Role of Vascular Cell Adhesion Molecule-1 and Fibronectin Connecting Segment-1 in Monocyte Rolling and Adhesion on Early Atherosclerotic Lesions

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Abstract—Atherosclerotic lesion development seems to be inflammatory in nature and involves the recruitment of monocytes to the vessel wall. In this study, we investigated the role of vascular cell adhesion molecule-1 (VCAM-1) and fibronectin (FN) connecting segment-1 containing the amino acid sequence ILDV as functional ligands for $\alpha_\beta_1$ integrin (VLA-4) in monocyte rolling and adherence to early atherosclerotic lesions. Carotid arteries of apolipoprotein E–deficient mice were isolated and perfused with monocytes or U937 cells. Cell adhesion was reduced 95±4% by monoclonal antibodies HP1/2 and HP2/1, which block VLA-4 binding to both VCAM-1 and FN connecting segment-1. mAb HP1/3 preferentially blocked interaction of VLA-4 with FN but not VCAM-1 and decreased adhesion by 30±8%. In contrast, blocking VCAM-1 by perfusing the isolated carotid artery with mAb MK-2.7 reduced adhesion by 75±12%. Mononuclear cell adhesion to the early atherosclerotic endothelium was inhibited by 68±10% in the presence of EILDVPST but not in the presence of control peptide EIDVLPST. When VLA-4 or VCAM-1 was blocked, more mononuclear cells rolled on early lesions at significantly higher (approximately doubled) rolling velocities. These data demonstrate that (1) blockade of VCAM-1 can abrogate the majority (75±12%) of VLA-4–dependent monocyte adhesion on early atherosclerotic endothelia and (2) ILDV peptide interferes with VLA-4 binding to both VCAM-1 and FN and may be useful in limiting monocyte adhesion to atherosclerotic lesions. (Circ Res. 2000;87:153-159.)

Key Words: atherosclerosis • monocyte • fibronectin • connecting segment-1 • vascular cell adhesion molecule-1

The development of an atherosclerotic lesion requires a complex interplay between mononuclear cells, endothelia, vascular smooth muscle cells, growth factors, and cytokines.1 An established atherosclerotic lesion forms through a sequence from fatty streak to fibrofatty matrix and fibrous plaque.2 During this series of stages, monocyte rolling and adhesion to the vascular endothelial lining and subsequent diapedesis are not only the first steps, but also seem to be crucial events in the pathological process.3 The importance of monocyte recruitment to the endothelium of a lesion area is supported by several recent studies. In these studies, formation of atherosclerotic lesions was found to be significantly decreased in mutant mice that do not express macrophage colony-stimulating factors,4 monocyte chemoattractant protein-1,5 monocyte chemoattractant protein-1 receptors,6,7 or interleukin-8 receptors.8 Other mutant mice that do not express one or two adhesion molecules contributing to monocyte recruitment, such as P-selectin, E-selectin, or intercellular cell adhesion molecule-1 (ICAM-1),9–12 can form atherosclerotic lesions, but they do so at a reduced degree compared with wild-type mice. At least 4 families of adhesion molecules, selectins, selectin ligands, integrins, and immunoglobulin-like molecules have been shown to contribute to the interaction of leukocytes with the endothelium. For monocytes, $\alpha_\beta_1$ integrin (VLA-4) is a major ligand mediating rolling and firm adhesion of monocytes to the endothelium.13 In vitro studies14 and our previous study in the isolated perfused carotid artery of apolipoprotein E–deficient (apoE−/−) mice have defined a role of VLA-4 in mononuclear cell rolling on the endothelium.

There are 2 known ligands for VLA-4. VLA-4 binds to sites within the first and forth immunoglobulin-like domains of the full-length 7-domain form of vascular cell adhesion molecule-1 (VCAM-1).15 VCAM-1 is highly expressed on endothelia prone to develop atherosclerosis in such atherosclerotic models as apoE−/− mice, LDL receptor–deficient mice (LDLR−/−), mice, and rabbits fed with an atherogenic diet.16–19 Another ligand for VLA-4 is fibronectin (FN). VLA-4 recognizes a motif containing the sequence EILDVPST within the alternatively spliced connecting segment-1 (CS-1) region of FN,20 with the LDV sequence being most critical.21 Although FN serves mainly as an extracellular matrix component, recently it has been shown that FN CS-1 expression is increased on cultured endothelial cells activated with minimally modified LDL and on the atherosclerotic...
endothelium of human coronary arteries. In a reconstituted in vitro system, isolated VCAM-1, but not FN, coated on the lower wall of a flow chamber can support VLA-4-dependent cell adhesion under flow conditions.

The binding sites on VLA-4 for VCAM-1 and FN are very close to each other or overlapping, but they have some functional differences. For example, VLA-4 interaction with VCAM-1 is supported by calcium ions but VLA-4 interaction with FN is not. Some antibodies preferentially inhibit only the adhesive interaction between VLA-4 and FN. Antibody cross-blocking and competitive binding studies show that the two binding sites overlap but are not identical. An alternative interpretation of these results is that the VCAM-1 and FN binding sites may indeed be identical, but the binding affinity of VLA-4 for FN could be lower. In either case, mAb HP1/3 is a useful reagent to preferentially block cell binding to FN. Short peptides from the CS-1 region of FN have been used to block leukocyte-endothelium interactions and diminish VLA-4-dependent inflammatory reactions and formation of atherosclerotic lesions.

Although some data suggest an involvement of FN CS-1 in the development of atherosclerosis, it is unclear whether FN CS-1 serves as a functional ligand for VLA-4 and is important for monocyte rolling and adhesion in atherosclerotic lesions. Moreover, the functional role of VCAM-1 in firm adhesion is uncertain. In the present study, we used isolated carotid arteries from apoe−/− mice. These mice develop spontaneous atherosclerotic lesions in the arterial vasculature, with advanced lesions morphologically similar to those seen in humans. We perfused the mice ex vivo to study the molecular basis of mononuclear cell adhesion to early atherosclerotic endothelium. In a previous study, we showed that mononuclear cell rolling in the apoe−/− atherosclerosis-prone mouse strains is largely P-selectin- and PSGL-1-dependent. Here, we used specific function-blocking monoclonal antibodies against VCAM-1, FN binding site of VLA-4, and ILDV peptides to directly demonstrate the roles of VCAM-1 and FN CS-1 in monocyte rolling and adhesion on early atherosclerotic lesions.

Materials and Methods

Monoclonal Antibodies and Peptides

HP1/3 (anti-α4 epitope A, blocking FN binding to VLA-4), HP2/1 and HP1/2 (anti-α4 epitope B, blocking both FN and VCAM-1 binding to VLA-4), Lia (anti-α4, nonblocking) were gifts from Dr Sanchez (Universidad Autonoma de Madrid, Madrid, Spain). mAb MK-2.7 (rat anti-mouse VCAM-1 IgG1, ATCC) was purified from hybridoma supernatants. CS-1 peptide, EILDVPST, and EIDVLPST are affinity purified peptide reagents to preferentially block cell binding to FN.

Monoclonal antibodies against VCAM-1, FN binding site of VLA-4, and ILDV peptides were used to block leukocyte-endothelium interactions and diminish VLA-4-dependent inflammatory reactions and formation of atherosclerotic lesions.

Statistical Analysis

Rolling flux and the number of adherent cells are mean±SEM. Comparisons between groups were performed by using a two-way ANOVA, followed by analysis using the Tukey-Kramer multiple comparison test. The rolling velocity distributions were compared using the Mann-Whitney U test. All statistical analysis was performed with the NCSS software package.

Results

Rolling and adhesion of mononuclear cells (U937) and monocytes were investigated under flow conditions (3 dyne/cm2) in carotid arteries obtained from apoe−/− mice fed a Western diet for 4 to 6 weeks. Rolling in this model requires interaction of endothelial P-selectin with PSGL-1 expressed on the monocyte surface.

Immunohistochemistry

VCAM-1 and ICAM-1 expression was determined on paraffin sections (5 μm thick) of murine common carotid artery blocked with 10% horse serum (Vector Laboratories) and incubated with primary antibody (polyclonal goat antimouse VCAM-1 or polyclonal goat antimouse ICAM-1, 5 μg/mL, Santa Cruz Biotechnology, Inc) overnight at 4°C followed by biotin-conjugated horse antigen antibody, avidin-biotin complex, and 3, 3′-diaminobenzidine as substrate (Vector Laboratories).

Cellular markers

The human monocytic cell line U937 (stably transfected with human L-selectin [gift from Dr G.S. Kansas, Northwestern University, Evanston, Ill]) was maintained in RPMI-1640 supplemented with 10% FBS (Atlanta Biologicals), glutamine (2 mmol/L), penicillin (100 U/mL), and streptomycin (100 μg/mL) (Gibco BRL).

Human blood monocytes were isolated from leukocyte-rich plasma obtained from healthy donors using hypotonic NaCOprep 1.068 density gradient centrifugation (Nycomed). Platelets were removed by centrifugation of the monocyte suspension at 300g, yielding pure (>90%), unactivated monocytes.

Animals

Male homozygous apoe−/− mice were from at least a fifth generation backcross onto a C57BL/6J background and obtained from Jackson Laboratory (Bar Harbor, Maine). At 6 weeks of age, mice were placed on a Western-type diet (21% fat, 0.15% cholesterol wt/wt). At Teklad Adjusted Calories Diet TD 88137, Harlan Teklad) for 4 to 5 weeks. As previously described, the carotid artery was perfused with heparinized MOPS-buffered physiological salt solution supplemented with 1% human serum albumin at 10 μL/min, resulting in a perfusion pressure of 30 to 60 mm Hg and a wall shear stress of 3.0±0.1 dyne/cm2. U937 cells or monocytes labeled with calcein AM were infused at 3×106 cells/mL. To block VCAM-1, carotid arteries were perfused with 1 mL of a 40 to 50 μg/mL mAb MK-2.7 solution for 10 to 15 minutes. Cell rolling and adhesion were recorded on videotape using stroboscopic epifluorescence illumination with an intravital microscope. At the end of each experiment, endothelial integrity of the isolated carotid artery was assessed by Evans Blue staining.

Flow Cytometry

U937 cells at 3×106 cells/mL were stained by monoclonal antibodies (mAbs) at different dilutions for 30 minutes at room temperature, washed twice, incubated with antimouse FITC-IgG, fixed in 1% paraformaldehyde and PBS, and analyzed by flow cytometry on a FACScan (Becton Dickinson).

Expression of Adhesion Molecules

Carotid arteries harvested from apoe−/− mice expressed VCAM-1 and ICAM-1 along the endothelial lining but not in the media or adventitia (data not shown). This confirms recent data obtained by Nakashima et al. The intima and media did not contain significant numbers of macrophages, as shown by insignificant staining for the macrophage marker F4/80 (data not shown). Age-matched C57BL/6 mice did not show expression of either ICAM-1 or VCAM-1 (data not shown). These findings suggest that expression of endothelial
ICAM-1 and VCAM-1 reflects the earliest changes in the endothelial lining before the development of atherosclerotic lesions.

The U937 cells used in this study expressed significant amounts of \( \alpha_4 \) integrins (Figure 1). Saturation of binding sites for mAbs Lia, HP1/2, and HP1/3, all recognizing \( \alpha_4 \), were achieved at a concentration of 1:100 (Figure 1), and this concentration was used for all function-blocking experiments. We also found expression of LFA-1, Mac-1, and the common \( \beta \) chain, CD18, expressed on U937 cells (Figure 1).

Mononuclear Cell Adhesion Under Flow

In a previous study, we showed that U937 cells do not roll or adhere in carotid arteries obtained from wild-type C57BL/6 mice fed a chow diet. In carotid arteries from apoE\(^{-/-} \) mice fed a Western diet, U937 cell rolling and adhesion under flow require P-selectin and PSGL-1. Monocytes or U937 cells accumulated around the bifurcation area (Figure 2), which represents a known lesion-prone site in apoE\(^{-/-} \) mice, as described earlier. Incubation of U937 cells with mAb HP1/2 to VLA-4 integrin almost completely abrogated their accumulation on the lesion-prone endothelium (Figure 2). The number of adherent cells was sharply reduced at the end of a 5-minute period of perfusion when treated with mAb HP1/2 to VLA-4 or mAb MK-2.7 to VCAM-1 but not when treated with control antibodies (Figure 3). To investigate the dynamics of mononuclear cell adhesion, we recorded cell accumulation during each minute after the onset of cell perfusion for 5 minutes (Figure 4).
lated perfused carotid artery is almost completely dependent on VLA-4 integrin, which binds mostly (70% to 80%) to VCAM-1 and shows a small but consistent (20% to 30%) contribution of alternatively spliced FN.

Impact of VLA-4 and Its Ligands on Rolling Flux and Velocity

In a previous study, we showed that blocking either VLA-4 integrin or VCAM-1 increased rolling velocities to a similar extent. The impact of these molecules on rolling flux was still unclear, because blockade of VLA-4 integrin reduced rolling flux in carotid arteries of wild-type C57BL/6 mice fed a Western-type diet but increased rolling flux in carotid arteries from apoE−/− mice under the same conditions. Therefore, we reexamined the role of VLA-4 integrin and VCAM-1 more thoroughly.

All manipulations blocking VLA-4 or VCAM-1, mAb HP2/1, mAb MK-2.7, or LDV peptide, but not mAb HP1/3s blocking αL integrins binding to CS-1 peptides only, caused a significant increase in the number of rolling U937 cells (Figure 6). We confirmed that this rolling was P-selectin- and PSGL-1–dependent (data not shown). The increased rolling flux after blockade of αL, or VCAM-1 was probably a direct consequence of the reduced number of adherent cells. This can be seen by comparing the numbers in Figure 6 with the accumulation numbers in Figure 4, which suggests that the cells that cannot adhere when VLA-4 or VCAM-1 is blocked continue to roll.

We confirmed that blocking VLA-4 by mAb HP1/2 or blocking VCAM-1 by mAb MK-2.7 significantly elevated the velocity of rolling mononuclear cells in this model (Figure 7), elevating mean rolling velocity from 106 ± 52 μm/s to 293 ± 86 μm/s and 227 ± 77 μm/s, respectively (P < 0.01). Treating the U937 cells with HP1/3 also caused a small increase in rolling velocity, from 106 ± 52 to 135 ± 49 μm/s (P < 0.01). We extended these findings by investigating the impact of FN-derived peptides. LDV-containing peptides also significantly elevated rolling velocity (Figure 7), whereas the...
control peptide containing the inverted sequence, DVL, had no effect.

**Discussion**

Our data show that U937 cell adhesion to carotid arteries isolated from atherosclerosis-prone mice before the development of manifest lesions is mediated by VLA-4 binding to VCAM-1, with a minor contribution of alternatively spliced FN as an alternative VLA-4 ligand. This functional finding is supported by morphological demonstration of VCAM-1 expression on sites prone to develop lesions but not on normal endothelium.

Several studies have shown VCAM-1 expression on endothelia at atherosclerotic lesions of humans, mice, and rabbits; however, functional data are limited. Adhesion assays using cultured endothelial cells activated by cytokine treatment showed a major contribution of VCAM-1 to monocyte adhesion. This is in contrast to findings in cultured endothelial cells treated with minimally oxidized LDL and specific oxidized lipids, where almost all monocyte adhesion was mediated by alternatively spliced FN, and VCAM-1 was not expressed at significant levels. This apparent discrepancy is most likely due to differences in the models used. First, cultured endothelial cells are known to be much more permeable to solutes than endothelia in situ. Specifically, significant gaps exist between cultured endothelial cells, through which extracellular matrix material containing FN may be exposed to the luminal surface. The lack of VCAM-1 expression in endothelial cells treated with oxidized LDL and the presence of VCAM-1 on the endothelial surface of carotid arteries obtained from atherosclerosis-prone mice suggest that the treatment with oxidized LDL may only incompletely mimic the pathophysiological process of endothelial activation in atherosclerosis in vivo. In atherosclerotic lesions, both cytokines and

![Figure 6. Effect of blocking VLA-4 (HP1/2), VCAM-1 (MK-2.7), and CS-1 peptide (ILDV) on rolling flux of U937 cells under continuous flow at 3 dyne/cm² in carotid arteries of apoE⁻/⁻ mice fed a Western-type diet for 4 to 6 weeks. Compared with the control group treated with the nonblocking mAb (Lia), the number of rolling cells was significantly increased by mAbs MK-2.7, HP1/2, and ILDV peptide. *P<0.01. Data are mean±SEM of at least 4 experiments per group.](image)

![Figure 7. Increase of rolling velocity after blocking VLA-4 (HP1/3) or VCAM-1 (MK-2.7) or after infusing CS-1 peptide (ILDV). Rolling velocities of U937 cells under continuous flow at 3 dyne/cm² in carotid arteries of apoE⁻/⁻ mice fed a Western-type diet for 4 to 6 weeks. Treating U937 cells with HP1/3 slightly increased the rolling velocity, and nonblocking mAb Lia and control peptide IDVL had no effect. N=4 vessels, n=80 rolling cells per histogram. Arrows indicate mean rolling velocity in each group.](image)
chemokines have been detected in addition to oxidized lipoproteins. The profile of adhesion molecule expression in our model is likely to result from a combination of these and other potential factors.

The crucial roles of VLA-4 and VCAM-1 demonstrated in our ex vivo model are supported by in vivo expression data and peptide-based in vivo experiments. Gene-targeting experiments showing the importance of VLA-4 and VCAM-1 for atherosclerotic lesion development have been hampered by the unavailability of appropriate knockout mice. Null mutations for VCAM-1 and FN all lead to embryonic lethality so that no adult mice are available to study the impact of these molecules on atherosclerosis. Recently, a VCAM-1 hypomorph mouse has been developed, which holds promise for additional clarification of the role of VCAM-1 for atherosclerosis in vivo (H. Li, M. Chen, M. Liyama, J.-C. Gutierrez-Ramous, D.S. Milstone, M.I. Cybulsky, unpublished data). Cell-specific and inducible strategies have been developed that seem able to eliminate VLA-1 only in endothelial cells or eliminate VLA-4 only in monocyte macrophages; however, these strategies have met with significant technical problems, and no informative gene-targeted mice with conditional mutations in VLA-4 or VCAM-1 are available at this time.

In conclusion, our study links expression of VCAM-1 in early atherosclerotic lesions and the shoulder region of established atherosclerotic lesions to a crucial function in mononuclear cell adhesion and accumulation. This link provides a mechanistic basis for understanding the ability of LDV-containing peptides to curb the development of atherosclerotic lesions in animal models. Our study suggests that interfering with VLA-4 binding to VCAM-1 prevents the adhesion of monocytes with the vascular endothelium under flow conditions typical of recirculation zones and zones of disturbed flow where atherosclerotic lesions develop in vivo. These findings strengthen the rationale for the development of therapies aimed at inhibiting the interaction between VLA-4 and VCAM-1 to prevent the development of atherosclerotic lesions and their complications.

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References


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