

**Vascular cell adhesion molecule-1 and smooth muscle cell activation during atherogenesis.**

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**Editorial**

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*Vascular cell adhesion molecule-1: more than an endothelial-leukocyte adhesion molecule*

Initial studies of vascular cell adhesion molecule-1 (VCAM-1) focused on its role in endothelial-leukocyte interactions (1, 2). A member of the immunoglobulin gene superfamily, this transmembrane protein on the surface of endothelial cells interacts with the  $\beta_1$  integrin very late antigen-4 expressed by mononuclear leukocytes (3). In the context of atherosclerosis, this molecule warrants particular interest because of its early and focal expression on endothelial cells just where monocytes first accumulate at the sites of fatty streak formation (4, 5).

The case of VCAM-1 illustrates a general principal that the restriction of expression of a molecule decreases as a function of time that the molecule is studied. Early surveys disclosed VCAM-1 expression not only on endothelium but on follicular dendritic cells in lymph nodes (6). Others reported VCAM-1 expression on skeletal muscle cells and postulated a role for this molecule in myogenesis (7). Elsewhere in this issue, O'Brien et al. report that in human atheroma not only endothelial cells, but certain lesional macrophages and smooth muscle cells also express VCAM-1 (8). In addition, atherogenic diets induce VCAM-1 expression by a subset of intimal smooth muscle cells in experimental atherosclerotic lesions in rabbits (9). Interestingly, although luminal endothelial cells express VCAM-1 within the first week after initiating the atherogenic diet, VCAM-1 expression by intimal smooth muscle cells does not occur until after the sixth week of consumption of the atherogenic diet. A similar sequence may pertain during human atherogenesis as O'Brien et al. find only rare expression of VCAM-1 on luminal endothelial cells at a stage in evolution of the human atherosclerotic lesion when intimal smooth muscle cells often bear this molecule.

O'Brien and colleagues made the additional important observation that the endothelial cells of plaque microvessels also express VCAM-1. Advanced human atheroma contain regions of microvascular plexi that provide a large surface area for macrophage recruitment. Indeed, macrophages colocalize to regions of plaque neovascularization (10). Taken together, these observations support the view that the plaque microvasculature may furnish an important portal for monocyte recruitment during human atherogenesis. Nonetheless, it is premature to conclude that VCAM-1 plays an exclusive or even primary role as a monocyte adhesion molecule during human atherogenesis. VCAM-1 does bind selectively monocytes and lymphocytes, the very types of leukocytes found in atheroma, yet other endothelial leukocyte adhesion molecules (e.g. intercellular adhesion molecule-1, E-selectin) or as yet undiscovered molecules may participate in this interaction.

*VCAM-1 on smooth muscle cells, a molecule in search of a function*

Although it is easy to envisage a role for endothelial VCAM-1 in monocyte recruitment, the function of leukocyte adhesion

molecules on smooth muscle cells within the atherosclerotic plaque seems obscure. Phagocytes and T cells tend to wander, exhibiting more mobility than most parenchymal cells. Perhaps smooth muscle cell VCAM-1 retards the migration of monocytes and T cells, encouraging their more permanent residence within the atherosclerotic plaque. However, VCAM-1 may have functions during atherogenesis unrelated to its adhesion function per se. Increasing evidence points to ongoing immune stimulation during human atherogenesis. While the nature of the antigenic stimulus remains unclear, atheroma contain T lymphocytes in a chronic state of activation (11). While vascular smooth muscle cells stimulate allogeneic immune responses relatively poorly, they present foreign antigens splendidly (12). VCAM-1 in other contexts can provide costimulatory signals for T cell activation (13, 14). Thus, VCAM-1 expression by lesional smooth muscle cells may enhance their ability to stimulate T cells.

*Activation of intimal smooth muscle cells during atherogenesis*

Regardless of its functional consequences, the finding of VCAM-1 in advanced human atherosclerotic plaques and in the maturing experimental atheroma serve as a marker of "activation" of smooth muscle cells. The concept of "phenotypic modulation" of smooth muscle cells during atherogenesis gained currency some years ago (15). The original concept that intimal smooth muscle cells in the atherosclerotic plaque differ from those in the normal tunica media has proven a valuable paradigm over the years. The nomenclature that describes the intimal smooth muscle cells as "synthetic" and the normal medial smooth muscle cells as "contractile" seems less helpful as few actually measure biosynthetic or contractile function when using these terms.

The increasing availability of specific molecular markers permits a more precise definition of the "activated" smooth muscle cell found in the arterial intima during atherosclerosis. Smooth muscle cells in regions of the atherosclerotic plaque express class II histocompatibility antigens, cell surface molecules required for antigen presentation to helper T cells (16). Many cells within the atherosclerotic intima express intercellular adhesion molecule-1, a member of the immunoglobulin superfamily that may also participate in retention of leukocytes (17, 18). Compared with normal medial smooth muscle cells, those in the atherosclerotic intima display increased levels of the complement regulatory decay accelerating factor (19), and genes for certain growth-promoting molecules, including isoforms of platelet-derived growth factor (20) and tumor necrosis factor (21).

*What signals induce smooth muscle activation during atherogenesis?*

In vitro studies have established that cytokines regulate most of these markers of activation expressed by intimal smooth muscle cells. Interestingly, we find that the lymphokines gamma interferon and IL-4, products of activated T cells, induce VCAM-1 expression on human smooth muscle cells, while the monokines IL-1 and tumor necrosis factor, products of activated mononuclear phagocytes and intrinsic vascular cells, do

not (9). These observations raise the intriguing possibility that the signals for VCAM induction in smooth muscle cells during atherogenesis derive from activated T lymphocytes. However, mediators other than cytokines may induce VCAM-1 expression. For example, constituents of modified lipoproteins such as lysophosphatidylcholine can induce VCAM-1 expression by human endothelial cells in culture (22). Other potential stimuli such as hypoxia or glycated proteins have yet to be investigated in this regard.

Despite the advances considered here, we have far to go before achieving a complete understanding of atherogenesis. Fortunately, emerging experimental approaches should permit us to test critically many of the notions proposed above and determine whether VCAM-1 and the other activation markers expressed by smooth muscle cells actually serve the functions that we currently postulate, play no functional role at all, or contribute to lesion evolution in ways not yet imagined.

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