

# Bone marrow–derived immune cells regulate vascular disease through a p27<sup>Kip1</sup>-dependent mechanism

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**The cyclin-dependent kinase inhibitors are key regulators of cell cycle progression. Although implicated in carcinogenesis, they inhibit the proliferation of a variety of normal cell types, and their role in diverse human diseases is not fully understood. Here, we report that p27<sup>Kip1</sup> plays a major role in cardiovascular disease through its effects on the proliferation of bone marrow–derived (BM-derived) immune cells that migrate into vascular lesions. Lesion formation after mechanical arterial injury was markedly increased in mice with homozygous deletion of p27<sup>Kip1</sup>, characterized by prominent vascular infiltration by immune and inflammatory cells. Vascular occlusion was substantially increased when BM-derived cells from p27<sup>-/-</sup> mice repopulated vascular lesions induced by mechanical injury in p27<sup>+/+</sup> recipients, in contrast to p27<sup>+/+</sup> BM donors. To determine the contribution of immune cells to vascular injury, transplantation was performed with BM derived from RAG<sup>-/-</sup> and RAG<sup>+/+</sup> mice. RAG<sup>+/+</sup> BM markedly exacerbated vascular proliferative lesions compared with what was found in RAG<sup>-/-</sup> donors. Taken together, these findings suggest that vascular repair and regeneration is regulated by the proliferation of BM-derived hematopoietic and nonhematopoietic cells through a p27<sup>Kip1</sup>-dependent mechanism and that immune cells largely mediate these effects.**

## Introduction

Vascular regeneration and repair are essential to the survival of blood vessels. Arterial healing requires the coordinated temporal and spatial expression of proteins that regulate vascular cell proliferation. Inflammation and immunity are also essential components of the pathogenesis of cardiovascular diseases (ref. 1; reviewed in refs. 2–4), but the role of immune progenitors in vascular proliferation and inflammation has not been established.

p27<sup>Kip1</sup>, a member of the Cip/Kip family of cyclin-dependent kinase inhibitors, binds and alters the activities of cyclin D-, cyclin E-, and cyclin A-dependent kinases in quiescent cells, leading to failure of G<sub>1</sub>/S transition and cell cycle arrest (5, 6). An increase in the levels of p27<sup>Kip1</sup> causes proliferating cells to exit the cell cycle, and a decrease in p27<sup>Kip1</sup> is necessary for quiescent cells to resume division. Environmental stresses also regulate p27<sup>Kip1</sup> levels; for example, hypoxia causes a hypoxia-inducible factor-1 $\alpha$ -dependent increase in p27<sup>Kip1</sup> (7). p27<sup>-/-</sup> mice develop hyperplasia in multiple organs, including endocrine tissues, thymus, and spleen (8–10); however, the vascular phenotype of these mice is not known. Defining the role of p27<sup>Kip1</sup> in vascular diseases is critical not only to understanding disease pathogenesis, but importantly, to the design of vascular therapeutics. For example, p27<sup>Kip1</sup> mediates the antiproliferative and antimigratory activity of sirolimus-coated stents (11–13).

Bone marrow–derived (BM-derived) cells are increasingly recognized as key components of vascular regeneration (14–16). After vascular injury, progenitor cells from arterial and BM compart-

ments are mobilized by cytokine activation (15). It is hypothesized that BM-derived cells circulate, home to sites of vascular damage, proliferate, and form arterial lesions in conjunction with cellular components from the local artery. However, the molecular mechanisms that regulate the contributions of BM-derived cells to vascular lesion formation are not well understood. We hypothesized that p27<sup>Kip1</sup> directly regulates the proliferation of BM-derived cells that migrate into damaged blood vessels and reconstitute vascular lesions. Surprisingly, we found that BM-derived hematopoietic and nonhematopoietic cells give rise to most of the cell proliferation in blood vessels during repair, and that indeed, repopulation occurs through a p27<sup>Kip1</sup>-dependent mechanism. This mechanism directly links vascular inflammation and proliferation, and suggests that immunity and inflammation are important targets in treatment of cardiovascular diseases.

## Results

**p27<sup>-/-</sup> mice develop extensive arterial lesions.** To determine whether p27<sup>Kip1</sup> regulates arterial wound repair, we subjected p27<sup>-/-</sup>, p27<sup>+/-</sup>, and p27<sup>+/+</sup> mice to a wire injury in the femoral artery and examined cell proliferation and lesion formation 1 week and 2 weeks later. Cell proliferation was significantly increased in the intima of p27<sup>-/-</sup> arteries compared with p27<sup>+/+</sup> arteries (p27<sup>-/-</sup>, 37.7%  $\pm$  1.4% vs. p27<sup>+/+</sup>, 18.0%  $\pm$  4.4%,  $P < 0.01$ ) (Figure 1A, left). Arterial lesion size was also markedly increased in p27<sup>-/-</sup> mice compared with p27<sup>+/+</sup> mice (intima/media ratios at 1 week: p27<sup>-/-</sup>, 0.4  $\pm$  0.1 vs. p27<sup>+/+</sup>, 0.2  $\pm$  0.1,  $P < 0.05$ ; at 2 weeks: p27<sup>-/-</sup>, 2.2  $\pm$  0.1 vs. p27<sup>+/+</sup>, 0.5  $\pm$  0.1,  $P < 0.0001$ ) (Figure 1A, right, and Figure 1B). p27<sup>Kip1</sup> heterozygous mice presented an intermediate phenotype (Figure 1A). Many of the intimal cells were putative VSMCs, determined by  $\alpha$ -actin staining (Figure 1B), suggesting increased proliferation of this cell type. These findings are consistent with in vitro experiments in which p27<sup>Kip1</sup>-deleted VSMCs proliferate at accelerated rates compared with p27<sup>+/+</sup> cells

**Nonstandard abbreviations used:** bone marrow (BM); monocyte chemoattractant protein-1 (JE/MCP-1).

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(Supplemental Figure 1, A–C; supplemental material available at <http://www.jci.org/cgi/content/full/114/3/419/DC1>).

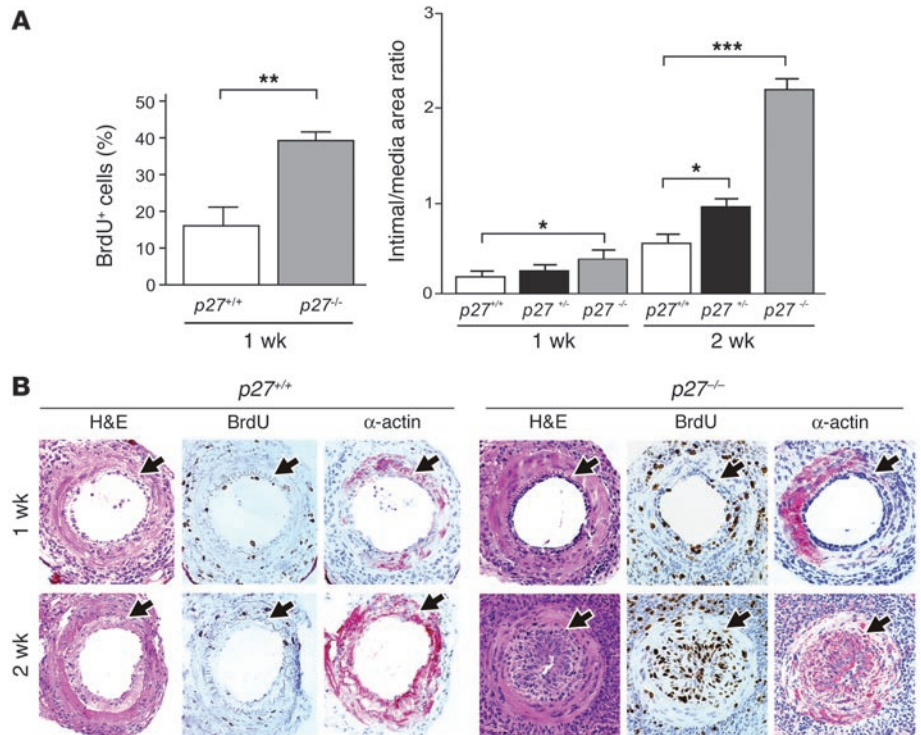
**Knockout of *p27* increases the inflammatory response to vascular injury.** We observed an intense inflammatory reaction in the adventitia of *p27*<sup>-/-</sup> arteries compared with *p27*<sup>+/+</sup> arteries following wire injury (Figure 1B, H&E staining). Since *p27*<sup>Kip1</sup> regulates division of macrophages (17) and T lymphocytes (18–21), we reasoned that *p27*<sup>Kip1</sup> controls the proliferation of macrophages, neutrophils, and/or T lymphocytes in response to vascular injury. We measured tenfold and 13-fold increases at 1 week and 2 weeks, respectively, in the percentage of arterial macrophages in *p27*<sup>-/-</sup> arteries compared with *p27*<sup>+/+</sup> arteries (1 week: *p27*<sup>+/+</sup>, 1.7% ± 1.1% vs. *p27*<sup>-/-</sup>, 16.2% ± 2.5%, *P* < 0.0005; 2 weeks: *p27*<sup>+/+</sup>, 3.2% ± 1.7% vs. *p27*<sup>-/-</sup>, 41.3% ± 3.1%, *P* < 0.0001) (Figure 2, A and D). Whereas T lymphocytes were rare in *p27*<sup>+/+</sup> vessels, these cells were significantly increased in *p27*<sup>-/-</sup> lesions (1 week: *p27*<sup>+/+</sup>, 0.9% ± 0.5% vs. *p27*<sup>-/-</sup>, 3.7% ± 1.4%, *P* < 0.005; 2 weeks: *p27*<sup>+/+</sup>, 0.5% ± 0.2% vs. *p27*<sup>-/-</sup>, 3.8% ± 1.3%, *P* < 0.005) (Figure 2B). Neutrophils in *p27*<sup>-/-</sup> arteries increased threefold and fourfold compared with *p27*<sup>+/+</sup> arteries at 1 week and 2 weeks, respectively (1 week: *p27*<sup>+/+</sup>, 3.7% ± 0.9% vs. *p27*<sup>-/-</sup>, 11.0% ± 1.7%, *P* < 0.01; 2 weeks: *p27*<sup>+/+</sup>, 5.2% ± 1.8% vs. *p27*<sup>-/-</sup>, 18.7% ± 2.3%, *P* < 0.0005) (Figure 2, C and D). The number of infiltrating inflammatory cells was higher in the adventitia than in the intima (Figure 2D). These findings suggest that *p27*<sup>Kip1</sup> regulates the proliferation of leukocytes that infiltrate sites of injury.

To determine the physiological importance of the effect of *p27*<sup>Kip1</sup> on hematopoietic cells, we measured *p27*<sup>Kip1</sup> expression in circulating and intralesional CD45<sup>+</sup> cells. Nuclear *p27*<sup>Kip1</sup> was expressed in 92.5% ± 2.3% of circulating CD45<sup>+</sup> cells, but only 18.0% ± 1.8% of intralesional CD45<sup>+</sup> cells, 7 days after vascular injury (*P* < 0.0001) (Figure 2, E and F). These data suggest that *p27*<sup>Kip1</sup> has an important effect on hematopoietic cells: the activation of infiltrating leukocytes during arterial wound repair.

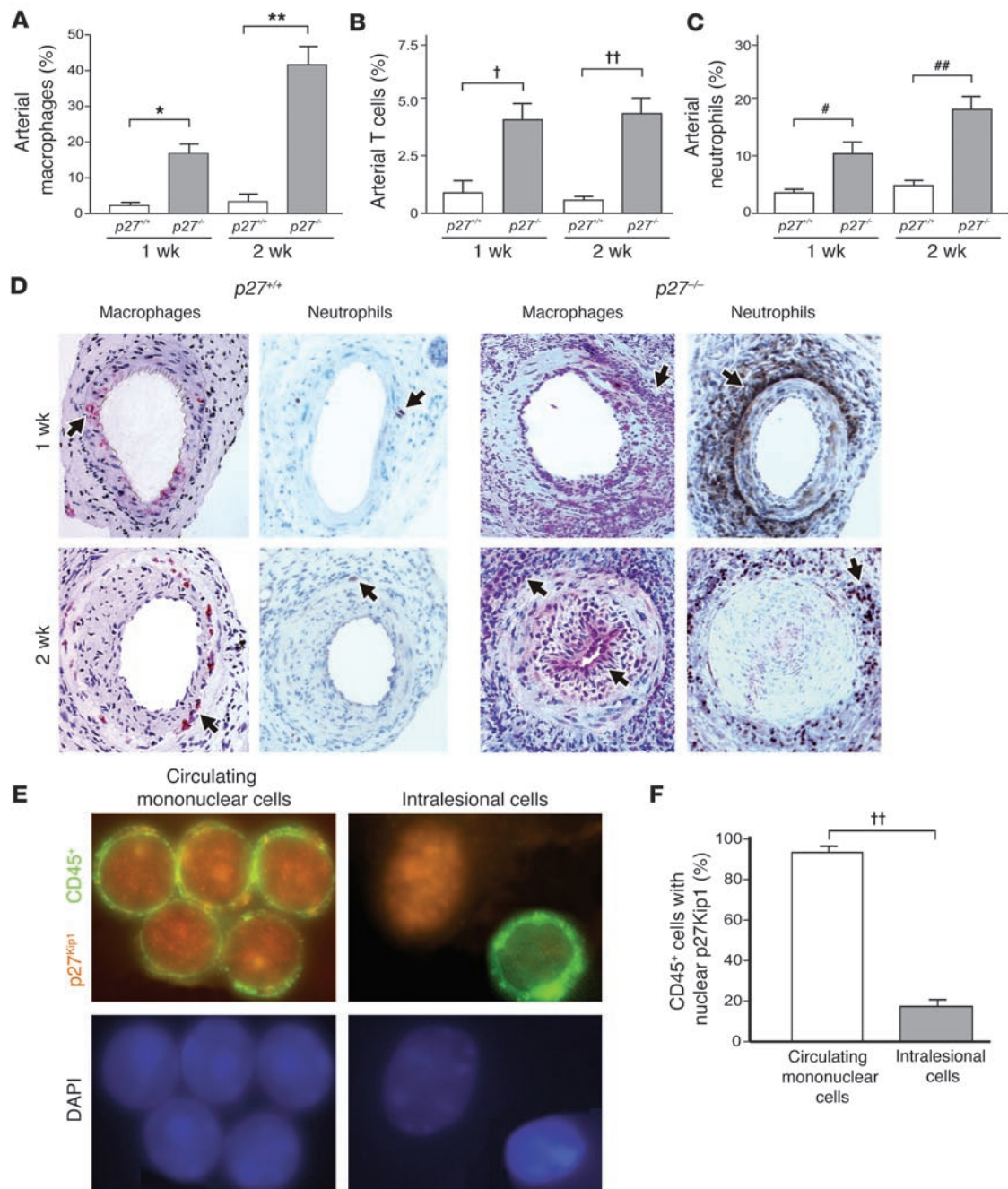
We hypothesized that chemokines and cytokines, mediators of inflammation, might be elevated in *p27*<sup>-/-</sup> arteries. To determine the effects of *p27*<sup>Kip1</sup> on inflammatory mediators, serum and arterial cytokine levels were measured in *p27*<sup>-/-</sup> and *p27*<sup>+/+</sup> mice at baseline and at 3 days and 7 days after vascular injury. No differences in cytokine levels were observed in *p27*<sup>-/-</sup> and *p27*<sup>+/+</sup> arteries under basal conditions. However, 3 days and 7 days after injury, significant increases in macrophage, T lymphocyte, and neutrophil chemokines and cytokines were detected in *p27*<sup>-/-</sup> arteries compared with *p27*<sup>+/+</sup> arteries (Figure 3A and Supplemental Figures 2 and 3). These proinflammatory mediators included monocyte chemoattractant protein-1 (JE/MCP-1), TNF- $\alpha$ , IL-6, IL-10, IL-18, GM-CSF, macrophage chemoattractant factors MIP-1 $\alpha$  and Rantes, and the anti-inflammatory cytokine TGF- $\beta$ .

We hypothesized further that if *p27*<sup>Kip1</sup> has an important effect on nonhematopoietic cells, levels of cytokines and chemokines should be elevated in *p27*<sup>-/-</sup> arteries, even after transfer of *p27*<sup>+/+</sup> BM. To test this hypothesis, we performed BM transplant and vascular injury experiments, measuring vascular cytokines and chemokines at baseline and 3 days and 7 days after injury in *p27*<sup>-/-</sup> mice receiving *p27*<sup>+/+</sup> BM versus *p27*<sup>+/+</sup> mice transplanted with *p27*<sup>+/+</sup> BM. We found that the levels of several vascular cytokines, including JE/MCP-1 and MCP-5, were significantly increased in *p27*<sup>-/-</sup> chimeras receiving *p27*<sup>+/+</sup> BM (Figure 3B). These results mirror the finding of elevated vascular cytokines in *p27*<sup>-/-</sup> mice undergoing vascular injury (Figure 3A) and demonstrate that *p27*<sup>Kip1</sup> has an important physiological role in nonhematopoietic cells in addition to hematopoietic cells. Taken together, these data suggest that *p27*<sup>Kip1</sup> deficiency initiates a complex cascade of events through its effects on hematopoietic and nonhematopoietic cells, including proliferation of inflammatory cells and release of chemokines and cytokines, which in turn stimulate the proliferation of inflammatory cells and VSMCs (3), forming a cellular lesion.

***p27*<sup>Kip1</sup> directly determines the origin of cells within the intima.** To determine the origin of the inflammatory cells, we performed BM transplantation experiments from *p27*<sup>-/-</sup> or *p27*<sup>+/+</sup> donors (D) into *p27*<sup>+/+</sup> and *p27*<sup>-/-</sup> recipient (R) mice. Lethally irradiated mice received 3 × 10<sup>6</sup> BM cells, and complete engraftment of donor BM, without persistence of recipient BM, was confirmed. Following engraftment, we injured the femoral arteries of recipient mice and quantified lesion size and composition 2 weeks later. *p27*<sup>-/-</sup> BM consistently increased lesion size



**Figure 1** Impaired wound healing in *p27*<sup>-/-</sup> mice in vivo. (A) Increased cell proliferation (left) and enlarged vascular lesions (right) in *p27*<sup>-/-</sup> arteries. \**P* < 0.05; \*\**P* < 0.01; \*\*\**P* < 0.0001. (B) Representative cross sections of *p27*<sup>+/+</sup> (left) and *p27*<sup>-/-</sup> (right) arteries stained with H&E, BrdU, and smooth muscle  $\alpha$ -actin, 1 week and 2 weeks after injury. Arrows indicate the internal elastic lamina. Original magnification,  $\times 200$ .



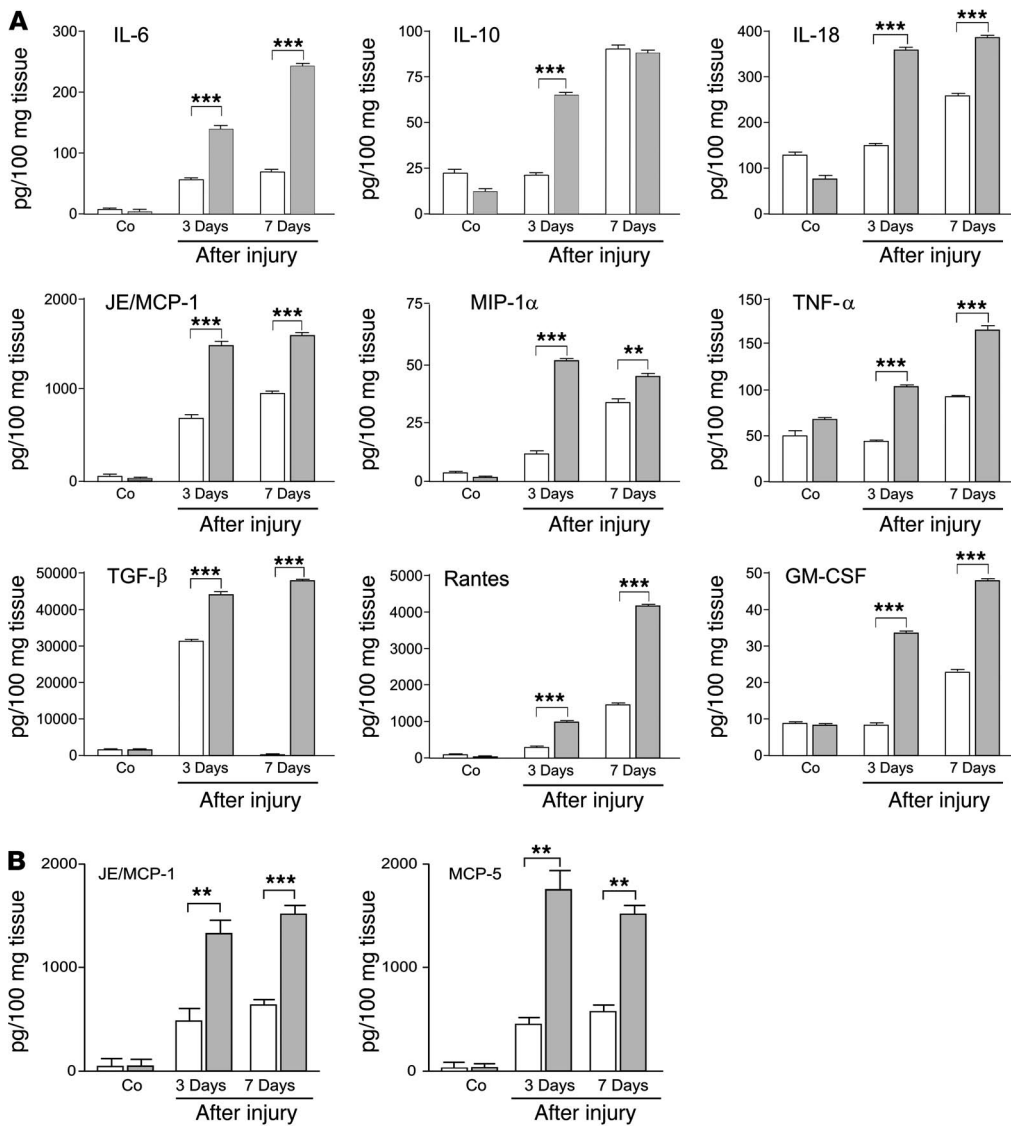
**Figure 2**

*p27<sup>-/-</sup>* mice develop arterial inflammation after vascular injury. (A–C) Accumulation of macrophages (\**P* < 0.0005; \*\**P* < 0.0001) (A), T lymphocytes (†*P* < 0.005; ††*P* < 0.001) (B), and neutrophils (#*P* < 0.01; ##*P* < 0.0005) (C) in *p27<sup>+/+</sup>* (white bars) and *p27<sup>-/-</sup>* (gray bars) arteries after injury. (D) Representative photomicrographs of cross sections of *p27<sup>+/+</sup>* (left) and *p27<sup>-/-</sup>* (right) arteries immunostained for macrophages (arrow, red cytoplasmic staining) and neutrophils (arrow, brown cytoplasmic staining). Original magnification, ×200. (E) Immunofluorescence of circulating mononuclear (upper left) and intralésional cells (upper right) demonstrating coexpression of CD45 (membranes, green) and p27<sup>Kip1</sup> (nuclei, red). Nuclear DAPI expression (blue) is also shown (lower panels). Original magnification, ×1000. (F) Quantitative analysis of coexpression of endogenous nuclear p27<sup>Kip1</sup> in circulating CD45<sup>+</sup> mononuclear cells (white bar) and intralésional cells (gray bar). Results are expressed as a percentage of CD45<sup>+</sup>, p27<sup>Kip1</sup><sup>+</sup> cells compared with CD45<sup>+</sup> cells alone.

when transplanted into either *p27<sup>+/+</sup>* or *p27<sup>-/-</sup>* recipients (intima/media ratios: *Dp27<sup>-/-</sup>* → *Rp27<sup>+/+</sup>*, 1.1 ± 0.1 vs. *Dp27<sup>+/+</sup>* → *Rp27<sup>+/+</sup>*, 0.3 ± 0.1, *P* < 0.0005; *Dp27<sup>+/+</sup>* → *Rp27<sup>-/-</sup>*, 1.8 ± 0.1 vs. *Dp27<sup>-/-</sup>* → *Rp27<sup>-/-</sup>*, 2.7 ± 0.2, *P* < 0.0001) (Figure 4, A and D). Importantly, we found that *p27<sup>-/-</sup>* BM also significantly increased the percentage of arterial macrophages in

*p27<sup>+/+</sup>* or *p27<sup>-/-</sup>* recipient mice compared with *p27<sup>+/+</sup>* donor BM (*Dp27<sup>-/-</sup>* → *Rp27<sup>+/+</sup>*, 14.2% ± 1.4% vs. *Dp27<sup>+/+</sup>* → *Rp27<sup>+/+</sup>*, 3.8% ± 1.9%, *P* < 0.005; *Dp27<sup>-/-</sup>* → *Rp27<sup>-/-</sup>*, 43.6% ± 1.8% vs. *Dp27<sup>+/+</sup>* → *Rp27<sup>-/-</sup>*, 29.6% ± 1.6%, *P* < 0.0001) (Figure 4, B and E). Thus, p27<sup>Kip1</sup> directly regulates vascular lesion size through its effects on BM-derived inflammatory cells.





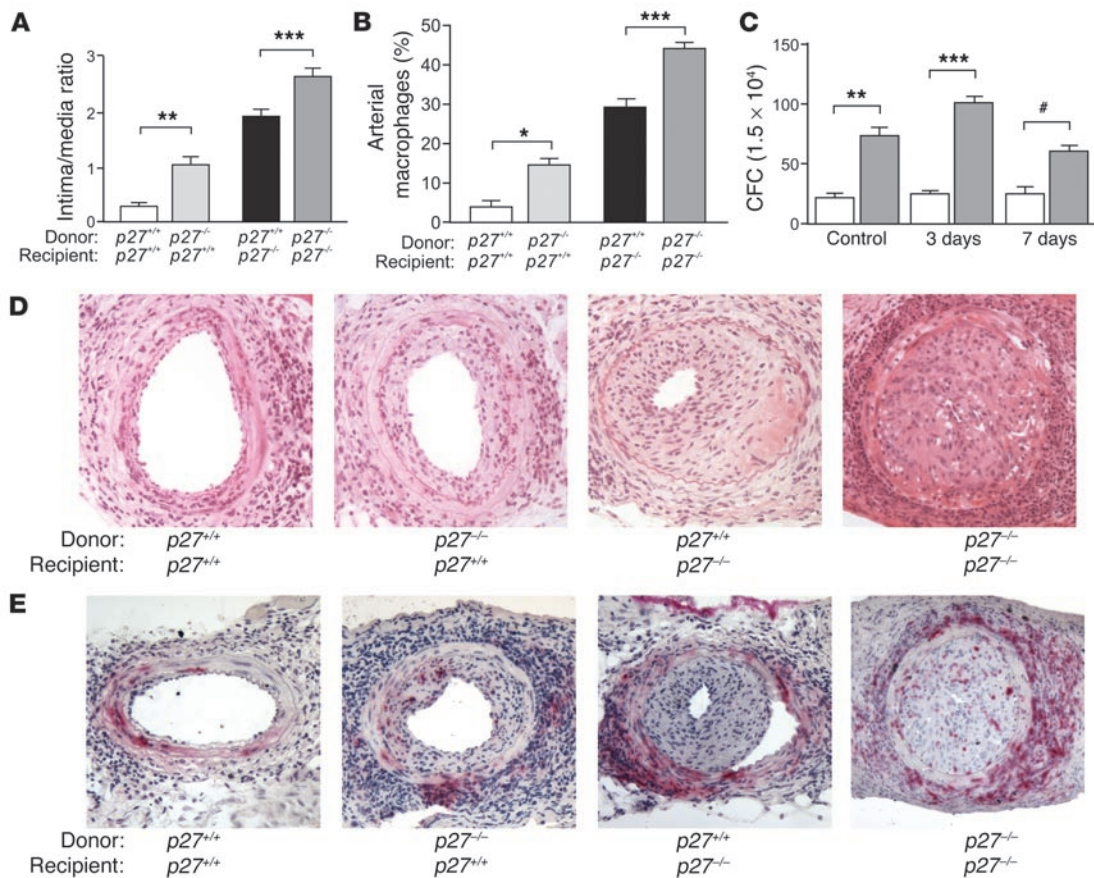
**Figure 3** Cytokine levels are increased in *p27<sup>-/-</sup>* arteries following vascular injury. (A) Artery samples were collected from *p27<sup>+/+</sup>* (white bars) and *p27<sup>-/-</sup>* (gray bars) mice at baseline (Co) and at 3 days and 7 days after injury. (B) Vascular tissues were extracted from *p27<sup>+/+</sup>* (white bars) and *p27<sup>-/-</sup>* (gray bars) mice receiving *p27<sup>+/+</sup>* BM at baseline and at 3 days and 7 days after injury. \*\**P* < 0.005; \*\*\**P* < 0.0005.

To determine whether *p27<sup>Kip1</sup>* regulates the proliferation of BM-derived cells, we quantified hematopoietic BM cells from *p27<sup>-/-</sup>* and *p27<sup>+/+</sup>* mice at baseline and at 3 days and 7 days following arterial injury. We found a significant increase in CFCs in *p27<sup>-/-</sup>* mice compared with *p27<sup>+/+</sup>* mice under baseline conditions and at 3 days and 7 days after injury (baseline: *p27<sup>-/-</sup>*,  $73.6 \pm 7.1$  vs. *p27<sup>+/+</sup>*,  $23.2 \pm 3.6$  colonies, *P* < 0.0005; 3 days: *p27<sup>-/-</sup>*,  $100.2 \pm 6.0$  vs. *p27<sup>+/+</sup>*,  $26.4 \pm 1.8$  colonies, *P* < 0.0001; 7 days: *p27<sup>-/-</sup>*,  $61.0 \pm 5.0$  vs. *p27<sup>+/+</sup>*,  $26.4 \pm 5.5$  colonies, *P* < 0.001) (Figure 4C). These data provide evidence that *p27<sup>Kip1</sup>* directly mediates proliferation of BM-derived hematopoietic cells under basal conditions and during healing of a blood vessel.

We confirmed the BM origin of cells within the vascular lesions by performing BM transplants from male donors into female recipients and analyzing the presence of Y chromosomes within arteries. We found many Y chromosome-positive cells within the adventitia of *p27<sup>-/-</sup>* and *p27<sup>+/+</sup>* recipient mice, suggesting the presence of BM-derived hematopoietic cells (T cells, monocytes, and neutrophils). In the intima, *p27<sup>-/-</sup>* donor BM yielded a significant increase in Y chromosome-positive cells compared with

*p27<sup>+/+</sup>* donor BM (Figure 5A). Some of these intimal cells were Y chromosome<sup>+</sup>, CD45<sup>+</sup>,  $\alpha$ -actin<sup>-</sup>, while other cells were Y chromosome<sup>+</sup>, CD45<sup>-</sup>,  $\alpha$ -actin<sup>+</sup> (Figure 5, B and C). These findings confirm earlier reports by Sata et al. (15) that a significant portion of the neointima is formed by BM-derived cells. Our observations suggest that BM-derived cells repopulate vascular lesions through a *p27<sup>Kip1</sup>*-dependent mechanism.

*p27<sup>Kip1</sup>* directly regulates BM-derived immune cells infiltrating vascular lesions. The absence of *p27<sup>Kip1</sup>* permits clonal expansion of T lymphocytes in vitro and in vivo (21). To determine whether this mechanism determines the abundance of BM-derived immune cells within the arteries of *p27<sup>-/-</sup>* mice, we performed vascular injury experiments in *RAG<sup>+/-</sup>* mice (22). First, we performed vascular injury in *RAG<sup>+/+</sup>* and *RAG<sup>-/-</sup>* arteries. We found that *RAG<sup>-/-</sup>* mice had significantly smaller lesions than did *RAG<sup>+/+</sup>* mice (intima/media ratios: 1 week: *RAG<sup>-/-</sup>*,  $0.10 \pm 0.05$  vs. *RAG<sup>+/+</sup>*,  $0.15 \pm 0.07$ ; 2 weeks: *RAG<sup>-/-</sup>*,  $0.21 \pm 0.08$  vs. *RAG<sup>+/+</sup>*,  $0.55 \pm 0.14$ ; *P* < 0.05) (Figure 6A). *RAG<sup>-/-</sup>* arteries contained reduced numbers of inflammatory cells (data not shown). These findings suggest that reduced inflammation in the native artery contributes to improved vascular heal-

**Figure 4**

$p27^{Kip1}$  determines vascular proliferation and BM progenitor pool size. (A)  $p27^{-/-}$  BM accelerates arterial lesion formation when transplanted into  $p27^{+/+}$  or  $p27^{-/-}$  recipient mice. Following engraftment, arteries were injured and intima/media ratios were measured 2 weeks later.  $**P < 0.0005$ ;  $***P < 0.0001$ . (B)  $p27^{-/-}$  BM significantly increased the percentage of arterial macrophages in  $p27^{+/+}$  and  $p27^{-/-}$  recipient arteries compared with  $p27^{+/+}$  BM.  $*P < 0.005$ . (C) CFCs are significantly elevated in  $p27^{-/-}$  BM (gray bars) compared with  $p27^{+/+}$  BM (white bars) at the indicated time points after vascular injury. Each data point was generated by three limiting dilutions.  $\#P < 0.001$ . (D) Representative H&E-stained cross sections of recipient  $p27^{+/+}$  (left two panels) and  $p27^{-/-}$  (right two panels) arteries following transplantation with donor  $p27^{+/+}$  and  $p27^{-/-}$  BM, as indicated, followed by vascular injury. Original magnification,  $\times 200$ . (E) Representative cross sections of recipient  $p27^{+/+}$  (left two panels) and  $p27^{-/-}$  (right two panels) arteries immunostained for macrophages following transplantation with donor  $p27^{+/+}$  and  $p27^{-/-}$  BM, as indicated, followed by vascular injury. Original magnification,  $\times 200$ .

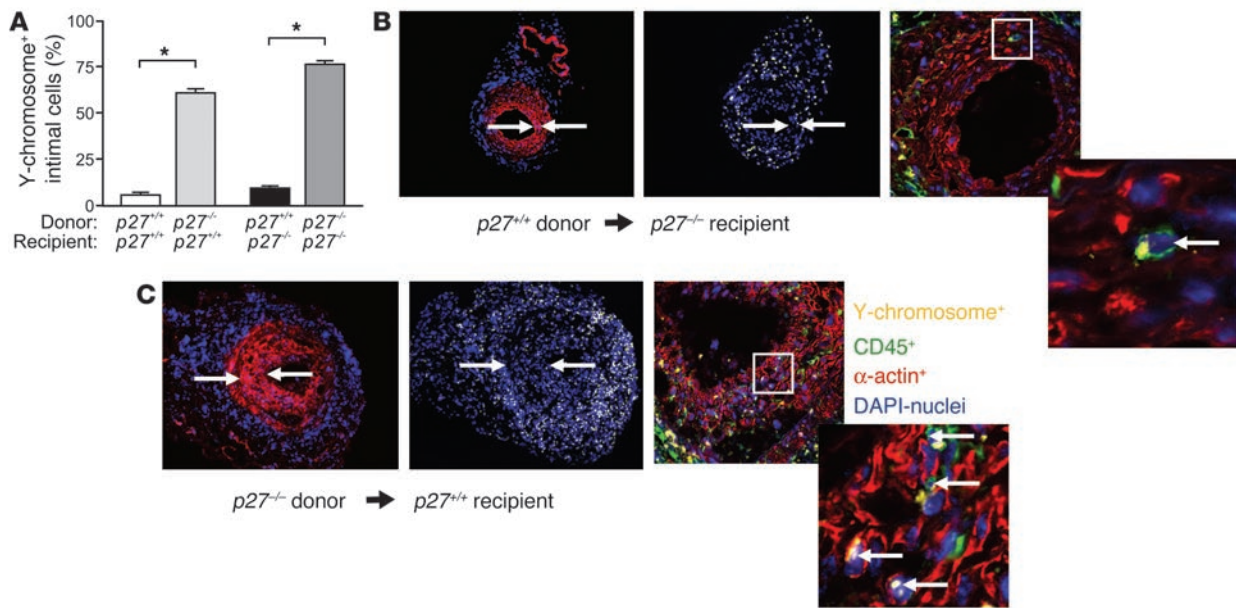
ing. To ascertain whether an absence of T cells and B cells in the BM also protects against lesion development, we transplanted  $RAG^{+/+}$  or  $RAG^{-/-}$  BM into  $p27^{+/+}$  or  $p27^{-/-}$  recipient mice, confirmed engraftment, and then performed arterial injury.  $RAG^{-/-}$  BM transplanted into WT mice significantly reduced lesion formation compared with  $RAG^{+/+}$  BM (intima/media ratios:  $DRAG^{-/-} \rightarrow Rp27^{+/+}$ ,  $0.16 \pm 0.05$  vs.  $DRAG^{+/+} \rightarrow Rp27^{+/+}$ ,  $0.33 \pm 0.07$ ,  $P < 0.05$ ) (Figure 6B).  $RAG^{-/-}$  donor BM also significantly reduced arterial lesion size in  $p27^{-/-}$  recipients compared with  $RAG^{+/+}$  BM. Surprisingly, the magnitude of the  $RAG^{-/-}$  BM effect was greater in  $p27^{-/-}$  recipients than in  $p27^{+/+}$  recipients, suggesting that native cells in  $p27^{-/-}$  arteries also contribute to the size of vascular lesions (intima/media ratios:  $DRAG^{-/-} \rightarrow Rp27^{-/-}$ ,  $0.4 \pm 0.1$  vs.  $DRAG^{+/+} \rightarrow Rp27^{-/-}$ ,  $1.8 \pm 0.1$ ,  $P < 0.0001$ ) (Figure 6B).

To further delineate the relative contribution of T and B cells, we performed a thymectomy on recipient  $p27^{+/+}$  mice and transplanted  $p27^{-/-}$  or  $p27^{+/+}$  BM. After successful engraftment, we performed vascular injury and examined the neointima 2 weeks later. After thymectomy in recipient  $p27^{-/-}$  mice, the percentage of circulating T cells

significantly decreased, from  $38.2\% \pm 2.2\%$  before thymectomy to  $18.1\% \pm 2.2\%$  at the time of sacrifice ( $P < 0.0005$ ). As anticipated, the thymectomy did not produce a reduction in B cells. We found that the partial T cell depletion significantly reduced neointima formation in thymectomized  $p27^{+/+}$  mice receiving  $p27^{-/-}$  BM compared with nonthymectomized  $p27^{+/+}$  mice receiving  $p27^{-/-}$  BM (intima/media ratios:  $Dp27^{-/-} \rightarrow Rp27^{+/+}$  thymectomized,  $0.44 \pm 0.06$  vs.  $Dp27^{-/-} \rightarrow Rp27^{+/+}$  nonthymectomized,  $1.07 \pm 0.10$ ,  $P < 0.0005$ ) (Figure 6C). These findings further support the conclusion that mature T cells contribute to the inflammatory response during arterial wound repair.

## Discussion

Vascular diseases are characterized by inflammation and proliferation, but a mechanistic role for the immune system in these lesions has not been shown. Here we provide direct genetic evidence for  $p27^{Kip1}$  as a determinant of vascular inflammation and proliferation. In response to injury,  $p27^{Kip1}$  is required to promote the healing process and protect against the excessive proliferation

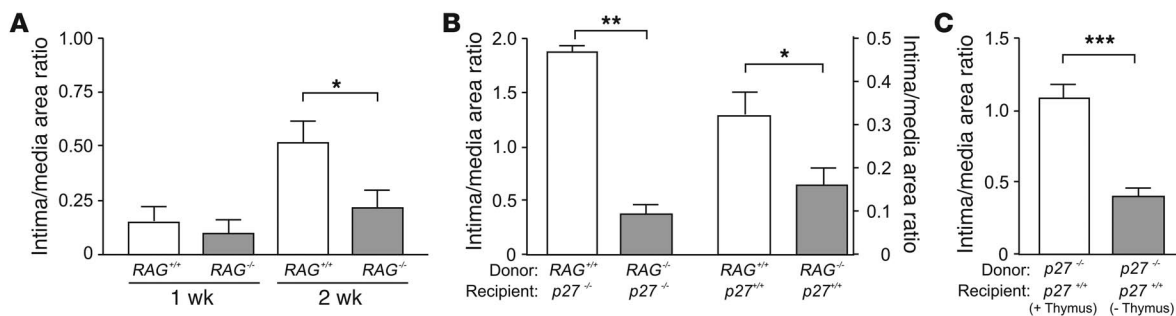


**Figure 5**  
 $p27^{-/-}$  BM-derived cells reconstitute the intima and adventitia of vascular lesions during repair. (A) The percentage of Y chromosome–positive nuclei in the intima was determined 2 weeks after injury using FISH techniques. \* $P < 0.0001$ . (B and C) Representative cross sections of recipient  $p27^{+/+}$  female arteries following transplantation of male  $p27^{+/+}$  (B) or  $p27^{-/-}$  (C) donor BM. Left two panels: Y chromosome+ cells (yellow),  $\alpha$ -actin+ cells (red), and nuclei (DAPI stain, blue). Arrows indicate the margins of the intima as determined by the internal and external elastic lamina. Right two panels: triple immunofluorescence detects Y chromosome+ cells (yellow), CD45+ cells (green),  $\alpha$ -actin+ cells (red), and nuclei (DAPI stain, blue). Arrows indicate Y chromosome+ nuclei. Original magnification,  $\times 100$  (left two panels of B and C); right two panels: confocal microscopy.

of inflammatory cells and VSMCs that occurs in pathological remodeling. We now report that  $p27^{kip1}$  regulates these processes through its effects on hematopoietic and nonhematopoietic cells, inhibiting both the proliferation of BM-derived cells that migrate into vascular lesions and the proliferation of local VSMCs. Cytokines and chemokines from these BM-derived inflammatory cells also drive the proliferation of vascular lesions. Furthermore,  $RAG^{+/+}$  donor BM exacerbates vascular proliferative lesions compared with  $RAG^{-/-}$  donor BM when transplanted into  $p27^{+/+}$  or  $p27^{-/-}$  recipients, and thymectomy experiments further confirm the contribution of mature T cells and the immune system to vascular injury and remodeling.

The role of BM cells in vascular repair and regeneration has not been well-defined. Accumulating evidence suggests that somatic stem

cells in the BM differentiate into various lineages, including vascular endothelial cells (23, 24) and smooth muscle cells (25, 26). In animal models of graft vasculopathy and hyperlipidemia-induced atherosclerosis, BM cells may give rise to a substantial percentage of VSMCs that contribute to arterial remodeling (15, 16, 27). The contribution of these cells to human vascular disease has not been proven, although circulating smooth muscle progenitor cells have been identified in human peripheral blood (28). We demonstrate here that  $p27^{kip1}$ , through its effects on the number of BM progenitor cells, directly regulates the contribution of BM-derived cells that repopulate the vascular neointima following injury. We find that  $p27^{-/-}$  cells competitively infiltrate the vascular lesion in substantially higher percentages than do  $p27^{+/+}$  donor cells. Some of the proliferative effects on local VSMCs could be attributed to mature T cells, monocytes, and neutrophils.



**Figure 6**  
 Knockout of  $RAG$  confers protection against vascular proliferation. (A)  $RAG^{-/-}$  arteries are protected against abnormal lesion formation 1 week and 2 weeks after vascular injury compared with  $RAG^{+/+}$  arteries. \* $P < 0.05$ . (B)  $RAG^{-/-}$  BM directly reduces arterial lesion size in  $p27^{+/+}$  or  $p27^{-/-}$  recipient mice. \*\* $P < 0.0001$ . (C) Thymectomy (T cell depletion) in  $p27^{+/+}$  mice reduces neointima development following transplantation with  $p27^{-/-}$  BM. \*\*\* $P < 0.0005$ .





Inflammation is central to the pathogenesis of vascular diseases such as atherosclerosis. Directed migration of leukocytes through the endothelium initiates an inflammatory process in which monocytes, macrophages, and T lymphocytes in the vascular lesion interact with each other, endothelial cells, and VSMCs in complex ways through cell-cell contact and the production of chemokines, cytokines, and growth factors (reviewed in refs. 3, 29, 30). The adventitia is also an important source of vascular progenitor cells that can differentiate into VSMCs and contribute to vascular lesions (31). In this study, we also found a substantial percentage of Y chromosome<sup>+</sup> cells in the adventitia. Many of these adventitial cells were CD45<sup>+</sup>, suggesting a hematopoietic origin, and were likely immune and inflammatory cells. These inflammatory cells may stimulate the proliferation of local VSMCs through the release of cytokines and chemokines. The observation that p27<sup>Kip1</sup> regulates the proliferation of these BM-derived hematopoietic cells is supported by recent observations of atherosclerotic lesion formation in *apoE*<sup>-/-</sup> mice receiving p27<sup>-/-</sup> BM (32).

Here we provide direct genetic evidence of immune system involvement in lesion progression and composition that is mediated by p27<sup>Kip1</sup> regulation of the BM. We find that lymphocytes are obligatory for lesion progression, since *RAG*<sup>+/-</sup> BM exacerbated lesions, whereas *RAG*<sup>-/-</sup> BM conferred protection against vascular proliferation. Furthermore, vascular proliferation was increased fourfold when *RAG*<sup>+/-</sup> BM was transplanted into p27<sup>-/-</sup> recipients. The role of T cells in vascular repair was defined further in the thymectomy experiments; partial depletion of T cells resulted in a much smaller vascular lesion, confirming the physiological importance of T cells in vascular inflammation and injury. Lymphocytes also play an important role in early atherogenesis, as demonstrated by genetic crosses of LDL receptor null and *RAG* null mice (33).

In summary, our findings indicate that p27<sup>Kip1</sup> plays a major role in vascular repair and regeneration through its effects on the proliferation of BM-derived hematopoietic and nonhematopoietic cells. This mechanism directly links vascular proliferation and inflammation and suggests that therapeutics directed at immune and inflammatory cells are important in treating cancer and cardiovascular, autoimmune, and other human diseases.

## Methods

**Generation of homozygous mice.** We obtained heterozygous 129/BL6 p27<sup>+/-</sup> mice from Andrew Koff (Memorial Sloan-Kettering Cancer Center, New York, New York, USA). We backbred the mice for 12 generations against a C57BL/6 background and studied male and female mice at 10 weeks of age. p27<sup>+/-</sup> littermates were used as controls. *RAG*<sup>-/-</sup> mice (strain B6.129S7-*Rag1*<sup>tm1Mom</sup>, on a C57BL/6 background) were obtained from The Jackson Laboratory (Bar Harbor, Maine, USA). *RAG*<sup>+/-</sup> littermates were used as controls. Genotyping was performed by PCR amplification of mouse tail DNA using allele-specific probes. Each experimental group contained a minimum of five mice. All experiments were conducted according to the guidelines of the Animal Care and Use Committee of the National Heart, Lung, and Blood Institute.

**Wire injury in mice.** p27<sup>-/-</sup>, p27<sup>+/-</sup>, and p27<sup>+/-</sup> mice were investigated using an established model of vascular wire injury (34). This procedure was performed by one surgeon (H. San) who was blinded to genotype. This injury led to complete endothelial denudation and medial VSMC apoptosis. The cellularity of the media was decreased and became repopulated by proliferating VSMCs. Each group consisted of at least five mice and ten arteries. The percentage of BrdU-positive cells, macrophages, T lymphocytes, and neutrophils in the intima, media, and adventitia were counted in 40

sections per artery and were analyzed by computer-assisted morphometry. BrdU (25 mg/kg) was injected 1 hour before sacrifice. Intima and media cross-section areas were measured by two independent observers blinded to genotype, using a computerized measuring system (34).

**Thymectomy in adult mice.** The mice were anesthetized and placed in a ventrodorsal position on a water heated pad. The skin was shaved from the neck to the thorax and the mice were intubated and connected to a ventilator with 100% oxygen. A longitudinal midline incision was made through the skin and superficial fascia from the level of the angle of the mandible to the fourth rib. The pretracheal muscles were separated down to the sternum and the trachea was exposed. The thymus was completely removed by performing sharp or blunt dissection and separating it from the pleural linings. The pretracheal muscles and the sternum were closed with Vicryl suture (Ethicon Inc., Somerville, New Jersey, USA), and the skin incision was closed with stainless steel staples.

**BM transplantation.** BM was obtained from 8- to 12-week-old male p27<sup>-/-</sup>, p27<sup>+/-</sup>, *RAG*<sup>-/-</sup>, and *RAG*<sup>+/-</sup> mice after euthanizing with CO<sub>2</sub>. Marrow cell suspensions were flushed from femurs and tibiae, filtered, and stored on ice until use. Recipient female mice were lethally irradiated with 9 Gy of whole-body irradiation. Three million unfractionated cells were injected intravenously into the tail vein of each recipient mouse. Twelve weeks later, successful engraftment was confirmed by quantitative PCR to determine the presence or absence of p27<sup>Kip1</sup> or *Sry* to distinguish female and male BM cells and by FACS to determine the absence of T and B lymphocytes in *RAG*<sup>-/-</sup> BM. Five mice (ten femoral arteries) were studied per group. Four sections were analyzed per artery.

**Tissue disaggregation and cell isolation.** Circulating blood mononuclear cells were obtained by Ficoll gradient purification using lymphocyte separation medium (ICN Biomedicals Inc., Aurora, Ohio, USA). Vascular infiltrating leukocytes were obtained as described (35) with minor modifications. Subsequently, cells were spun down onto glass slides.

**Immunohistochemistry and in situ hybridization.** Immunohistochemistry was performed using an ABC immunoperoxidase (BrdU or MAC-2) or alkaline phosphatase ( $\alpha$ -actin) protocol. An anti- $\alpha$ -actin antibody against vascular smooth muscle  $\alpha$ -actin (1:1,000; Roche Diagnostics Corp., Indianapolis, Indiana, USA), a MAC-2 antibody against macrophages (1:16,000; Cedarlane Laboratories Ltd., Hornby, Ontario, Canada), antibody CL8993B against neutrophils (1:10, Cedarlane Laboratories Ltd.), an antibody against CD3 used to identify T lymphocytes (Santa Cruz Biotechnology Inc., San Cruz, California, USA), and an alkaline phosphatase-conjugated mouse monoclonal antibody against BrdU (1 U/ml, Roche Diagnostics Corp.) were used as primary antibodies.

Immunofluorescence cytochemistry was performed using the Cytofix/Cytoperm system (BD Biosciences — Pharmingen, San Diego, California, USA). Double labeling was performed using a rabbit anti-p27<sup>Kip1</sup> antibody (C19) (1:50, Santa Cruz Biotechnology Inc.), an FITC-conjugated rat anti-mouse CD45 antibody (1:50, BD Biosciences — Pharmingen), and a TRITC-conjugated anti-rabbit secondary antibody (1:200; Sigma-Aldrich, St. Louis, Missouri, USA), followed by mounting in DAPI-containing media (Vector Laboratories Inc., Burlingame, California, USA).

In situ hybridization immunohistochemistry was performed as described (36) with modifications. Staining with  $\alpha$ -actin was performed using a Cy3-conjugated antibody (Sigma-Aldrich). CD45 staining of sections was followed by use of an FITC-labeled tyramide signal amplification system (PerkinElmer Inc., Boston, Massachusetts, USA), and Y chromosome was detected with a Cy5-labeled pY35316 RNA probe using the tyramide signal amplification system. DAPI counterstaining identified cell nuclei. Fluorescence emission images were obtained with a confocal microscope system and collected with a C-Apochromat (1.2 NA) water lens (Carl Zeiss Inc., Thornwood, New York, USA). For conventional fluo-



rescence microscopy, samples were viewed using a fluorescence microscope (Eclipse E800; Nikon Inc., Melville, New York, USA). A minimum of 100 cells was scored for each slide.

**Serum and arterial cytokine concentrations.** We measured the concentration of serum cytokines using a mouse SearchLight proteome array (Pierce Biotechnology Inc., Rockford, Illinois, USA).

**CFC assay.** CFC frequency was measured by standard protocol (37).

**Statistical analysis.** Experimental data were analyzed by ANOVA followed by Dunn correction or unpaired two-tailed *t* test. Results are expressed as mean ± SEM.

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