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J Immunol 2001; 167:5708-5718; doi: 10.4049/jimmunol.167.10.5708
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Superantigen-Induced T Cell:B Cell Conjugation Is Mediated by LFA-1 and Requires Signaling Through Lck, But Not ZAP-70

Margaret M. Morgan,* Christine M. Labno,* Gijs A. Van Seventer,2‡ Michael F. Denny,† David B. Straus,†‡ and Janis K. Burkhardt3∗‡

The formation of a conjugate between a T cell and an APC requires the activation of integrins on the T cell surface and remodeling of cytoskeletal elements at the cell-cell contact site via inside-out signaling. The early events in this signaling pathway are not well understood, and may differ from the events involved in adhesion to immobilized ligands. We find that conjugate formation between Jurkat T cells and EBV-B cells presenting superantigen is mediated by LFA-1 and absolutely requires Lck. Mutations in the Lck kinase, Src homology 2 or 3 domains, or the myristoylation site all inhibit conjugation to background levels, and adhesion cannot be restored by the expression of Fyn. However, ZAP-70-deficient cells conjugate normally, indicating that Lck is required for LFA-1-dependent adhesion via other downstream pathways. Several drugs that inhibit T cell adhesion to ICAM-1 immobilized on plastic, including inhibitors of mitogen-activated protein/extracellular signal-related kinase kinase, phosphatidylinositol-3-kinase, and calpain, do not inhibit conjugation. Inhibitors of phospholipase C and protein kinase C block conjugation of both wild-type and ZAP-70-deficient cells, suggesting that a phospholipase C that does not depend on ZAP-70 for its activation is involved. These results are not restricted to Jurkat T cells; Ag-specific primary T cell blasts behave similarly. Although the way in which Lck signals to enhance LFA-1-dependent adhesion is not clear, we find that cells lacking functional Lck fail to recruit F-actin and LFA-1 to the T cell:APC contact site, whereas ZAP-70-deficient cells show a milder phenotype characterized by disorganized actin and LFA-1 at the contact site. The Journal of Immunology, 2001, 167: 5708–5718.

The formation of a conjugate between a T cell and an APC requires the activation of integrins on the T cell surface via inside-out signaling pathways that are not well understood. The cell surface integrins are not constituatively adhesive, but are able to engage their ligands strongly after stimulation through other cell membrane receptors. Th cell adhesion to B cells, monocytes, and other APCs has been shown to occur via two main pathways: CD2 binds to the ligand LFA-3, and the β2 integrin LFA-1 binds to the intracellular adhesion molecules ICAM-1, ICAM-2, and ICAM-3 (1–4). In contrast, T cell adhesion to VCAM-1 and extracellular matrix proteins such as fibronectin is mediated by the β2 integrin subfamily (5).

LFA-1 and CD2 participate in T cell adhesion in distinct ways. The adhesion mediated by CD2 interaction with LFA-3 is present in resting T cells, but becomes more active over a period of hours following T cell activation (4). CD2 ligation can mediate or enhance T cell activation (4), and triggering through CD2 results in the persistent activation of LFA-1 (6). In contrast, LFA-1 binding to ICAMs is transiently up-regulated within minutes of TCR stimulation (2–4). It has been suggested that the CD2 pathway plays a critical role in initiating cell-cell interactions before the engagement of the TCR, and that LFA-1 strengthens the T cell-APC contact following TCR engagement (7).

Activation of both LFA-1 and the β2 integrins in T cells has been the focus of numerous studies; adhesion mediated by both integrins is quickly up-regulated following TCR cross-linking or activation with phorbol esters (2, 6, 8–10). The stimulation through cell surface receptors is thought to produce intracellular second messengers that alter the adhesive state of integrins, a process termed inside-out signaling. This rapid modulation of adhesion is due to an increase in avidity brought about by qualitative rather than quantitative changes in the cell surface expression of integrins (3, 4, 8, 11–13). Evidence suggests that rather than conformational changes being involved, increased adhesion results from the transient release of the integrins from the actin cytoskeleton, allowing them to move more freely in the membrane to find their ligands and to cluster at the cell-cell contact site, where they reassociate with F-actin in an organized adhesion complex (14–16).

Numerous studies have attempted to identify and characterize the inside-out signaling pathways that regulate integrin avidity in T cells and other cell types (reviewed in Refs. 17 and 18). Although the results of these studies are somewhat variable, they have established that signaling through protein kinase C (PKC)4 (2) plays an important role in the activation of adhesion (17). Other

4 Abbreviations used in this paper: PKC, protein kinase C; CMAC, 7-amino-4-chloromethylcoumarin; ERK, extracellular signal-regulated kinase; GEF, guanine exchange factor; GFP, green fluorescent protein; HE, hydroethidine; LAD, leukocyte adhesion deficiency; MAPK, mitogen-activated protein kinase; MEK, mitogen-activated protein kinase; PI3, phosphatidylinositol 3-kinase; PLC, phospholipase C; PTK, protein tyrosine kinase; SEE, staphylococcal enterotoxin E; SF-RPMI, serum-free RPMI 1640; SH, Src homology; Tg, transgenic.

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0022-1767/01/$02.00
late signaling molecules have also been implicated in TCR-induced, LFA-1-mediated adhesion; roles for the Ras/mitogen-activated protein kinase (MAPK) pathway, phosphatidylinositol-3 (PI-3) kinase, calpain, and cytohesin-1 have all been reported (19–23). By comparison with these later signaling requirements, relatively little is known about the proximal signaling events that regulate TCR-activated integrin adhesion.

Many studies of integrin adhesion have used as an experimental model the binding of previously activated T cells to purified ligands immobilized on plastic. Others have examined the interaction between T cells and B cells following T cell activation with PMA or CD3 cross-linking. Because it is now recognized that there are significant differences in T cell responses to Abs and immobilized ligands as opposed to bona fide APCs, we tested the role of early signaling molecules in T-B adhesion without prior activation of the T cells. We developed an assay to study supertantigen-dependent conjugation of Jurkat cells to EBV-B cells, and used the Lck-deficient mutant JCaM1 and the ZAP-70-deficient mutant P116 to ask about the proximal signaling events involved. Our results show that adhesion is largely mediated by LFA-1, and requires Lck and downstream signaling molecules, but is independent of ZAP-70 activity. At least part of the role of Lck in adhesion is to organize actin and LFA-1 at the cell-cell contact site in response to TCR engagement.

Materials and Methods

Abs and reagents

The anti-CD5 mAb OKT3 was purchased from Orthobiotech (Raritan, NJ), and anti-LFA-1 α-chain TS1/22 was obtained from Endogen (Woburn, MA). The anti-LFA-1 β-chain TS1/18, anti-LFA-1 α-chain TS2/4, and anti-class I W6/32 hybridomas were obtained from American Type Culture Collection (Manassas, VA); anti-CD2 Ab 95-549 was a gift from R. Gress (National Cancer Institute, Bethesda MD); and anti-CD29 Ab Lial1/2 was purchased from Becton Dickinson (Mountain View, CA). anti-class I W6/32 hybridomas were obtained from American Type Culture Collection (Manassas, VA); anti-CD2 Ab 95-5-49 was a gift from R. Gress (National Cancer Institute, Bethesda MD); and anti-CD29 Ab Lial1/2 was purchased from Becton Dickinson (Mountain View, CA). The anti-TCR chain c305 has been described (24), and the rabbit anti-mitogen-activated protein/extracellular signal-regulated kinase (ERK) kinase (ERK) kinase 1 (MEK1) was a gift from M. Rosner (University of Chicago, Chicago, IL). Rabbit polyclonal anti-phospho-MEK and anti-phospho-ERK were obtained from New England Biolabs (Beverley, MA), and anti-phosphotyrosine mAb 4G10 was purchased from Upstate Biotechnology (Lake Placid, NY). Purified rICAM-1-Fc protein was supplied by P. Hoffman (ICOS, Bothell, WA). Fcγ-specific goat anti-human IgG was purchased from ICN (Costa Mesa, CA). HRP-conjugated secondary Abs were obtained from Jackson ImmunoResearch (West Grove, PA). Alexa-488-conjugated secondary Abs were purchased from Molecular Probes (Eugene, OR). Partially purified staphylococcal enterotoxin E (SEE) was obtained from Toxin Technology (Sarasota, FL). The p-EGFP actin plasmid was purchased from CLONTECH Laboratories (Palo Alto, CA).

Cell lines and plasmids

Human cell lines were cultured in RPMI 1640 supplemented with 10% heat-inactivated FBS, glutamine, penicillin, and streptomycin (all from Life Technologies, Grand Island, NY) at 37°C for 1 h. B cells were then washed again and resuspended in serum-free RPMI 1640 (SF-RPMI) at 1 × 10^6 cells/ml. Jurkat cells were incubated in RPMI 1640 containing 0.15 μg/ml calcein-AM for 30 min at 37°C, then washed twice with RPMI 1640 and resuspended in SF-RPMI at 1 × 10^6 cells/ml. Jurkat cells were incubated in RPMI 1640 containing 0.15 μg/ml calcein-AM for 30 min at 37°C, then washed twice with RPMI 1640 and resuspended in SF-RPMI at 1 × 10^6 cells/ml. EBV-B cells were then washed again and resuspended in serum-free RPMI 1640 (SF-RPMI) at 1 × 10^6 cells/ml. Just before conjugation, EBV-B cells were pelleted and resuspended in SF-RPMI at 1 × 10^6 cells/ml. Jurkat cells were incubated in RPMI 1640 containing 0.15 μg/ml calcein-AM for 30 min at 37°C, then washed twice with RPMI 1640 and resuspended in SF-RPMI at 1 × 10^6 cells/ml. For conjugation, 0.5 ml of EBV-B cells were combined with 0.5 ml of Jurkat cells in 6-mL polystyrene tubes, and pelleted at 500 rpm for 5 min at room temperature. A total of 0.5 ml supernatant was aspirated from each tube, and the pellets were incubated at 37°C for 10–15 min. The tubes were vortexed for 5–10 s to resuspend the cells, then fixed by the addition of 0.5 μL of PBS/0.6% paraformaldehyde. The relative proportion of red, green, and red/green events in each tube was determined by two-color flow cytometric analysis using a FACS-based conjugation assay.

FACS-based conjugation assay

EBV-B cells were used as the APCs were stained with HE or PKH26. For HE staining, EBV-B cells were incubated in RPMI 1640 containing 3 μg/ml HE at 37°C for 30 min. washed twice with RPMI 1640, then resuspended by co-culture with irradiated splenocytes (2500 rad, 6 × 10^6/well) and 0.15 μg/ml OVA 232–339, peptide in complete medium (DMEM supplemented with 10% heat-inactivated FBS, 100 U/ml penicillin, 100 μg/ml streptomycin, 0.29 mM L-glutamine, nonessential amino acids, 10 mM HEPES, and 5 × 10^-5 M 2-ME). By comparison with these later signaling requirements, relatively little is known about the proximal signaling events that regulate TCR-activated integrin adhesion.

Our results show that adhesion is largely mediated by LFA-1, and requires Lck and downstream signaling molecules, but is independent of ZAP-70 activity. At least part of the role of Lck in adhesion is to organize actin and LFA-1 at the cell-cell contact site in response to TCR engagement.
incubated in RPMI 1640 containing drug for 6 h at 37°C, then labeled by adding calcein-AM to a final concentration of 0.125 μg/ml and incubating another 30 min at 37°C. Cells were then washed and resuspended in SF-RPMI containing the appropriate concentration of LY294002. Unless otherwise indicated, drug concentrations were adjusted upon addition of APCs to maintain the indicated concentrations throughout the conjugation. Where indicated, T cells or B cells were treated with drugs for 30 min before conjugation, washed, and added to conjugation reactions in the absence of additional drug.

Immunoblotting of whole cell lysates

Jurkat cell suspensions (1 × 10^6 cells/ml in PBS or RPMI 1640) were unstimulated, stimulated for 2 min at 37°C with c305, or stimulated for 5 min at 37°C with OKT3. Alternatively, cells were stimulated by conjugation with SEE-coated (or control) EBV-B cells. Cells suspensions of Jurkat and EBV-B cells (2 × 10^6 cells/ml in RPMI 1640) were combined, pelleted at 500 rpm (room temperature), and incubated for 10 min at 37°C. In each case, cells were lysed at 4°C in 1% (v/v) Nonidet P-40, 10 mM Tris (pH 7.8), 150 mM NaCl, 1 mM Pefabloc, 1 mM sodium orthovanadate, 10 mM NaF, 0.5 μg/ml leupeptin, 4 μg/ml aprotinin, 0.5 μg/ml N-tosyl-l-phenylalanine chloromethyl ketone, and 1 μg/ml pepstatin. Debris was removed by centrifugation at 12,500 × g for 10 min at 4°C. Lysates were resolved by SDS-PAGE and transferred to nitrocellulose. Filters were probed with 4G10 anti-phosphotyrosine, anti-phospho-ERK, anti-phospho-MEK, or anti-MEK1.

Results

EBV-B cells were used as the APCs for conjugation with green fluorescent protein (GFP) actin-transfected Jurkat cells, and the LAD B cell line BBN was used as the APCs for LFA-1 immunofluorescence. B cells were stained by incubation in SF-RPMI containing 10 μM CMAC cell tracker blue for 30 min at 37°C, washed, and incubated in RPMI 1640 with or without 2 μg/ml SEE at 37°C for 1.5 h. The cells were then washed and resuspended in SF-RPMI at 10^6 cells/ml. Before use, live GFP actin-transfected Jurkat cells were separated from dead cells by passage over Ficoll, washed, and resuspended in SF-RPMI at 10^6 cells/ml. Conjugations were performed as above, except that after vortexing, cells were pipetted onto poly-l-lysine-coated slides and incubated at 37°C for 5–10 min. Slides were rinsed briefly in PBS and fixed in 3% paraformaldehyde/PBS for 20 min at room temperature. For the GFP actin transfected, slides were dipped in water and mounted (see below).

For LFA-1 immunofluorescence, slides were quenched in 50 mM ammonium chloride, then blocked in PBS/0.25% fish skin gelatin (PBS/gel) for 15 min at room temperature. A total of 20 μl of primary Ab diluted in PBS/gel was added to each well, and the slides were incubated for 45 min at room temperature. Slides were washed in PBS/gel and incubated with Alexa-488-conjugated secondary Ab diluted in PBS/gel for 45 min at room temperature. The slides were then washed, dipped in water, and mounted in Mowial 488 (Hoechst Celanese) with 10% 1.4 diazobicyclo-[2.2.2]octane (Sigma-Aldrich) as an antifade. Slides were viewed using a Zeiss Axioplan microscope equipped with a Photometrics PXL-cooled CCD camera. Image capture and deconvolution analysis was performed using Openlab version 2.06 (Improvision, Coventry, U.K.).

Adhesion to ICAM-1-Fc

Nunc Maxi-Sorp 96-well plates (Naperville, IN) were coated with 0.5 μg/well goat anti-human IgG (Fcγ specific) overnight at 4°C, blocked with 1% BSA in PBS, then incubated with 0.3 μg/well ICAM-1-Fc at room temperature for 90 min. Wells were rinsed with PBS and blocked with PBS/1% BSA for 1 h before use. Jurkat cells were labeled with 5 μM CFSE in SF-RPMI for 20 min at 37°C. The reaction was quenched with PBS/gel, and the cells were washed twice in RPMI 1640 and resuspended in SF-RPMI. A total of 2 × 10^6 cells was added per well, followed by the addition of either PBS, the anti-TCR Ab c305 to a final concentration of 5 μg/ml, PMA to a final concentration of 20 ng/ml, or MgCl2/EgTA to a final concentration of 2 mM Mg/5 mM EGTA. Cells were allowed to adhere for 1 h at 37°C, then the wells were carefully washed three times with 0.2 ml HBK1. Bound primary Abs were detected by HRP-conjugated secondary Abs and chemiluminescence. For quantitation, bands were scanned using a FluorChem imager (Alpha Innotech, San Leandro, CA). The peak area for each band was determined, and only measurements falling within the linear response range were used. Phospho-MEK and ERK values were corrected for protein loading based on total MEK values, and expressed as percentage of the positive control response for each set of conditions.

PMA and Mg2+ conjugation experiments

EBV-B cells were stained with PKH26, and Jurkat cells were stained in calcine-AM, as described above. For Mg/EGTA conjugations, the EBV-B and Jurkat cells were resuspended in serum-free, Mg/EGTA RPMI 1640 at 1 × 10^6 cells/ml. Mg/EGTA was added to a final concentration of 2 mM Mg/5 mM EGTA, then the conjugation was conducted as described above. For PMA experiments, Jurkat cells were resuspended in SF-RPMI at 1 × 10^6 cells/ml. PMA was added to 20 ng/ml, and the cells were incubated at 37°C for 15 min. Conjugation with EBV-B cells was conducted as previously described. PMA levels were adjusted upon the addition of the APCs to maintain a concentration of 20 ng/ml during the conjugation.

Transient transfection of Jurkat cells with p-EGFP actin

Wild-type and mutant Jurkat cells were seeded in 100 ml of RPMI 1640 in 150-cm² flasks at 1.5 × 10^6 cells/ml and grown at 37°C until cells were ~4 × 10^9 cells/ml (typically 3–4 days). Cells were washed with RPMI 1640 and resuspended in RPMI 1640 at 8 × 10^5 cells/ml. A total of 2 × 10^6 cells was combined with 20 μg p-EGFP actin in an electroporation cuvette and mixed gently. The cells were pulsed at 240 V, 1500 μF using a Bio-Rad (Richmond, CA) Gene Pulser II apparatus, then placed on ice for 8 min. The cells were then transferred into 15 ml RPMI and incubated overnight at 37°C.
Adhesion requires the activity of Lck, but not ZAP-70

Wild-type Jurkat cells (E6), or Jurkat lines lacking Lck (JCaM1) or ZAP-70 (P116) were tested for their ability to form stable conjugates with SEE-pulsed B cells. The level of conjugation observed for each of the mutant cell lines in the absence of SEE was not significantly different from that observed for E6 cells (data not shown). In the presence of SEE (Fig. 3A), JCaM1 cells failed to form conjugates above the background levels observed in the absence of SEE. This was specifically due to the absence of Lck, since conjugation was restored in JCaM1 cells stably transfected with wild-type Lck. In contrast, the ZAP-70-deficient cell line P116 formed conjugates as well as wild-type cells. This indicates that the increased adhesion mediated by LFA-1 in response to SEE requires the activity of Lck, but not ZAP-70.

To further study the requirement for Lck, we tested a series of JCaM1 cell lines that stably express functional domain mutants of Lck. These include the Src homology (SH) 2 domain mutant R154K, the kinase-dead mutant K273A, and the myristoylation mutant G2A, all of which fail to initiate TCR signaling (28) (our unpublished data). Also tested was the SH3 domain mutant, W97A, which initiates TCR signaling through ZAP-70, but is defective in the MAPK pathway (29). Finally, since Fyn can restore some aspects of TCR signaling, we tested JCaM1 cells expressing Fyn at levels similar to that of Lck in wild-type Jurkat cells (30) to

FIGURE 3. SEE-induced LFA-1-mediated adhesion requires Lck, but not ZAP-70. Conjugations were carried in the absence (o) or presence (f) of SEE, using a panel of T cell lines. A. In comparison with control Jurkat cells (wild-type, WT) and ZAP-70-deficient cells (P116), Lck-deficient cells (JCaM) fail to show SEE-induced increases in conjugation. This is restored in JCaM cells stably expressing wild-type Lck (JCaM/Lck). B. Lck domain mutants fail to restore conjugation to JCaM1 cells. All proteins are expressed in JCaM1 cells, and unless specified are expressed at levels comparable with Lck in control E6 Jurkat cells. Lck, wild-type Lck; Lck 20%, wild-type Lck at 20% normal levels; KD, kinase-dead Lck (K273A); SH3, SH3 domain mutant (W97A); Myrist, myristoylation site mutant (G2A); SH2, SH2 domain mutant (R154K) at 20% normal levels; Fyn, wild-type Fyn. Background levels of conjugation for the mutant cell lines in the absence of SEE were similar to that observed for E6 cells (data not shown). Data are means of at least three independent experiments ± SD.

FIGURE 1. Quantitation of T:B conjugates by dual-color flow cytometry. Jurkat T cells and EBV-B cells were labeled with calcein-AM or HE, respectively. After pulsing B cells with SEE, T and B cells were mixed in a 1:1 ratio, pelleted, and allowed to interact for 10–15 min at 37°C. Cells were then resuspended, fixed, and analyzed by flow cytometry. Conjugates appear in the upper right quadrant. Percentage of conjugated T cells = (number of red/green events (upper right) divided by the total number of green events (upper right plus lower right)) × 100. A, No superantigen, percentage of conjugation = 12.6%. B, With superantigen, percentage of conjugation = 53.9%.

FIGURE 2. SEE-induced conjugation is mediated by LFA-1. Conjugations were conducted after incubation of Jurkat cells (and, in the case of LFA-1 Abs, B cells) with blocking Abs to the indicated proteins, all at 20 μg/ml, before mixing T cells and APCs. In the absence of superantigen (□), conjugate formation was inhibited by anti-CD2, and by Abs to the αL- and β2 chains of LFA-1 (alone or in combination). In the presence of SEE (□), only the LFA-1-specific Abs inhibited conjugate formation. Data are means of at least three independent experiments ± SD.
ask whether Fyn can substitute for Lck in signaling APC-induced adhesion. All cell lines except the SH2 domain mutant R154K express levels of Lck (or Fyn) equivalent to Lck levels in wild-type Jurkat cells (28, 29) (data not shown). Since the SH2 domain mutant expresses Lck at ~20% of normal levels, a transfectant expressing similar levels of wild-type Lck (28) was included as the matched control for this mutant. As shown in Fig. 3B, only wild-type Lck could restore normal conjugation to JCaM1 cells. Even matched control for this mutant. As shown in Fig. 3, only wild-type Lck could restore normal conjugation to JCaM1 cells. Even the expression of wild-type Lck at only 20% of normal levels was sufficient to restore a significant level of conjugation. In contrast, none of the altered forms of Lck could rescue the JCaM1 conjugation phenotype. For the Lck myristoylation, SH2 domain, and kinase-dead mutants, the defect in adhesion can be attributed to the failure of these cells to initiate TCR signaling. However, cells expressing the Lck SH3 domain mutant recruit and activate ZAP-70, and flux calcium normally (29), but these cells still failed to form conjugates. Furthermore, although the expression of Fyn in Lck-deficient T cells has been reported in other systems to partially restore TCR signaling (30), we found that Fyn could not compensate for Lck in our conjugation assay. Taken together, these results indicate that adhesion to APCs via LFA-1 depends upon signaling through Lck, but not ZAP-70.

Conjugation does not require MEK activation, but is sensitive to PKC and phospholipase C (PLC) inhibitors

Since cells expressing the Lck SH3 domain mutant are defective in MEK activation (29), one possibility was that signaling through MEK might be required for conjugation. In keeping with this, it has been reported that inhibition of MEK activity partially inhibits the TCR-mediated adhesion of murine T cells to immobilized ICAM-1 (21). We therefore looked for evidence that the MAPK pathway functions downstream of Lck in the SEE-induced activation of LFA-1-dependent conjugation. When Jurkat E6 cells pretreated with the MEK inhibitor PD98059 were tested, no inhibition of conjugation was observed (Fig. 4). The inhibition of MEK phosphorylation was confirmed by Western blotting with anti-phospho-MEK (data not shown). Thus, if the defect in conjugation requires signaling in the Ras-MAPK pathway, the relevant molecules must lie upstream of MEK.

In a search for alternative signaling pathways, we tested the effect of a panel of inhibitors on conjugation (Table I). An inhibitor of p38 MAPK (42) failed to inhibit conjugation. The PI-3 kinase inhibitors wortmannin and LY294002, which have been reported to inhibit T cell adhesion to immobilized ICAM-1 (19), did not inhibit conjugation, even when the Jurkat cells were treated for extended periods of time. Similarly, the calpain inhibitor calpeptin, which also inhibits binding to immobilized ICAM-1 (23), had no effect.

Table I. Inhibition of conjugate formation

<table>
<thead>
<tr>
<th>Enzyme Inhibited</th>
<th>Drug</th>
<th>Highest Dose</th>
<th>% Untreated Control</th>
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<tr>
<td>PI-3 kinase</td>
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<tr>
<td>PI-3 kinase</td>
<td>LY294002</td>
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<td>MEK</td>
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<td>Calpain</td>
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<tr>
<td>PLC</td>
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<td>3.5 μM</td>
<td>104</td>
</tr>
<tr>
<td>PKC</td>
<td>Calphostin C</td>
<td>200 nM</td>
<td>17</td>
</tr>
<tr>
<td>PLC</td>
<td>U73122</td>
<td>1 μM</td>
<td>4</td>
</tr>
</tbody>
</table>

* Jurkat T cells were pretreated with inhibitors at concentrations up to the highest dose indicated, and conjugates with EBV-B cells were formed in the continued presence of inhibitor, all as described in Materials and Methods. Percent conjugation was determined and is expressed relative to untreated control conjugates prepared in parallel. Data are representative of results from two or three independent experiments.

Based upon studies using immobilized ICAM-1, PKC is thought to play an important role in LFA-1-dependent T cell adhesion. In the conjugation assay, we could not bypass the requirement for TCR signaling by treatment with PMA (see Fig. 7); however, we found that the PKC inhibitor calphostin C profoundly inhibited SEE-dependent conjugation (Table I). Two interpretations of these findings are possible. Activation of PKC may be necessary, but not sufficient, to induce conjugation. Alternatively, conjugation may require the localized activation of PKC at the cell-cell contact site, which cannot be adequately mimicked by treatment with soluble PMA. The other inhibitor that affected conjugation was the general PLC inhibitor U73122. This drug was recently reported to inhibit IL-3-induced integrin activation in BaF3 cells (43). Importantly, calphostin C and U73122 had similar effects on both wild-type Jurkat T cells, and Jurkat cells lacking a functional ZAP-70 (Fig. 5, A and B). This suggests that the PLC isoform required for activation-induced conjugation is not dependent on ZAP-70. To verify that calphostin C and U73122 inhibit conjugation by affecting T cell signaling rather than APC-dependent processes, control experiments were conducted in which T cells or B cells were preincubated with the inhibitors, which were then removed during conjugate formation. Inhibition was observed only when T cells were preincubated with drug (Fig. 5C), showing that the relevant PKC- and PLC-dependent events occur in the T cell.

The strong dependence of conjugate formation on signaling through PKC and PLC family members was not restricted to Jurkat T cells, nor to superantigen-induced conjugate formation. Similar results were obtained with Ag-specific T cells from DO-11.10 TCR Tg mice conjugated to A20 B cells pulsed with OVA-253-330 peptide. As shown in Fig. 5D, treatment of the murine T cells with PD98059 had little effect on conjugate formation, and LY294002 inhibited conjugation only partially. By contrast, both U73122 and calphostin C completely blocked conjugation, indicating that the requirement for signaling through PKC and PLC extends to this system as well.

**U73122 inhibits the MAPK signaling pathway**

Since the Lck SH3 domain mutation and the PLC inhibitor U73122 both inhibited conjugation, we looked for evidence that they affect the same signaling pathways. Initially, Jurkat cells were pretreated with U73122 and stimulated with anti-TCR Abs. Western blots of whole cell lysates were then probed with Abs that recognize activated MEK and activated ERK. Under these conditions, inhibition of PLC induced only a partial reduction in MEK
Inhibitors of PLC and PKC inhibit the conjugation of wild-type and ZAP-70-deficient Jurkat T cells, and Ag-specific primary T cell blasts. A, Inhibition of Jurkat: EBV-B conjugation by the PLC inhibitor U73122. Following calcein-AM labeling, wild-type (E6, solid line) and ZAP-70-deficient (P116, dashed line) Jurkat T cells were incubated with the indicated concentrations of U73122 for 30 min, combined with SEE-to-target B cells. B, Inhibition by the PKC inhibitor calphostin C. Following calcein-AM labeling, wild-type (E6, solid line) and ZAP-70-deficient (P116, dashed line) Jurkat T cells were incubated with 200 nM calphostin (Calph.) C for 30 min, combined with SEE-presenting or control B cells in the continued presence of inhibitor, and assayed for conjugation efficiency. Both wild-type and ZAP-70-deficient cells showed a dose-dependent inhibition of conjugation to levels found in the absence of inhibitor. B, Inhibition of Jurkat: EBV-B conjugation by the PLC inhibitor U73122. Following calcein-AM labeling, wild-type (E6, solid line) and ZAP-70-deficient (P116, dashed line) Jurkat T cells were incubated with the indicated concentrations of U73122 for 30 min, combined with SEE-presenting or control B cells in the continued presence of inhibitor, and assayed for conjugation efficiency. Both wild-type and ZAP-70-deficient cells showed a dose-dependent inhibition of conjugation to levels found in the absence of inhibitor.

To exclude the possibility that the defect in MEK activation is due to a failure of the cells to maintain contact long enough to initiate the TCR signaling cascade, Western blots of cells activated in the absence or presence of U73122 were probed with antiphosphotyrosine. Dramatically increased levels of tyrosine phosphorylation were observed in the lysates of all the TCR- or B cell-stimulated samples, irrespective of whether U73122 was present, indicating that the early signaling cascade was initiated (data not shown).

Adhesion involves avidity changes and protein tyrosine kinase (PTK)-dependent cytoskeletal remodeling

In studies of LFA-1-dependent binding of preactivated T cells to immobilized ICAM-1, it has been shown that changes in either avidity or affinity can lead to increased binding. In keeping with this, we find that binding of unactivated wild-type Jurkat cells to immobilized ICAM-1 can be activated by either incubation with Mg-EGTA, under conditions that induce the high-affinity conformation of LFA-1 (44), or by treatment with PMA, which results in enhanced avidity (16). Binding under either of these conditions consistently exceeded that of stimulation with anti-TCR (Fig. 7A).
FIGURE 6. MAPK activation is sensitive to PLC inhibition. A. Activation with anti-TCR Ab. Jurkat cells were incubated in the presence or absence of the pan-PLC inhibitor U73122 at 1 μM for 30 min, and then stimulated with anti-TCR Ab c305. Jurkat cells activated with 50 ng/ml PMA were used as a positive control. MEK and ERK activation were evaluated by blotting lysates with Abs that recognize the phosphorylated forms. B. Activation with SEE-pulsed APCs. Jurkat cells treated as in A were combined with EBV-B cells that were previously pulsed with SEE, and drug concentration was maintained at 1 μM during the conjugation. Jurkat cells prepared in parallel were incubated with APCs in the absence of SEE to determine basal levels of phosphorylation (−SEE). After 10 min at 37°C, conjugates were lysed, and lysates were probed with Abs that recognize activated MEK and ERK. Blots are loaded with a dilution series of cell equivalents (indicated values × 10^4 cells/lane), to facilitate quantitation. The bottom panel shows the MEK-PO_4 blot reprobed after stripping with anti-MEK1, to confirm equal protein loading. Note that the inhibition of MEK phosphorylation is virtually complete (and much greater than that observed with anti-TCR activation), and that inhibition of ERK phosphorylation is also apparent. Negative controls of EBV-B cells alone with SEE and Jurkat cells alone with SEE were not significantly different from the unstimulated (−SEE) sample, and conjugates treated with PMA showed MEK and ERK phosphorylation similar to EBV-B/SEE-stimulated Jurkat cells in the absence of U73122 (data not shown). Results for A and B are representative of three separate experiments. C. Quantitation of MEK and ERK phosphorylation in response to anti-TCR in the presence and absence of U73122. D. Quantitation of MEK and ERK phosphorylation in response to conjugation with SEE-pulsed APCs in the presence and absence of U73122. Signal intensity in each band was determined as described in Materials and Methods. Data are expressed as a percentage of the untreated control (+anti-TCR or +SEE) responses.

We then asked whether we could bypass the requirement for TCR signaling in the conjugation assay in each of these ways. As shown in Fig. 7B, PMA treatment failed to activate conjugate formation in the absence of SEE, while incubation with Mg-EGTA induced only a 2-fold increase in conjugation. Varying the conditions under which these experiments were done, for example altering the timing of PMA stimulation or stimulating with PMA + ionomycin, failed to induce additional conjugate formation (data not shown).

Although we saw no enhancement of conjugation by PMA treatment, this could be explained by a requirement for the localized activation of PKCs at the cell-cell contact site that cannot be adequately mimicked by treatment with soluble PMA. However, the finding that induction of the high affinity form of LFA-1 by incubation with Mg-EGTA could not account for the large increase induced by SEE-dependent signaling suggests that adhesion to APCs involves a significant component of increased avidity. These results indicate that the requirements for plate-bound adhesion and conjugate formation differ, and must be assayed in different ways.

It seemed likely that the T cell mutants that fail to conjugate properly might be defective in actin remodeling and recruitment of LFA-1 to the cell-cell contact site. To evaluate the remodeling of actin in the T cell only, without visualizing actin in the bound B cell, wild-type and mutant T cells were transiently transfected with GFP actin and conjugates were analyzed by fluorescence microscopy. Wild-type T cells typically formed a slightly cupped contact with an accumulation of actin severalfold brighter than in the rest of the T cell (Fig. 8, A and B). The length of the contact site (approximately equal to one T cell in diameter) was quite uniform.
among conjugates. As expected, JCaM1 T cells formed very few conjugates. In those that did form, the contact site morphology was relatively normal, although on average it was narrower than in wild-type cells, and no actin response was observed (Fig. 8C). JCaM1 T cells expressing either the Lck SH3 domain mutant (Fig. 8D) or Fyn (Fig. 8E) behaved similarly; few conjugates were formed, and little or no actin remodeling was observed. The contact site was less than one T cell diameter in length and has a slightly cupped shape, features that were consistent in wild-type conjugates. In conjugates formed using JCaM1 cells (C), or JCaM1 cells expressing the Lck SH3 domain mutant W97A (D) or Fyn (E), very little actin accumulation is apparent. The contact site is often short (C and E) or exhibits an extended neck (D). F, A conjugate formed using the ZAP-70-deficient T cell P116. The contact site is abnormally extended, and although actin accumulation does occur, it is disorganized.

To ask whether the defects in actin remodeling in the PTK mutants are accompanied by defects in LFA-1 recruitment to the contact site, conjugates were analyzed for LFA-1 by immunofluorescence microscopy. Recruitment of LFA-1 in wild-type T cells was characterized by a sharp, bright band at the cell-cell interface (A). In both JCaM1 cells (B) and cells expressing the Lck SH3 domain mutant (C), many conjugates were found that did not localize LFA-1 to the contact site. In some conjugates, a smaller contact was formed, and LFA-1 could be observed as a short bright band (D). LFA-1 in wild-type T cells was characterized by a sharp, bright band at the cell-cell interface (A). In both JCaM1 cells (B) and cells expressing the Lck SH3 domain mutant (C), many conjugates were found that did not localize LFA-1 to the contact site. In some conjugates, a smaller contact was formed, and LFA-1 could be observed as a short bright band (D). LFA-1 in wild-type T cells was characterized by a sharp, bright band at the cell-cell interface (A). In both JCaM1 cells (B) and cells expressing the Lck SH3 domain mutant (C), many conjugates were found that did not localize LFA-1 to the contact site. In some conjugates, a smaller contact was formed, and LFA-1 could be observed as a short bright band (D).
apparently occur in the absence of gross actin remodeling. As observed in the actin studies, conjugates made using the ZAP-70-deficient T cells were more heterogeneous than conjugates made using either wild-type T cells or the Lck mutants. In roughly half of the ZAP-70-deficient T cells, accumulation of LFA-1 at the contact site was apparent (Fig. 9E), although in many of these labeling was dimmer or more disorganized than in wild-type conjugates (Fig. 9F). In the remainder, very little LFA-1 accumulated at the contact site (Fig. 9G), or a short, bright band was formed (Fig. 9H). In general, the actin and LFA-1 phenotype of the Lck mutants was much more severe than the ZAP-70-deficient cells. This finding is consistent with the conjugation data, and suggests that Lck plays a role in LFA-1-dependent adhesion that is somehow distinct from that played by ZAP-70.

Discussion

Although the requirement for inside-out signaling in integrin-dependent adhesion has been demonstrated in numerous studies (17, 45), remarkably little is known about the early signaling events required for stable conjugate formation during T cell:B cell interactions. In this study, we have taken advantage of existing mutant cell lines to address the role of the PTKs Lck and ZAP-70 in T cell:B cell conjugate formation. Conjugate formation in our assay system exhibits the basic properties demonstrated in previous studies of T:B conjugates (7, 46, 47). Both CD2 and LFA-1 contribute to modest Ag-independent T:B adhesion, while LFA-1 is primarily responsible for Ag-dependent conjugate formation. In the presence of Ag, conjugate formation is accompanied by recruitment of LFA-1 and actin to the contact site, consistent with cytoskeleton-dependent avidity increases resulting from inside-out signaling.

The finding that Lck activity is required for conjugate formation is not surprising, since signaling through Lck is required to initiate all aspects of TCR-mediated signaling (27). However, our results show that activation of ZAP-70, the protein normally thought to lie directly downstream of Lck in the TCR signaling pathway, is dispensable for conjugation. Two pieces of evidence support this conclusion. First, we find that ZAP-70-deficient T cells conjugate as efficiently as wild-type T cells. Second, we find that JCam1 cells expressing an SH3 domain mutant of Lck are deficient in conjugate formation, even though these cells have been shown to activate ZAP-70 normally (29). These results indicate that Lck participates in LFA-1-dependent conjugate formation by a pathway distinct from simple activation of ZAP-70.

Since binding to plate-bound ligands has been used extensively to analyze later events in the inside-out signaling pathway, we attempted to directly measure the adhesion of the Lck and ZAP-70 mutant T cells to immobilized ICAM-1. Unfortunately, the results were inconclusive because of high variability of the mutants in the ICAM-1-binding assay (data not shown). However, with wild-type cells in which the two assays could be performed in parallel, we found that binding to immobilized ICAM-1 differs significantly from superantigen-induced conjugation to APCs. Specifically, we found that inhibitors of calpain, PI-3 kinase, and MEK, all of which have been reported to inhibit binding to immobilized ICAM-1 (19, 21, 23), had no effect on superantigen-induced conjugation. These findings indicate that T:B conjugate formation is regulated by signaling pathways that are distinct from those involved in adhesion to immobilized ligands. It seems likely that the interaction of multiple receptor-ligand pairs results in the generation of redundancies in key signaling pathways that are not observed in a more simplified assay system. In addition, the generation of adhesive strength during T:B conjugation is likely to involve substantial changes in cytoarchitecture that are qualitatively and/or quantitatively different from those that occur in response to immobilized ligands. For example, we have observed that the T:B interface labels much more strongly for F-actin than does the interface with anti-TCR-coated beads, even though both interactions induce activation of CDC42 (38, 48). This is most likely due to the synergistic effect of multiple receptor-ligand interactions in sculpting the cortical cytoskeleton. Finally, the redistribution of ligand-bound receptors within the immunological synapse, which cannot take place in contacts with immobilized ligands, is likely to contribute to optimal adhesion to APCs. Thus, while the more reductionist approach of studying adhesion to immobilized ligands has been very informative, a full understanding of the factors that contribute to adhesive strength during conjugate formation will require additional analysis in model systems like the one described in this work.

Although analysis of conjugate formation introduces complexities into analyzing the signaling pathways involved, it also has benefits. In particular, it is illuminating to view the morphology of the interacting cells, and the distribution of proteins involved in the mechanics of adhesion. It is well established that signaling-dependent increases in avidity involve the recruitment of LFA-1, tethered to the cortical actin cytoskeleton, to the T cell:APC binding site (2, 15, 16, 49). Our results show that Lck-deficient T cells exhibit dramatic defects in actin remodeling and LFA-1 recruitment in response to B cell binding. In most conjugates formed with Lck-deficient T cells, little or no actin accumulates at the cell-cell contact site, consistent with a failure to activate localized actin polymerization. LFA-1 recruitment also fails to occur. These defects almost certainly affect the avidity of T:B binding, and are likely to account for (or at least contribute to) the adhesion defects in these cells. Importantly, similar defects are also observed in cells expressing the Lck SH3 domain mutant, suggesting that a ZAP-70-independent process is involved. Although cytoskeletal defects were also observed in the ZAP-70-deficient T cells, some remodeling was initiated in most of these cells, and many more achieved a wild-type phenotype. Remarkably, ZAP-70-deficient T cells actually tended to form an abnormally large contact site with the APC, suggesting that the structure of the cortical cytoskeleton was abnormally organized. Although the nature of the defect in these cells is still unclear, the remodeling that does occur is apparently adequate to allow conjugation at normal levels.

We have begun to characterize the signaling pathways downstream of Lck that ultimately result in the actin and LFA-1 remodeling required for conjugate formation. Clues about what pathways may be involved come from the known defects in T cells expressing the Lck SH3 domain mutant. Exactly how this mutant perturbs TCR signaling is an area of active investigation. Many proteins have been shown to interact with the SH3 domain, and the mutation is expected to disrupt these interactions. In addition, however, Lck activity is regulated by conformational changes, so that the mutation may perturb enzymatic activity through complex effects on tertiary structure. One known defect in cells expressing this mutant is in the activation of MEK (29). Since the MAPK pathway has been shown to be required for murine T cell adhesion to immobilized ICAM-1 (21), this pathway was a good candidate. Using the MEK inhibitor PD98059, we show that MEK and ERK are unlikely to be involved in the activation of LFA-1; however, this does not rule out a role for proteins upstream of MAPK. Indeed, our inhibitor studies suggest that conjugation depends on the activity of members of the PLC and PKC families. Classical models of TCR signaling pathways include ZAP-70-dependent activation of PLCγ1, which leads to downstream activation of PKC, and PKC has been implicated in integrin activation in many cell systems (49–54). We find that conjugation is independent of ZAP-70 activity, and that conjugation of ZAP-70-deficient T cells is as...
sensitive as wild-type cells to the PLC inhibitor U73122. Thus, the relevant PLC may not be PLCγ1, but rather another isoform such as PLCε, which has been shown to have Ras/guanine exchange factor (GEF) activity and to interact with Ras and its antagonist, Rap-1 (55, 56). Alternatively, PLCγ1 may be activated in a ZAP-70-independent manner under conjugation conditions. If PLCγ1 is the relevant isoform, it could influence adhesion either by activation of PKC, or by activation of the Ras pathway (57–60). In support of the latter possibility, we find that the effects of the PLC inhibitor U73122 on MAPK activation are much more pronounced when APCs are used to stimulate the T cells. In addition to showing defects in MAPK signaling, T cells expressing the Lck SH3 domain mutant are defective in costimulation through CD82 (61). Interactions of proline-rich sequences in CD28 with the Lck SH3 domain influence Ras activity via the Ras antagonist Rap-1, and domain in Interactions of proline-rich sequences in CD28 with the Lck SH3 domain influence Ras activity via the Ras antagonist Rap-1, and a role in Vav-1-dependent NF-AT activation (62, 63). Thus, defective cytoskeletal remodeling and poor conjugate formation could occur as a result of aberrant activation of Vav-1, a GEF for Rac-1. Intriguingly, overexpression of constitutively active mutants of both Rap-1 and Rac-1 strongly activates the adhesion of T cells to immobilized ICAM-1 (64).

Taken together, our results show that Lck plays a key role in regulating cortical cytoskeletal rearrangements and LFA-1-dependent conjugate formation. Our findings indicate that Lck activity is crucial to initiate actin polymerization and remodeling. To the extent that ZAP-70 is also required, it appears to play a role in fine-tuning the organization of actin at the cell-cell contact site. Although additional work will be needed to elucidate the relevant signaling pathways involved, it seems clear that small GTP-binding proteins will play a crucial role. In particular, the activation of Rho family members is likely to direct actin remodeling via effectors such as p21-activated protein kinase and Wiskott-Aldrich syndrome protein. Activation of Rho family members and their effectors in response to TCR engagement has been shown to depend on Lck activity (65–67), and cells in which Rho proteins are inhibited (68–70), lacking the Rho GEF Vav (71, 72) or the Rho effector Wiskott-Aldrich syndrome protein (73, 74), all show defects in actin-dependent aspects of T cell function. Although we still know relatively little about the regulation of Rho protein activity under conjugation conditions, our group has found that CDC42 is activated in a Lck-dependent fashion at the site of APC engagement, and that interfering with CDC42 activity perturbs conjugate formation (48).

Although it will be interesting to pursue the specific role of these proteins, this analysis will be challenging since these proteins function in complex cascades, and their function is highly location specific. Future analysis of signaling pathways that regulate cytoskeletal remodeling will be important for understanding T cell function, but will require new experimental approaches taking into account the complexities of actual cell-cell interactions.

Acknowledgments

We thank Drs. Robert Abraham, Marsha Rosner, Ron Gress, Michael Dus-tin, and Hans Ochs for gifts of cell lines and Abs, and Pat Hoffman for ICAM1-Fc. We are indebted to Drs. Jim Miller, Anne Sperling, and members of the Polarity Group for many helpful discussions. FACS analysis and microscopy studies were conducted using the University of Chicago Cancer Research Center Flow Cytometry Facility and Digital Light Microscopy Facility. We thank Julie Auger, Donna Peace, and Shirley Bond for assistance with data analysis, and Jill Voss and Renell Morgan for assistance with this manuscript.

References


