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Dual-Specificity Phosphatase 14 (DUSP14/MKP6) Negatively Regulates TCR Signaling by Inhibiting TAB1 Activation

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T cell activation is dependent upon phosphorylation of MAPks, which play a critical role in the regulation of immune responses. Dual-specificity phosphatase 14 (DUSP14; also known as MKP6) is classified as a MAPK phosphatase. The in vivo functions of DUSP14 remain unclear. Thus, we generated DUSP14-deficient mice and characterized the roles of DUSP14 in T cell activation and immune responses. DUSP14 deficiency in T cells resulted in enhanced T cell proliferation and increased cytokine production upon T cell activation. DUSP14 directly interacted with TGF-β–activated kinase 1 (TAK1)–binding protein 1 (TAB1) and dephosphorylated TAB1 at Ser438, leading to TAB1–TAK1 complex inactivation in T cells. The phosphorylation levels of the TAB1–TAK1 complex and its downstream molecules, including JNK and IκB kinase, were enhanced in DUSP14-deficient T cells upon stimulation. The enhanced JNK and IκB kinase activation in DUSP14-deficient T cells was attenuated by TAB1 short hairpin RNA knockdown. Consistent with that, DUSP14-deficient mice exhibited enhanced immune responses and were more susceptible to experimental autoimmune encephalomyelitis induction. Thus, DUSP14 negatively regulates TCR signaling and immune responses by inhibiting TAB1 activation. The Journal of Immunology, 2014, 192: 000–000.

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T lymphocytes play a critical role in the regulation of immune responses. Engagement of TCR triggers LCK activation, which leads to phosphorylation of the ITAMs of CD3, resulting in ZAP70 recruitment and activation. ZAP70 activation induces the assembly of the proximal signaling complex, which includes LAT, GRB2, GADS, phospholipase C-γ1 (PLC-γ1), VAV, and SLP-76 (8). SLP-76 is negatively feedback regulated by hematopoietic progenitor kinase 1 (HPK1; MAP4K1) (9). The activated PLC-γ1 hydrolyzes inositol phospholipids into inositol triphosphates and diacylglycerols. The production of inositol triphosphates leads to the release of intracellular Ca2+. TCR-induced production of diacylglycerols results in the activation of two major pathways involving Ras and protein kinase C-0 (PKC-0) (10). GCK-like kinase (GLK; MAP4K3) can directly activate PKC-0 during TCR signaling (11). PKC-0 can phosphorylate CARMA1, which leads to the formation of a trimeric complex comprising CARMA1, BCL-10, and MALT1 (12). This complex can lead to the activation of IκB kinase (IKK) and downstream transcriptional factor NF-κB (12). Also, PKC-0 regulates TGF-β–activated kinase 1 (TAK1), a member of the MAPKK kinase family, leading to activation of IκK and NF-κB in a CARMA1-independent manner in the TCR pathway (12). TAK1 can also activate MKK4/7 and MKK3/6, resulting in the activation of JNK and p38, respectively. The major pathway involved in ERK activation is mediated by the sequential activation of Ras, Raf, and MEK1/2 (8).
TAK1 kinase activity is controlled by TAK1-binding protein 1 (TAB1) (13, 14). The activation of TAK1 is impaired in TAB1-deficient mouse embryonic fibroblasts during IL-1 or TNF-α signaling (15). The association between TAB1 and TAK1 causes a conformational change of the catalytic domain, induced the kinase activity of TAB1 (16). TAB1 is phosphorylated at Ser435, Thr431, and Ser439 in response to LPS, proinflammatory cytokines, and cellular stresses (17). p38 negatively regulates TAK1 kinase activity by phosphorylating TAB1 at Ser435 and Thr431 during IL-1 or TNF-α signaling (17). TAB1 is essential for JNK and NF-κB activation during TCR signaling in primary T cells (18); however, the role of TAB1 in TCR signaling is still unknown.

To study the in vivo function of DUSP14 in TCR signaling and immune responses, we generated DUSP14-deficient mice. In this article, we report genetic evidence that T cell activation and proliferation are enhanced in DUSP14-deficient T cells. DUSP14-deficient mice showed enhanced immune responses in vivo. Furthermore, our results indicate that DUSP14 negatively regulates TCR signaling and immune responses by inhibiting TAB1 activation.

Materials and Methods

Generation of DUSP14-deficient mice

A 129 mouse embryonic stem cell clone with DUSP14 gene deficiency from the International Gene Trap Consortium was injected into C57BL/6 blastocysts to generate chimeric mice at the Transgenic Mouse Model Core, National Research Program for Genomic Medicine (Taipei, Taiwan). The heterozygous DUSP14 progeny from the crossing of the chimeras with C57BL/6 mice were used to generate DUSP14-deficient mice. For genotyping by PCR, common 3′ primer, wild-type (WT)-specific 5′ primer, and knockout (KO)-specific 5′ primer were mixed together in the same reaction, which generated 900-bp and 1300-bp DNA fragments for the WT and KO PCR products. Mice used in this study were 6–12 wk old and were backcrossed to C57BL/6 for at least five generations.

Flow cytometry analysis and purification of T cells

Thymocytes, splenocytes, and lymph node cells were dissected and crushed in RPMI 1640 medium containing 10% FBS. Debris was removed by cell strainer, and RBCs were depleted by ACK lysing buffer. Cells were stained with different fluorescently labeled Abs at 4°C for 15–20 min, washed twice, and analyzed on a FACSCanto II (BD Biosciences). Flow cytometry data were analyzed with FlowJo software (TreeStar).

Flow cytometry analysis were as described (20).

In vitro T cell differentiation

CD4+CD25+ T cells were purified from the spleen of mice. Cells were activated with 2 µg/ml anti-CD3 (145-2C11) plus 2 µg/ml anti-CD28 (37.51; eBioscience) Abs, or PMA (Sigma) and ionomycin (1 µg/ml; Sigma) at Tyr145 (2419-1) were from Epitomics. Abs to DUSP14 and to ERK phosphorylated at Thr202 and Tyr204 (2.5 µg/ml; BioLegend) for 4 d. For Th1 differentiation, cells were cultured in RPMI 1640 plus 10% FBS medium containing IL-12 (2.5 ng/ml; R&D Systems), anti–IFN-γ (2.5 µg/ml; BioLegend) and anti–IFN-γ (2.5 µg/ml; BioLegend) for 4 d. For Th1 differentiation, cells were cultured in RPMI 1640 plus 10% FBS medium containing IL-12 (2.5 ng/ml; R&D Systems), IL-2 (2.5 µg/ml; BioLegend) and anti–IL-4 (0.625 µg/ml; BioLegend) for 5 d. Cells were re-stimulated with PMA plus ionomycin in the presence of GolgiStop (BD Biosciences) for 3 h. Cells were then permeabilized and stained with the appropriate Abs.

Pharmacological analysis

Ab to PKC-δ phosphorylated at Thr508 (4508), ZAP70 phosphorylated at Tyr192 (2717), MKK4 phosphorylated at Ser357/Thr358 (9156), IKK phosphorylated at Ser32, Th2, (2094), TAK1 (3226), and TAB1 (4505) were from Cell Signaling. Ab to JNK phosphorylated at Thr183/Tyr185 (9050) was from Abcam. Ab to ERK phosphorylated at Thr202/Tyr204 (61293) was from BD Biosciences. For intracellular staining, cells were permeabilized for 1 h in 100 µl Cytofix/Cytperm buffer (BD Biosciences) and then stained for intracellular cytokines at 4°C for 1 h. To purify T cells, RBC-depleted splenocytes and lymph node cells were isolated and negatively selected using a mixture of anti-B220, anti-CD11b, and anti-CD49d Abs (BioLegend) on a MACS column (Miltenyi Biotec).

Flow cytometry

CD4+CD25+ T cells were purified from the spleen of mice. Cells were activated with 2 µg/ml anti-CD3 (145-2C11) plus 2 µg/ml anti-CD28 (37.51; both from BD Biosciences) Abs. Th1 differentiation, cells were cultured in RPMI 1640 plus 10% FBS medium containing IL-12 (20 ng/ml; R&D Systems), TGF-β (10 ng/ml; Sigma), IL-23 (50 ng/ml; R&D Systems), anti–IL-4 (2.5 µg/ml; BioLegend), and anti–IFN-γ (2.5 µg/ml; BioLegend) for 4 d. For Th1 differentiation, cells were cultured in RPMI 1640 plus 10% FBS medium containing IL-12 (2.5 ng/ml; R&D Systems), IL-2 (2.5 µg/ml; R&D Systems), and anti–IL-4 (0.625 µg/ml; BioLegend) for 5 d. Cells were re-stimulated with PMA plus ionomycin in the presence of GolgiStop (BD Biosciences) for 3 h. Cells were then permeabilized and stained with the appropriate Abs.

Liquid chromatography–mass spectrometry

The sample preparation and liquid chromatography–mass spectrometry analysis were as described (20).

Plasminoids, Abs, and purified proteins

Ab to PKC-δ phosphorylated at Thr508 (07-885) was from Upstate Bio-technology. Abs to PLC-γ-phosphorylated at Thr508 (4508), ZAP70 phosphorylated at Tyr192 (2717), MKK4 phosphorylated at Ser357/Thr358 (9156), IKK phosphorylated at Ser32, Th2, (2094), TAK1 (3226), and TAB1 (4505) were from Cell Signaling. Abs to JNK phosphorylated at Thr183/Tyr185 (2155-1) and SLP-76 phosphorylated at Tyr145 (2419-1) were from Epitomics. Abs to TAB1 phosphorylated at Thr431 (06-1335) and TAB1 phosphorylated at Thr431 (06-1335) were from Cell Signaling. Abs to JNK phosphorylated at Thr183/Tyr185 (2155-1) and SLP-76 phosphorylated at Tyr145 (2419-1) were from Epitomics. Abs to TAB1 phosphorylated at Thr431 (06-1335) and TAB1 phosphorylated at Thr431 (06-1335) were from Cell Signaling. Abs to JNK phosphorylated at Thr183/Tyr185 (2155-1) and SLP-76 phosphorylated at Tyr145 (2419-1) were from Epitomics. Abs to TAB1 phosphorylated at Thr431 (06-1335) and TAB1 phosphorylated at Thr431 (06-1335) were from Cell Signaling. Abs to JNK phosphorylated at Thr183/Tyr185 (2155-1) and SLP-76 phosphorylated at Tyr145 (2419-1) were from Epitomics. Abs to TAB1 phosphorylated at Thr431 (06-1335) and TAB1 phosphorylated at Thr431 (06-1335) were from Cell Signaling.
plasmids were constructed by subcloning DUSP14 cDNA into the vector pCMV6-AC-Flag (OriGene Technologies) or pcDNA4-Myc-His (Invitrogen). The pCMV6-DUSP14 (C111S) mutant plasmid was generated by PCR mutagenesis. For in vitro binding assays, purified TAB1 proteins were isolated from HEK293T cells transfected with Flag–TAB1, followed by Flag-peptide elution. Purified TAB1 proteins were incubated with either GST only or rGST-DUSP14 proteins at 4°C for 2 h, followed by GST pull-down assays. rGST-TAK1 proteins were incubated with either purified DUSP14 or TAB1 proteins at 4°C for 2 h, followed by GST pull-down assays. The lysates were washed, boiled in 2× sample buffer, and analyzed by immunoblotting.

**Transient transfection and T cell activation**

For transient transfection assays, cells were transfected with a Neon Transfection System (Invitrogen). Electroporation settings were as follows: 1440 V for a duration of 40 ms and one pulse for Jurkat (J-TAg clone) T cells and 2200 V for a duration of 20 ms and one pulse for primary T cells. For induction of T cell activation, Jurkat (J-TAg clone) T cells were stimulated with anti-CD3 Ab (3 μg/ml; OKT3; eBioscience) for the indicated times at 37°C. Primary T cells were stimulated with biotin-conjugated anti-CD3 (3 μg/ml) and anti-CD28 (3 μg/ml; 37.51; eBioscience) Abs plus streptavidin (3 μg/ml) or PMA (0.02 μg/ml; Sigma) plus ionomycin (0.2 μg/ml; Sigma) for the indicated times at 37°C. Murine primary T cells were transfected with a mixture of four unique 29-mer GFP-tagged TAB1 short hairpin RNAs (shRNAs) or a scrambled GFP-tagged shRNA (both from OriGene Technologies) for 36 h. Cells were stimulated with biotin-conjugated anti-CD3 (3 μg/ml; 500A2; eBioscience) Ab plus streptavidin (3 μg/ml; Sigma) for 15 min, followed by intracellular staining for p-JNK (Cell Signaling), p-IKK (Santa Cruz), or p-ERK (Cell Signaling). The GFP-tagged shRNA-transfected cells were GFP gated for flow cytometry analysis.

**Alpha technology/protein–protein interaction assay**

Alpha technology experiments were performed according to the manufacturer’s protocol (PerkinElmer Life Sciences). HEK293T cells were cotransfected with Myc-DUSP14 plus either Flag–TAK1 or Flag–TAB1 for 24 h. The cells were lysed in lysis buffer (50 mM Tris-HCl, 125 mM NaCl, 5% glycerol, 0.2% Nonider P-40, 1.5 mM MgCl2, 25 mM NaF, 1 mM Na3VO4). The cell lysates were incubated with anti-Myc beads for 60 min and then incubated with anti-Flag beads (both from PerkinElmer) for another 60 min. The Alpha signaling was determined by an EnVision 2104 Multilabel Reader (PerkinElmer).

**Statistical methods**

The p values were determined using the Student t test. Values < 0.05 were considered statistically significant.

**Results**

**Normal lymphoid organ development in DUSP14-deficient mice**

To study the function of DUSP14 in TCR signaling, we generated DUSP14-deficient mice. An insertion vector containing a splice
acceptor, β-gal and neomycin resistance genes, and a polyadenylation sequence was inserted in the intron between exons 2 and 3 of the targeted DUSP14 allele (Supplemental Fig. 1A). Successful targeting was confirmed by PCR analysis of genomic DNA from mice tails (Supplemental Fig. 1B). Western blot analysis confirmed the loss of DUSP14 expression in the thymus of the DUSP14-deficient mice (Supplemental Fig. 1C). DUSP14-deficient mice were born at the expected Mendelian ratio and survived to adulthood without any obvious physical abnormalities. We next examined whether loss of DUSP14 expression might show any defect in the lymphocyte development in DUSP14-deficient mice. Total thymic cellularity was similar in WT and DUSP14-deficient mice. Flow cytometric analysis showed that DUSP14 deficiency did not alter the development of CD4⁺CD8⁻ double-negative, CD4⁺CD8⁺ double-positive, CD4⁺ single-positive, or CD8⁺ single-positive thymocytes (Fig. 1A). The expression pattern of CD44 or CD25 on CD4⁺CD8⁻ double-negative thymocytes was also unaffected by DUSP14 deficiency (Fig. 1B). In the spleen and lymph nodes, there were similar numbers of CD3⁺ T cells, CD4⁺ T cells, CD8⁺ T cells, and B220⁺ B cells between WT and DUSP14-deficient mice (Fig. 1C, Supplemental Fig. 1D). The frequencies of naive (CD44⁻CD62L⁺), effector memory (CD44⁺CD62L⁻), and memory (CD44⁺CD62L⁺) T cells in the spleen were also unaffected in DUSP14-deficient mice (Fig. 1D). Cell numbers of regulatory T cells (CD4⁺Foxp3⁺) in thymus, spleen, and lymph nodes were also unaffected in DUSP14-deficient mice (Fig. 1E, Supplemental Fig. 1E). These data suggest that DUSP14 is not essential for lymphocyte development.

**T cell activation and proliferation are enhanced in DUSP14-deficient T cells**

After TCR ligation, T cells undergo a series of signaling events, including upregulation of cell surface activation markers, proliferation, and cytokine production. To examine the role of DUSP14 in TCR signaling, we purified naïve T cells from WT and DUSP14-deficient mice and determined T cell activation upon anti-CD3 Ab stimulation. The percentages of activated CD69⁺ T cells (Fig. 2A) or CD25⁺ T cells (Fig. 2B) were increased in DUSP14-deficient T cells upon anti-CD3 Ab stimulation. We further studied the effect of DUSP14 on T cell proliferation using [³H]thymidine incorporation assays. DUSP14 deficiency significantly enhanced T cell proliferation induced by stimulation with anti-CD3 Ab. 

**Figure 2.** DUSP14-deficient (DUSP14-KO) T cells are hyperproliferative in response to anti-CD3 alone or PMA plus ionomycin stimulation. (A and B) Flow cytometry analysis of T cell activation markers, CD69 and CD25, in WT and DUSP14-KO T cells upon anti-CD3 Ab stimulation for 16 h. Three mice were analyzed for each genotype. Numbers are the percentages of CD69⁺ or CD25⁺ cells in live cells. (C) Proliferation of T cells stimulated with anti-CD3 Ab for 72 h was analyzed by [³H]thymidine incorporation. (D) Flow cytometry analysis of CD4⁺ CD8⁺ thymocytes obtained 48 h after mice were injected with PBS or 10 µg/ml anti-CD3 Ab. (E) Viability of T cells pre-activated with PMA plus ionomycin for 24 h, incubated in IL-2, and restimulated with plate-bound anti-CD3 (left panel) or anti-Fas (right panel) for 48 h. Cells negative for staining with annexin V were considered viable. (F) ELISAs of IL-2, IFN-γ, and IL-4 in culture supernatants of anti-CD3 Ab-stimulated T cells isolated from WT and DUSP14-KO mice. Three mice were analyzed for each genotype. (G) CFSE dilution assays of WT or DUSP14-KO T cells treated for 48 h with PMA plus ionomycin. Proliferation indices (mean ± SEM) analyzed by FlowJo software are also shown. (H) PMA plus ionomycin–induced cytokine-production profiles at 48 h in purified splenic T cells. Three mice were analyzed for each genotype. Data are mean ± SEM. *p < 0.05, two-tailed t test.
Next, we studied whether the hyperproliferation of DUSP14-deficient T cells is due to a reduction in apoptosis. To study activation-induced cell death in vivo, we examined CD4+CD8+ thymocyte death induced by injection of anti-CD3 Ab. We found that anti-CD3–induced thymocyte deletion was similar between WT and DUSP14-deficient mice (Fig. 2D). Furthermore, WT and DUSP14-deficient T cells showed similar percentages of cell death induced by anti-CD3 Ab or anti-Fas Ab restimulation in vitro (Fig. 2E). These results indicate that the hyperproliferation of DUSP14-deficient T cells is not due to a reduction in apoptosis.

To examine the effect of DUSP14 deficiency on T cell cytokine production, we purified naive T cells from WT and DUSP14-deficient mice and determined cytokine production upon T cell activation using ELISA assays. Upon anti-CD3 Ab stimulation, DUSP14-deficient T cells also produced more IL-2, IFN-γ, and IL-4 than did WT T cells (Fig. 2F). CD28 provides a costimula-

(FIG. 2C). Next, we studied whether the hyperproliferation of DUSP14-deficient T cells is due to a reduction in apoptosis. To study activation-induced cell death in vivo, we examined CD4+CD8+ thymocyte death induced by injection of anti-CD3 Ab. We found that anti-CD3–induced thymocyte deletion was similar between WT and DUSP14-deficient mice (Fig. 2D). Furthermore, WT and DUSP14-deficient T cells showed similar percentages of cell death induced by anti-CD3 Ab or anti-Fas Ab restimulation in vitro (Fig. 2E). These results indicate that the hyperproliferation of DUSP14-deficient T cells is not due to a reduction in apoptosis. To examine the effect of DUSP14 deficiency on T cell cytokine production, we purified naive T cells from WT and DUSP14-deficient mice and determined cytokine production upon T cell activation using ELISA assays. Upon anti-CD3 Ab stimulation, DUSP14-deficient T cells also produced more IL-2, IFN-γ, and IL-4 than did WT T cells (Fig. 2F). CD28 provides a costimula-

FIGURE 3. DUSP14 interacts with TAB1 in T cells. (A) Sequence of TAB1. Five TAB1 peptides (underlined) were identified by mass spectrometry. (B) DUSP14 interacts with TAB1 in HEK293T cells. Coimmunoprecipitation and immunoblot analysis of DUSP14 and TAB1 in lysates of HEK293T cells transfected with empty vector or plasmid encoding Flag–TAB1, with or without plasmid encoding Myc–DUSP14. (C) DUSP14 interacts with TAB1 in Jurkat T cells. Coimmunoprecipitation and immunoblot analysis of DUSP14 and TAB1 in lysates of Jurkat (J-TAg clone) T cells transfected with plasmid encoding Flag–DUSP14. (D) Interaction of endogenous DUSP14 and TAB1 in murine primary T cells. Coimmunoprecipitation and immunoblot analysis of DUSP14 and TAB1 in lysates of primary T cells.

FIGURE 4. DUSP14 interacts directly with TAB1 and dephosphorylates TAB1 at Ser438. (A) DUSP14 interacts directly with TAB1 in vitro. In vitro binding assays of purified Flag–TAB1 and GST–DUSP14 proteins. (B) DUSP14 does not interact directly with TAK1 in vitro. In vitro binding assays of GST–TAK1 proteins with either purified Flag–DUSP14 proteins or purified Flag–TAB1 proteins. (C) DUSP14–TAB1 interaction was determined by Alpha technology protein–protein interaction assay. Data are representative of at least three independent experiments. (D) DUSP14–mediated TAB1 dephosphorylation at Ser438 in HEK293T cells. HEK293T cells were transfected with Flag–TAB1 WT or Flag–TAB1 mutant (S438A) plus either Flag–DUSP14 WT or Flag–DUSP14 mutant (C111S). The cells lysates were immunoblotted with Abs to p-TAB1 at Ser438 and Thr431. (E) In vitro phosphatase assays of purified DUSP14 WT or phosphatase-dead mutant C111S (CS), using purified Flag–TAB1 WT or Flag–TAB1 mutant (S438A) as substrates. (F) Immunoblotting of lysates of Jurkat (J-TAg clone) T cells stimulated with anti-CD3 Ab at the indicated times. The lysates were immunoblotted with Abs to p-TAB1 at Ser438 or Thr431. (G) Coimmunoprecipitation and immunoblot analysis of phosphatase-dead DUSP14 mutant (C111S) and Ser438-phosphorylated TAB1 in lysates of Jurkat (J-TAg clone) T cells transfected with plasmid encoding DUSP14 mutant (C111S).
DUSP14/MKP6 INHIBITS TAB1-MEDIATED TCR SIGNALING

FIGURE 5. DUSP14 negatively regulates activation of the TAB1–TAK1 complex and its downstream molecules. Purified T cells were stimulated with anti-CD3 plus anti-CD28 Abs (A) or PMA plus ionomycin (C) at the indicated times. The cells were lysed; the lysates were immunoblotted with Abs to p-TAB1 at Ser438 or Thr431, p-TAK1, p-IKK, p-JNK, p-ERK, p-p38, and β-actin. (B, D) The relative phosphorylation levels were determined by densitometry analysis.
TCR signaling (Supplemental Fig. 2B). Consistently, TCR-induced activation of LCK, ZAP70, and SLP-76 was not affected by DUSP14 deficiency (Supplemental Fig. 2C). The activation of IKK, JNK, and ERK was significantly reduced in DUSP14 WT, but not in DUSP14 mutant (C111S), overexpressed cells upon TCR stimulation (Supplemental Fig. 2D). Furthermore, compared with vector control, DUSP14 WT overexpression inhibited the activation of IKK, MKK4, JNK, and ERK upon PMA plus ionomycin stimulation (Supplemental Fig. 2E), suggesting that ERK may be a direct target of DUSP14 upon T cell activation. In addition, the activation of MKK4 and IKK is inhibited by DUSP14; thus, DUSP14 may function upstream of both MKK4 and IKK upon T cell activation.

DUSP14 directly dephosphorylates and inactivates TAB1 in TCR signaling

Because the activation of MKK4 and IKK is blocked by DUSP14, DUSP14 may target a signaling molecule upstream of both MKK4 and IKK in the TCR-signaling pathway. Thus, we searched for the target(s) of DUSP14 in TCR signaling using mass spectrometry. Jurkat (J-TAg clone) T cells were transfected with Flag–DUSP14 and then stimulated with anti-CD3 Ab. DUSP14-associated proteins were coimmunoprecipitated with anti-Flag Ab and then fractionated by SDS-PAGE. The excised protein bands were analyzed by liquid chromatography–mass spectrometry. We found that a protein with an Mr ∼60 kDa coimmunoprecipitated with DUSP14; mass spectrometry identified this as TAB1 (Fig. 3A, Supplemental Fig. 3). An interaction of DUSP14 with TAB1 was detected using a coimmunoprecipitation assay in HEK293T cells (Fig. 3B). To determine whether DUSP14 regulates TAB1 activation during TCR signaling, we investigated the potential interaction between DUSP14 and TAB1 during TCR signaling by coimmunoprecipitation assays. DUSP14 constitutively interacted with TAB1 in Jurkat (J-TAg clone) T cells (Fig. 3C) during TCR signaling. Coimmunoprecipitation of DUSP14 also pulled down TAK1, possibly through TAB1 because TAB1 is a TAK1-binding protein (Fig. 3C). The interaction between endogenous DUSP14 and TAB1 proteins in murine primary T cells was further confirmed using coimmunoprecipitation assays (Fig. 3D). We further studied whether DUSP14 interacts directly with TAB1 in vitro. We found a direct interaction between DUSP14 and TAB1 in vitro using purified GST-DUSP14 and Flag–TAB1 proteins (Fig. 4A). In contrast, DUSP14 did not interact directly with TAK1 in vitro using purified proteins, whereas a direct interaction between TAK1 and TAB1 was detectable as expected (Fig. 4B). Alpha technology is a bead-based assay used to study protein–protein interaction up to 200 nm in solution. HEK293T cells were transfected with Myc–DUSP14 plus either Flag–TAK1 or Flag–TAB1. The cells were lysed; the lysates were incubated with anti-Myc beads and then anti-Flag beads. A direct interaction between DUSP14 and TAB1, but not DUSP14 and TAK1, was detected (Fig. 4C).

TAB1 is phosphorylated at Ser438, Thr431, and Ser423 in several inflammatory signaling pathways (13). Next, we studied whether DUSP14 dephosphorylates TAB1 in vivo and in vitro. HEK293T cells were cotransfected with DUSP14 WT or DUSP14 mutant (C111S) plus either TAB1 WT or TAB1 mutant (S438A). The in vivo phosphatase assay showed that DUSP14 WT dephosphorylated TAB1 at Ser438, but not Thr431, whereas the phosphatase-dead DUSP14 mutant (C111S) did not dephosphorylate TAB1.

**FIGURE 6.** The enhanced JNK and IKK activation of DUSP14-deficient T cells is attenuated by TAB1 knockdown. (A) Flow cytometry analysis of TAB1 expression in TAB1 shRNA-transfected cells. Murine primary T cells were transfected with GFP-tagged TAB1 shRNAs or a scrambled GFP-tagged shRNA for 36 h, followed by intracellular staining for TAB1. The GFP-tagged shRNA-transfected cells were GFP gated for flow cytometry analysis. Samples were stained with the secondary Ab only as negative controls (shaded graph). (B and C) WT and DUSP14-deficient (DUSP14-KO) T cells were transfected with GFP-tagged TAB1 shRNAs or a scrambled GFP-tagged shRNA for 36 h and then stimulated with anti-CD3 Ab for 15 min. The phosphorylation of JNK (B) and IKK (C) in shRNA-transfected cells (GFP gated) was examined by intracellular staining. Data (mean ± SEM) are representative of three independent experiments. *p < 0.05, two-tailed t test.
(Fig. 4D). Consistently, purified Flag–DUSP14 WT proteins dephosphorylated purified Flag–TAB1 proteins at Ser\(^{438}\) using in vitro phosphatase assays (Fig. 4E). These results suggest that DUSP14 directly interacts with TAB1 and dephosphorylates TAB1 at Ser\(^{438}\). We studied whether Ser\(^{438}\) phosphorylation of TAB1 is regulated by DUSP14 during TCR signaling. First, we investigated TAB1 phosphorylation at Ser\(^{438}\) during TCR signaling. Jurkat (J-TAg clone) T cells were stimulated with anti-CD3 Ab, followed by immunoblot analysis. We found that TAB1 was inducibly phosphorylated at Ser\(^{438}\) and Thr\(^{431}\) residues upon TCR signaling (Fig. 4F). The in vivo and in vitro phosphatase assays showed that DUSP14 dephosphorylated TAB1 at Ser\(^{438}\) but not at Thr\(^{431}\) (Fig. 4D, 4E). Thus, we studied whether DUSP14 interacts with Ser\(^{438}\)-phosphorylated TAB1 during TCR signaling. Because it may be difficult to detect the interaction between DUSP14 and phosphorylated TAB1, because phosphatases may quickly dissociate from their substrates after dephosphorylation, we used the phosphatase-dead DUSP14 mutant (C111S) to study the interaction. Jurkat (J-TAg clone) T cells were transfected with phosphatase-dead DUSP14 mutant (C111S) and then stimulated with anti-CD3 Ab. Coimmunoprecipitation assays showed that phosphatase-dead DUSP14 mutant (C111S) inducibly interacted with Ser\(^{438}\)-phosphorylated TAB1 during TCR signaling (Fig. 4G). Our results indicated a novel role for DUSP14 in negatively regulating TCR signaling.

DUSP14 controls immune responses in vivo

To investigate whether the enhanced in vitro proliferation of DUSP14-deficient T cells correlates with in vivo activation of DUSP14-deficient T cells, we immunized mice with a T cell–dependent Ag: KLH. After KLH immunization, the lymph nodes were isolated from immunized mice and restimulated with KLH in vitro. DUSP14-deficient cells showed markedly increased Ag-specific T cell proliferation (Fig. 7A) and cytokine production (Fig. 7B), as measured by \(^{[3}H\)thymidine-incorporation and ELISA assays. To determine whether DUSP14 activity influences T cell–dependent humoral responses, we measured Ag-specific Ab production in sera from immunized WT and DUSP14-deficient mice. The Ag-specific IgM, IgG1, and IgG2b levels were increased in DUSP14-deficient mice during the primary immune response (Fig. 7C). Thus, the enhanced Ag-specific T cell activation in DUSP14-deficient T cells may contribute to the enhanced Ab production in DUSP14-deficient mice. In addition to T cells, DUSP14 deficiency in B cells may also contribute to the enhanced Ab production in DUSP14-deficient mice.

To determine whether DUSP14-deficient mice are more susceptible to autoimmune disease, we immunized mice with MOG in CFA to induce EAE. DUSP14-deficient mice were more susceptible to EAE induction and displayed severe paralysis of forelimbs and hindlimbs (Fig. 8A). Serum IL-17A and IFN-γ levels were higher in DUSP14-deficient mice than in WT mice (Fig. 8B). More CD4\(^+\) T cells infiltrated the brain tissues of diseased DUSP14-deficient mice, whereas similar numbers of CD11b\(^+\) cells infiltrated the brain tissues of diseased DUSP14-deficient mice (Fig. 8C). The percentage of Th17 cells in the infiltrating CD4\(^+\) T cells in the brain and spinal cords of diseased mice at day 14 was significantly higher in DUSP14-deficient mice than in WT mice (Fig. 8D).

Restimulated DUSP14-deficient lymph node T cells obtained from MOG-immunized mice showed enhanced proliferation (Fig. 8E) and increased production of cytokines, including IFN-γ and IL-17A (Fig. 8F). To investigate whether the enhanced Th17 and Th1 responses in DUSP14-deficient mice are T cell intrinsic, we determined the in vitro Th17 and Th1 differentiation of DUSP14-deficient T cells. Consistent with the results obtained above, the in vitro differentiation of Th17 and Th1 were enhanced in DUSP14-deficient cells (Fig. 8G). Thus, DUSP14 deficiency promotes the proliferation and the activation of autoreactive T cells, leading to enhanced EAE induction in DUSP14-deficient mice (Fig. 9). In addition to T cells, other immune cells may also contribute to the exacerbated EAE symptoms in DUSP14-deficient mice.
Discussion

At least 25 members of the DUSP family have been identified. Only two DUSPs (DUSP4 and DUSP10) are reported to be involved in T cell activation and T cell–mediated immune responses using KO mice (21–23). DUSP10 (also named MKP5) is a positive regulator in T cell proliferation and T cell–mediated immune responses (22). DUSP4 (also named MKP2) suppresses CD4+ T cell proliferation but induces normal Th1/Th2 responses following KLH immunization (23), whereas DUSP4 enhances Th1 responses following *Leishmania mexicana* infection (21). To our knowledge, our study demonstrates for the first time a novel immune function for DUSP14 in T cells in vivo. A key finding of our study is the identification of DUSP14 as a negative regulator upon T cell activation and immune responses using DUSP14-deficient mice. DUSP14-deficient T cells proliferate more and produce excess IL-2, IFN-γ, and IL-4 upon stimulation with anti-CD3, anti-CD3 plus anti-CD28, or PMA plus ionomycin. Also, DUSP14-deficient mice are more susceptible to EAE induction. A previous report (5) showed that DUSP14 interacts with CD28 in overexpressing systems. Primary human peripheral blood T cells transduced with a dominant-negative DUSP14 mutant secrete more IL-2 in response to anti-CD3 plus anti-CD28 costimulation but not anti-CD3 alone or PMA plus ionomycin. Dominant-negative mutants may show artifacts; it is plausible that ectopically expressed dominant-negative DUSP14 mutant could compete with endogenous DUSP14 proteins for binding to a DUSP14-interacting protein involved in the CD28-signaling pathway, thus indirectly affecting CD28 signaling.

In this study, we also show that TCR-induced ERK activation is enhanced in DUSP14-deficient T cells and that the activation of upstream kinase MEK1/2 is unaffected. DUSP14 was shown to dephosphorylate ERK in vitro; our data from DUSP14-deficient T cells are consistent with these findings. However, our data only demonstrate that the enhanced ERK activation in DUSP14-deficient T cells is TAB1 independent. Our data show that DUSP14 is dispensable for T cell development. In contrast, DUSP5-transgenic and DUSP6 (also called MKP3)-transgenic mice show impaired thymocyte positive selection by inhibiting ERK activation (24, 25). This may be because expression of DUSP14 is much less than that of other DUSPs, including DUSP5 and DUSP6, in thymus (26).

Another key finding of our study is that DUSP14 directly dephosphorylates TAB1 at Ser18, leading to TAB1–TAK1 complex inactivation during TCR signaling (Fig. 9). TAB1 is required for TAK1 activation (14); TAK1 is not activated by IL-1 or TNF-α in TAB1-KO mouse embryonic fibroblasts (15). p38 phosphorylates TAB1 at Ser213 and Thr221 upon IL-1 or TNF-α stimulation, leading to feedback inhibition of TAK1 activation (17). However, the roles of TAB1 in T cells are still unknown. In this report, we...
The role of TAK1 in IL-4 and IFN-γ regulation in T cells, as well as ERK2 in IL-2 regulation in T cells, needs to be addressed. ERK2-deficient CD4 T cells show impaired Th1, but not Th17, differentiation in vitro (28). Thus, the enhanced Th1 differentiation in vitro in DUSP14-deficient T cells may be due to the effect of ERK2 hyperactivation. The results from TAK1–small interfering RNA knockdown in myeloid cells and TAK1-conditional KO in glia cells suggest that TAK1 is required for Th1 and Th17 differentiation and in vivo induction of autoimmune (29, 30). ERK1-deficient mice in the 129 Sv, but not the C57BL/6, genetic background are more susceptible to EAE induction (31). Thus, the enhanced Th1/Th17 differentiation in vivo and exacerbated EAE symptoms in DUSP14-deficient mice are likely due to the effect of TAK1 hyperactivation. In summary, DUSP14 attenuates TCR signaling and immune responses by inhibiting both TAB1–TAK1 and ERK activation.

Acknowledgments

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Disclosures

The authors have no financial conflicts of interest.

References


Supplementary Figure 1. Generation of the DUSP14-deficient mice.

(A) The structure of the gene-trap vector. SA, splicing acceptor; β-geo (a fusion of β-galactosidase and neomycin resistance genes); pA, polyadenylation; the box with numbers, the exon of DUSP14; dotted arrow, the primers for PCR. (B) Genotyping of mice from the progeny of “heterozygous-by-heterozygous” mating. The PCR products of the higher band (1300 bp) indicate the DUSP14 mutant (DUSP14-KO) allele; and the lower band (900 bp) indicate the wild-type (WT) allele. (C) Western blot analysis
of thymic cell lysates from wild-type (WT) and DUSP14-deficient (DUSP14-KO) mice using anti-DUSP14 antibodies. (D) Flow cytometry of surface marker expression including CD3^+ T cells, CD4^+ T cells, CD8^+ T cells, and B220^+ B cells on lymph nodes. (E) Flow cytometry of regulatory T (CD4^+Foxp3^+) cells in the lymph node. Percentage of cells within each quadrant is shown on the plots. Five mice were analyzed for each genotype. Data are presented as mean ± s.e.m.
Supplementary Figure 2. DUSP14 overexpression inhibits anti-CD3 or PMA plus ionomycin signaling.

(A) HEK293T cells were transfected with vector alone, Flag-DUSP14 wild-type (WT), or Flag-DUSP14 (C111S) mutant for 24 h. Flag-DUSP14 wild-type (WT) and Flag-DUSP14 (C111S) mutant proteins were immunoprecipitated with anti-Flag antibodies. The immunoprecipitates were then subjected to phosphatase assays. (B)
Jurkat (J-TAg clone) T cells were transiently transfected with empty vector, DUSP14 wild-type (WT), or DUSP14-mutant (C111S) for 36 h. These cells were treated with anti-CD3 antibody at the indicated times. The levels of proteins in cell extracts were examined by immunoblotting. (C) Immunoblot analysis of Lck, phosphorylated (p-) ZAP-70, and p-SLP-76 in lysates of purified wild-type (WT) or DUSP14-deficient (DUSP14-KO) T cells after stimulation with anti-CD3 antibody. (D, E) Jurkat (J-TAg clone) T cells were transiently transfected with empty vector, DUSP14 wild-type (WT), or DUSP14-mutant (C111S) for 36 h. These cells were treated with anti-CD3 antibody (D) or PMA plus ionomycin (E). The levels of proteins in cell extracts were examined by immunoblotting.
A

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B

Images of mass spectra with peaks at different m/z values, showing relative abundance graphs for the peptides identified.
Supplementary Figure 3. Identification of TAB1 as a DUSP14-binding protein by mass spectrometry.

(A) Mass spectrometry profile of TAB1. Jurkat (J-TAg clone) T cells were transfected with FLAG-DUSP14 wild-type (WT). The transfected cells were treatment with anti-CD3 antibody for 15 min. Flag-DUSP14 proteins were then isolated from the cell lysate using anti-Flag affinity agarose gel. DUSP14-interacting protein bands from silver-stained SDS-polyacrylamide gels were excised, destained, and digested with trypsin, and then subjected to LC-MS/MS. (B) The MS/MS fragmentation spectra of the tryptic peptides of TAB1 contain the $^{105}$V-$^{115}$, $^{116}$S-$^{128}$, $^{178}$L-$^{187}$, $^{337}$I-$^{348}$, and $^{490}$L-$^{504}$ fragments.
Supplementary Figure 4. The enhanced ERK activation of DUSP14-deficient T cells upon T-cell activation are not attenuated by TAB1 knockdown.

(A, B) DUSP14-deficient T cells were transfected with GFP-tagged TAB1 shRNAs or a scrambled GFP-tagged shRNA for 36 h, and then stimulated with anti-CD3 antibody for 15 min. The phosphorylation of ERK in shRNA-transfected cells (GFP-gated) was examined by intracellular staining. Data are representative of three independent experiments. Data are presented as mean ± s.e.m. * P<0.05 (two-tailed t-test).