RGS10 Restricts Upregulation by Chemokines of T Cell Adhesion Mediated by $\alpha 4\beta 1$ and $\alpha L\beta 2$ Integrins

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RGS10 Restricts Upregulation by Chemokines of T Cell Adhesion Mediated by α4β1 and αLβ2 Integrins

David García-Bernal, Ana Dios-Esponera, Elena Sotillo-Mallo, Rosa García-Verdugo, Nohemí Arellano-Sánchez, and Joaquin Teixidó

Chemokines rapidly and transiently upregulate α4β1 and αLβ2 integrin-mediated adhesion during T lymphocyte extravasation by activating Go-dependent inside-out signaling. To limit and terminate Go-mediated signaling, cells can use several mechanisms, including the action of regulator of G protein signaling (RGS) proteins, which accelerate the GTPase activity of Go subunits. Using human T cells silenced for or overexpressing RGS10, we show in this article that RGS10 functions as an inhibitor of Go-dependent, chemokine-upregulated T cell adhesion mediated by α4β1 and αLβ2. Shear stress-dependent detachment and cell spreading analyses revealed that RGS10 action mainly targets the adhesion strengthening and spreading phases of α4β1-mediated cell attachment. Associated with these observations, chemokine-stimulated Vav1–Rac1 activation was longer sustained and of higher intensity in RGS10-silenced T cells, or inhibited in cells overexpressing RGS10. Of importance, expression of constitutively activated Rac1 forms in cells overexpressing RGS10 led to the rescue of CXCL12-stimulated adhesion to VCAM-1 to levels similar to those in control transfectants. Instead, adhesion under flow conditions, soluble binding experiment, flow cytometry, and biochemical analyses revealed that the earlier chemokine-triggered integrin activation step was mostly independent of RGS10 actions. The data strongly suggest that RGS10 opposes activation by chemokines of the Vav1–Rac1 pathway in T cells, leading to repression of adhesion strengthening mediated by α4β1. In addition to control chemokine-upregulated T cell attachment, RGS10 also limited adhesion-independent cell chemotaxis and activation of cdcd42. These results identify RGS10 as a key molecule that contributes to the termination of Go-dependent signaling during chemokine-activated α4β1- and αLβ2-dependent T cell adhesion.


Chemokines stimulate cell migration and activation, and exert their functions upon binding to heterotrimeric guanine nucleotide-binding (G) protein-coupled receptors (GPCR) (1–3). In the immune system, chemokines promote the migration of immune cells from lymph and blood circulation into lymphoid tissues and sites of inflammation during immune surveillance (4–7). For T lymphocytes, this process is achieved after rapid and transient stabilization of α4β1 and αLβ2 integrin activity by chemokines presented on the endothelium. Thus, chemokine binding to GPCR induces activation of intracellular effector molecules that lead to integrin-mediated upregulation of lymphocyte adhesion, a process called inside-out signaling (8, 9). Key inside-out molecules that regulate the activation of α4β1 and αLβ2 include talin and kindlin-3, as well as the Vav1–Rac1 and RAPL–Rap1 pathways (10–15).

Heterotrimeric G proteins consist of an α subunit and a complex formed by β and γ subunits (16–18). Basally, Gβγ and GDP-bound Go are associated, and following interaction with an activated receptor, GTP replaces GDP and GTP−Go dissociates from the Gβγ dimer. These two elements interact with effector proteins, leading to the activation of distinct signaling pathways. The GTPase activity inherent to Go limits G protein activation, as GTP hydrolysis causes reassociation of GDP−Go and Gβγ. G proteins are classified into four subfamilies—Go, Gαo, Gαq/11, and G12/13—according to the Go protein present in the complex (17, 18).

Heterotrimeric G proteins can be regulated by members of the regulators of G protein signaling (RGS) family (19–22). RGS proteins contain a 120-aa-long region called RGS domain, which is responsible for binding to Go subunits and for GTPase accelerating activity (21). This activity promotes the return of Go to its inactive form, which leads to faster termination of G protein-dependent signaling. Therefore, RGS proteins control the timing and duration of specific responses involving GPCR signaling. In T lymphocytes, constitutive or regulated expression of RGS2, RGS3, RGS4, RGS14, and RGS16 has been previously reported (23–27). Both migration and G protein-mediated signaling activation has been shown to be a target of regulation by these RGS proteins.

RGS10 belongs to the R12 subfamily of the RGS family (19–22). RGS proteins contain a 120-aa-long region called RGS domain, which is responsible for binding to Go subunits and for GTPase accelerating activity (21). This activity promotes the return of Go to its inactive form, which leads to faster termination of G protein-dependent signaling. Therefore, RGS proteins control the timing and duration of specific responses involving GPCR signaling. In T lymphocytes, constitutive or regulated expression of RGS2, RGS3, RGS4, RGS14, and RGS16 has been previously reported (23–27). Both migration and G protein-mediated signaling activation has been shown to be a target of regulation by these RGS proteins.

Although considerable effort has been made to identify molecules that are required for integrin activation in T lymphocytes, little is known about the mechanisms controlling the termination of integrin-mediated adhesion, a process that contributes to the homeostasis of the immune response. RGS proteins represent good.
candidates to regulate the strength and duration of GPCR-dependent signaling leading to integrin activation in lymphocytes. In the present work, we have investigated whether RGS10 could represent such a regulatory molecule in the control of integrin-dependent T cell adhesion. The results indicate that RGS10 represses the strength of chemokine-dependent T lymphocyte adhesion mediated by α4β1, and therefore suggest that RGS10 may control the duration of GPCR-dependent signaling required for upregulation of this adhesion.

Materials and Methods

Cells, Abs, and reagents

Human Molt-4 and Jurkat T cell lines, as well as peripheral blood T lymphocytes (PBL-Ts), were cultured and prepared as described (31). The Consejo Superior de Investigaciones Científicas Ethics Committee (Madrid, Spain) approved the protocols used to obtain and process the human blood samples. Human CD4+ T cells were purified using anti-CD4–coated microbeads (Miltenyi Biotec, Auburn, CA). Control P3X63 anti-α4 HP1/2, anti-β1 T52/16, and anti-CD45 R/P2/21 mAbs were gifts from Dr. Francisco Sánchez-Madrid (Hospital de la Princesa, Madrid, Spain), and polyclonal anti-β1A Abs were from Dr. Guido Tareno (Tarin University, Turin, Italy). The MEM-148 anti-β2 mAb and Abs to RGS10, Go4, Vav1, phosphotyro-sine, Rap1, and RhoA were from Santa Cruz Biotechnology (Santa Cruz, CA); anti-Rac1 and anti-Cdc42 were from BD Biosciences Pharmingen (San Diego, CA); and anti-GFP was from Molecular Probes (Eugene, OR). Abs to β-actin, hemaggulutinin (HA), paxillin, and talin clone SD4 were obtained from Sigma-Aldrich (St. Louis, MO), and anti-ephrin-2/1 and Ephr-2/1 Abs were from Cell Signaling Technology (Danvers, MA). Anti-CXCR4 mAb and CXCL12 were purchased from R&D Systems (Minneapolis, MN). CCL21 was obtained from Peprotech (Rocky Hill, NJ), and pertussis toxin was from Sigma-Aldrich.

Transfections and RNA interference

HA-fused RGS10 in the pcDNA3.1 vector was obtained from Missouri S&T CDNA Resource Center (Rolla, MO), and vectors coding for wild-type and active (V12) Rac1 fused with GFP were from Dr. F. Sánchez-Madrid. Two small interfering RNA (siRNA) duplexes against human RGS10 (RGS10.1, sense: 5′-CAAAGGAGACUCAUCACtt-3′; and RGS10.2, sense: 5′-GAACCGCAACCUCUGAUnGt-3′) were purchased from Dharmaco (Chicago, IL). Synthetic oligonucleotides (64-mer) that included the 19-mer sequence from the RGS10.1 siRNA sequence were synthesized, annealed, and ligated into pSuper vector, as described (32), to generate the pSuper-RGS10 short hairpin RNA (shRNA). The pSuper vector was used as the control in transfections involving pSuper-RGS10. Human Rac1 and Rap1, or control siRNA (31), were purchased from Ambion (Austin, TX). Vectors and siRNA were nucleofected (Amaxis, Cologne, Germany) following the described procedure (31). Molt-4 or PBL-T siRNA transfectants were assayed 22–24 h posttransfection, and transfection did not affect cell viability, as assessed in flow cytometry cell-cycle analyses.

Cell adhesion, chemotaxis, and spreading assays

For static adhesions, cells were plated on wells coated with CXCL12 or CCL21 (650 ng/ml), together with the fibronectin fragment FN-H89 or VCAM-1, and plates were incubated for 2 min at 37°C, according to the described method (31). Extent of adhesion was quantified with a fluores- cence analyzer (BMG Labtechnologies, Offenburg, Germany). For flow chamber adhesion assays, we followed the reported protocol (33). In brief, cells were infused at a flow rate of 1 dyne/cm2 into flow chambers containing coimmobilized VCAM-1 and CXCL12. Rolling cells that subsequently firmly attached for at least 20 s were expressed as stable arrest, whereas tethering cells that did not arrest at any moment were expressed as rolling cells. To evaluate shear resistance, cells were allowed to attach and then were subjected to incremental increases of the flow rate. The number of cells remaining bound was determined as the percentage of total adhered cells after the adhesion step. For chemotaxis assays, we used the reported procedure (34). Migrated cells were counted in a flow cytometer (Coulter Epics XL; Beckman Coulter, Miami, FL) by passing each sample in the same predetermined time and flow conditions. For cellular spreading, CXCL12-stimulated cells attached on VCAM-1 were fixed and analyzed as recently described (33). For cell binding to VCAM-1 (R&D Systems), cells were stimulated for 45 s with CXCL12 before adding VCAM-1–Fc for 75 s. For cell binding to ICAM-1–Fc (R&D Systems), cells (2 × 105) were resuspended in HEPES buffer (HEPES 20 mM, pH 7.4; NaCl 140 mM; glucose 2 g/l; BSA 0.1% w/v) with or without 5 mM Mg2+ and 1 mM EGTA. ICAM-1–Fc (200 μg/ml) was added to samples, and after a 30-min incubation at 37°C, cells were stimulated for 60 s with CXCL12. Detection of VCAM-1–Fc and ICAM-1–Fc was performed by flow cytometry using PE-conjugated AffiniPure F(ab′)2 fragment goat anti-human IgG, Fcγ fragment specific (Jackson Immunoresearch Laboratories, West Grove, PA).

Flow cytometry and calcium mobilization assays

For detection of high-affinity LFA-1, cells resuspended in HEPES buffer containing 1% FBS were incubated for 10 min at 37°C with the MEM-148 mAb (10 μg/ml), followed by exposure for 5 min to CXCL12. After washing, cells were incubated with FITC-conjugated rabbit anti-mouse IgG (Jackson Immunoresearch Laboratories) for 30 min at 4°C. For calcium mobilization, cells were washed with labeling medium (HBSS containing 1% FBS, CaCl2 1 mM, MgCl2 1 mM), followed by an incubation step of 45 min at 37°C with the Ca2+-sensitive fluorescent dyes Fluo-3-AM and Fura-Red-AM (Molecular Probes) to a final concentration of 4 μM and 10 μM, respectively. After cell stimulation with CXCL12, we measured the ratio of Fluo-3-AM/Fura-Red-AM fluorescence by flow cytometry. Ionomycin (Sigma-Aldrich) was used as a positive control for Ca2+ mobilization.

Immunoprecipitation, immunoblotting, and GTPase assays

For immunoprecipitation, cells were solubilized in lysis buffer containing 1% digitonin, and after preclearing with protein G-Sepharose beads (Amersham Pharmacia Biotech, Uppsala, Sweden), supernatants were in- cubated with Abs followed by coupling to protein G-Sepharose. Proteins were resolved by SDS-PAGE, then transferred to membranes that were sequentially incubated with primary Abs and with HRP-conjugated secondary Abs. Proteins were visualized using SuperSignal Chemiluminescent Substrate (Pierce, Rockford, IL). For GTPase assays, we followed the method described (31). Briefly, cells exposed to CXCL12 were lysed, and aliquots from extracts were separated for total lysate controls and for incuba- tion either with GST-PK-CD (for active Rac1 and cdc42), GST-RalGDS (for active Rap1), or GST-C21 (for active RhoA) fusion proteins, followed by incubation with glutathione-agarose beads. Bound proteins were eluted and subjected to immunoblotting using anti-Rac1, anti-cdc42, anti-Rap1, or anti-RhoA Abs.

Statistical analyses

Data were analyzed by one-way ANOVA, followed by Tukey–Kramer multiple comparisons. In both analyses, the minimum acceptable level of significance was p < 0.05.

Results

RGS10 controls chemokine-stimulated T cell adhesion mediated by α4β1 and αLβ2 integrins

RGS10 was found to be expressed in PBL-Ts and in the CD4+ subpopulation, as well as in the human T cell lines Molt-4 and Jurkat (Fig. 1A). CXCL12 rapidly and transiently stimulated the association of RGS10 with Go4 (Fig. 1B), suggesting that RGS10 might regulate Go4-dependent signaling pathways in T cells. To investigate whether adhesion of T cells to α4β1 ligands that is upregulated by CXCL12 can be controlled by RGS10, we silenced its expression in Molt-4 and PBL-T cells by siRNA or shRNA, and tested transfectants in static adhesion assays to CS-1/fibronectin (FN-H89) and to VCAM-1. RGS10.1 siRNA reduced the expression of RGS10 by 70% and 90% in Molt-4 and PBL-T cells silenced for RGS10 expression showed sig- nificantly stronger attachment to FN-H89 and VCAM-1 immobilized with CXCL12 than to control siRNA or shRNA transfectants (Fig. 1D, 1E). Under basal conditions (no CXCL12 stimulation), the attachment of RGS10 knockdown T cells to VCAM-1 was slightly increased compared with control siRNA transfectants, although the extent of this increase was always smaller than the upregulation of adhesion seen in RGS10-depleted cells incubated...
with CXCL12. Pertussis toxin, an inhibitor of Goi-triggered signaling, blocked both the CXCL12-stimulated T cell adhesion to VCAM-1 in control shRNA transfectants and the further upregulation of adhesion seen in RGS10 shRNA counterparts (Fig. 1F), indicating that RGS10 was exerting its regulatory actions on adhesion through Goi.

To determine whether the regulation by RGS10 of α4β1-dependent T cell adhesion could also be detected with chemokines other than CXCL12, we used CCL21, a chemokine that binds to the CCR7 receptor on the surface of T lymphocytes and that has been demonstrated to activate integrin-mediated lymphocyte adhesion (35, 36). The results indicated that RGS10-silenced T cells attached to VCAM-1 more strongly than did control siRNA transfectants when exposed to CCL21 (Fig. 1G), indicating that RGS10 controls α4β1-dependent T cell adhesion in response to multiple Goi-coupled chemokine receptors.

Further support for the involvement of RGS10 in the control of T cell adhesion mediated by α4β1 in response to chemokines came from experiments using T cells that overexpressed RGS10. Thus, Molt-4 cells overexpressing RGS10-HA displayed a significant reduction in CXCL12-upregulated attachment to FN-89 and VCAM-1, compared with mock transfectants (Fig. 2A, 2B). To analyze whether RGS10 could regulate other adhesions in T cells, in addition to α4β1-dependent attachment, we studied the effect of silencing or overexpressing RGS10 on αLβ2-mediated adhesion. RGS10-depleted Molt-4 and PBL-T cells displayed higher attachment to ICAM-1 than did control siRNA transfectants when exposed to CXCL12; conversely, transfectants overexpressing RGS10 displayed a significant inhibition of CXCL12-triggered adhesion, compared with control transfectants (Fig. 3A, 3B). In addition, RGS10 silencing led to stronger adhesion to ICAM-1 triggered by CCL21 than to cells transfected with control siRNA (Fig. 3C). Together, these results indicate that RGS10 functions as a controller of chemokine-stimulated T cell adhesion involving integrins α4β1 and αLβ2.

RGS10 controls the chemokine-upregulated T cell adhesion strengthening and spreading steps mediated by α4β1

The adhesion process dependent on lymphocyte integrins can be divided into an initial step involving generation of high-affinity activated integrins that support firm interaction with their ligands, a subsequent phase of increase in avidity that includes...
enhanced valency of the adhesions, followed by a phase of adhesion strengthening that supports final cell spreading (9). To study which of these steps can be regulated by RGS10, we first performed adhesion assays under flow conditions to mimic the initial phases of the adhesion cascade. Adhesion under shear stress revealed a moderate and statistically nonsignificant (p > 0.05) increase in rapid (<20 s) stable cell arrest on VCAM-1 coimmobilized with CXCL12 of both PBL-T and Molt-4 RGS10 siRNA transfectants, when compared with control counterparts (Fig. 4A). Control experiments indicated that adhesion was abolished by pretreatment of cells with pertussis toxin (not shown). Dissociation of Vav1 from talin and increase in talin-β1 association in response to chemokines constitute early events that lead to integrin activation (13). Neither Vav1–talin dissociation nor talin-β1 assembly was significantly affected by RGS10 silencing (Fig. 4B); furthermore, RGS10-depleted T cells displayed binding capacity to soluble VCAM-1–Fc comparable to that in control counterparts (Fig. 4C). In addition, soluble binding to Molt-4 cells of ICAM-1–Fc or MEM-148, an anti-β2 mAb that recognizes high-affinity states of αLβ2 (37), was not altered by RGS10 knocking down (Fig. 4D). These results strongly suggest that the initial steps of chemokine-triggered T cell adhesion that generate active α4β1 and αLβ2 are not significantly controlled by RGS10 function.

Notably, RGS10-silenced PBL-T and Molt-4 cells developed higher resistance to detachment at increased shear stress than did control siRNA transfectants (Fig. 4E). Moreover, RGS10 knockdown cells displayed higher spreading on VCAM-1 than did control siRNA transfectants, and interference reflection microscopy analyses showed that the ligand-bound focal plane of RGS10-depleted cells had a larger area than did control transfectants (Fig. 4F). Therefore, these data indicate that the adhesion strengthening and spreading steps of α4β1-mediated T cell adhesion following stimulation by chemokines are targeted by RGS10 activity.

Control by RGS10 of α4β1-dependent T cell adhesion involves regulation of Vav1–Rac1 activation

Activation by chemokines of the Vav1–Rac1 pathway is required for α4β1-mediated T cell adhesion strengthening (31). RGS10-depleted Molt-4 cells displayed a more sustained Vav1 tyrosine phosphorylation and Rac1 activation in response to CXCL12 than did control siRNA transfectants (Fig. 5A). On the contrary, RGS10 overexpression led to reduced Vav1 phosphorylation levels and to a decrease in Rac1 activation compared with findings in control transfectants (Fig. 5B). As also shown before (31), Rac1 silencing completely abolished CXCL12-stimulated Molt-4 cell adhesion to VCAM-1 (Supplemental Fig. 1). Remarkably, reduction in CXCL12-stimulated adhesion to VCAM-1 in cells overexpressing RGS10 was rescued by coexpression of GFP-fused active Rac1 (V12), under both static and flow conditions (Fig. 5C, 5D). These data indicate that control of Vav1–Rac1 activation by RGS10 in chemokine-dependent signaling underlies the regulation of α4β1-mediated T cell adhesion by RGS10.

Rap1 activation in response to CXCL12 was only minimally increased at 2.5 min in RGS10 knockdown cells compared with control transfectants (Fig. 5E, left panel), whereas longer incubations with the chemokine caused no changes in Rap1 activation between these transfectants (not shown). In addition, Rap1 depletion led to partial (40%) inhibition of CXCL12-stimulated Molt-4 cell adhesion to VCAM-1 (Fig. 5E, right panel).
Therefore, these results indicate that a major consequence of RGS10 actions is the limitation of Vav1–Rac1 activation by chemokines, which then results in reduction in α4β1-dependent T cell attachment.

**RGS10 regulates T cell chemotaxis and cdc42 activation**

Finally, we investigated whether RGS10 is capable of controlling T cell responses to chemokines other than cell adhesion. Chemotaxis to CXCL12 of RGS10 knockdown Molt-4 transfectants was significantly higher than that of control siRNA counterparts, whereas cells overexpressing RGS10 migrated clearly less than mock transfectants (Fig. 6A). In addition, RGS10 silencing led to sustained cdc42 activation in response to CXCL12 (Fig. 6B), whereas no substantial alterations were detected for RhoA activation (Fig. 6C). Phosphorylation of the Erk1/2 MAPK was only modestly increased in RGS10 knockdown cells (Fig. 6D), and no

**FIGURE 4.** RGS10-depleted T cells show increased adhesion strengthening and spreading on VCAM-1. A, PBL-T or Molt-4 cells transfected with control or RGS10 siRNA were perfused in flow chambers coated with VCAM-1 immobilized with CXCL12, and analyzed for rolling and stable cell arrest (n = 4). Data are presented as mean ± SD of number of interacting cells or cell percentages from the total cell population either rolling, or rolling and subsequently stably sticking. B, Molt-4 siRNA transfectants were subjected to immunoprecipitation with anti-Vav1, anti-β1, or Ctr Abs, followed by Western blotting with Abs to the indicated proteins. Numbers under gel represent densitometer analyses in arbitrary units. C, Control or RGS10 siRNA Molt-4 transfectants were analyzed for binding of VCAM-1-Fc following stimulation with CXCL12. D, The same transfectants were incubated with or without CXCL12 and tested for MEM-148 anti-β2 mAb, or for ICAM-1–Fc binding. E, Control or RGS10 siRNA PBL-T or Molt-4 transfectants attached on immobilized VCAM-1 and CXCL12 in flow chambers were subjected to cell detachment after increasing shear stress. Data show mean ± SD of cell percentages from the initial number of bound cells remaining attached at the indicated shear stresses. F, Control or RGS10 shRNA transfectants were allowed to attach to VCAM-1 immobilized with CXCL12, and spreading was analyzed by Nomarski or by IRM. Percentage of cell spreading was determined from a significant number of cells from different fields of view (n = 2500–3000). Spreading was significantly stimulated. *p < 0.05. Ctr, control; IRM, interference reflection microscopy.
changes in the activation of the PI3K downstream effector Akt were observed (not shown). Furthermore, RGS10 depletion did not significantly affect Ca\(^{2+}\) mobilization triggered by CXCL12 (Fig. 6E). Thus, RGS10 is capable of regulating not only α\(4β1\)- and α\(Lβ2\)-dependent T cell adhesion but also migration and activation of specific signaling pathways.

**Discussion**

Lymphocyte extravasation at sites of tissue injury or at lymphoid organs depends on chemokine-activated adhesion mediated by α\(4β1\) and α\(Lβ2\) integrins (8, 9). This activation must be rapid to deliver tight cell attachment to resist the blood shear stress, but also transient to allow lymphocyte locomotion on and diapedesis across endothelial layers. The chemokine-dependent integrin activation step in lymphocytes requires an inside-out signaling that impinges on the integrin β subunit cytoplasmic domains, a key event for transmitting conformational changes to the extracellular regions that leads to increase in integrin affinity (11). Talin and kindlins are recipients of this inside-out signaling, which promotes their binding to the β cytoplasmic domains, finally stimulating the transition to high-affinity α\(4β1\) and α\(Lβ2\) conformations (10–12).

The transient nature of integrin activation by chemokines indicates that an active molecular machinery limits and ultimately inhibits the signaling stimulated following G\(\alpha\)-coupled chemokine receptor interaction with their ligands. To limit and terminate this signaling, cells use several mechanisms, including the action of RGS proteins, which accelerate the GTPase activity of G\(\alpha\) subunits (19, 21). In this work, we show that RGS10 opposes the chemokine-stimulated signaling that is needed for T cell adhesion mediated by α\(4β1\) and α\(Lβ2\). Thus, upregulation of adhesion to α\(4β1\) and α\(Lβ2\) ligands in response to CXCL12 and CCL21 was significantly stronger in RGS10-depleted cells than in control transfectants. On the contrary, when RGS10 was overexpressed, stimulation of adhesion by these chemokines was limited. RGS10 transiently associated to G\(\alpha\)i in T cells following exposure to CXCL12, and pertussis toxin blocked chemokine-upregulated adhesion to VCAM-1 of both control and RGS10-silenced cells.

**FIGURE 5.** RGS10-dependent control of chemokine-stimulated, α\(4β1\)-mediated adhesion is associated with regulated activation of the Vav1–Rac1 pathway. A, Control or RGS10 siRNA Molt-4 transfectants were incubated with CXCL12 for the indicated times, and subsequently subjected to immunoprecipitation with control or anti-Vav1 Abs, followed by immunoblotting with the indicated Abs (left), or tested in Rac GTPase assays (right). B, Molt-4 cells were transfected with empty vector (Mock) or with RGS10-HA, and transfectants were analyzed as in A. C, Molt-4 cells were left untransfected, or were transfected either with GFP vector alone, or with GFP or GFP-RacV12 vectors together with the RGS10-HA plasmid. Cells were then analyzed by flow cytometry for GFP expression (left), examined by Western blotting with the indicated Abs (middle), or subjected to static adhesion assays to VCAM-1 immobilized with or without CXCL12 (right). Adhesion was significantly rescued. *\(p<0.05\). D, The same GFP transfectants were tested in flow chambers for cell detachment after increasing shear stress. Data show mean ± SD of cell percentages from the initial number of bound cells remaining attached at the indicated shear stresses. E, Control or Rap1 siRNA transfectants were analyzed by immunoblotting or were tested in adhesion assays to VCAM-1 immobilized with or without CXCL12. Adhesion was significantly inhibited. *\(p<0.05\).
suggesting that RGS10 is inhibiting the adhesion mediated by α4β1 by repressing Goi-dependent signaling.

Flow chamber adhesion experiments that measure rapid firm cell attachment under shear stress revealed that RGS10 silencing caused only moderate and statistically nonsignificant increases in T cell firm arrest to VCAM-1 following the rolling step. Moreover, chemokine-stimulated increase in talin-β1 association, an early event leading to high-affinity α4β1 that is competent for VCAM-1 binding and that is linked with Vav1–talin dissociation (13), was not altered by RGS10 depletion. Correlating with this observation, binding of soluble VCAM-1–Fc, as well as interaction of ICAM-1–Fc with αLβ2, was comparable in control and RGS10 knockdown T cells. In addition, generation of αLβ2 high-affinity states was not affected by RGS10 depletion. Instead, chemokine-stimulated Rac1 activation, a process taking place during the strengthening of adhesion after the integrin activation step (31), was longer sustained and of higher intensity in RGS10-depleted than control cells, without further increase in talin-β1 binding, suggests a more sustained Goi-dependent activation in cells silenced for RGS10, with no alterations in the rapid and earlier α4β1 activation.

Rap1 activation in the T-cell adhesion to VCAM-1 was reduced by RGS10 depletion as compared with control T cells suggesting a minor role for RGS10 in the adhesion mediated by α4β1. Rap1 activation has been reported to mediate chemokine-promoted, integrin-dependent T cell adhesion (14, 40, 41). We found that Rap1 silencing partially (40%) affects CXCL12-stimulated T cell adhesion to VCAM-1. However, our results indicated that Rap1 activation by CXCL12 was not significantly altered in RGS10 knockdown T cells, suggesting minor roles for Rap1 in mediating the increased adhesion seen in RGS10 knockdown cells.

In addition to repressing chemokine-upregulated T cell adhesion dependent on α4β1 and αLβ2, RGS10 also inhibited adhesion-independent cell chemotaxis and cdc42 activation in response to CXCL12. The mechanisms underlying the control by RGS10 of these two processes has not been addressed in the current study, but they also likely involve termination of Gi-dependent signaling.

The following model can be proposed from present and earlier data. Chemokine binding to their receptors triggers Goi-dependent signaling that leads to changes in molecular associations between Vav1, talin, and β1, resulting in early α4β1 activation (13), but also promotes Goi association with RGS10. Although the initial steps of adhesion are not targeted following RGS10–Goi associ-
ation, the consequence of the assembly of this complex may well be the gradual termination of Vav1–Rac1 activation that triggers chemokine-upregulated strengthening of the adhesion mediated by α4β1.

Other RGS proteins, such as RGS2, RGS3, RGS4, RGS14, and RGS16, have been reported to be expressed in T cells, either resting or activated (23–27). Therefore, it could be speculated that some of them might contribute together with RGS10 to the inhibition of chemokine-stimulated, α4β1- and αLβ2-dependent T cell adhesion. Thus, an early work showed that overexpression of RGS1, RGS3, and RGS4 in a pre-B cell line led to reduced adhesion to VCAM-1 following chemotractant activation (42). In addition, overexpression of RGS16 results in inhibition of CXC1L2-induced migration and MAPK and Akt activation in the progenitor Mo7e model cell line (43). Furthermore, RGS1 and RGS3 inhibit CXC1L2-triggered B cell chemotaxis (44). Therefore, RGS protein function in lymphoid cells appears to be highly relevant for physiological termination of chemokine signals that control important processes such as cell adhesion and migration, as well as cell activation.

Not only do RGS proteins associate to G protein subunits and accelerate their GTPase activity, but they are also capable of acting as effector antagonists by competing with effector molecules for GTP-bound G protein subunits, and they can also directly interact with effectors (21, 45, 46). For instance, RGS2 binds adenyl cyclase (47), and RGS4 antagonists by competing with effector molecules for GTP-bound Gα subunits, and they can also directly interact with effectors (21, 45, 46). In addition, RGS4 interacts with phospholipase Cβ and phosphatidic acid (48, 49).

In addition, RGS14 binds activated H-Ras forms, as well as Raf kinases (50, 51), and regulates their subcellular localization and activities. RGS10 belongs to the same D/R12 subfamily of RGS4, but nevertheless it lacks the RBD domains responsible for binding to active H-Ras. In future work, it will be important to determine whether structural and/or functional relationships exist between RGS10 and the molecular signaling required for chemokine-stimulated T cell adhesion mediated by α4β1.

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Disclosures

The authors have no financial conflicts of interest.

References


Supplemental data

**Supplemental figure S1. Electrophysiology assay.** To determine whether SPAK overexpression primarily effect on inflammatory cytokine expression or barrier function, Caco2-BBE cells were transfected with SPAK or vector using electroporation by Neon transfection system (Invitrogen). The first group of cells were plated at 2.5 $\times$ 10^5/well used for transepithelial resistance assay with electric cell-substrate impedance sensing (ECIS) system (Applied BioPhysics) that measures intestinal epithelial resistance in real time. SPAK and vector transfected Caco2-BBE cells showed similar degrees of exponential growth after plating of cells on the ECIS electrode. However, Caco2-BBE wild-type cells attained a maximal and plateau resistance higher than those of Caco-2-BBE cells overexpressing SPAK after 20 hours. The experiments were repeated three times. This suggests that SPAK overexpression by epithelial cells decreases *in vitro* barrier function.
Supplemental data

Normalized folds of IL-17 mRNA

Normalized folds of TNF-α mRNA

Normalized folds of IL-1 mRNA

Normalized folds of IFN-γ mRNA
Supplemental figure S2. To determine whether the effect of SPAK over-expression is primarily on inflammatory cytokine expression or on barrier function. Caco2-BBE cells were transfected with SPAK or vector using electroporation by the Neon transfection system (Invitrogen). The cells were divided into different groups, the first group of cells were used for resistance assay (supplemental figure s1). The second group of cells was plated in 6-well plates at 2.5*10^5/well. Total RNA was prepared from these cells at different time points (0, 8, 16, 24, 36, 48 hours) and used for real-time PCR to determine the mRNA level of cytokines IL-1β, IFN-γ, TNF-α and IL-17. The supernatant from these wells were analyzed by ELISA for the same cytokines using the same time course (0, 8, 16, 24, 36, 48 hours). However, we did not see significant differences in cytokine expression at the mRNA level until 36 hours later. Additionally, we did not find any of these four inflammatory cytokines detectable by ELISA, which suggests any effect of SPAK on the intestinal barrier in vitro is not mediated by cytokine secretion (we added this information to our supplementary data). Together, the results suggest that SPAK primarily effects epithelial barrier function. Black solid bar represents data from SPAK transfected cells and gray solid bar represents data from vector transfected cells. NS: no significant, *p<0.05, ** p<0.01
Supplemental figure S3. 200 mg of Colon tissue from WT littermate and TG mice were cultured for 12 hours, the supernatant were collected and analyzed by ELISA assay, no significant change in cytokine levels were observed for IL-1beta, TNF-alpha, IL-17 and IFN-gamma, which means th protein levels of pro-inflammatory cytokines did not rise above baseline in the absence of DSS treatment. In conclusion, intestinal barrier defect in TG mice is not caused by inflammatory cytokines tested. **NS:** No significant
Supplemental data

Supplemental figure S4. TG mice and WT littermate mice display no significant different expression of ZO-1 by immunoflurescence, real time PCR and Western blot. NS: No significant
Supplemental data

Supplemental figure S5. TG and WT littermate control mice display no significant different expression of ZO-2 by immunofluorescence, real time PCR and Western blot. NS: No significant
Supplemental figure S6. TG mice demonstrated significant decreased expression of tight junction protein occludin by immunofluorescence, real time PCR and Western blot. * p<0.05
Supplemental figure S7. TG and WT littermate control mice display no significant different expression of Claudin-1 by immunofluorescence, real time PCR and Western blot. NS: No significant
Supplemental data

Supplemental figure S8. TG and WT littermate control mice display no significant different expression of claudin-2 by immunofluorescence, real time PCR and Western blot. NS: No significant
Supplemental figure S9. TG and WT littermate control mice display no significant different expression of claudin-4 by immunofluorescence, real time PCR and Western blot. NS: No significant
### Supplemental table s1: Primers used for real-time PCR

<table>
<thead>
<tr>
<th>Primers</th>
<th>Nucleotides Sequences</th>
</tr>
</thead>
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<tr>
<td>ZO-1For</td>
<td>CGAGTTGCAATGGTTAACGGA</td>
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<tr>
<td>ZO-1Rev</td>
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</tr>
<tr>
<td>ZO-2For</td>
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<tr>
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