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**Commentary**

Vascularized organ transplants often fail because of smooth muscle cell migration and proliferation in the intima of graft arteries, leading to progressive lumenal narrowing and resultant ischemic damage. Graft arterial disease is caused by IFN-γ secreted by alloreactive T cells. New evidence indicates that IFN-γ dysregulates expression of the enzymes eNOS and iNOS in graft-infiltrating leukocytes. Dysregulated NO synthase expression occurs prior to and is causally linked to intimal smooth muscle cell accumulation.

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The link between IFN-γ and allograft arteriopathy: is the answer NO?

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Vascularized organ transplants often fail because of smooth muscle cell migration and proliferation in the intima of graft arteries, leading to progressive lumenal narrowing and resultant ischemic damage. Graft arterial disease is caused by IFN-γ secreted by alloreactive T cells. New evidence indicates that IFN-γ dysregulates expression of the enzymes eNOS and iNOS in graft-infiltrating leukocytes (see the related article beginning on page 846). Dysregulated NO synthase expression occurs prior to and is causally linked to intimal smooth muscle cell accumulation.

Graft arteriosclerosis is the major cause of late allograft failure. Pathologic features include arterial intimal hyperplasia due to recruitment and proliferation of smooth muscle cells (SMCs), which eventually causes lumenal obstruction and allograft ischemia (Figure 1, A and B). Although the mechanisms underlying graft arteriosclerosis are not well understood, the condition most likely results from a form of ongoing immune rejection, and most evidence suggests critical dependence on host T cell alloantigen recognition (1). Nevertheless, graft arteriosclerosis is resistant to standard immunosuppressive therapies. Of a plethora of candidate effector molecules, IFN-γ—a proinflammatory cytokine produced by effector T cells—has long been suspected of being a major player in graft arteriosclerosis.

IFN-γ causes graft arterial disease
To dissect the molecular mechanisms underlying this process, in vivo models that recapitulate the changes observed following human organ transplants have been developed; indeed, murine cardiac allografts develop arterial changes pathologically identical to the human disease. Using this model, arteriopathy does not develop in allografts transplanted into IFN-γ-deficient hosts or after treatment with anti–IFN-γ; this finding provided the first direct evidence that IFN-γ is necessary to induce graft arteriosclerosis (2–4). However, the relevance of findings in a mouse model to human arteriopathy must be weighed in light of known interspecies differences in vascular cell phenotype and function, including those in endothelial cells (ECs) and SMCs (5).

Jordan Pober and colleagues previously addressed the issue of species differences using a model of graft arterial disease involving human arterial segments interposed in the infrarenal aorta of lymphocyte and NK cell–deficient (SCID/beige) mice (6–8). These arterial xenografts remain histologically normal in the immunodeficient host mice. However, if human IFN-γ is administered, intimal thickening occurs as a result of SMC accumulation. Because the host mice are immunodeficient and murine cytokines do not have biological activity on human cells, the results indicate that IFN-γ is also sufficient to induce graft arterial disease. Moreover, human arterial grafts in SCID/beige hosts injected with allogeneic PBMCs also develop arteriopathy, associated with human IFN-γ–expressing T cell infiltrates. Administering anti–IFN-γ reduces the intimal thickening caused by PBMC injection (6–8).

NO and arterial dysfunction
Although the data from murine allograft and xenograft models clearly establishes a central role for IFN-γ in graft arterial disease, the pathologic mechanisms downstream of IFN-γ are not clear. One possibility is that IFN-γ dysregulates vascular wall production of and response to NO (9, 10). ECs synthesize NO from L-arginine via constitutively expressed eNOS; leukocytes can synthesize NO through iNOS. Induction of vasodilation (through vascular SMC relaxation) is one of the principal roles of NO synthesized by ECs. However, NO does have other activities related to vascular wall function including inhibiting SMC proliferation and reducing platelet and leukocyte adhesion (11).

Dysregulated eNOS production—reflecting a more global EC dysfunction—can be assessed by measuring the vasomotor responsiveness of arteries to eNOS-dependent vasodilators. EC dysfunction is implicated in atherosclerosis and graft arteriosclerosis. In addition, failure of SMCs to relax in response to NO (SMC dysfunction) is also implicated in graft arteriosclerosis. Since both IFN-γ and dysregulation of NO responses are associated with graft arterial disease, a logical question to ask is whether IFN-γ is the cause of EC and vascular SMC dysfunction. In a report by Pober, Koh, and colleagues in this issue of the JCI, elegant experiments that establish this causal link are described (12).
IFN-\(\gamma\) dysregulates graft arterial eNOS and iNOS expression

Pober and colleagues again turn to the human-to-mouse arterial interposition graft model. They show that 7–9 days after allogeneic PBMC transfer (before intimal thickening can be detected), excised grafts have impaired responses to NO-dependent vasodilators bradykinin and substance P, compared with grafts from mice that did not receive allogeneic PBMCs (12). At that time, SMCs were observed to contract normally in response to prostaglandin \(F_2\alpha\) and relax normally in response to the NO-donor nitroprusside. EC dysfunction persisted for two weeks after PBMC transfer, and at that time, SMC dysfunction was also evidenced by impaired responses to both prostaglandin \(F_2\alpha\) and nitroprusside. These results indicate early vascular graft dysfunction in a model that eventually
develops intimal hyperplasia. Blocking antibodies were employed to demonstrate that IFN-γ is required for PBMC-induced EC and SMC dysfunction.

The Pober group also shows that EC and SMC dysfunction in the grafts correlates with dysregulated NOS expression (12). Consistent with endothelial dysfunction, eNOS mRNA was reduced, but, unexpectedly, iNOS expression was increased. Immunohistochemical data suggest that iNOS is expressed by infiltrating human T cells. Anti-IFN-γ also blocked the PBMC-induced changes in eNOS and iNOS expression. A causal link between iNOS expression and SMC dysfunction was demonstrated using 1400W, a specific iNOS expression and SMC dysfunction. A causal link between the PBMC-induced changes in eNOS and the downregulation of eNOS by CD4+ T cells in vitro, we do not know if EC dysfunction is necessary for subsequent SMC dysfunction or intimal hyperplasia. Recent data indicate that intimal smooth muscle cell accumulation after mechanical arterial injury is also enhanced by T lymphocytes (15). In light of the findings of the Pober study, it will be of great interest to examine the INF-γ-NO link in the setting of mechanical injury as well as in other forms of vascular disease.

Caution is warranted in extrapolating the findings from the arterial graft model to graft arteriopathy in intact organ transplants since alloresponses in the parenchyma may well contribute to the vascular disease. Finally, it is important to acknowledge that IFN-γ has many biological effects on the vessel wall. Some are proinflammatory, such as upregulation of endothelial adhesion molecules (5), while others are anti-inflammatory, such as induction of negative regulators of T cell activation (16, 17). In mouse allograft models, the absence of IFN-γ significantly enhances acute rejection (18, 19). Therefore, therapeutically targeting IFN-γ to prevent dysregulated NO production may have unintended consequences.

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