Single Perivascular Delivery of Mitomycin C Stimulates p21 Expression and Inhibits Neointima Formation in Rat Arteries

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Objective—Mitomycin C (MMC) is an antibiotic that exerts a potent antiproliferative effect in tumor cells. Because the proliferation of vascular smooth muscle cells (VSMCs) plays a prominent role in the development of restenosis after percutaneous coronary interventions, the present study examined the effect of MMC on VSMC proliferation and on neointima formation after arterial balloon injury.

Methods and Results—Treatment of cultured rat aortic VSMCs with MMC (1 nmol to 30 μmol/L) inhibited smooth muscle cell (SMC) proliferation in a concentration-dependent manner. Whereas high concentrations of MMC (1 to 30 μmol/L) induced SMC apoptosis, as reflected by DNA laddering and caspase-3 activation, lower concentrations of MMC (1 to 300 nmol) directly inhibited SMC growth by arresting cells in the G2/M phase of the cell cycle. The antiproliferative action of MMC was associated with a selective increase in the expression of the cyclin-dependent kinase inhibitor p21, and with a decrease in cyclin B1-cyclin-dependent kinase-1 complex activity. Finally, the local perivascular delivery of MMC immediately after balloon injury of rat carotid arteries induced p21 expression and markedly attenuated neointima formation.

Conclusion—These studies demonstrate that MMC exerts a potent inhibitory effect on VSMC proliferation and neointima formation after arterial injury. MMC represents a potentially new therapeutic agent in treating and preventing vasculoproliferative disease. (Arterioscler Thromb Vasc Biol. 2005;25:0-0.)

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The healing response to stent implantation starts immediately after injury, generally peaks at 2 weeks after the initial insult has occurred, and is mainly regulated by vascular smooth muscle cells (VSMCs).1,2 Drug-eluting stents reduce restenosis by decreasing the formation of a neointima caused by excessive cellular activation after arterial injury.3,4 The successful development of drug-eluting stents has relied on the controlled release of antiproliferative agents over several weeks to regulate the activation and proliferation of VSMCs.2,3 Accordingly, potent antiproliferative agents have the potential of decreasing the degree of neointimal formation after stent implantation of cytostatic rather than cytotoxic tissue levels can be achieved at the site of injury.

Mitomycin C (MMC) is an antibiotic agent with antiproliferative properties derived from the soil fungus Streptomyces caespiotosus.6 In addition to cancer therapy,7 MMC is a well-recognized antifibroblastic drug. In vitro studies using cultured human fibroblasts have shown that after exposure to a single dose of MMC, there is a profound inhibition of the proliferative phase of the wound-healing response, specifically through the inhibition of fibroblast replication.8 These findings have led to the successful clinical use of MMC as an adjuvant in procedures displaying excessive late-onset scar tissue formation,8–10 and suggest that MMC may be suitable as an agent to decrease neointima formation. Accordingly, we sought to evaluate the growth modulating potential of MMC on cultured rat arterial VSMCs and the impact of MMC on neointima formation in a rat model of arterial balloon injury.

Methods

Materials

MMC was purchased from Henan Kangtai Pharmaceutical Group (Zhengzhou, China). Streptomycin and serum were from Gibco BRL (Rockville, Md). Antibodies against cyclin D1, cyclin E, cyclin A, cyclin B1, p21, p27, cdk1, and nonimmune IgG were from Santa Cruz Biotechnology (Santa Cruz, Calif). A phosphorylation-specific antibody against retinoblastoma protein was from Cell Signaling Technologies (Beverley, Mass); [32P]UTP (400 Ci/mmoll) was from Amersham (Arlington Heights, Ill); γ[32P]ATP (3000 Ci/mmoll) was from NEN-Dupont (Boston, Mass). All other reagents were from Sigma Chemical (St. Louis, Mo).
Cell Culture
VSMCs were isolated by elastase and collagenase digestion of rat thoracic aorta and characterized by morphological and immunologic criteria. Cells (passages 6 to 18) were serially cultured in minimum essential medium containing 10% serum; Earle’s salts, 5.5 mmol/L glucose, 2 mmol/L L-glutamine, 5 mmol/L L-Tes, 5 mmol/L Heps and 100 U/mL streptomycin.

Proliferation and Cell Cycle Analysis
VSMCs were seeded at a density of 2.5 × 10^4 cells/well in 12-well plates in serum (10%)-containing media. After 24 hours, culture media were exchanged for serum-free media for an additional 48 hours. VSMCs were then treated with serum (5%) in the presence or absence of MMc. Media with appropriate additions were replenished every second day. Cell number determinations were performed after 7 days of treatment by dissociating cells with trypsin and counting cells in a Coulter Counter (model ZF; Coulter Electronics, Hileah, Fla). For cell cycle analysis, quiescent VSMCs were treated with serum (5%) in the presence and absence of MMc for 24 hours. Cells were then stained with propidium iodide and DNA fluorescence measured in a Dickinson FACScan flow cytometer (Franklin Lakes, NJ).

Apoptosis
Apoptosis was monitored by measuring DNA fragmentation and caspase-3 activation, as we have previously described.

Protein Analysis
VSMCs were lysed in electrophoresis buffer (125 mmol/L Tris [pH 6.8], 12.5% glycerol, 2% SDS, and trace bromphenol blue) and proteins resolved by SDS-polyacrylamide gel electrophoresis (PAGE). Blots were blocked in phosphate-buffered saline (PBS) and nonfat milk (5%) and then incubated with antibodies directed against cyclin D1 (1:500), cyclin E (1:500), cyclin A (1:500), cyclin B1 (1:500), cdk1 (1:100), p21 (1:500), p27 (1:300), or phosphorylated histone H1 (2.0 μg/mL aprotinin, 10 μg/mL leupeptin, 1 mmol/L PMSF, 1 mmol/L Na3VO4, 50 mmol/L NaF, and 1 mmol/L EDTA, 2.0 mmol/L EGTA, 10% glycerol, 0.1% Tween-20, 1 mmol/L Na3VO4), and then incubated with kinase buffer, histone H1 (2.0 μg; Roche, Indianapolis, Ind), ATP (50 μmol/L), and γ-[32P]ATP (6 μCi) for 20 minutes at 30°C. Reactions were terminated by adding Laemmli buffer and boiling samples for 5 minutes. Proteins were separated by SDS-PAGE, fixed and exposed to X-ray film. Lysates immunoprecipitated with nonimmune IgG did not express kinase activity, confirming the specificity of the assay.

Animal Experiments
Sprague-Dawley rats (400 to 450 grams; Charles River Laboratories, Wilmington, Mass) were anesthetized (ketamine, xylazine, acepromazine; 0.5 mL/kg, intramuscularly; VetMed Drugs, Houston, Tex) and the left common carotid artery injured with an enbolectomy catheter, as we previously described. Immediately after balloon injury, a local perivascular polymer-based delivery system was used to administer MMc to the injured vessel wall in one group of animals (n = 8). A separate cohort of animals received an empty gel (n = 8). Previous studies from our laboratory and others confirmed that the empty gel has no effect on neointima formation. The delivery system consisted of 250 μg of a 25% copolymer gel (PLF127; BASF Corporation, Florham Park, NJ) containing MMc at a concentration of 1 μg/mL (maximal saturation load of the polymer) that was topically applied in a circumferential manner to the exposed adventitia of the carotid artery. PLF127 gels exhibit reverse thermal behavior remaining liquid at refrigerator temperature, but becoming soft gels at body temperature. In vitro release experiments using this gel have indicated that PLF127 acts as a rate-controlling barrier serving as a vehicle for sustained-release preparations of MMc; releasing an accumulative amount of drug over a 3-hour period of ~5.5% from a PLF127-mitomycin C gel containing 25% of PLF127. Based on this study, we estimated that the delivered dose at 3 hours was 13.75 μg.

Histology
Two weeks after arterial injury, all animals were euthanized and the vasculature perfusion-fixed with 10% buffered formalin. The common carotid artery was excised, paraffin-embedded, and sections (5 μm) stained with Verhoffs–Van Gieson for measurement of vessel dimensions. Microscopic quantitation of vessel dimensions was performed using Zeiss Image 3.0 (Media Cybernetics) and Adobe Photoshop 6.0 software linked through a charge-coupled device (CCD) color camera (Leaf Microlumina; Leaf Systems, USA) to a Zeiss Axioskop 50 light microscope (Carl Zeiss, Germany), as we have previously described. Apoptosis was also monitored by terminal deoxynucleotidyl transferase-mediated dUTP nick end-labeling (TUNEL) staining.

Statistics
Results are expressed as the means ± SEM. Statistical analysis was performed with the use of a Student 2-tailed t test, and an analysis of variance with the Bonferroni post-hoc test when >2 treatment regimens were compared. P < 0.05 was considered statistically significant.

Results
Dose Response Effect of MMc on VSMC Proliferation
Treatment of VSMCs with MMc inhibited serum-stimulated proliferation in a concentration-dependent manner (Figure 1). VSMC growth inhibition was evident at a dose of 3 mmol (22% inhibition) and doses >100 nmol resulted in near-total abolition of cell growth. VSMC proliferation was inhibited by ~50% at MMc concentration of 10 nmol. MMc concentrations <1 μmol/L did not stimulate DNA laddering (Figure IA, available online at http://atvb.ahajournals.org). In contrast, doses of MMc of 1 μmol/L and higher (1 to 30 μmol/L) induced cell rounding and blebbing (data not shown) that was associated with pronounced DNA fragmentation and a marked increase in caspase-3 activity (Figure IA and IB).
Effect of Nonapoptotic Doses of MMc on Cell Cycle Progression

The effect of lower, nonapoptotic concentrations of MMc on cell cycle progression was determined by flow cytometry. Subconfluent VSMCs accumulated in the G0/G1 phase of the cell cycle after serum deprivation for 48 hours. Administration of serum for 24 hours induced cell cycle progression and the population of cells in G0/G1 decreased, whereas the number of cells in S and G2M increased (Figure 2). However, MMc (3 to 100 nmol) induced a concentration-dependent increase in the fraction of cells in G2M and this was accompanied by a decrease in the percentage of cells in G0/G1 (Figure 2A). At a 100 nmol MMc concentration, ≈2-fold increase of VSMCs in G2M was observed (Figure 2B). No apparent toxicity with these lower doses of MMc was noted as reflected by the lack of a sub-G0/G1 fraction (Figure 2A).

To elucidate the mechanism by which MMc disrupts cell cycle progression, we examined the effect of this drug on cell cycle regulatory proteins. MMc failed to inhibit the serum-stimulated expression of the G1 cyclins, cyclin D1, E, A, the phosphorylation/activation of retinoblastoma protein, or the serum-mediated downregulation of the cdk inhibitor, p27 (Figure 3). In fact, MMc enhanced the expression of cyclin E (Figure 3). Interestingly, MMc potentiated the serum-stimulated expression of p21 protein (Figure 3), and this was associated with a time-dependent increase in p21 mRNA (Figure 4A and 4B). MMc also induced p21 expression under serum-free conditions (Figure 3 and 4A and 4B). Because the progression of cells through G2 and entry into mitosis is under the control of the cyclin B1–cdk1 complex,20 the effect of MMc on the activity of this complex was also examined. We found that MMc potently inhibited the serum-stimulated activity of the cyclin B1–cdk1 complex while having no effect on the expression of cyclin B1 or cdk1 protein (Figure 4C and 4D).

Impact of MMc on Neointima Formation

The effect of a single-use delivery of MMc on neointimal proliferation was investigated in an in vivo rat model of carotid artery injury. Figure 5A depicts representative cross-sections of perfusion-fixed, Verhoffs–Van Gieson-stained tissues 2 weeks after injury. Two weeks after initial injury, the maximal neointimal thickness was 0.046±0.009 mm in the MMc group versus 0.100±0.021 mm in the control group (P<0.05) (Figure 5B). Morphometric analysis further re-
revealed that intimal area was $0.079 \pm 0.017 \text{ mm}^2$ in the MMc group versus $0.169 \pm 0.030 \text{ mm}^2$ in the control group ($P < 0.05$) that represents a 50% reduction in neointima formation in vessels treated with the MMc-containing gel (Figure 5B). In contrast, despite the fact the intima/media area ratio was also reduced by 50% ($0.393 \pm 0.30$ in the MMc group versus $0.780 \pm 0.138$ in the control group, $P < 0.05$), the medial area was not changed in MMc-treated segments ($0.127 \pm 0.007 \text{ mm}^2$ in the MMc group versus $0.126 \pm 0.008 \text{ mm}^2$ in the control group) (Figure 5B). In the MMc-treated vessels, there was no evidence of vascular toxicity including fibrin deposition, excessive infiltration of inflammatory cells, or tissue necrosis. TUNEL staining evaluation for evidence of apoptosis revealed no difference in the rate of apoptosis in empty gel-treated vessels ($2.1 \pm 0.4\%$) compared with MMc-treated vessels ($2.5 \pm 0.3\%$). Finally, perivascular application of MMc stimulated the expression of p21 protein in balloon-injured arteries (Figure 5C).

**Discussion**

The present study demonstrates that MMc is a potent inhibitor of VSMC proliferation and neointima formation. These inhibitory actions of MMc are associated with the induction of the cyclin-dependent kinase inhibitor, p21, and the arrest of VSMCs in the G2M phase of the cell cycle. These findings suggest a potentially important therapeutic role for MMc in treating occlusive vascular disease.

Although MMc exerts a powerful antiproliferative effect in tumor cells and fibroblasts, its action on VSMC growth has not been fully characterized. In the current study, we found that MMc is a robust inhibitor of VSMC proliferation. Analysis of cell cycle distribution indicates that MMc inhibits cell cycle progression by specifically arresting VSMC in the G2M phase. Previous work established that the cyclin B1–cdk1 complex functions as a master mitotic regulator and is the ultimate target of most agents that prevent mitotic entry. Consistent with such a hypothesis, we found that MMc-

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**Figure 3.** Effect of mitomycin C (MMc) on the expression of cell cycle regulatory proteins. A, Effect of MMc on the expression of cyclin D1, E, and A, p21, and p27 protein, and the phosphorylation of retinoblastoma protein (pRb-P). VSMCs were treated with serum (5%) for 24 hours in the presence or absence of MMc (100 nmol). B, Quantification of protein expression by scanning densitometry relative to serum-free controls. Results are means ± SEM of 6 separate experiments. *Statistically significant effect of serum. †Statistically significant effect of MMc.

**Figure 4.** Effect of mitomycin C (MMc) on p21 mRNA expression and cyclin B1–cdk1 complex activity. A, VSMCs were treated with MMc (100 nmol) for various times (0 to 24 hours) and mRNA levels determined by Northern blotting. B, Quantification of p21 mRNA levels by scanning densitometry relative to serum-free controls. VSMCs were incubated with or without serum (5%) in the presence and absence of MMc (100 nmol). C, VSMCs were treated with MMc (100 nmol) for 24 hours and cyclin B1–cdk1 complex kinase activity determined as described in Methods section, whereas cyclin B1 and cdk1 protein levels were monitored by Western blotting. D, Quantification of cyclin B1–cdk1 complex kinase activity and protein expression by scanning densitometry. VSMCs were incubated with or without serum (5%) for 24 hours in the presence and absence of MMc (100 nmol). Results are means ± SEM of 4 separate experiments. *Statistically significant effect of serum. †Statistically significant effect of MMc.
induced G2M arrest is associated with a marked decrease in cyclin B1-cdk1 complex kinase activity that occurs independent of any change in the level of either cyclin B1 or cdk1. However, MMC selectively increases the expression of p21, which has been shown to promote G2M arrest and block the activation of the cyclin B1-cdk1 complex.24,25 Thus, it is likely that the elevation in p21 expression contributes to the inhibition of cell cycle progression and VSMC growth by MMC. Although p21 can also mediate G1 arrest by inhibiting the activity of the G1 cdk’s,26 flow cytometry experiments did not detect G1 arrest by MMC. Moreover, MMC had no effect on the phosphorylation of retinoblastoma protein, a key event required for S phase entry. Failure of p21 to inhibit G1 to S phase transition following MMC treatment may be due to the delayed induction of p21 expression or, alternatively, the inhibitory activity of p21 on G1 cdk’s may be countered by increases in the expression of G1 cyclins, such as cyclin E. Interestingly, induction of p21 by MMC has also been reported in other cell types and may provide a general mechanism by which this agent inhibits cell growth.27,28 The mechanism by which MMC stimulates p21 expression is not well known but it may involve the induction of p53, which has been shown to promote G2M arrest and block the reentry of the cell cycle and this is associated with an increase in p21 expression and a decrease in cyclin B1-cdk1 complex activity. Therefore, MMC represents a likely p21 dependent approach applying MMC topically to the adventitia of the blood vessel was used with a specific local delivery copoly-mer. Our laboratory and others have successfully used this approach applying MMC topically to the adventitia of the blood vessel was used with a specific local delivery copoly-mer. Our laboratory and others have successfully used this approach to delivery drugs and oligonucleotides to the vessel wall.14,15–17,37,38 This local delivery system allows for the sustained delivery of MMC over the course of several days and avoids possible nonspecific effects associated with the systemic administration of the drug. We found that local application of MMC markedly attenuates neointima formation after arterial injury which is associated with the induction of p21 expression in the vessel wall. The inhibition of intimal thickening by MMC is independent of any overt signs of toxicity or with an increase in apoptosis, suggesting that vessel wall MMC levels were below the cytotoxic range. Of note, in one early study, MMC failed to block neointima formation in balloon-injured rabbit iliac arteries. However, this study used only a single acute intramural infusion of MMC into the arterial wall, and the rate and extent of MMC penetration into the vessel wall was not determined. A sustained delivery of MMC may be necessary to inhibit the vascular remodeling response following balloon injury. In conclusion, the present study demonstrates that MMC is a potent inhibitor of VSMC proliferation with a broad range of cytostatic doses, and that it markedly attenuates neointima formation after arterial balloon injury in rat carotid arteries. In addition, it shows that MMC arrests VSMCs in the G2M phase of the cell cycle and this is associated with an increase in p21 expression and a decrease in cyclin B1-cdk1 complex activity. Thus, MMC represents an attractive therapeutic agent for attenuating the vascular response to injury, and may also
prove efficacious in preventing restenosis when eluted from the surface of a stent.

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References

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Figure I. Effect of mitomycin C (MMc) on VSMC apoptosis. A. Effect of MMc (0.1 – 30 µM) on DNA laddering. Data are representative of three separate experiments. B. Effect of mitomycin C (1-30 µM) on caspase-3 activity. Results are means ± SEM of three separate experiments. *Statistically significant effect of MMc.