Role of Sp1 in the Induction of p27 Gene Expression in Vascular Smooth Muscle Cells In Vitro and After Balloon Angioplasty

Vicente Andrés, Jesús Ureña, Enric Poch, Donghui Chen, David Goukassian

Abstract—The abnormal proliferation of vascular smooth muscle cells (VSMCs) plays an important role in atherosclerosis and restenosis. Although several studies have implicated the growth inhibitory protein p27Kip1 (p27) in the control of myocyte growth and hypertrophy, little is known about the molecular mechanisms that regulate p27 expression in the cardiovascular system. In the present study, we demonstrate the interaction of the transcription factor Sp1 with 2 GC-rich sequences within the p27 promoter in cultured VSMCs. Importantly, point mutations that disrupted Sp1 binding markedly reduced p27 promoter activity, demonstrating that Sp1 is required for efficient p27 gene transcription in cultured VSMCs. Because p27 expression is upregulated after balloon angioplasty, we investigated Sp1 expression and activity in control and balloon-injured rat carotid arteries to assess the role of Sp1 as a physiological regulator of p27 expression. Although immunohistochemical analysis disclosed Sp1 protein expression in both control and balloon-injured arteries, a high level of Sp1 DNA-binding activity was found only in response to balloon angioplasty. Collectively, these results demonstrate that Sp1 is essential for maximum p27 promoter activity in VSMCs and suggest that posttranslational induction of Sp1 DNA-binding activity contributes to the induction of p27 expression and VSMC growth arrest at late time points after balloon angioplasty. (Arterioscler Thromb Vasc Biol. 2001;21:342-347.)

Key Words: vascular smooth muscle cell ■ cell cycle ■ Sp1 ■ p27 ■ angioplasty

Excessive vascular smooth muscle cell (VSMC) growth is involved in the pathogenesis of vascular proliferative diseases, including atherosclerosis and restenosis (see reviews1–3). With several animal models of arterial injury, it has been shown that “activated” VSMCs resume a quiescent phenotype within 2 to 6 weeks after angioplasty.4–8 Therefore, a better understanding of the molecular mechanisms that limit VSMC proliferation during the remodeling process is of utmost importance to develop novel therapies for the treatment of vascular proliferative diseases.

Cell cycle progression is controlled by several cyclin-dependent protein kinases (CDKs), which can associate with activating subunits, the cyclins, and with CDK inhibitory proteins (CKIs).9,10 p27 and p21CIP1 (p21) are related CKIs that associate with CDK2-, CDK4-, CDK6-, and CDC2-containing complexes, thereby abrogating their catalytic activity leading to growth arrest.9,11 Recent studies have suggested a physiological role of p21 and p27 as regulators of VSMC growth during the pathogenesis of cardiovascular diseases (see review12). In vitro experiments have shown that VSMC responsiveness to growth signals is highly dependent on changes in specific components of the extracellular matrix through αv integrin–dependent regulation of p27 and p21.13 Reduced CDK2 activity and the decline in VSMC proliferation that takes place at late time points after angioplasty correlated with a marked induction of p27 and p21.14–16 Moreover, overexpression of p27 efficiently blocked mitogen- and c-fos–dependent induction of cyclin A promoter activity in cultured VSMCs,15,17 and adenovirus-mediated overexpression of p2715 and p2114,18,19 limited neointimal thickening after balloon denudation. In contrast, recent studies with p27 knockout mice have demonstrated that the loss of p27 results in prolonged proliferation of cardiac myocytes.20 Moreover, p27 plays an important role in the regulation of cardiomyocyte hypertrophy20 and angiotensin II–stimulated VSMC hypertrophy.21,22

Although these studies identify p27 and p21 as important regulators of the phenotypic response of cardiac and vascular myocytes to mitogenic and hypertrophic stimuli, little is known about the molecular mechanisms involved in the regulation of CKI gene expression in the cardiovascular system. Therefore, we investigated the transcriptional mechanisms that control p27 gene expression and obtained results that demonstrate the trans–acting nuclear factor Sp1 is required for maximum p27 promoter activity in cultured VSMCs. Moreover, using the rat carotid model of balloon...
angioplasty, we provide evidence that suggests posttranslational activation of Sp1 contributes to the upregulation of p27 gene expression and the reestablishment of the quiescent phenotype in VSMCs at late time points after vascular injury.

**Methods**

**Cell Culture and Transient Transfection Assays**

E19P cells (gift from C. Shanahan, University of Cambridge, Cambridge, UK) were obtained from explant cultures of embryonic day 19 aorta from Fischer rats. Through Northern blot analysis, these cells express SM22α, calponin, and smooth muscle α-actin mRNAs (C. Shanahan, personal communication). Cells were maintained in M199 supplemented with 10% FBS at 37°C (95% air and 5% CO₂).

Cells were seeded onto 6-well dishes, and on the next day (~60 to 80% confluence), they were transiently transfected with SuperFect reagent (Qiagen) and 2 μg of the indicated luciferase reporter plasmids driven by the murine p27 promoter fragments spanning from −170 to +54 relative to the transcriptional initiation site6 (gift from S. Lin, National University of Singapore). To correct for differences in transfection efficiency, luciferase activity was normalized relative to the alkaline phosphatase activity produced from M199 supplemented with 10% FBS at 37°C (95% air and 5% CO₂).

**Balloon Angioplasty and Tissue Extraction**

Male Sprague-Dawley rats (400 to 500 g) were anesthetized with an intraperitoneal injection of sodium pentobarbital solution (45 mg/kg body wt) for performance of balloon denudation of the left common carotid artery in accordance with institutional guidelines as described previously.5,26 At the indicated times after angioplasty, rats were euthanized with sodium pentobarbital (IP injection, 100 mg/kg body wt) for performance of balloon denudation of the left common carotid artery (see later).

**Immunohistochemistry**

Saline perfusion was followed by in situ fixation, cleaned of adventitia and fat tissue, and both injured and uninjured common carotid arteries were harvested without in situ fixation, cleaned of adventitia and fat tissue, and stored at −80°C (95% air and 5% CO₂). Cells and arteries were lysed in ice-cold buffer that contained 20 mmol/L HEPES buffer, pH 7.5, 10 mmol/L EGTA, 40 mmol/L β-glycerophosphate, 1% NP-40, 2.5 mmol/L MgCl₂, 2 mmol/L orthovanadate, 1 mmol/L DTT, 1 mmol/L PMSF, 10 μg/mL aprotinin, and 10 μg/mL leupeptin. Protein extracts were prepared from the pooled tissue from 3 animals with Tri-Reagent according to the recommendations of the manufacturer (GIBCO BRL). Ten micrograms of RNA was electrophoresed on 1% agarose gels that contained 2.2 μmol/L formaldehyde, transferrered to nylon membranes (Hybond-N; Amersham), and immobilized by short-wave UV irradiation (UV-Stratalinker 1800; Stratagene). Blots were hybridized with radiolabeled cDNA probes for p27 and GAPDH. Autoradiographs were scanned (Microtek Scan Maker II), and band intensity was determined after background subtraction with the densitometric program Sigma Gel (Jandel Scientific).

**Preparation of Protein Extracts and Electrophoresis Mobility Shift Assays**

Cells and arteries were lysed in ice-cold buffer that contained 20 mmol/L HEPES buffer, pH 7.5, 10 mmol/L EGTA, 40 mmol/L β-glycerophosphate, 1% NP-40, 2.5 mmol/L MgCl₂, 2 mmol/L orthovanadate, 1 mmol/L DTT, 1 mmol/L PMSF, 10 μg/mL aprotinin, and 10 μg/mL leupeptin. Protein extracts were prepared from the pooled tissue from 7 to 9 animals at each time point. Lysates were cleared with centrifugation in a microfuge, and the supernatants were stored at −80°C. Western blot analysis with mouse monoclonal anti-p27 antibody (Ab-2, dilution 1:75; Oncogene) was performed with an ECL detection system (Amersham). The following radiolabeled probes that span the murine p27 promoter regions from −140 to −109 and from −101 to −72 and contain 2 GC-rich boxes (box I −133 to −117, box II −87 to −72) were used for electrophoresis mobility shift assays (EMSAs) (binding sites are underlined, and point mutations are given in lowercase letters): box I (wild-type), 5′-GGCGGGAGAGCCGGGCGGCGGCGCCGGCGGGCCGGCCGGCCGGCCGGCCGGCCGGCCGGGCCC

**Results**

**Sp1 Interacts With Two GC-Rich Sequences**

Within the p27 Gene Promoter That Are Required for Maximum Transcriptional Activity in VSMCs

Analysis of the proximal promoter region of the murine p27 gene revealed 2 GC-rich regions (box I −133 to −117, box II −87 to −72), which are putative binding sites for the transcription factor Sp1. As shown in the EMSA in Figure 1A, the incubation of E19P cell extracts with the box II probe leads to the formation of a slow migrating nucleoprotein complex (lane 2), which was disrupted when an excess of unlabeled wild-type box II oligonucleotide was added to the binding reaction (lane 3). A mutated box II oligonucleotide that disrupted the putative Sp1 binding site did not compete for binding (Figure 1A, lane 4), demonstrating the requirement of the GC-rich motif for nucleoprotein complex formation. Two additional faster migrating bands that could not be disrupted with either wild-type or mutated box II oligonucleotides corresponded to nonspecific interactions (Figure 1A, NS). Although less intense compared with autoradiographs with box II probe, a retarded band of the same electrophoretic mobility was seen with the box I probe (data not shown).

A series of experiments were then performed to demonstrate the interaction of Sp1 with these GC-rich motifs within the p27 proximal promoter region. First, the electrophoretic mobility of the specific complex detected with the wild-type box II probe was identical to that observed with a probe containing an Sp1 consensus site (Figure 1A, compare lanes 2 and 7). Similar results were obtained with the wild-type box I probe (data not shown). Moreover, the DNA-binding specificity of the factor bound by box I, box II, and the Sp1 consensus probes was indistinguishable on the basis of cross-competition experiments. Although both wild-type box I and box II efficiently competed for binding to the Sp1 consensus probe (Figure 1B, lanes 3 to 5 and 9 to 11), their
Sp1 and p27 Spatial and Temporal Pattern of Expression After Balloon Angioplasty

To assess the role of Sp1 as a physiological regulator of p27 expression in vivo, we investigated the spatial and temporal patterns of expression of these factors in control and balloon-injured rat carotid arteries. VSMC proliferation in this model of vascular injury peaks during the first week and then declines thereafter to return to baseline levels within 2 to 3 weeks.5,6,27 In agreement with previous studies that reported the induction of p27 in balloon-injured arteries,15,16 immunohistochemical analysis disclosed elevated p27 protein expression in uninjured arteries and up to 2 days after angioplasty compared with uninjured arteries (Figure 4B). Moreover, averaged over 2 independent experiments, Northern blot analysis disclosed a 3.5-fold induction of p27 steady-state mRNA level at 2 weeks after angioplasty compared with uninjured arteries (Figure 4B).

Immunohistochemical analysis revealed abundant expression of Sp1 in both control and balloon-injured carotid arteries (Figure 3). Importantly, lower p27 mRNA and protein expression in uninjured arteries and up to 2 days after angioplasty correlated with lower Sp1 DNA-binding activity (Figure 4C, lanes 2 to 4). By day 5 after angioplasty, Sp1 DNA-binding activity was markedly induced and remained elevated until day 18 (Figure 4C, lanes 5 to 7). The specificity of the nucleoprotein complex was demonstrated by the ability of unlabeled homologous oligonucleotide (lanes 8 to 13), but not unrelated AP1 oligonucleotide (lanes 14 and 15), to compete for binding.

Previous studies demonstrated a rapid induction in the expression and activity of AP1 transcription factors after balloon angioplasty, suggesting that early proto-oncogene expression contributes to injury-induced VSMC proliferation.17,28,29 Consistent with these findings, and in contrast to the temporal pattern of Sp1 DNA-binding activity, maximum
**AP1-DNA–binding activity was induced shortly after balloon angioplasty and then declined at later time points (Figure 4D, lanes 2 to 7). Unlabeled AP1 oligonucleotide (Figure 4D, lanes 8 to 13), but not unrelated Sp1 oligonucleotide (Figure 4D, lanes 14, 15), competed for binding to the AP1 consensus probe, demonstrating the specificity of the nucleoprotein complex. These results reveal striking differences between the temporal and spatial patterns of expression and activity of AP1 and Sp1 proteins in the arterial wall.**

### Discussion

High levels of the CKIs p21 and p27 have been found in VSMCs at later phases of arterial remodeling that correlated with reduced CDK2 activity and the decline in VSMC growth that takes place after the initial burst of proliferation.\(^{14–16}\) Thus, the upregulation of p21 and p27 may contribute to VSMC growth arrest at late time points after angioplasty. In agreement with this hypothesis, adenovirus-mediated overexpression of p21\(^{14,18,19}\) and p27\(^{15}\) attenuated neointimal thickening in balloon-injured arteries. Despite all of these findings that implicate p21 and p27 as inhibitors of VSMC proliferation, little is known about the molecular networks that regulate CKI expression during arterial remodeling in vivo.

The purpose of the present study was to elucidate regulatory mechanisms that control p27 gene expression in VSMCs in vitro and in the setting of balloon angioplasty. Our EMSAs demonstrated the interaction of the trans-acting factor Sp1 with 2 GC-rich regions within the p27 proximal promoter region. Moreover, maximum transcription from the p27 promoter was markedly reduced when VSMCs were transiently transfected with reporter genes harboring point mutations that disrupted both Sp1 binding sites. Although these results suggested that Sp1 is an important regulator of p27 gene expression in cultured VSMCs, the induction of p27 mRNA and protein expression after balloon angioplasty of the rat carotid artery did not correlate with changes in Sp1 protein expression. Importantly, a lower level of Sp1 DNA-binding activity was found in uninjured arteries and during the early time points after angioplasty, when p27 expression is lower and maximum VSMC proliferation is detected. Consistent with a role of Sp1 as a transcriptional activator of p27 in balloon-injured arteries, elevated p27 expression at late time points during vascular remodeling correlated with a

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**Figure 3.** Immunohistochemical localization of Sp1 and p27 in control and balloon-injured rat carotid arteries. Arterial cross-sections were incubated with goat polyclonal anti-Sp1 (left) and rabbit polyclonal anti-p27 (right) antibodies. Photomicrographs of Sp1 and p27 localization at each time point correspond to the same region from 2 consecutive sections. Immunocomplexes were detected with a biotin/streptavidin peroxidase system. AEC substrate was used to detect p27 in uninjured arteries, and DAB substrate was used in the remainder of the specimens. Arrowheads indicate the external (black) and internal (white) elastic laminae.
marked induction of Sp1 DNA-binding activity. Therefore, posttranslational induction of Sp1 in the injured vessel wall may contribute to transcriptional activation of p27 gene expression and the cessation of VSMC proliferation at later phases during arterial remodeling. However, we cannot rule out the possibility that increased mRNA stability plays an important role in the upregulation of steady-state p27 mRNA levels in the injured arterial wall. It is also noteworthy that induction of Sp1 DNA-binding activity at 5 days after injury preceded the upregulation of p27 gene expression, suggesting that another factor or factors independent of Sp1 are necessary for maximum p27 gene expression in vivo. In this regard, we have shown that activity of the box I+II mutant reporter gene was reduced to 35% of that seen with the wild-type promoter; however, these mutations did not abolish p27 promoter activity (Figure 2). Thus, although these results suggest that Sp1 plays an important role as a transcriptional activator of p27 gene expression, additional factors appear to be required for maximum p27 gene transcription.

Our immunohistochemical studies suggested distinct regulation of Sp1 expression in medial and neointimal VSMCs. Sp1 immunoreactivity was high within the neointima at all time points analyzed, but expression of Sp1 in medial VSMCs was low up to 10 days after angioplasty compared with uninjured vessels or 2 weeks after angioplasty. Thus, future studies should address whether Sp1 expression and DNA-binding activity are regulated during phenotypic modulation of VSMCs and the molecular mechanisms that underlie this regulation.

Our results with cultured VSMCs and balloon-injured arteries extend previous studies that demonstrate binding of Sp1 to both of the GC-rich motifs in the proximal p27 gene regulatory region is required for p27 promoter activity in cancerous human HeLa and U937 cells. Likewise, several studies have demonstrated that Sp1 binds specifically to oligonucleotides that correspond to Sp1-like motifs clustered within the proximal p21 promoter region and that this interaction is essential for constitutive p21 promoter activity in transiently transfected human hepatoma HepG2 cells. In vitro studies with different cell types have shown that inducible p21 gene transcription also requires functional Sp1 binding sites; these include the induction of p21 promoter by nerve growth factor in PC12 pheochromocytoma cells, by fumonisin B1 in CV1 cells, by transforming growth factor-β in HaCaT human keratinocytes, and by phorbol esters and okadaic acid in U937 human leukemic cells. Collectively, these studies implicate Sp1 as a physiological regulator of CKI gene expression in several cell types and pathophysiological processes. In contrast to the response to vascular injury, where p27 upregulation may limit pathological VSMC proliferation, reduced expression of p27 in several human cancers appears to correlate with neoplastic growth and poor patient survival rates. In this context, it will be interesting to determine whether reduced Sp1 expression, function, or both may play a role in the inhibition of p27 gene expression during neoplastic growth.

In conclusion, we show here that Sp1 is required for maximum p27 gene transcription in VSMCs via its interaction with 2 GC-rich sequences within the p27 promoter. Using the rat carotid model of balloon angioplasty, we provide evidence that Sp1 may contribute to inducible p27 expression in vivo. Given that Sp1 is also an important transcriptional activator of p21, it is tempting to speculate that elevated Sp1 DNA-binding activity in the injured arterial wall contributes to p27 and p21 upregulation, which may in turn promote VSMC growth arrest at later phases during the vascular response to balloon denudation. The observation that Sp1 protein is expressed in uninjured arteries, which disclosed lower Sp1 DNA-binding activity, suggests that its induction after angioplasty is likely mediated by a posttranslational modification of Sp1. These results illustrate a link between the transcriptional and cell cycle machinery that may be relevant to the pathogenesis of vascular proliferative disorders.

**Acknowledgments**

This work was supported in part by grants from the Spanish Dirección General de Educación Superior e Investigación Científica (PM97-0136, 1FD97-1035-C02-02) and from the American Heart Association, Massachusetts Affiliate (9860022T) to Dr Andrés. We thank C. Shanahan (University of Cambridge, UK) for the gift of...
E19P cells and S. Lin (National University of Singapore) for p27 reporter constructs. We are also grateful to María J. Andrés for preparation of the figures.

References


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doi: 10.1161/01.ATV.21.3.342

Arteriosclerosis, Thrombosis, and Vascular Biology is published by the American Heart Association, 7272 Greenville Avenue, Dallas, TX 75231
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Print ISSN: 1079-5642. Online ISSN: 1524-4636

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