA damage (at 1 hour), but significantly accelerated DNA repair, with complete repair by 4 hours (Figure 2A).

To examine the effect of atorvastatin on activation of DNA repair pathways, we studied the induction of P-ATM and γ-H2AX using time points from 0 to 5 hours (Figure 2B) or 0 to 45 minutes (Figure 2C). Phosphorylation of these proteins was induced by t-BHP at 1 hour (P-ATM) or 5 hours (γ-H2AX) (Figure 2B). Atorvastatin accelerated ATM phosphorylation to 15 minutes (Figure 2C) and γ-H2AX phosphorylation to 1 hour (Figure 2B). Mevalonate, an intermediate of cholesterol synthesis downstream of HMG-CoA reductase, reversed the atorvastatin effects, confirming that atorvastatin was acting through HMG-CoA reductase inhibition (Figure 2B). Atorvastatin accelerated P-ATM foci formation at 15 to 30 minutes (Figure 2D), which paralleled the changes seen on Western blotting (Figure 2D).

Acceleration of DNA Repair by Atorvastatin Requires NBS-1

To examine how atorvastatin accelerates DNA repair, we examined signaling molecules upstream of ATM and H2AX, focusing first on the MRN complex and, in particular, NBS-1. Although NBS-1 is an ATM substrate, NBS-1 is required for efficient ATM recruitment to DNA damage sites and its activation. NBS-1 expression and posttranslational modification are also important regulators of DNA repair.
showed minimal basal expression in VSMCs but appeared 15 minutes after t-BHP treatment in atorvastatin-treated cells (Figure 2C). Atorvastatin also accelerated induction of NBS-1 and γ-H2AX after treatment with the topoisomerase inhibitor etoposide (from 5 hours to 1 hour) and accelerated DNA repair (supplemental Figures II and III), confirming that its effect was not limited to oxidant stress-induced DNA damage. Neither RAD50 nor MRE were induced by atorvastatin (Figure 2C).

To determine whether NBS-1 was required for the atorvastatin effect, we studied cells with differing expression levels of NBS-1. Wild-type human dermal fibroblasts (HDFs), HDFs lacking NBS-1 (HDFnbs1−/− cells), and HDFnbs1−/− cells containing retrovirus-mediated constitutive expression of NBS-1 (HDFnbs1+/+ cells) were incubated with t-BHP. Similar to VSMCs, atorvastatin accelerated ATM phosphorylation in HDFs (to 30 minutes) (Figure 3A) and H2AX phosphorylation from 7 to 2 hours (data not shown), confirming that the atorvastatin effect was not confined to VSMCs. Atorvastatin did not accelerate ATM or H2AX phosphorylation in HDFnbs1−/− cells or HDFnbs1+/+ cells (Figure 3A and data not shown). t-BHP induced DNA damage in wild-type HDFs, with recovery by 7 hours; atorvastatin accelerated DNA repair in HDFs with recovery by 2 hours (Figure 3B). In contrast, HDFnbs1−/− cells showed defective DNA repair, with incomplete repair even at 7 hours, which was not affected by atorvastatin (Figure 3B). DNA repair was rapid in HDFnbs1+/+ cells, with complete repair by 2 hours, but was not also accelerated by atorvastatin. Thus, the ability of atorvastatin to accelerate DNA repair requires NBS-1 and is seen in other mesenchymal cells.

**NBS-1 Induction by Atorvastatin Requires Hdm2**

The induction of NBS-1 by atorvastatin at 15 minutes (Figure 2C) suggests that NBS-1 regulation is determined by post-translational mechanisms. Indeed, atorvastatin did not alter NBS-1 mRNA expression (data not shown). NBS-1 regulates the nuclear import of MRE11 and RAD50 via the importin αKPNA2. Statins can inhibit synthesis of isoprenoid intermediates, which serve as lipid attachments for numerous intracellular signaling molecules. We, therefore, examined NBS-1 expression in cytoplasmic and nuclear fractions after

---

**Figure 1.** Human atherosclerotic plaques demonstrate persistent markers of DNA damage and repair. A, Immunohistochemistry for phosphorylation of ATM/ATR substrates or γ-H2AX (brown) in human normal aorta or atherosclerotic plaques, colocalized with α-smooth muscle cell actin–positive VSMCs (blue). Arrows indicate double-positive cells. Insets show high-power fields. Scale bar=100 μm. Graphs demonstrate percentages of VSMCs positive for each marker with increasing severity of atherosclerosis assessed by American Heart Association Grade I to V (n=8). B, Western blot for P-ATM and γ-H2AX in cultured normal or plaque VSMCs. C, Immunocytochemistry demonstrating nuclear foci of P-ATM and γ-H2AX in normal and plaque VSMCs under basal conditions. D, DNA strand breaks quantified (left) and demonstrated (right) by comet tail length in normal or plaque VSMCs. Data are means±SEM (n=4). *P<0.05.
treatment with atorvastatin. Atorvastatin rapidly induced the appearance of nuclear NBS-1 (Figure 3C). However, cytoplasmic NBS-1 was undetectable even before t-BHP treatment, indicating that increased nuclear NBS-1 after atorvastatin was not attributable to increased import (Figure 3C). Statins can also inhibit proteasomal activity, although the potency of this effect is unclear.24 We, therefore, incubated VSMCs with lactacystin, an inhibitor of proteasomal degradation, and compared with atorvastatin. Like atorvastatin, lactacystin induced NBS-1 appearance 15 minutes after t-BHP treatment. However, atorvastatin did not demonstrate significant chymotrypsin-like activity (supplemental Figure IV), indicating that although atorvastatin results in inhibition of NBS-1 degradation, which ultimately occurs through the proteasome, atorvastatin is not a direct proteasomal inhibitor.

Statins can induce Ser166 phosphorylation on the ubiquitin ligase Hdm2,17 enhancing its nuclear localization and increasing p53 degradation.17,25,26 Hdm2 phosphorylation also alters its E3 ligase or protein-degrading activity or substrate specificity, independent of Hdm2 localization, binding to its substrate or Hdm2 levels.27–29 The ability of Hdm2 to bind to NBS-1 at DSBs and inhibit DNA repair requires the NBS-1 binding domain but is apparently independent of its ubiquitin ligase activity.30 However, statins also reduce Hdm2 half-lives,17 indicating that the decreased Hdm2 activity observed in the presence of statins is due to decreased levels of Hdm2, rather than decreased activity of Hdm2.

Figure 2. Atorvastatin accelerates DNA repair and activation of DNA repair pathways. A, Human VSMCs were pretreated with 100 nmol/L atorvastatin for 48 hours before administration of 80 μmol/L t-BHP for 1 hour. Left, DNA comet tail length was determined by alkaline agarose gel electrophoresis and quantified using NIH Image (data are means±SEM, *P<0.05, n=3). Right, Representative images of comet tails 1 or 3 hours after t-BHP treatment or controls. B, Western blot for P-ATM and γ-H2AX 0 to 5 hours after t-BHP with or without atorvastatin and with or without 100 μmol/L mevalonate pretreatments. C, Western blot for P-ATM and MRN complex proteins (NBS-1, MRE11, Rad50) 0 to 45 minutes after t-BHP with or without atorvastatin pretreatment. D, Formation of nuclear foci of P-ATM 0 to 45 minutes after t-BHP with or without atorvastatin pretreatment. Graph quantifies ATM-P foci per nucleus (data are means±SEM, *P<0.05, n=4).

Figure 3. NBS-1 is required for atorvastatin to accelerate DNA repair. A, Western blot for P-ATM 0 to 45 minutes after t-BHP with or without atorvastatin pretreatment in human dermal fibroblasts (HDFs), HDFnbs-1−/− cells, and HDFnbs-1−/+ cells. B, Comet tail length over 7 hours for HDFs, HDFnbs-1−/− cells, and HDFnbs-1−/+ cells with or without atorvastatin pretreatment. Data are means±SEM (n=4), *P<0.01. C, Western blot for NBS-1 in nuclear (N) and cytoplasmic (C) subfractions 0 to 45 minutes after t-BHP with or without atorvastatin or lactacystin pretreatments for 48 hours. The cytoplasmic marker heat shock protein 60 (HSP60) is shown as a control.
life, and it is unclear whether subsequent alterations in Hdm2 expression or phosphorylation alter expression of Hdm-2-bound proteins. In VSMCs, atorvastatin pretreatment for 48 hours induced robust Ser166Hdm2 phosphorylation, which normalized 30 minutes after DNA damage (Figure 4A), with minimal changes in total Hdm2 expression. Using immunoprecipitation, atorvastatin pretreatment reduced NBS-1 binding to Hdm2 by 32% at time 0 and 44% at 15 minutes after t-BHP (Figure 4B), suggesting that changes in NBS-1 bound to Hdm2 determined NBS-1 expression. To prove that the effect of atorvastatin on NBS-1 required Hdm2, we incubated VSMCs with siRNA to HDM2 and studied NBS-1 induction. Hdm2 inhibition accelerated the appearance of NBS-1 after DNA damage with similar kinetics to atorvastatin (Figure 4C). Furthermore, atorvastatin markedly extended NBS-1 half-life after cycloheximide treatment (from 7 to 14 minutes), siRNA to Hdm2 also significantly extended the half-life of NBS-1 (to 32 minutes), with no additional effect of atorvastatin (Figure 4D). These data suggest that the effect of atorvastatin on NBS-1 is mediated through inhibition of Hdm2-mediated degradation of NBS-1.

**Atorvastatin Inhibits Telomere Shortening, Accelerates DNA Repair, Reduces VSMC Death, and Inhibits DNA Damage Markers in Atherosclerosis**

Although atorvastatin accelerated DNA repair in VSMCs in vitro, these data do not indicate whether atorvastatin can prevent physiologically relevant DNA damage or accelerate DNA repair in vivo. We, therefore, incubated VSMCs with low-concentration t-BHP, which we have previously shown accelerates telomere shortening in culture. Senescence-associated β-galactosidase activity and telomere shortening were accelerated by t-BHP, but attenuated by atorvastatin treatment (Figure 5A). In endothelial progenitor cells, statins protect telomere function in part by induction of TRF-2. In contrast, in VSMCs, atorvastatin did not alter telomerase activity or expression of the telomere-associated proteins TRF1 or -2, POT1, or PARP-1 (data not shown). Furthermore, atorvastatin reduced telomere shortening and accelerated DNA repair in VSMCs expressing ectopic hTERT, indicating that the effect of atorvastatin was not mediated by telomerase expression or activity or expression of telomere-associated proteins.

To examine the effect of atorvastatin on the kinetics of DNA repair and cell death after acute DNA damage in vivo, we administered atorvastatin to mice for 2 weeks before sublethal irradiation, harvested organs 0 to 48 hours later, and studied γ-H2AX and apoptosis. In pilot studies, the intestine demonstrated the most reproducible DNA damage and repair response to this regime. Atorvastatin pretreatment did not reduce γ-H2AX expression at 1 hour but significantly reduced γ-H2AX expression after 2 to 4 hours indicating more rapid DSB repair. At 48 hours, statin administration markedly reduced apoptosis (Figure 5B).

In contrast to acute effects on DNA damage and repair after irradiation, DNA damage in atherosclerosis develops slowly over months (animals) or years (man) and resolves equally slowly. To examine the effects of atorvastatin on DNA damage markers in atherosclerosis, we studied rabbits that had undergone a balloon injury followed by high-fat feeding...
to develop a preexisting lesion (Figure 6A). After 9 months, rabbits were treated either with a low-fat diet or low-fat diet/statin, and ATM/ATR substrate expression was examined after a further 6 months. Statin treatment reduced the percentage of cells demonstrating ATM/ATR substrate phosphorylation (Figure 6B) associated with plaque regression (change in vessel wall area: $-13 \pm 4\%$ (low-fat diet/statin) versus $2.5 \pm 3\%$ (low-fat diet), $P<0.05$). In both mice and rabbits, statin administration did not reduce serum lipids (data not shown).

### Discussion

DNA damage is present in both the circulating cells and atherosclerotic plaques of patients with coronary artery disease. Blood cells from coronary artery disease patients have a higher micronucleus index (a marker of genetic instability) than healthy controls, which correlates with disease severity, and increased DNA strand breaks, oxidized pyrimidines, and altered purines. Human plaques show markers of DNA damage, including DNA strand breaks, expression of 8-oxo-G (an oxidative guanine modification), and activation of base excision or nonspecific DNA repair enzymes. Plaques also show critically short telomeres in the fibrous cap, the areas most prone to plaque rupture. DNA damage is also directly correlated with extent of atherosclerosis in experimental animals. For example, cholesterol feeding of rabbits induces 8-oxo-G staining, DNA strand breaks and apopto-
VSMCs in culture maintain ATM and whose frequency increases with disease severity. Plaque have previously shown that plaque VSMCs show multiple cientes to repair the accumulated damage, or both. Indeed, we environment, or that their DNA repair pathways are insuffi-
plaque VSMCs continue to generate high levels of DNA-
and DNA strand breaks. These findings suggest either that
lation, organized into nuclear foci at sites of DNA damage,
markers of activation of DNA repair pathways (ATM/ATR
expression of the DNA repair enzymes poly(ADP-ribose) polymerase 1, DNA-dependent protein
ploy,1,36 with increased expression of the DNA repair enzymes
sis, with increased expression of the DNA repair enzymes
poly(ADP-ribose) polymerase 1, DNA-dependent protein
kine kinase, and x-ray repair cross-complementing 1 (XRCC1),
and p53 and p53 activation (Ser15 and Ser392 phosphoryla-
tion).1,36 Finally, there is evidence indicating that DNA
damage can directly promote atherosclerosis from diseases
such as Werner syndrome, which is characterized by defects
in DNA repair pathways and accelerated aging including
atherosclerosis. Werner protein plays an integral role in base
excision repair and at telomeres.37 Although these data
indicate that DNA damage is evident in atherosclerosis, it is
not known whether damage can be repaired or prevented, and
the mechanism of any effect.
In human plaques, we demonstrate that VSMCs show
markers of activation of DNA repair pathways (ATM/ATR
substrate activity in aortic neointimal lesions of rabbits treated with
a high-fat diet (HFD), a low-fat diet (LFD), or low-fat diet + statin
(LFD+S). A, Top, Hematoxylin/eosin–stained sections of neointi-
mal lesions for each group. Bottom, ATM/ATR substrate phosphor-
ylation, which is quantified graphically below in B. Scale bars
represent 100 μm. Data are means±SEM. *P<0.05, **P<0.01.

Figure 6. Statin treatment reduces markers of DNA damage in athero-
sclerosis. Immunohistochemistry and quantification of ATM/ATR
substrate activity in aortic neointimal lesions of rabbits treated with
a high-fat diet (HFD), a low-fat diet (LFD), or low-fat diet + statin
(LFD+S). A, Top, Hematoxylin/eosin–stained sections of neointi-
mal lesions for each group. Bottom, ATM/ATR substrate phosphor-
ylation, which is quantified graphically below in B. Scale bars
represent 100 μm. Data are means±SEM. *P<0.05, **P<0.01.

Although DNA damage is extensive in atherosclerosis,
there has been little study of DNA repair in this disease.
Indeed, although DNA strand breaks can normalize within
weeks of dietary lipid lowering, 8-oxoG immunoreactivity
persists for much longer (12 to 24 weeks) in rabbits,32
suggesting that DNA repair is inefficient in atherosclerosis.
The antioxidant effects of 10 μmol/L atorvastatin on ROS
production have been described in VSMCs, acting via alter-
ations of growth factor-induced NADPH or catalase activi-
ties, or downregulation of angiotensin II type 1 receptor.13 In
contrast, we found that atorvastatin at a much lower concen-
tration (100 nmol/L) neither reduced the basal production of
free radicals in human VSMCs nor altered the extent of initial
DNA damage after (external) oxidant stress. However, 100
nmol/L atorvastatin accelerated DNA repair. This effect
occurred with other agents inducing DNA damage (eg,
etoposide) and other cell types, indicating that it is not limited
to VSMCs and oxidant stress. The accelerated DNA repair
coincided with the earlier appearance of P-ATM and NBS-1
and earlier formation of P-ATM foci at sites of DNA damage
to facilitate DNA repair. The rapid appearance of NBS-1 15
minutes after DNA damage after atorvastatin pretreatment
suggested that atorvastatin may be working through NBS-1.
Because NBS-1–null human VSMCs are not available, we
used HDFs, a mesenchymal cell type with growth control
mechanisms that are very similar to VSMCs. Atorvastatin
accelerated DNA repair in HDFs even quicker than in
VSMCs, associated with the accelerated appearance of
P-ATM. NBS-1– HDFs showed markedly impaired DNA
repair kinetics that were not affected by atorvastatin. In
contrast, constitutive overexpression of NBS-1 rapidly re-
paired DNA breaks, with the same kinetics as atorvastatin.
This suggests that NBS-1 expression levels immediately after
DNA damage are rate-limiting for DNA repair in VSMCs and
HDFs, an important finding with real therapeutic potential.
Although statins can reduce DNA damage in cultured
cells38 and in vivo in both animals and humans with athero-
sclerosis, after ionizing radiation or cytotoxic drugs,12,14,39 the
mechanisms underlying this effect are unknown and are
likely to be multiple. Statins can reduce oxidant stress,13
inhibit protein prenylation,40 and inhibit downstream signal-
ning from damaged DNA,17,18 all of which may suppress DNA
damage or the damage response. Statins can also lead to
Ser166 phosphorylation on the ubiquitin ligase mdm2, which
enhances its nuclear localization and its interaction with
p300, and inhibits its interaction with p19ARF, thus increasing
p53 degradation.25,26 We find that statins lead to robust
phosphorylation of Hdm2, reduced association of Hdm2 with
NBS-1, and reduced NBS-1 degradation. Despite the likely
multiple proteins affected by statin treatment, Hdm2 was
required for atorvastatin to accelerate DNA repair, because
Hdm2 knockdown mimicked the atorvastatin effect and
prevented any additional effect of atorvastatin. Previously,
Ser166 phosphorylation of Hdm2 was shown to increase its
ubiquitin ligase activity and thereby reduce expression of
proteins binding to mdm2, such as p53.17 In contrast, our
study is the first to demonstrate that Hdm2 phosphorylation
can reduce degradation of the Hdm2-bound protein, NBS-1.
The precise mechanism of this effect is not clear; for
example, in previous studies, although mdm2 bound NBS-1
d to atorvastatin and inhibited DNA repair, this effect required the
NBS-1 binding domain of mdm2 but was independent of its
ubiquitin ligase activity.40
For the effect of atorvastatin on DNA repair to be signif-
icant clinically, statins must inhibit physiological meaningful
DNA damage. ROS induce DNA strand breaks and base and
nucleotide modifications, particularly in sequences with high
guanosine content,40 such as telomeres.41 Telomere shorten-
ing induces a DNA damage response characterized by acti-
vation of the same proteins involved in oxidative DNA damage, including ATM, NBS-1, and H2AX.\textsuperscript{42,43} We have previously shown that oxidative DNA damage (using t-BHP) dose-dependently accelerates telomere shortening in VSMCs.\textsuperscript{2} Here, we find that atorvastatin prevents appearance of SAβG and telomere shortening in VSMCs. Although the effect on telomere shortening could be multifactorial, telomerase expression and expression of telomere-associated proteins was unchanged, and cells containing constitutive telomerase expression still showed accelerated DNA repair after atorvastatin treatment. Thus, we consider it most likely that statins accelerate repair of damaged telomeres, most likely also through NBS-1. Indeed, NBS-1 associates with TRF2 in human telomeres,\textsuperscript{44} and is required for telomere maintenance in eukaryotic\textsuperscript{45} and yeast cells.\textsuperscript{46}

To examine DNA repair acutely in vivo in whole animals, we subjected mice to whole-body irradiation and examined the kinetics of induction and reduction of γ-H2AX (as a marker of DSBs and their repair) and apoptosis. Atorvastatin pretreatment markedly accelerated the return to normal γ-H2AX expression and reduced apoptosis in intestinal mucosa. Although statins can reduce the long-term sequelae of radiotherapy,\textsuperscript{47} this is the first study to demonstrate that accelerated DNA repair may underlie some of this effect.

Finally, we show that long-term statin treatment in rabbits with established neointimal lesions reduces expression of ATM/ATR substrate activity. Although this effect was partially seen with lipid lowering, there was an additional effect with low dose statin, independent of any statin effect on serum lipids. Although it is impossible to determine the contribution that accelerating DNA repair (measured over hours) has on a process taking months to achieve, the studies indicate an additional beneficial action of statin treatment on DNA damage in atherosclerosis.

In summary, we have identified a novel mechanism by which statins accelerate DNA repair, via Hdm2 phosphorylation, NBS-1 stabilization, and more rapid ATM and H2AX phosphorylation. Statins attenuate DNA damage, cell senescence, and telomere shortening in VSMCs and may thereby promote plaque stability in atherosclerosis.

Acknowledgments

We are grateful to Mark O’Driscoll, Penelope Jeggo, and Malgorzata Zdzenicka for derivation of and supplying NBS1\textsuperscript{17} and NBS1\textsuperscript{17a,18} HDFs; Roberto Corti and Juan J. Badimon for supplying rabbit tissues; and to Steve Jackson for discussion and critical appraisal of the manuscript.

Sources of Funding

This work was supported by British Heart Foundation grants FS/05/008, PG/04/107, RG04/001, and CH/2000003, the Sackler Foundation, the European Vascular Genomics Network, and a Cambridge National Institute for Health Research Biomedical Research Centre grant.

Disclosures

None.

References


Statins Use a Novel Nijmegen Breakage Syndrome-1–Dependent Pathway to Accelerate DNA Repair in Vascular Smooth Muscle Cells

Melli Mahmoudi, Isabelle Gorenne, John Mercer, Nicola Figg, Trevor Littlewood and Martin Bennett

_Circ Res._ 2008;103:717-725; originally published online August 21, 2008;
doi: 10.1161/CIRCRESAHA.108.182899

_Circulation Research_ is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
Copyright © 2008 American Heart Association, Inc. All rights reserved.
Print ISSN: 0009-7330. Online ISSN: 1524-4571

The online version of this article, along with updated information and services, is located on the World Wide Web at:
http://circres.ahajournals.org/content/103/7/717

Data Supplement (unedited) at:
http://circres.ahajournals.org/content/suppl/2008/08/21/CIRCRESAHA.108.182899.DC1

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

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

**Subscriptions:** Information about subscribing to _Circulation Research_ is online at:
http://circres.ahajournals.org/subscriptions/
Supplemental methods

Cell culture
Human VSMCs were explant-cultured in DMEM+20% FCS from normal aortas of patients undergoing non-cardiac transplantation and plaque VSMCs from patients undergoing carotid endarterectomy respectively. Human tissue was derived from recipient hearts of patients undergoing cardiac transplantation for ischaemic cardiomyopathy after informed consent, and following full Ethical Committee approval. HDFs expressing different levels of NBS-1 were as previously described. 1

Nuclear Extract Preparation
Nuclear extracts were prepared by centrifugation of cells at 800g for 5 minutes at 4°C, the supernatant discarded, and cells suspended in NE Buffer 1 (20mM HEPES pH 7.9, 10mM KCl, 1mM MgCl₂, 0.5mM DTT, 0.5mM PMSF) with repeat centrifugation for 1min. Cells were resuspended in lysis buffer (0.4% NP40), incubated on ice for 12min, and centrifuged for 5min. The nuclear pellet was resuspended in NE Buffer 2 (20mM HEPES pH 7.9, 20mM KCl, 1mM MgCl₂, 0.5mM DTT, 0.5mM PMSF, 2.5% glycerol) and 100μl of NE buffer 3 (20mM HEPES pH 7.9, 0.5M KCl, 1mM MgCl₂, 0.5mM DTT, 0.5mM PMSF, 2.5% glycerol) and incubated on ice for 30min. The sample was then centrifuged for 15min at 4°C, and the supernatant stored at -80°C.
**Immunoprecipitation, Protein Electrophoresis, Western blotting**

Immunoprecipitation, protein electrophoresis, transfer and Western blotting were as previously described\(^2\) using primary antibodies to \(^{\text{ser166}}\)Phospho-Mdm-2, \(^{\text{ser198}}\)Phospho-ATM, \(^{\text{ser139}}\)Phospho-H2AX, HSP60, GAPDH, NBS-1 (all Cell Signaling Technology, USA), ATM (GeneTex, USA), and Mdm-2 (Calbiochem, USA).

**Immunocytochemistry and Immunohistochemistry**

Immunocytochemistry and immunohistochemistry were performed as previously described\(^2\) with primary antibodies against phospho-ATM/ATR substrate 1:100, phospho-H2AX 1:500 (both Cell Signaling Technology). For double labelling, sections were incubated with 1:500 mouse \(\alpha\)-smooth muscle actin (Dako). TUNEL was performed as previously described\(^3\).

**Proteasome Activity Assay**

Activity of the 20S proteasome was assayed by detection of the fluorophore 7-Amino-4-Methylcoumarin (AMC) following its cleavage from the labelled substrate LLVY-AMC following manufacturer’s instructions (Chemicon International, USA).

**Atherosclerosis in rabbits**

Aortic injury was performed after one month and again at three months of starting the HFD diet from the top of the aortic arch to the iliac bifurcation using a 4F Fogarty embolectomy catheter introduced through the iliac artery. All procedures were performed
under general anesthesia by an intramuscular ketamine injection (20 mg/kg, Fort Dodge Animal Health, Fort Dodge, Iowa) and xylazine (10 mg/kg, Bayer Corp., Shawnee Mission, Kansas). Complete plasma lipid profiles were analyzed at the end of the study. At nine months, rabbits were randomized into experimental groups and followed for an additional six months. The HFD diet group (n=6) continued on the atherogenic HFD diet without active drug therapy to determine atherosclerosis progression. The low fat diet (LFD) group (n=6) received normal rabbit chow without active drug therapy. The LFD plus statin group (n=6) received normal rabbit chow supplemented with simvastatin (5 mg/kg per day). The treatment continued for six months in each group. Atorvastatin was generously provided by Pfizer (New York), and Simvastatin by Merck & Company (Rathway, New Jersey).

References


Supplementary Figures

Supplementary Figure 1. Atorvastatin does not reduce reactive oxygen species in human VSMCs.
Fluorescence intensity (arbitrary units AU)) of the redox-sensitive dye H2DCFDA in VSMCs treated with increasing concentrations of atorvastatin or control. Data are means±SEM, n=3.

Supplementary Figure 2. Atorvastatin accelerates appearance of DNA repair proteins after etoposide treatment
Western blot for NBS-1 and γ-H2AX 0-5 hours after treatment with 100μM etoposide ±atorvastatin pre-treatment, demonstrating acceleration of NBS-1 and γ-H2AX induction from 5 to 1 hr.
Supplementary Figure 3. Atorvastatin accelerates DNA repair in VSMCs after etoposide treatment
Tail length assessed by Comet assay 0-6 hours after treatment with 100µM etoposide ±atorvastatin pre-treatment, demonstrating acceleration of DNA repair after atorvastatin treatment. n=50 nuclei.

Supplementary Figure 4. Atorvastatin does not inhibit proteasomal activity
Chymotrypsin-like activity of VSMC extracts treated with 100nM atorvastatin or 25µM lactacystin. Data are Means±SEM. *p<0.05. n=2.