ROLE OF LFA-1 AND VLA-4 IN THE ADHESION OF CLONED NORMAL AND LFA-1 (CD11/CD18)-DEFICIENT T CELLS TO CULTURED ENDOTHELIAL CELLS

Indication for a New Adhesion Pathway

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Patients with the leukocyte adhesion deficiency (LAD) syndrome have a genetic defect in the common β2-chain (CD18) of the leukocyte integrins. This defect can result in the absence of cell surface expression of all three members of the leukocyte integrins. We investigated the capacity of T cell clones obtained from the blood of a LAD patient and of normal T cell clones to adhere to human umbilical vein endothelial cells (EC). Adhesion of the number of LAD T cells to unstimulated EC was approximately half of that of leukocyte function-associated antigen (LFA)-1+ T cells. Stimulation of EC with human rTNF-α resulted in an average 2- and 2.5-fold increase in adhesion of LFA-1+ and LFA-1− cells, respectively. This effect was maximal after 24 h and lasted for 48 to 72 h. The involvement of surface structures known to participate in cell adhesion (integrins, CD44) was tested by blocking studies with mAb directed against these structures. Adhesion of LFA-1+ T cells to unstimulated EC was inhibited (average inhibition of 58%) with mAb to CD11a or CD18. Considerably less inhibition of adhesion occurred with mAb to CD11a or CD18 (average inhibition, 20%) when LFA-1+ T cells were incubated with rTNF-α-stimulated EC. The adhesion of LFA-1− cells to EC stimulated with rTNF-α, but not to unstimulated EC, was inhibited (average inhibition, 56%) by incubation with a mAb directed to very late antigen (VLA)-4 (CDw49d). In contrast to LAD T cell clones and the LFA-1+ T cell line Jurkat, mAb to VLA-4 did not inhibit adhesion of normal LFA-1+ T cell clones to EC, whether or not the EC had been stimulated with rTNF-α. We conclude that the adhesion molecule pair LFA-1/intercellular adhesion molecule (ICAM)-1 plays a major role in the adhesion of LFA-1+ T cell clones derived from normal individuals to unstimulated EC. Adhesion of LFA-1− T cells to TNF-α-stimulated EC is mediated by VLA-4/vascular cell adhesion molecule (VCAM)-1 interactions. Since we were unable to reduce significantly the adhesion of cultured normal LFA-1+ T cells to 24 h with TNF-α-stimulated endothelium with antibodies that block LFA-1/ICAM-1 or VLA-4/VCAM-1 interactions, and lectin adhesion molecule-1 and endothelial leukocyte adhesion molecule-1 appeared not to be implicated, other as yet undefined cell surface structures are likely to participate in T cell/EC interactions.

Lymphocyte traffic allows continuous immune surveillance of the body. In secondary lymphoid organs including lymph nodes, tonsils, adenoids, Peyer's patches, appendix, and mucosa-associated lymphoid tissues leukocyte extravasation occurs predominantly in specialized postcapillary venules which are lined by high endothelium (see Reference 1 for review). Some of the adhesive properties of high endothelium in inflamed tissue can be mimicked by exposing cultured human umbilical vein EC5 to cytokines such as TNF-α (2, 3), IL-1 (2, 3), or LPS (2). In man, leukocyte/EC interactions may therefore be studied with cytokine-treated allogeneic cultured umbilical vein EC.

Several sets of adhesion molecules, e.g., the ligand/receptor pairs leukocyte function-associated antigen (LFA)-1 intercellular adhesion molecule (ICAM)-1 (4), LFA-1/ICAM-2 (5), very late antigen (VLA)-4 vascular cell adhesion molecule (VCAM)-1 (6, 7), the lymphocyte homing receptor lectin adhesion molecule (LECAM)-1 (8, 9), endothelial leukocyte adhesion molecule (ELAM)-1 (10, 11), and the endothelial granule membrane protein-140 molecule (12) are involved in the antigen-independent interaction of EC and leukocytes. The human counterstructures of the last three molecules are as yet partly characterized (13). LFA-1 integrin expression on T cells from normal individuals strongly contributes to binding of these cells to their counterstructures on EC (11, 14, 15).

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5 Abbreviations used in this paper: EC, endothelial cell; PBS-BSA, PBS containing 0.01% CaCl2, 0.01% MgCl2 and 0.25% BSA; LFA, leukocyte function-associated antigen; ICAM, intercellular adhesion molecule; VCAM-1, vascular cell adhesion molecule-1; ELAM-1, endothelial leukocyte adhesion molecule-1; VLA, very late antigen; LAD, leukocyte adhesion deficiency; HEV, high endothelial venule; ECGF, endothelial cell growth factor.
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15), thereby velling the possible involvement of other molecules in the leukocyte/EC interaction. Therefore, in this study we investigated the adhesive properties of LFA-1+ T cells derived from a patient with leukocyte adhesion deficiency (LAD) to determine the contribution of other cell surface molecules in T cell/EC interactions. Complexes of α and β precursors of leukocyte integrins are required for processing and transport to the cell surface (16). We generated T cell clones from peripheral blood of a patient with LAD whose leukocytes completely lack cell surface expression of the three leukocyte integrin molecules LFA-1, Mac-1, and p150,95 as a result of the incapability of the cells to produce mRNA coding for the β2 subunit of the leukocyte integrins. Such patients suffer from life-threatening recurrent bacterial infections and persistent neutrophilia. The impaired granulocyte-monocyte function caused by this defect is demonstrated by the failure of migration and adhesion of the polymorphonuclear leukocytes. LAD patients, however, have shown no clinical manifestation of defects in T cell or NK cell functions, suggesting that other adhesion pathways could be effectively utilized in lymphocytes in vivo to compensate for CD11/CD18 deficiency in these cells (17).

In this study we have characterized cell surface molecules that are involved in the adhesion of cytotoxic and noncytotoxic CD4+ and cytotoxic CD8+ T cell clones from both normal individuals and an LAD patient. The results demonstrate that the LFA-1/ICAM-1 interaction predominately mediates binding of T cells from healthy individuals to unstimulated endothelium and that VLA-4/VCAM-1 Interaction plays a major role in the binding of T cells from LFA-1- patients to EC activated for 24 h by TNF-α.

Materials and Methods

EC. Human EC were isolated from umbilical vein by collagenase digestion (18). The cells were cultured in 0.2% gelatin-coated 75-cm² flasks (3275, Costar, Cambridge, MA) in M199 (Flow Laboratories, Irvine, Scotland) in the presence of penicillin and streptomycin (GIBCO Europe, Paisley, Scotland), 10% heat-inactivated human serum (Central Laboratory of the Blood Transfusion Service, Amsterdam, The Netherlands), bovine serum albumin 10 mg/ml, T-NEC (5 mg/ml, Boehringer Mannheim, FRG), heparin (10 µg/ml, Sigma, St. Louis, MO), BOA (0.25%, fraction V, Boehringer Mannheim), and the ingredients transferrin (0.036%), bovine pancreatin insulin (5 µg/ml), linoleic acid (1 µg/ml), oleic acid (1 µg/ml), and palmitic acid (1 µg/ml), all from Sigma, which have been described as components of a chemically defined medium for generating T cell clones (19). The cells were serially passaged by trypsin treatment. Cells from passages 4 through 7 were used for the experiments. More than 95% of the cells were considered EC as they stained with mAb CLB-RAG-35 to the von Willebrand factor (20) in an immunofluorescence test on acetone-fixed cells grown on fibronectin-coated coverslips.

Cells. The allo-MHC specific cytotoxic T cell clones JS132 (CD8+) and JS136 (CD4+) were from the same individual and have been described previously by Vorst et al. (21). The tetanus toxoid specific T-helper clone HY527 has been described by Yssel et al. (22). The LFA-1-negative T cell clones LAD1, LAD4, LAD6.6, and LAD19 were raised by limiting dilution of PBL from a patient with LAD lacking cell surface expression of the CD18 protein (6). The clones were grown in iscove’s medium (Flow Laboratories) containing 5% heat-inactivated human serum by weekly stimulation with 2 × 10⁶ irradiated algae

Monoclonal antibodies. The mAb used in the adhesion test and their final concentrations are listed in Table I. No differences were observed among antibodies purified from different batches. Additional mAb used for phenotyping T cell clones and EC were obtained from several laboratories: CLB-10G11 (anti-VLA-2, CD49b) (24) and C17 (anti-β2-integrin, CD11b) (45) from A. Sonnenberg, Amsterdam; CLB-1D2 (anti-IL-2R, CD25) (46) from R. van Lier, Amsterdam; CLB-FcR-gran1 (anti-Fc receptor III, CD16) (47) from P. Tetteroo, Amsterdam; CLB-RAG-35 (anti-von Willebrand factor) (20) from J. van Mourik, Amsterdam; ENA-2 (anti-ELAM-1) from J. Leeuwenberg, Maastricht; J143 (anti-VLA-3, CD49c) (48) from E. Klein, Uln; B-6 (anti-p150,95, CD11c) (49) from S. Poppema, Edmonton; TS2/16 (anti-β2-integrin, CD59) (50) from T. Springer, Boston; and B-5401 (anti-VLA-4, CD49d) (51) from M. Hemler, Boston. Leu7-anti-CD11b (anti-CR3, CD15b) was obtained from E. Bearl, Bearl (anti-CR3, CD11b) (27) and HP1/3 (anti-VLA-4, CD49d) (37) have been described previously.

Adhesion Test. Endothelial cells were trypsin treated, and 2 × 10⁴ cells in 100 µl of M199 containing 20% heat-inactivated human serum (but without ECGF, heparin, and the components of chemically defined medium; see above) were seeded into 0.2% gelatin-coated 96-well plates (3596, Costar). After incubation overnight the cells were stimulated with human rTNF-α (supernatant of CD4+ T cells) or PHA for 72 h using the concentranate indicated in the experiments. Before initiation of the adhesion experiment the wells were washed twice with 0.3 ml of sterile PBS-BSA, and the wells were filled with 100 µl of DMEM containing 5 mm HEPES, pH 7.0, and 0.25% BSA. Subsequently, 50 µl containing 5,000 to 10,000 T cells that had been labeled with 51Cr (Na2CrO4, 350 to 600 mCi/mg; Amersham; Buckinghamshire, UK: 0.1 mCi/× 10⁶ cells, followed by washing three times in DMEM) were added. Adhesion was allowed for 30 min at 37°C in the CO2 incubator. Nonadhering cells were removed by washing three times with 0.3 ml of PBS-BSA. The adherent cells were solubilized for 30 min with 50 µl of 0.25% SDS, 1% Triton X-100, 0.5% sodium deoxycholate, and 5 mm EDTA and counted in a gamma counter (Multi-Prias 1, Packard Instrument Co., Downers Grove, IL). Inhibition was calculated according to the formula

% inhibition = \frac{\text{cpm with mAb to test} - \text{cpm with irrelevant control mAb}}{\text{cpm with mAb to test}} × 100.

For inhibition experiments EC and lymphocytes were preincubated with mAb and used without further washing.

Fluorescence analysis. A suspension of EC was obtained by digestion of EC cultures with collagenase (125 U/ml in 137 m NaCl, 4 mg KCl, and 10 mm HEPES, pH 7.0) for 5 min at 37°C. EC and T cells were washed in ice-cold PBS containing 0.25% BSA and 0.02% NaN₃ and suspended to 2 × 10⁶ (EC) or 10 × 10⁶ T lymphocytes) cells/ml. Fifty µl were transferred to 6-mi tubes and incubated for 30 min at 4°C with 50 µl 1/500 diluted mAb containing ascites. The cells were washed 2 ml of PBS containing 0.25% BSA and 0.02% NaN₃ and incubated with 50 µl of affinity-purified goat anti-rabbit IgG (Fab’-conjugated [100 µg/ml antibody]; Zymed, San Francisco, CA). The cells were washed once in PBS containing 0.02% NaN₃ in the presence of 0.25% BSA and once in PBS containing 0.02% NaN₃ in the absence of BSA, fixed in 1.5% paraformaldehyde in PBS, and measured in the FACSscan (Becton and Dickinson, Mountain View, CA). Anti-Chx expression was presented as the mean fluorescence intensity (arbitrary units).

Results

Cell Surface Expression of T Cell Clones and EC

Cells. Analysis of cell surface molecules expressed by the cloned T cell clones JS132, JS136, LAD1, LAD4, LAD6.6, and LAD19 is presented in Table II. No differences were observed between two cytotoxic LAD clones (LAD1 and LAD6.6) (52). P. Van de Wiel-Van Kemenade, unpublished observations) and two non-cytotoxic LAD clones (LAD4 and LAD19). Furthermore, LFA-1- and LFA-1+ T cell clones did not differ significantly in the expression of cell surface molecules other than leukocyte integrins. Notably, all of the T cell clones tested expressed an equal amount of VLA-4, irrespective whether they did or did


9 J. Leeuwenberg, Maastricht. The mAb is directed to a different epitope as ENA-1 (43).
not express the β2-chain of the leukocyte integrins (CD18). A striking feature was that in contrast to granulocytes (feeder cells) and PHA but also after culturing the T cell clones lacked expression of LECAM-1, not only 1 wk after restimulation of the cells with allogeneic lymphocytes and T lymphocytes that had been isolated from peripheral blood by centrifugal elutriation (not shown), (CD18). A striking feature was that in contrast to granulocytes (feeder cells) and PHA but also after culturing the T cell clones lacked expression of LECAM-1, not only 1 wk after restimulation of the cells with allogeneic lymphocytes and T lymphocytes that had been isolated from peripheral blood by centrifugal elutriation (not shown), (CD18). A striking feature was that in contrast to granulocytes (feeder cells) and PHA but also after culturing the T cell clones lacked expression of LECAM-1, not only 1 wk after restimulation of the cells with allogeneic lymphocytes and T lymphocytes that had been isolated from peripheral blood by centrifugal elutriation (not shown), (CD18). A striking feature was that in contrast to granulocytes (feeder cells) and PHA but also after culturing the T cell clones lacked expression of LECAM-1, not only 1 wk after restimulation of the cells with allogeneic lymphocytes and T lymphocytes that had been isolated from peripheral blood by centrifugal elutriation (not shown),

**TABLE I**

<table>
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**TABLE II**

Phenotypic analysis of LFA-1+ and LFA-1+ T cell clones as analyzed in the FACScan.

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* Mean fluorescence intensity: -, < 10; (+), < 20; +, < 50; ++, ≥ 50.

* Rat mAb; others are murine mAb.

* See Footnote 7.

**Comparison of adhesion of T cell clones to EC**

Adhesion of LFA-1+/LFA-1+ T cells. We first investigated the ability of different T cell clones to adhere to both unstimulated and rTNF-α-stimulated EC. Maximal adhesion of both LFA-1+ and LFA-1+ T cells was obtained after stimulation of EC with rTNF-α for 24 h (Fig. 2).
Figure 1. Phenotypic expression of surface molecules on EC as analyzed in the FACScan. EC were stimulated with 100 U/ml rTNF-α for 24 h (-- -- ; unstimulated EC, ----). Relative fluorescence

Figure 2. Adhesion of T cell clones to EC. EC were cultured in the presence of rTNF-α (•, 100 U/ml; A, 200 U/ml) or medium (O, control). JS136 and HY827 are antigen-specific CD4+ LFA-1+ T cell clones; LAD4 and LAD19 are CD4+ LFA-1− T cell clones. The SE bars represent three independent tests within a representative of two experiments. To enable proper comparison, the tests with JS136 and LAD4 were performed simultaneously, as were the tests with HY827 and LAD19.

Although the LFA-1− T cell clones bound to untreated EC in much fewer numbers than the LFA-1+ cells, the LFA-1− and LFA-1+ T cells showed a similar enhancement of adhesion when the EC were pretreated with rTNF-α (Figs. 2 and 3). From these results we conclude that although LFA-1− T cells showed reduced adhesion to EC because of absence of LFA-1/ICAM-1 and LFA-1/ICAM-2 interactions, T cells from LAD patients possess additional molecules that are involved in adhesion to cytokine-stimulated EC.

Cytotoxic/noncytotoxic T cells. No marked differences in adhesion to EC were obtained between the LFA-1+/CD4+ cytotoxic T cell clone JS136 and the tetanus toxoid-specific T helper cell clone HY827 (Fig. 2) or between the LFA-1−/CD4+ cytotoxic T cell clone LAD6.6 compared with the noncytotoxic T cell clones LAD4 and LAD19 (Fig. 3).

CD4/CD8 T cells. Adhesion to EC of the LFA-1+/CD4+ T cell clones JS136 and HY827 was similar to that of the LFA-1+/CD8+ T cell clone JS132. Likewise, adhesion of the LFA-1+/CD4+ T cell clones LAD4, LAD6.6, and LAD19 was similar to that of the LFA-1+/CD8+ T cell clone LAD1 (Fig. 3).

Structures involved in adhesion of T cell clones to EC

To investigate which molecules are responsible for T cell adhesion, we incubated T cells as well as EC with mAb before the adhesion assay. Effects on adhesion to EC of the LFA-1+/CD8+ cytotoxic T cell clone JS132 and the LFA-1−/CD8+ cytotoxic T cell clone LAD1, which, because of considerably slower growth rates than the CD4+ clones, were not available in sufficient amounts, were tested with a limited set of mAb (HLA class I, HLA-DR/DQ, CD3, CD8, LFA-1, p150,95, the β2-chain of the leukocyte integrins, the Hermes-1 Ag (CD44), and the vitronectin receptor). The inhibition of JS132 by mAb was comparable to that obtained with JS136 and HY827. Likewise, the inhibition of adhesion of LAD1 by mAb was comparable with that of LAD4, LAD6.6, and LAD19 (not shown). mAb to VCAM-1 was tested with JS136, HY827, and LAD19 (see below). No difference was noticed whether preincubation of T cells with mAb was performed at 4 or 37°C or whether preincubation of T cells and EC was performed for 30 min vs 60 min (compare Fig. 4 with Figs. 6 and 7, and Fig. 5 with Fig. 6).

LFA-1/ICAM-1. Several groups have reported that the leukocyte integrins play an important role in adhesion to EC. Notably, LFA-1 (CD11a) is involved in adhesion of unstimulated and phorbol dibutyrate-stimulated peripheral T lymphocytes to unstimulated EC (14, 15, 53, 54). In our experiments adhesion of LFA-1− T cell clones to
unstimulated EC was inhibited 58% (mean of 24 experiments) by mAb to the LFA-1 α-chain (CD11a) or the common β3-chain of the leukocyte integrins (CD18) (see also JS136 and HY827 in Figs. 6 through 7). Inhibition of adhesion of LFA-1⁺ T cell clones by mAb to either LFA-1 (CD11a) or CD18 was either much lower or absent when the EC had been stimulated with rTNF-α (Figs. 4 through 7). Results obtained after simultaneous treatment of LFA-1⁺ T cell clones with mAb to CD11a and CD18 were similar to those obtained with treatment with either mAb alone (Fig. 5). With mAb to ICAM-1 (CD54), which is one of the counterstructures of LFA-1 on endothelial cells, inhibition of adhesion of LFA-1⁺ T cells to unstimulated EC was far less (23% inhibition of adhesion; Fig. 4).

Effect of phorbol ester: PMA has been shown to enhance LFA-1-dependent adhesion of T lymphocytes to cultured EC (14, 15, 53, 54). Anti-LFA-1 antibodies inhibited (69% inhibition) the 2.5-fold enhanced adhesion of HY827 cells that had been pretreated with the phorbol ester PMA to unstimulated EC (data not shown). Pretreatment of LFA-1⁺ T cells with PMA had no effect on the adhesion to rTNF-α-stimulated EC. Together, our results with cloned T cells show that LFA-1 is the main structure involved in adhesion of T cells to unstimulated but not to rTNF-α-stimulated EC (24 h) and confirm the finding of others (14, 15, 53, 54) that PMA primarily stimulates LFA-1-dependent adhesion.

Role of VLA-4/VCAM-1. A structure on mouse lymphocytes showing homology with the human VLA-4 molecule is involved in adhesion to Peyer's patches and mucosal HEV (55). Several investigators have reported that in man adhesion of T lymphocytes and some T and B lymphoid cell lines to TNF-α or IL-1-stimulated EC can be inhibited by antibodies both against VLA-4 and its counterstructure on the EC VCAM-1 (6, 41, 54, 56-58). However, in our experiments the binding of LFA-1⁺/CD4⁺ cytotoxic and T helper cell clones JS136 and HY827 to EC was not affected either by anti-VLA-4 or by anti-VCAM-1 antibody, whether or not these EC had been stimulated with rTNF-α (Figs. 4, 6, and 7). Neither did incubation with anti-LFA-1 in the presence of anti-VLA-4 antibodies reduce the adhesion of these LFA-1⁺ T cells to TNF-α-stimulated EC (Fig. 6). This was not because of the anti-VLA-4 antibody used (as much as it was essential in inhibiting (70%) adhesion of the LFA-1-positive/ICAM-1-negative T cell line Jurkat to EC that were stimulated by rTNF-α. Adhesion to rTNF-α-stimulated, but not unstimulated, EC of the cytotoxic (LAD6.6) and the two noncytotoxic (LAD4 and LAD19) CD4⁺ LFA-1⁺ T cell clones tested was inhibited (average inhibition of 56%; mean of 13 experiments) by anti-VLA-4 (Figs. 6 and 7). An inhibition of 33% was obtained with mAb to VCAM-1 (Fig. 4). These results indicate that LFA-1⁺ T cells, like the LFA-1⁺ cell line Jurkat, adhere to rTNF-α-stimulated, but not to unstimulated, EC via the receptor/ligand pair VLA-4/VCAM-1. Since the adhesion of Jurkat cells to EC resembled more that of LFA-1⁺ than that of LFA-1⁺ T cells, the LFA-1 molecules on Jurkat cells are possibly not or not fully, functional.

CD44. The Hermes-1 Ag is mainly involved in binding of PBL to mucosal and synovial lymph node and to a lesser extent to peripheral lymph node HEV (59). Previously, a different mAb (NK1-P1) to this Ag was prepared which also inhibited adhesion of PBL to peripheral lymph
node HEV but at the same time stimulated homotypic aggregation of cells of the EBV-transformed cell line JY (36). In tests with cloned T cells, however, we never observed inhibition of adhesion to (TNF-α-stimulated) EC. Instead, in 6 out of 14 experiments we observed more than 50% increased adhesion of cloned T cells by this mAb to unstimulated EC (Figs. 4 and 5). The increased adhesion was observed with both cytotoxic and noncytotoxic LFA-1* and LFA-1* CD4+ T cell clones and was not dependent on preincubation of the T cells with anti-CD44 at 37°C compared with 4°C. The enhanced adhesion to unstimulated EC was only partially reduced by mAb to CD18 (Fig. 5). There are several explanations for this phenomenon, which will be discussed below.

No marked inhibitory or stimulatory effects on adhesion of the LFA-1* or LFA-1* T cell clones to rTNF-α-stimulated or unstimulated EC were observed with any of the other mAb tested, neither with mAb to CD8 and
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CD4, nor with mAb to LFA-3 and CD2 (Figs. 4 and 5). LFA-3 and CD2 have been shown recently to be involved in EC-augmented IL-2 production in T cells (60). In analogy with the observation with neutrophils (8, 42, 61), the cultured T cell clones probably lose LECAM-1 expression because they are activated during in vitro culturing. In accordance with this finding, no inhibition of adhesion of LFA-1* or LFA-1- T cells to EC was observed with the inhibiting mAb DREG-56 (42) (Fig. 4). ELAM-1, which is implicated in preferential adhesion of memory T lymphocytes to EC in the skin (11, 62), was, as discussed before, also not present any more on the EC after incubation with rTNF-α for 24 h (Fig. 1), and we found no inhibition of adhesion of cloned T cells after incubation of stimulated EC with anti-ELAM-1 mAb (Fig. 7).

**DISCUSSION**

The main points emerging from this study with T cell clones are the following. 1) LFA-1- T cells show reduced adhesion to EC compared with LFA-1+ cells. 2) Stimulation of EC with TNF-α enhances adhesion of LFA-1+ and LFA-1- T cells. 3) Adhesion of LFA-1- T cells to unstimulated EC is LFA-1 dependent. 4) Adhesion of PMA-activated T cells to unstimulated EC is increased and is LFA-1 dependent. 5) VLA-4 mediates adhesion of LFA-1- T cells to TNF-α-stimulated EC but not unstimulated EC. 6) Because VLA-4 does not mediate adhesion of cloned LFA-1+ T cells to TNF-α-stimulated (24 h) EC and because LECAM-1 or ELAM-1 did not contribute to adhesion of these cells, a new, as yet undefined, adhesion structure(s) must exist.

LECAM-1, which is implicated in adhesion of (memory) T cells and neutrophils to peripheral lymph node HEV (8, 9, 42), was not expressed by the T cell clones studied. Preliminary experiments (not shown) show that upon activation with PMA, peripheral T cells lose LECAM-1 expression similarly to what has been described for neutrophils (61). Therefore, LECAM-1 expression is not implicated in T cell adhesion to EC in our study.

LFA-1/ICAM-1 and VLA-4/VCAM-1 interactions have been reported to play a role in adhesion of peripheral blood T lymphocytes to cultured EC (4, 14, 41, 53, 58). In addition, ELAM-1 has been shown recently to mediate adhesion of CD4+ memory cells to 4- to 6-h rIL-1-stimulated EC (41, 54). We have deliberately stimulated the EC for 24 h with rTNF-α because after this period of time maximal adhesion of cloned T cells was obtained (Fig. 2). Preliminary experiments indicate also that after 24 h of stimulation of EC with rIL-1β maximal adhesion of these T cells is obtained (data not shown). However, after this prolonged incubation ELAM-1 is hardly expressed on EC (10, 43), thus excluding a role of ELAM-1 in this study.

VCAM-1 and ICAM-1, the Hermes-1 Ag (CD44), were up-regulated after stimulation of EC with rTNF-α. Our results with T cell clones show that VLA-4/VCAM-1 is an important alternative pathway if LFA-1/ICAM-1 interactions are absent. The data with LFA-1+ T cell clones are in contrast with data obtained with resting or PMA-stimulated peripheral T lymphocytes, their adhesion to activated EC being inhibited by a mixture of mAb to LFA-1 and either VLA-4 or VCAM-1 (7, 41, 54). Therefore, we conclude that cloned T cells, which are cultured in the presence of IL-2 and are strongly activated (63), behave differently. Our data with LFA-1- T cell clones confirm and extend for the greater part those obtained by Haskard et al. (64) and Schwartz et al. (57), who studied adhesion of LFA-1- EBV-transformed B lymphoblastoid cell lines to cultured EC. However, in contrast to the finding by Schwartz et al. (57) we generally observed that adhesion of LFA-1- T cell clones to unstimulated EC could not be inhibited by an antibody to VLA-4α. In our hands unstimulated EC did not express the counterstructure VCAM-1. Possibly differences in culture conditions of EC, notably the presence of xenogeneic serum and ECGF shortly before the adhesion experiment and the presence of serum during the experiments described by Schwartz et al., may have contributed to slight stimulation of EC. We avoided the use of serum during the assay, and 2 days before the assay the EC were deprived of ECGF and heparin. Moreover, we cultured the EC in human serum only. However, in one experiment with LAD4 cells (Fig. 7), in which a particular batch of human serum was used, the EC showed morphologically in culture an elongated appearance similar to TNF-α-activated EC. In this particular case inhibition by anti-VLA-4 can be observed, supporting the notion that particular culture conditions may stimulate VCAM-1 expression.

Recently, Kavanaugh et al. (58) also demonstrated that LAD T cells bind to endothelium by a VLA-4/VCAM-1 dependent mechanism (58). In contrast with their findings, we did not observe VLA-4-mediated binding of LAD T cells to unstimulated EC, but this may be a result of differences in the culture conditions, as discussed above. Furthermore, we observed repeatedly that adhesion of LFA-1+ T cells to EC (except Jurkat, which is discussed below) and to TNF-α-stimulated EC could not significantly be inhibited by VLA-4 or VCAM-1 antibodies even in the presence of anti-LFA-1 or anti-CD18 antibodies. This discrepancy may be a result of differences in the T cell clones used or differences in stimulation of EC (4 vs 24 h). Binding of LFA-1+ T cell clones to stimulated EC is dependent on VLA-4 both in our studies and in those of Kavanaugh.

A low number of Jurkat T cells, which showed a normal expression of LFA-1, adhered to unstimulated EC. In contrast to LFA-1+ T cell clones, the enhanced adhesion of Jurkat T cells to stimulated EC could be inhibited by mAb to VLA-4, similar to what we observed with LFA-1-deficient T cells. These and earlier observations that LFA-1 needs to be activated to enable cell adhesion (65, 66) indicate that the LFA-1 molecules on Jurkat cells might not be activated. Preliminary experiments with mAb NKI-L16 directed against the α-chain of LFA-1, which is able to activate LFA-1 (67), confirm this observation (Y. van Kooyk, unpublished observations).

Stimulation of LFA-1+ T cells by PMA increased adhesion of these cells to unstimulated EC, and this effect was completely LFA-1 dependent. This is in concordance with previous observations (66) and those of others (65), suggesting that LFA-1-dependent adhesion requires activation of LFA-1. In contrast, we repeatedly found that PMA was not able to enhance adhesion of LFA-1+ T cells to TNF-α-stimulated EC despite a much higher ICAM-1 expression on the EC. Similar results have been obtained by Kavanaugh et al. (58) with LFA-1+ T cell clones. This is in contrast to the data obtained with LFA-1+ T lymphocytes from peripheral blood, which, upon activation with phorbol ester, showed enhanced adhesion to IL-1-stimulated EC (14, 53, 54). This enhanced adhesion of phorbol ester-activated LFA-1+ T lymphocytes to IL-1-
These results suggest that phorbol ester-enhanced adhesion of resting LFA-1+ lymphocytes to IL-1-activated EC is also LFA-1 dependent. However, our findings suggest that compared with resting T lymphocytes from peripheral blood, LFA-1+ T cell clones use a different pathway for adhesion to activated EC.

We cannot completely rule out that the VLA-4/VCAM-1 pathway does not play a role in adhesion of the LFA-1+ T cell clones to EC. The possibility exists that an as yet unknown receptor/ligand pair contributes that much to adhesion of cloned T cells to EC that VLA-4/VCAM-1 interaction is obscured. However, other explanations are also possible, such as signals generated after the interaction of LFA-1 with ICAM-1 and/or ICAM-2, which may stimulate other adhesion pathways. A role for CD11b (which is highly expressed on JYS136 cells) in adhesion to activated EC can, however, be excluded since mAb to the β2-subunit of the leukocyte integrins did not inhibit the adhesion of JYS136 or HY8277 to TNF-α-stimulated EC. An additional possibility to be considered is that the LFA-1/VCAM-4-independent component of binding represents adhesion to matrix components that have been secreted upon activation of the EC rather than to an EC ligand. More experiments are necessary to prove this.

In a number of experiments the adhesion of LFA-1+ and LFA-1- T cells to unstimulated and rTNF-α-stimulated EC was markedly influenced by mAb to the herpesvirus Ag (CD44), known to induce homotypic aggregation of the EBV-transformed B cell line JY within 55 min (36). This result may be explained in several ways. Precalculation of T cells with anti-CD44 may have caused T cell aggregation, resulting in a higher number of T cells that bound to EC because of T cell/T cell interactions. However, microscopic examination at the end of the test did not support this possibility. Alternatively, cross-linking by mAb of CD44 molecules on EC and lymphocytes may explain enhanced binding. Finally, analogous to the observations with mAb NK1-L16 to LFA-1 (67), enhanced affinity of the CD44 molecule for its ligand hyaluronate (68) after binding of the antibody to a particular epitope of the CD44 antigen cannot be excluded.

Because adhesion of LFA-1-expressing T cell clones to TNF-α-stimulated EC could not be inhibited significantly by any of the mAb examined, we speculate that the latter adhesion is dependent on a hitherto unknown adhesion molecule.

REFERENCES


