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$\gamma\delta$ TCR recruits the Syk/PI3K axis to drive proinflammatory differentiation program

Ryunosuke Muro,^{1,2} Takeshi Nitta,² Kenta Nakano,³ Tadashi Okamura,^{3,4} Hiroshi Takayanagi,² and Harumi Suzuki¹

¹Department of Immunology and Pathology, Research Institute, National Center for Global Health and Medicine, Chiba, Japan. ²Department of Immunology, Graduate School of Medicine and Faculty of Medicine, The University of Tokyo, Tokyo, Japan. ³Department of Laboratory Animal Medicine, and ⁴Section of Animal Models, Research Institute, National Center for Global Health and Medicine, Tokyo, Japan.

$\gamma\delta$ T cells produce inflammatory cytokines and have been implicated in the pathogenesis of cancer, infectious diseases, and autoimmunity. The T cell receptor (TCR) signal transduction that specifically regulates the development of IL-17-producing $\gamma\delta$ T ($\gamma\delta$ T17) cells largely remains unclear. Here, we showed that the receptor proximal tyrosine kinase Syk is essential for $\gamma\delta$ TCR signal transduction and development of $\gamma\delta$ T17 in the mouse thymus. Zap70, another tyrosine kinase essential for the development of $\alpha\beta$ T cells, failed to functionally substitute for Syk in the development of $\gamma\delta$ T17. Syk induced the activation of the PI3K/Akt pathway upon $\gamma\delta$ TCR stimulation. Mice deficient in PI3K signaling exhibited a complete loss of $\gamma\delta$ T17, without impaired development of IFN- γ -producing $\gamma\delta$ T cells. Moreover, $\gamma\delta$ T17-dependent skin inflammation was ameliorated in mice deficient in RhoH, an adaptor known to recruit Syk. Thus, we deciphered lineage-specific TCR signaling and identified the Syk/PI3K pathway as a critical determinant of proinflammatory $\gamma\delta$ T cell differentiation.

Introduction

$\gamma\delta$ T cells have recently attracted considerable attention because of their inflammatory cytokine-producing potential and their contribution to various pathophysiological states. A subset of $\gamma\delta$ T cells that produces IL-17 (termed $\gamma\delta$ T17 cells) plays a pivotal role not only in protection against bacterial and fungal infection (1) but also in the progression of inflammatory disorders (2–4), tumor growth and metastasis (5–8), and tissue regeneration (9). The cytokine-producing potential of $\gamma\delta$ T cells is programmed during their development in the thymus (10, 11).

Unlike $\alpha\beta$ T cells, the development of which is dependent on positive and negative selections upon the interaction between $\alpha\beta$ T cell receptor ($\alpha\beta$ TCR) and peptide-MHC complexes, $\gamma\delta$ T cells do not require $\gamma\delta$ TCR recognition of ligands for their development in the thymus. Self-oligomerization of $\gamma\delta$ TCR at the cell surface of precursor thymocytes induces their differentiation into mature $\gamma\delta$ T cells (12, 13). It has been proposed that $\gamma\delta$ TCR-ligand interaction determines the effector function of $\gamma\delta$ T cells (14). $\gamma\delta$ T cells that receive the ligand-dependent strong or ligand-independent weak $\gamma\delta$ TCR signals are induced to differentiate into IFN- γ -producing or IL-17-producing subsets, respectively (12, 15). However, the molecular basis for this remains unclear.

Rearranged TCR chains (α/β or γ/δ), together with CD3 subunits (γ , δ , ϵ , and ζ), form TCR-CD3 complexes, which initiate the sequential phosphorylation of proximal tyrosine kinases and activation of downstream signaling pathways in response to ligand-dependent or ligand-independent oligomerization (16). A series of studies have indicated the differences between $\alpha\beta$ T and $\gamma\delta$ T cells

in terms of the TCR-CD3 complex structure and downstream signals. Although the CD3 δ subunit is contained in $\alpha\beta$ TCR, it is barely detectable in $\gamma\delta$ TCR complexes (17). CD3 δ subunit-deficient mice exhibit a developmental arrest of $\alpha\beta$ T cells but not $\gamma\delta$ T cells (18). The mutation of CD3 ϵ (C80G) that prevents conformational changes in TCR-CD3 complexes completely inhibits $\alpha\beta$ T cell development at an early stage. However, it does not impair the development of certain $\gamma\delta$ T cell subsets (19). A recent report showed that mice haploinsufficient for CD3 γ and CD3 δ (*CD3 γ ^{+/−} CD3 δ ^{+/−}*) have reduced TCR signaling and abnormal differentiation in $\gamma\delta$ T cells but not $\alpha\beta$ T cells (20). $\alpha\beta$ T and $\gamma\delta$ T cells also show differential requirements of the Src family kinases in their development. In *Lck/Fyn*-doubly deficient mice, $\alpha\beta$ T cell development is completely inhibited, whereas $\gamma\delta$ T cell development is partially impaired (21, 22). Moreover, $\gamma\delta$ T cells require *Blk*, an Src family kinase primarily expressed in B cells, for the induction of the $\gamma\delta$ T17 subset (23). These findings indicate that the TCR-CD3 complexes and TCR proximal signaling modules in $\gamma\delta$ T cells are distinct from those in $\alpha\beta$ T cells.

In the present study, we investigated the molecular mechanism underlying $\gamma\delta$ TCR signaling that determines the development and effector function of $\gamma\delta$ T cells. We found that Syk, a tyrosine kinase known to associate with the B cell receptor (BCR) and Fc receptor, was pivotal for $\gamma\delta$ TCR signal transduction and $\gamma\delta$ T17 development. Our present results revealed that the deficiency of Syk, but not Zap70, completely abolished the development of $\gamma\delta$ T17 and that Zap70 failed to functionally substitute Syk in $\gamma\delta$ T17 development. We also showed that Syk distinctively induced the development of $\gamma\delta$ T17 through activation of the PI3K/Akt pathway. These results provide a mechanistic insight into the Syk-mediated TCR signal transduction in the determination of $\gamma\delta$ T cell fate.

Results

Preferential requirement of Syk rather than Zap70 in $\gamma\delta$ TCR signals and $\gamma\delta$ T cell development. To characterize the intracellular signal

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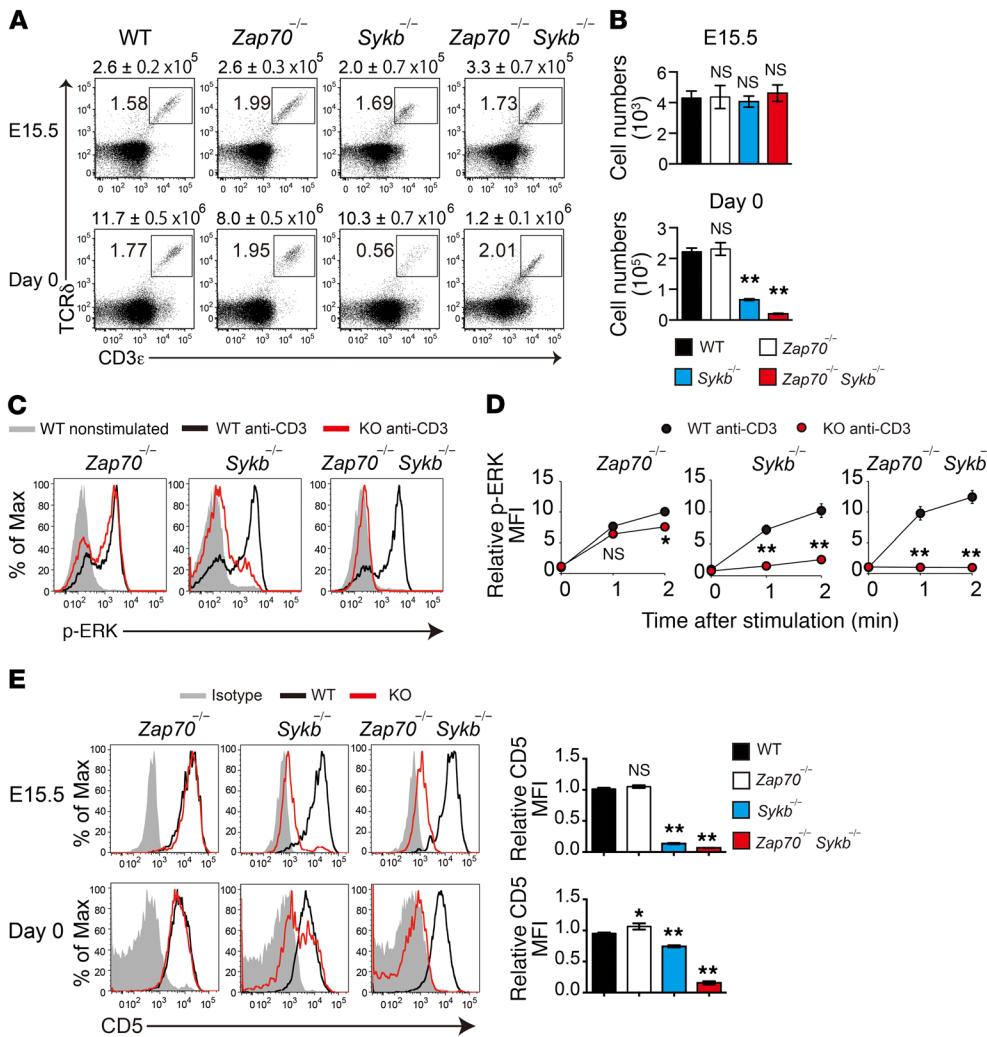


Figure 1. Syk plays a dominant role in $\gamma\delta$ TCR signaling and $\gamma\delta$ T cell development. (A and B) Flow cytometric analysis of CD3 ϵ and TCR δ expression in thymocytes from the indicated mice at E15.5 (WT, *n* = 16; *Zap70*^{-/-}, *n* = 10; *Sykb*^{-/-}, *n* = 8; and *Zap70*^{-/-} *Sykb*^{-/-}, *n* = 2) and on day 0 (WT, *n* = 19; *Zap70*^{-/-}, *n* = 4; *Sykb*^{-/-}, *n* = 7; and *Zap70*^{-/-} *Sykb*^{-/-}, *n* = 8). The total number of thymocytes is indicated above each flow cytometric plot (A). Graphs indicate the total number of $\gamma\delta$ T cells per mouse (B). (C and D) TCR-induced ERK phosphorylation in thymic $\gamma\delta$ T cells from the indicated mice on day 0 (*Zap70*^{-/-}, *n* = 3; *Sykb*^{-/-}, *n* = 4; and *Zap70*^{-/-} *Sykb*^{-/-}, *n* = 3). Histograms indicate p-ERK levels after a 2-minute stimulation (C). MFI relative to the nonstimulated control (D). (E) Histograms show CD5 expression in thymic $\gamma\delta$ T cells from the indicated mice at E15.5 (WT, *n* = 13; *Zap70*^{-/-}, *n* = 10; *Sykb*^{-/-}, *n* = 9; and *Zap70*^{-/-} *Sykb*^{-/-}, *n* = 2) and on day 0 (WT, *n* = 17; *Zap70*^{-/-}, *n* = 3; *Sykb*^{-/-}, *n* = 7; and *Zap70*^{-/-} *Sykb*^{-/-}, *n* = 5). Graphs indicate the MFI relative to WT mice. All data represent the mean \pm SEM. **P* < 0.05 and ***P* < 0.01, by 1-way ANOVA (B and E) and 2-way ANOVA (D). Data represent the combined results of 3 independent experiments (A, B, and E) or a single experiment (C and D). Max, maximum.

transduction downstream of $\gamma\delta$ TCR, we examined protein tyrosine phosphorylation in ex vivo $\gamma\delta$ T cells isolated from the mouse thymus. In response to $\gamma\delta$ TCR engagement with anti-CD3 ϵ antibody, we detected tyrosine phosphorylation of signaling proteins such as Zap70 and Lat in $\gamma\delta$ T cells (Supplemental Figure 1; supplemental material available online with this article; <https://doi.org/10.1172/JCI95837DS1>). Interestingly, we noticed that $\gamma\delta$ T cells exhibited TCR-induced tyrosine phosphorylation of Syk, a tyrosine kinase primarily responsible for signal transduction of the BCR, the Fc receptor, and certain innate receptors (24). Syk and Zap70, which belong to the Syk family kinases, preferentially associate with certain immune receptors in a cell-specific manner and phosphorylate downstream signaling proteins such as Lat and BLNK. It has been recognized that Zap70, but not Syk, is an essential $\alpha\beta$ TCR proximal kinase required for positive and negative selection of $\alpha\beta$ T cells (25–27). In the early stage of $\alpha\beta$ T cell development, Zap70 and Syk play a redundant role (28).

The phosphorylation of both Zap70 and Syk after $\gamma\delta$ TCR stimulation led us to investigate their role in $\gamma\delta$ TCR signals. We analyzed $\gamma\delta$ T cells in Zap70-deficient (*Zap70*^{-/-}), Syk-deficient (*Sykb*^{-/-}), and Zap70/Syk-doubly deficient (*Zap70*^{-/-} *Sykb*^{-/-}) mice. Because the deletion of Syk results in neonatal lethality, we examined $\gamma\delta$ T cells isolated from the thymus of these mice at E15.5 or at birth (day 0).

In the E15.5 thymus, we found that the number of CD3⁺TCR δ ⁺ $\gamma\delta$ T cells was comparable between WT and all mutant mice (Figure 1, A and B). On day 0, *Zap70*^{-/-} mice had a normal number of $\gamma\delta$ T cells in the thymus, whereas *Sykb*^{-/-} and *Zap70*^{-/-} *Sykb*^{-/-} mice showed a drastic reduction in the number of thymic $\gamma\delta$ T cells, suggesting a critical contribution of Syk to the development of $\gamma\delta$ T cells.

To assess the effect of Syk and/or Zap70 deficiency on $\gamma\delta$ TCR signaling pathways, we examined the phosphorylation of the MAP kinases ERK1 and ERK2 upon anti-CD3 ϵ stimulation (Figure 1, C and D). In *Zap70*^{-/-} $\gamma\delta$ T cells, ERK phosphorylation was mildly decreased (1 minute after stimulation, 16% reduction of mean fluorescence intensity [MFI]) compared with that detected in WT $\gamma\delta$ T cells. *Sykb*^{-/-} $\gamma\delta$ T cells showed a substantial reduction in ERK phosphorylation (79% reduction of MFI), whereas it was undetectable in *Zap70*^{-/-} *Sykb*^{-/-} $\gamma\delta$ T cells. These results indicate a dominant role for Syk, but not Zap70, in $\gamma\delta$ TCR signaling, despite their functional redundancy. Indeed, the surface expression of CD5, an indicator of in vivo TCR signal strength, was markedly reduced in *Sykb*^{-/-} $\gamma\delta$ T cells and was nearly undetectable in *Zap70*^{-/-} *Sykb*^{-/-} $\gamma\delta$ T cells, whereas it remained unaffected in *Zap70*^{-/-} $\gamma\delta$ T cells (Figure 1E). Taken together, our results demonstrate that Syk is the major $\gamma\delta$ TCR proximal tyrosine kinase in $\gamma\delta$ TCR signaling and $\gamma\delta$ T cell development in the thymus, whereas Zap70 has only a partial contribution.

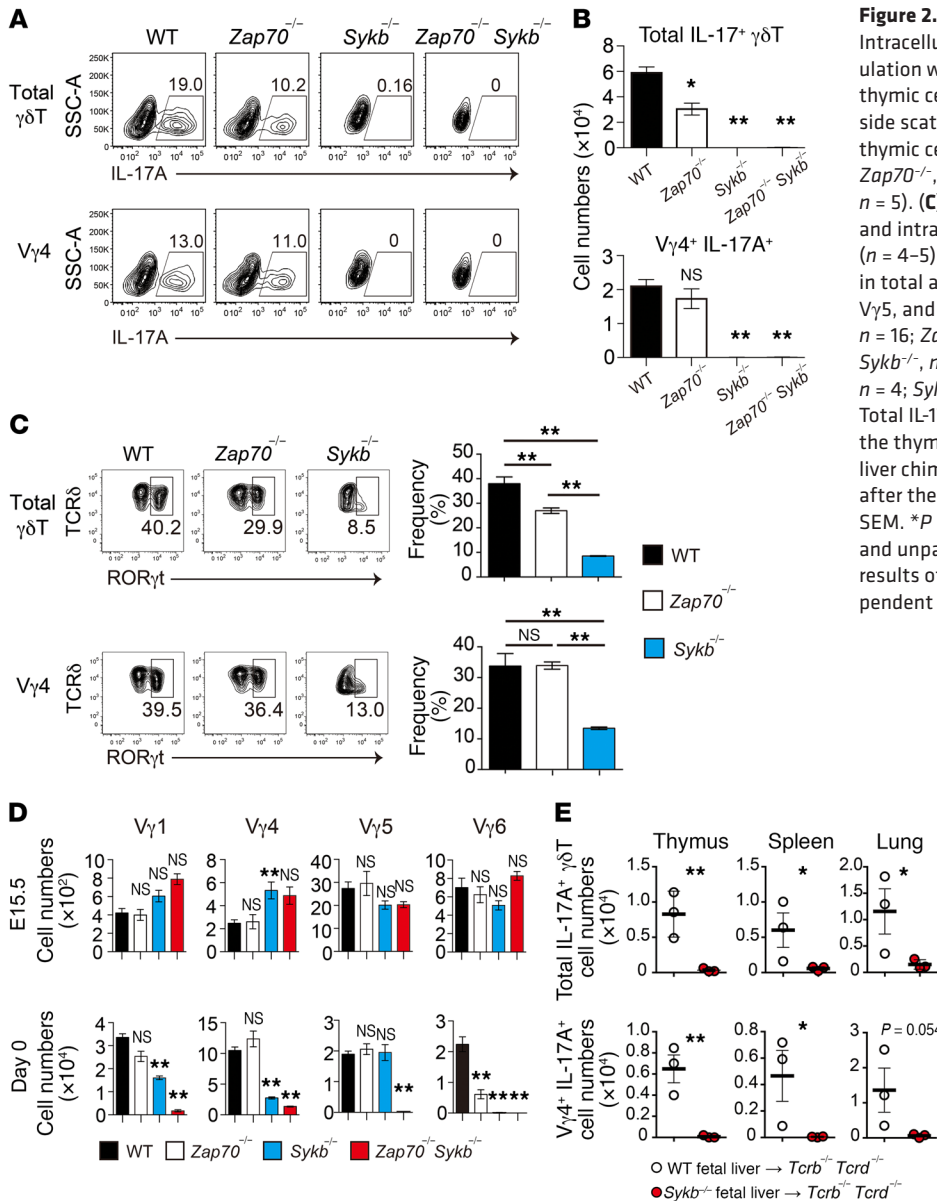


Figure 2. Syk is required for $\gamma\delta T17$ development. (A) Intracellular staining for IL-17A production after stimulation with PMA and ionomycin in total or $V\gamma 4^{+}$ $\gamma\delta T$ thymic cells from the indicated mice on day 0. SSC-A, side scatter area. (B) Total IL-17-producing and $V\gamma 4^{+}$ $\gamma\delta T$ thymic cell numbers per mouse on day 0 (WT, $n = 23$; $Zap70^{-/-}$, $n = 4$; $Sykb^{-/-}$, $n = 7$; and $Zap70^{-/-} Sykb^{-/-}$, $n = 5$). (C) Representative profiles for cell-surface TCR δ and intracellular ROR γT expression in thymic $\gamma\delta T$ cells ($n = 4-5$). Graphs indicate the frequency of ROR γT cells in total and $V\gamma 4^{+}$ $\gamma\delta T$ cells. (D) Number of $V\gamma 4$, $V\gamma 1$, $V\gamma 5$, and $V\gamma 6$ ($17D1^{+}V\gamma 5^{-}$) cells per mouse at E15.5 (WT, $n = 16$; $Zap70^{-/-}$, $n = 10$; $Sykb^{-/-}$, $n = 8$; and $Zap70^{-/-} Sykb^{-/-}$, $n = 2$) and on day 0 (WT, $n = 19$; $Zap70^{-/-}$, $n = 4$; $Sykb^{-/-}$, $n = 7$; and $Zap70^{-/-} Sykb^{-/-}$, $n = 8$). (E) Total IL-17-producing and $V\gamma 4^{+}$ $\gamma\delta T$ cell numbers from the thymus, spleen, and lungs of the indicated fetal liver chimeric mice. The mice were analyzed 8 weeks after the reconstitution. Data represent the mean \pm SEM. * $P < 0.05$ and ** $P < 0.01$, by 1-way ANOVA (B-D) and unpaired t test (E). Data represent the combined results of 3 independent experiments (A-D) or 2 independent experiments (E).

Syk, but not *Zap70*, is required for $\gamma\delta T17$ development. Subsequently, we examined the functional differentiation of $\gamma\delta T$ cells in mice at birth, as $\gamma\delta T17$ preferentially develops during the late embryonic stage. In the thymus of WT mice on day 0, a substantial fraction (nearly 20%) of $\gamma\delta T$ cells produced IL-17 upon stimulation with PMA and ionomycin (Figure 2A). The number of $\gamma\delta T17$ cells was reduced by approximately 50% in $Zap70^{-/-}$ mice (Figure 2, A and B), reflecting a marked reduction in $V\gamma 6^{+}$ cells (Figure 2D), which is a prominent subset of $\gamma\delta T17$ cells in mice. Another major $\gamma\delta T17$ subset, $V\gamma 4^{+}$ cells, was unaffected in $Zap70^{-/-}$ mice (Figure 2A). In contrast, both $Sykb^{-/-}$ and $Zap70^{-/-} Sykb^{-/-}$ mice showed a complete loss of $\gamma\delta T17$, including both $V\gamma 4^{+}$ and $V\gamma 6^{+}$ cell subsets (Figure 2, A and B). Consistent with these observations, the frequency of $\gamma\delta T$ cells expressing ROR γT , a transcription factor mandatory for IL-17 production, was reduced in $Zap70^{-/-}$ and $Sykb^{-/-}$ mice (Figure 2C). These results indicate that Syk is essential for $\gamma\delta T17$ differentiation and that Zap70 is solely required for the $V\gamma 6^{+}$ subset of $\gamma\delta T17$ cells.

We detected the expression of all $V\gamma$ chains ($V\gamma 1$, $V\gamma 4$, $V\gamma 5$, and $V\gamma 6$) in E15.5 fetal thymi from WT, $Zap70^{-/-}$, and $Sykb^{-/-}$ mice (Figure 2D). Analysis of day-0 neonatal thymus revealed that Zap70 was dispensable for the development of most $\gamma\delta T$ cells, including $V\gamma 1^{+}$, $V\gamma 4^{+}$, and $V\gamma 5^{+}$ cells, with the exception of $V\gamma 6^{+}$ cells. The number of $V\gamma 1^{+}$, $V\gamma 4^{+}$, and $V\gamma 6^{+}$ cells, but not $V\gamma 5^{+}$ cells, was significantly reduced in $Sykb^{-/-}$ neonatal mice. These $V\gamma$ cell subsets were further reduced in number or were nearly absent in $Zap70^{-/-} Sykb^{-/-}$ mice (Figure 2D). These results indicate the redundant and nonredundant roles of Zap70 and Syk in the development of different neonatal $\gamma\delta T$ cell subsets: $V\gamma 1^{+}$ and $V\gamma 4^{+}$ cells require Syk, $V\gamma 5^{+}$ cells require either Zap70 or Syk, and $V\gamma 6^{+}$ cells require both. Furthermore, to examine $\gamma\delta T17$ development in adult mice, hematopoietic progenitor cells from fetal liver were transplanted into T cell-deficient ($Tcrb^{-/-} Tcrd^{-/-}$) mice. We observed that WT progenitor cells differentiated into $\gamma\delta T17$ cells in the thymus, spleen, and lungs of the reconstituted mice (Figure 2E and Supplemental Figure 2, A and B). However, in mice reconstituted with

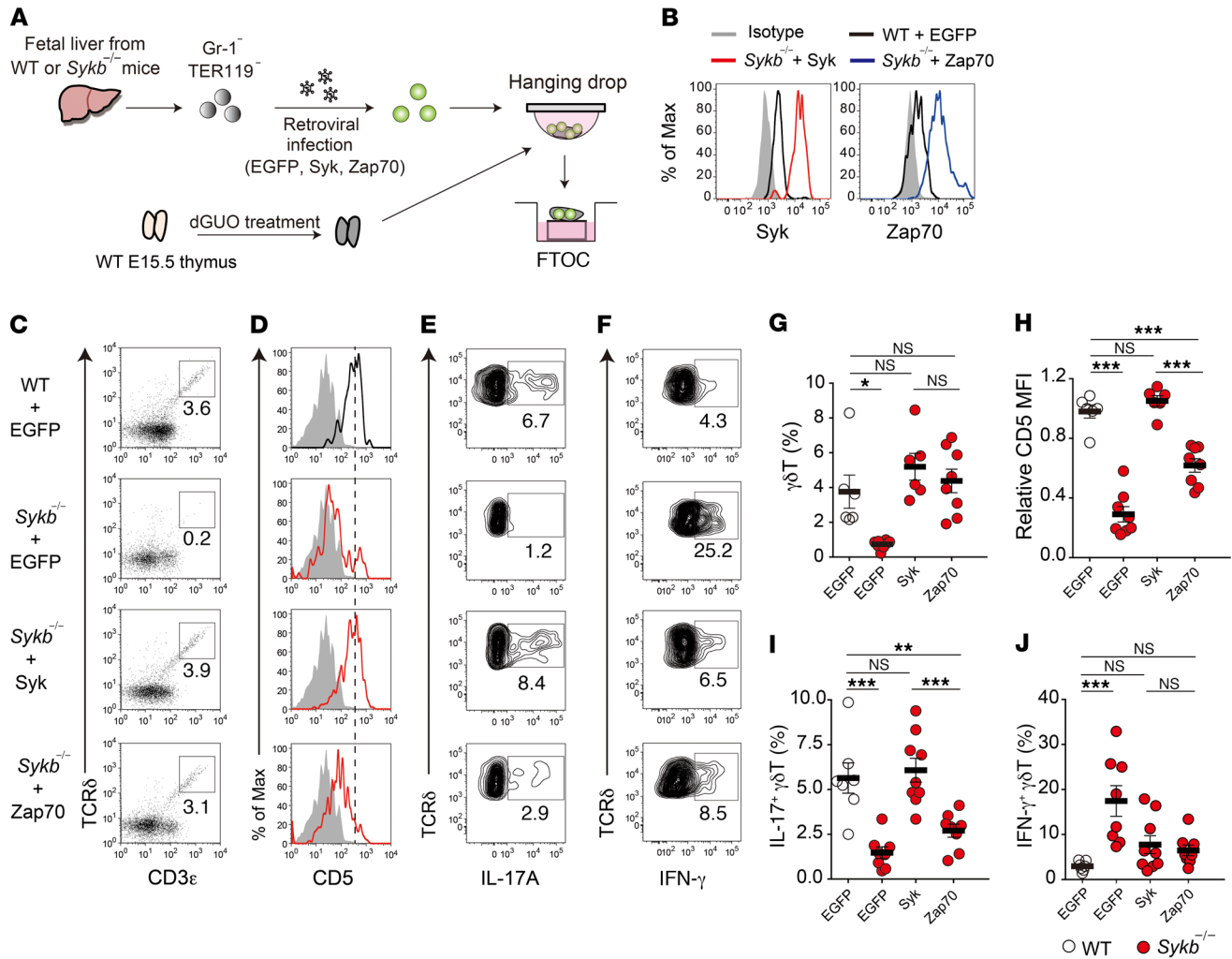


Figure 3. Zap70 fails to functionally substitute Syk in $\gamma\delta$ T17 development. (A) Scheme of the reconstitution of fetal liver T progenitor cells in FTOC. Gr-1-TER119⁻ fetal liver cells from WT or Syk-deficient mice at E15.5 were infected with retroviruses expressing EGFP alone or Syk or Zap70 along with EGFP. The infected cells were reconstituted in dGDUO-treated WT fetal thymic lobes, and the reconstituted thymic lobes were further cultured for 9 to 14 days. (B) Expression of Syk and Zap70 in EGFP⁺CD3ε⁺TCRδ⁺ cells from FTOC on day 9. (C) Expression of CD3ε and TCRδ in EGFP⁺ cells on day 9. (D) Expression of CD5 in EGFP⁺ $\gamma\delta$ T cells on day 9. (E and F) Intracellular staining for IL-17A and IFN- γ production in EGFP⁺ $\gamma\delta$ T cells on day 14. (G) Frequency of the total EGFP⁺ $\gamma\delta$ T cells shown in C (n = 6–8). (H) Relative MFI of CD5 expression in the $\gamma\delta$ T cells shown in D (n = 6–8). (I) Frequency of the IL-17A⁺ $\gamma\delta$ T cells shown in E (n = 7–9). (J) Frequency of the IFN- γ ⁺ $\gamma\delta$ T cells shown in F (n = 7–9). Graphs indicate the data for individual thymic lobes (circles) and the mean \pm SEM. *P < 0.05, **P < 0.01, and ***P < 0.001, by 1-way ANOVA (G–J). Data represent at least 2 independent experiments.

Syk-deficient fetal liver cells, $\gamma\delta$ T17 was completely undetectable. These results, along with those in neonatal mice, showed that Syk is required for $\gamma\delta$ T17 development throughout life.

In contrast, we found that IFN- γ -producing $\gamma\delta$ T cells were detectable in Zap70^{-/-}, Sykb^{-/-}, and Zap70^{-/-} Sykb^{-/-} mice (Supplemental Figure 3). In agreement with a previous report (29), the IFN- γ -producing potential was detectable in CD4/CD8 double-negative (DN) thymocytes from Rag2^{-/-} mice, indicating that immature thymocytes possess an IFN- γ -producing potential in response to certain extracellular stimuli. Given that Sykb^{-/-} $\gamma\delta$ T cell development was arrested at the immature CD5⁻ stage, we could not investigate the requirement of Syk in $\gamma\delta$ TCR-mediated IFN- γ production in mature $\gamma\delta$ T cells upon agonistic ligand stimulation.

Zap70 fails to functionally substitute for Syk in $\gamma\delta$ T17 development. To clarify the functional difference between Syk and Zap70, we examined whether Syk can be replaced by Zap70 in develop-

ing $\gamma\delta$ T cells. Fetal liver T progenitor cells from Sykb^{-/-} mice were infected with retroviruses expressing Syk or Zap70 along with EGFP and seeded into a fetal thymus organ culture (FTOC) (Figure 3A). Compared with WT cells, the retrovirus-infected Sykb^{-/-} cells in the FTOC expressed approximately 10-fold higher levels of Syk or Zap70 proteins (Figure 3B). Syk expression clearly recovered $\gamma\delta$ T cell development from Sykb^{-/-} T progenitor cells (Figure 3, C and G). We found that expression of CD5 in $\gamma\delta$ T cells was also completely restored by Syk expression (Figure 3, D and H). Most important, the differentiation of $\gamma\delta$ T17 cells was fully restored to WT cell levels (Figure 3, E and I). The overexpression of Zap70 in Sykb^{-/-} progenitors also restored the frequency of $\gamma\delta$ T cells (116% of WT and 84% of Syk expression). However, this overexpression failed to fully induce CD5 expression (63% of WT and 59% of Syk expression levels) and $\gamma\delta$ T17 development (48% of WT and 44% of Syk expression levels). The frequency of IFN- γ -producing $\gamma\delta$ T

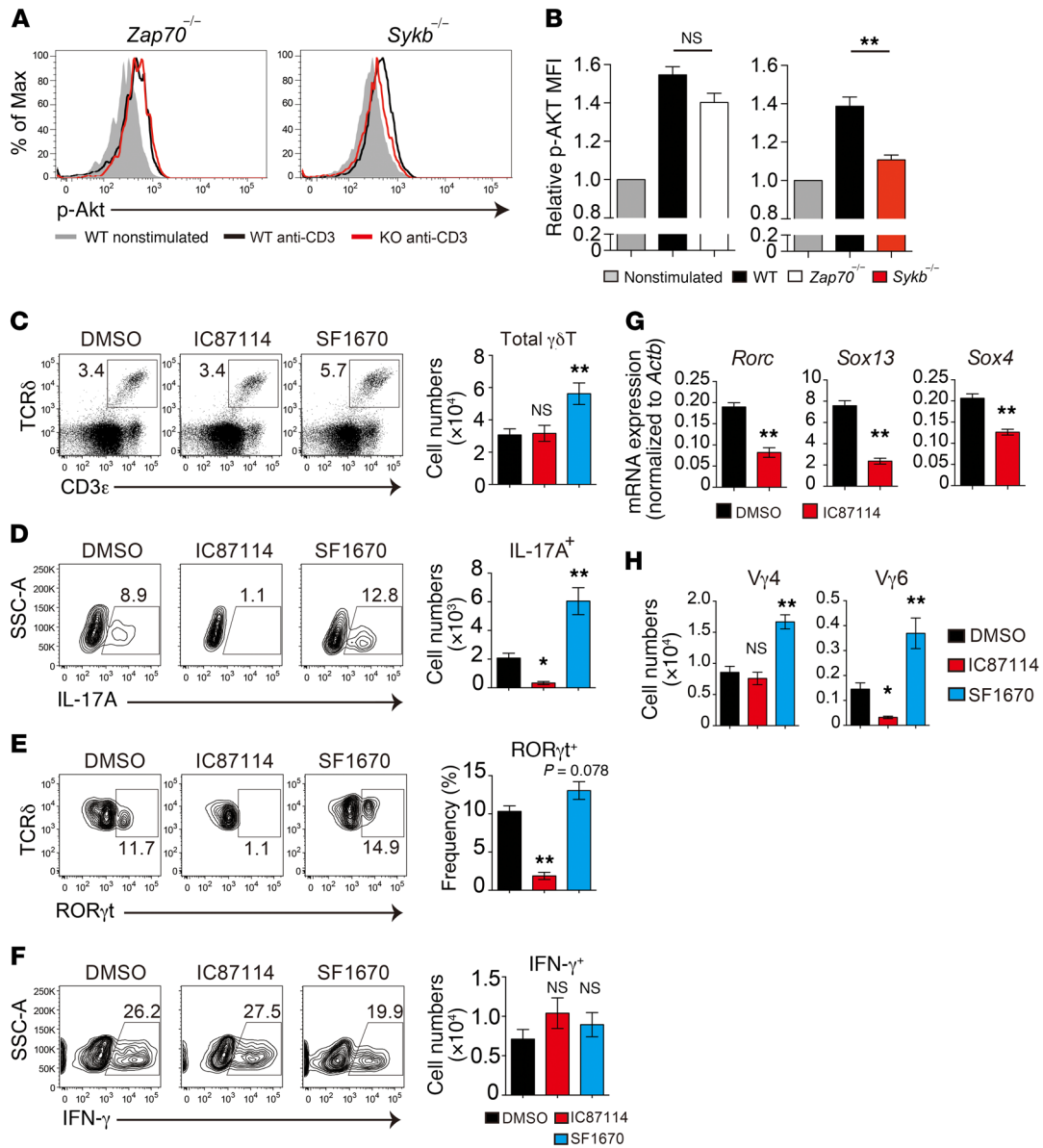


Figure 4. The PI3K pathway controls $\gamma\delta$ T17 development. (A and B) TCR-induced Akt phosphorylation in thymic $\gamma\delta$ T cells from *Zap70*^{-/-} or *Sykb*^{-/-} mice. Histograms show staining profiles of p-Akt in cells from WT (black lines) and mutant (red lines) mice, overlaid with nonstimulated profiles (shaded) after a 1-minute stimulation (A). MFI relative to nonstimulated controls (B). Thymocytes from adult *Zap70*^{-/-} mice (n = 3) and neonatal *Sykb*^{-/-} mice (n = 4) were used. (C–G) E15.5 fetal thymus from WT mice was cultured with vehicle alone (DMSO, 0.01%), IC87114 (1 μ M), or SF1670 (2.5 μ M) for 7 days (n = 5–11). (C) Flow cytometric profiles for CD3 ϵ and TCR δ expression and absolute number of $\gamma\delta$ T cells. (D) Intracellular staining profiles for IL-17A production in $\gamma\delta$ T cells and absolute number of IL-17A-producing $\gamma\delta$ T cells (per lobe). (E) Intracellular staining profiles for ROR γ t expression in $\gamma\delta$ T cells and frequency of ROR γ t⁺ $\gamma\delta$ T cells. (F) Intracellular staining profiles for IFN- γ production in $\gamma\delta$ T cells and absolute number of IFN- γ -producing $\gamma\delta$ T cells (per lobe). (G) mRNA expression of *Rorc*, *Sox13*, and *Sox4* in isolated $\gamma\delta$ T cells. Gene expression was normalized to β -actin (*Actb*) mRNA. (H) Number of V γ 4⁺ and V γ 6⁺ $\gamma\delta$ T cells. Data represent the mean \pm SEM. *P < 0.05 and **P < 0.01, by unpaired t test (B and G) and 1-way ANOVA (C–F and H). Data represent 2 independent experiments (A and B) or a single experiment (G), or the combined results of 2 independent experiments (C–F and H).

cells was significantly increased in the absence of Syk but was restored to WT levels by the overexpression of Syk or Zap70 (Figure 3, F and J). These results indicate that, although the expression levels of Zap70 are 10-fold higher than normal levels, Zap70 cannot be a substitute for Syk in $\gamma\delta$ TCR signal transduction and induction of $\gamma\delta$ T17 development in *Sykb*^{-/-} $\gamma\delta$ T cells, suggesting a nonredundant role of Syk in $\gamma\delta$ TCR signaling.

Requirement of Zap70 in $\gamma\delta$ T cells. Despite the critical role of Zap70 in $\alpha\beta$ T cell development, our results showed that its

requirement in $\gamma\delta$ T cell development in the thymus was limited to the V γ 6⁺ cell subset. We focused on V γ 6⁺ cells in *Zap70*^{-/-} mice and observed that CD5 expression levels were normal at E15.5. However, these levels were significantly reduced on day 0, suggesting that Zap70 is not essential for initial $\gamma\delta$ TCR signaling but rather is required for the thymic maturation of V γ 6⁺ cells, probably via continuous $\gamma\delta$ TCR signaling (Supplemental Figure 4, A and B). This idea is supported by the fact that the expression levels of Zap70 protein and mRNA were the highest in the V γ 6⁺ sub-

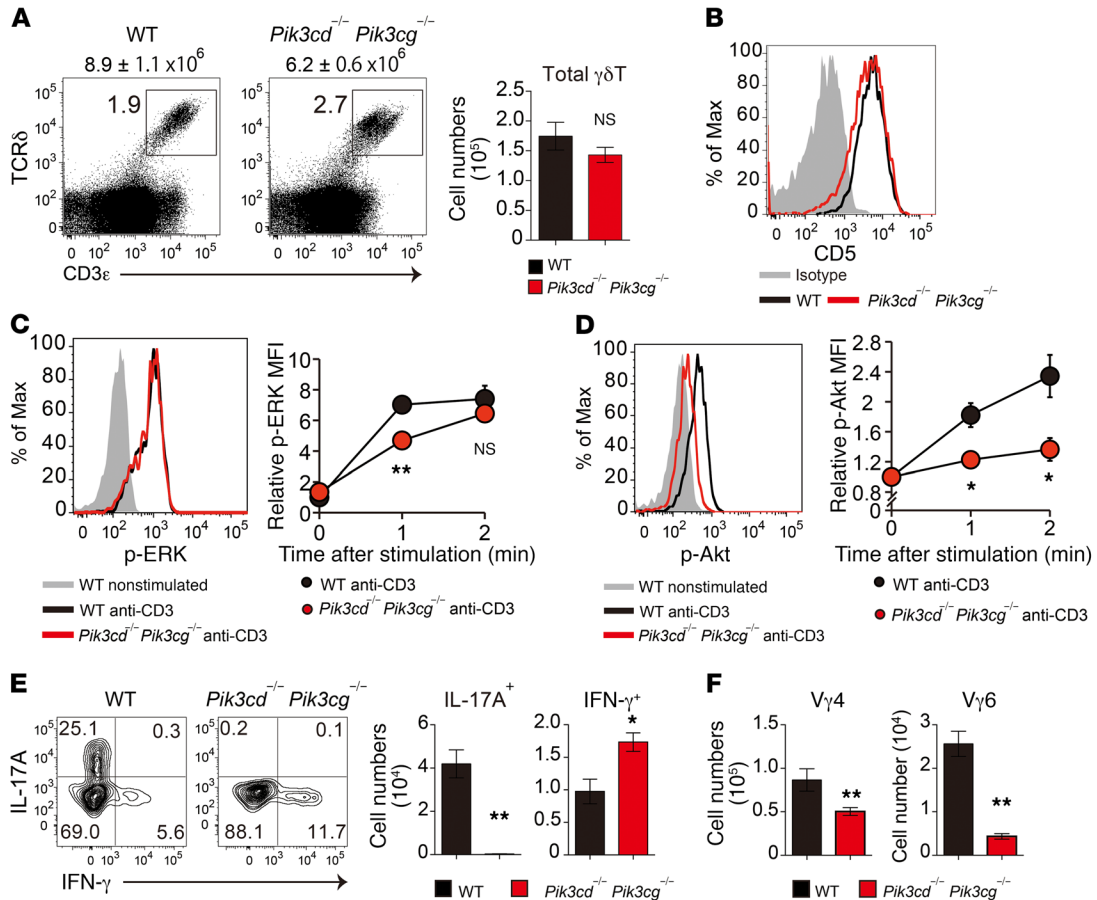


Figure 5. Impaired development of $\gamma\delta T17$ cells in PI3K-deficient mice. (A) Flow cytometric profiles for CD3 ϵ and TCR δ in total thymocytes from 0-day-old WT and *Pik3cd*^{-/-}*Pik3cg*^{-/-} mice. The total number of thymocytes is shown above each flow cytometric plot. Graph indicates the total number of $\gamma\delta T$ cells per mouse ($n = 4-6$). (B) Flow cytometric analysis of CD5 expression in thymic $\gamma\delta T$ cells ($n = 4-6$). (C and D) TCR-induced ERK (C) and Akt (D) phosphorylation in thymic V $\gamma 4^+$ $\gamma\delta T$ cells from 1-day-old WT and *Pik3cd*^{-/-}*Pik3cg*^{-/-} mice. Graphs indicate the MFI relative to the nonstimulated control. (E) Intracellular staining for IL-17A and IFN- γ production in neonatal thymic $\gamma\delta T$ cells from 0-day-old WT and *Pik3cd*^{-/-}*Pik3cg*^{-/-} mice after stimulation with PMA and ionomycin. The number of IL-17A⁺ and IFN- γ ⁺ $\gamma\delta T$ cells per mouse is shown ($n = 3-6$). (F) Number of V $\gamma 4^+$ and V $\gamma 6^+$ $\gamma\delta T$ cells (per mouse) in the indicated mice ($n = 4-6$). All data represent the mean \pm SEM. * $P < 0.05$ and ** $P < 0.01$, by 2-way ANOVA (C and D) and unpaired t test (A, E, and F). Data represent a single experiment using more than 7 neonatal mice per group.

set among $\gamma\delta T$ cells (Supplemental Figure 4C). These results are in agreement with previous findings that V $\gamma 6^+$ cell development is impaired in mutant mice harboring a hypomorphic *Zap70* mutation (30). *Zap70* is also required for peripheral V $\gamma 4^+$ cells, including the $\gamma\delta T17$ subset, as well as for IFN- γ -producing $\gamma\delta T$ cells in the spleen and lungs (Supplemental Figure 4, D and E). In contrast, the V $\gamma 1^+$ cell subset was normal or increased in the periphery of *Zap70*^{-/-} mice. Although it still remained unclear why peripheral V $\gamma 4^+$ $\gamma\delta T$ cells were reduced in *Zap70*-deficient mice, it is possible that *Zap70*-dependent TCR signals support the survival and/or migration of these cells. Thus, the requirement of *Zap70* in $\gamma\delta T$ cell development is limited to the thymic maturation of V $\gamma 6^+$ cells and peripheral maintenance of V $\gamma 4^+$ cells.

The PI3K/Akt pathway controls $\gamma\delta T17$ development. These results prompted us to examine the unique function of Syk in $\gamma\delta TCR$ signaling and $\gamma\delta T17$ development. Previous studies showed that Syk is recruited to the BCR and Fc ϵ receptor for the activation of PI3K in B cells and mast cells, respectively (31). The activated PI3K produces phosphatidylinositol (3,4,5)-trisphosphate (PIP3),

which in turn activates downstream protein kinases including Akt, PDK1, and Tec. The level of PIP3 is negatively regulated through its hydrolysis catalyzed by PTEN, a phosphoinositide phosphatase. In $\alpha\beta T$ cells, $\alpha\beta TCR$ signal-induced activation of the PI3K/Akt pathway requires CD28 costimulation (32), whereas in $\gamma\delta T$ cells, the $\gamma\delta TCR$ signal can induce Akt phosphorylation in the absence of costimulatory signals (19).

Although Akt phosphorylation induced by $\gamma\delta TCR$ stimulation was not altered in *Zap70*^{-/-} $\gamma\delta T$ cells, it was significantly reduced in *Sykb*^{-/-} $\gamma\delta T$ cells compared with WT $\gamma\delta T$ cells (Figure 4, A and B). We found that $\gamma\delta TCR$ -induced Akt phosphorylation, but not ERK phosphorylation, was completely inhibited by treatment with IC87114, an inhibitor of the p110 δ catalytic subunit of PI3K (Supplemental Figure 5, A and B). This finding indicates that Akt activation depends on PI3K in $\gamma\delta TCR$ signaling. These results demonstrate that Syk plays a critical role in $\gamma\delta TCR$ -induced activation of the PI3K/Akt pathway.

To examine the roles of PI3K and PTEN in $\gamma\delta T$ cell development, we cultured E15.5 fetal thymus from WT mice with IC87114 or SF1670, an inhibitor of PTEN. After 7 days of FTOC, the develop-

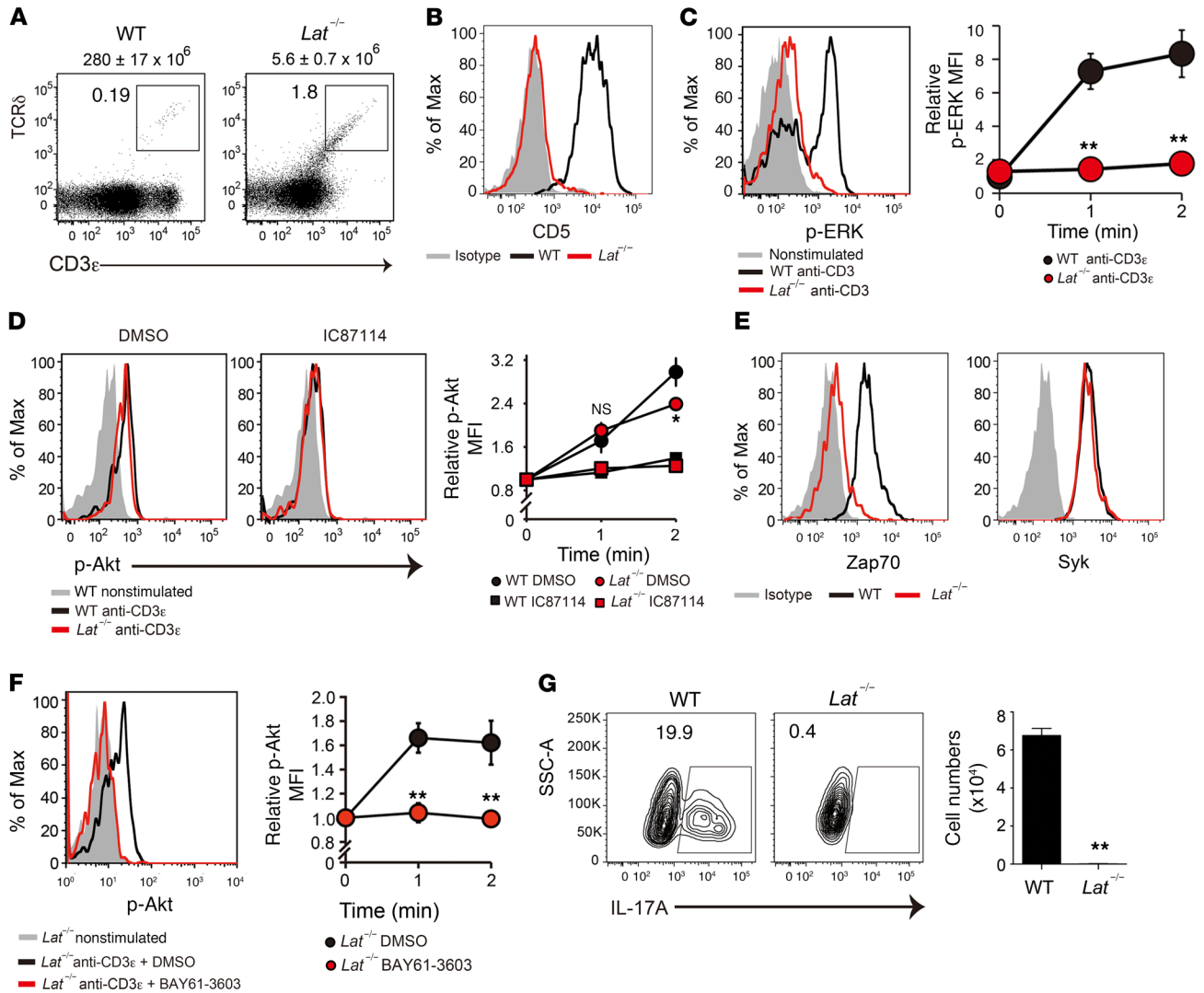


Figure 6. Syk mediates the Lat-independent TCR signal to the PI3K/Akt pathway. (A) Flow cytometric profiles for CD3ε and TCRδ in total thymocytes from 5-week-old WT and *Lat*^{-/-} mice. The total number of thymocytes is shown above each flow cytometric plot (*n* = 3). (B) Flow cytometric analysis of CD5 expression in thymic γδT cells (*n* = 3). (C) TCR-induced ERK phosphorylation in thymic γδT cells. Graph indicates the MFI relative to the nonstimulated control (*n* = 3). (D) TCR-induced Akt phosphorylation in thymic γδT cells pretreated or not with IC87114 (10 μM). Graph shows the MFI relative to the nonstimulated control (*n* = 3). (E) Flow cytometric analysis of Zap70 and Syk expression in thymic γδT cells from 5-week-old WT and *Lat*^{-/-} mice (*n* = 3). (F) TCR-induced Akt phosphorylation in *Lat*^{-/-} γδT cells pretreated or not with BAY61-3603 (10 μM). Graph shows the MFI relative to the nonstimulated control (*n* = 3). (G) Intracellular staining for IL-17A production in neonatal thymic γδT cells from WT mice (*n* = 3) and *Lat*^{-/-} mice (*n* = 5) after stimulation with PMA and ionomycin. The number of IL-17A⁺ γδT cells (per mouse) is shown. All data represent the mean ± SEM. **P* < 0.05 and ***P* < 0.01, by 2-way ANOVA (C, D, and F) and unpaired *t* test (G). Data represent 2 independent experiments (A, B, D, F, and G) or a single experiment (C and E).

ment of γδT17 cells and RORγt-expressing γδT cells was drastically impaired by treatment with IC87114, although the total number of γδT cells and IFN-γ-producing γδT cells was not decreased (Figure 4, C-F). We also found that IC87114 reduced the mRNA expression of *Rorc*, *Sox13*, and *Sox4*, the transcription factors essential for γδT17 induction, in γδT cells (Figure 4G). In contrast, we found that the number of γδT17 cells and RORγt-expressing γδT cells was increased by SF1670 treatment, whereas the number of IFN-γ-producing γδT cells was normal (Figure 4, D-F). Vγ6⁺ cell numbers were significantly reduced by IC87114 and increased by SF1670 treatment, while Vγ4⁺ cell numbers were increased by SF1670 (Figure 4H).

We further investigated the *in vivo* role of the PI3K pathway in γδT cell development, using mice doubly deficient in the PI3K

catalytic subunits p110γ and p110δ (*Pik3c*^{-/-} *Pik3cd*^{-/-}). The *Pik3c*^{-/-} *Pik3cd*^{-/-} mice had a normal total number of γδT cells and CD5 expression in γδT cells in neonatal thymus (Figure 5, A and B), indicating that PI3K is not required for γδTCR signaling or thymic γδT cell development. ERK phosphorylation occurred in response to γδTCR stimulation (Figure 5C), although γδTCR-induced Akt phosphorylation was severely impaired in *Pik3c*^{-/-} *Pik3cd*^{-/-} γδT cells (Figure 5D). These γδT cells showed a complete loss of IL-17-producing capacity (Figure 5E) and a significant reduction in Vγ4⁺ and Vγ6⁺ subsets (Figure 5F). Notably, we found that the development of IFN-γ-producing γδT cells was not impaired in *Pik3c*^{-/-} *Pik3cd*^{-/-} mice (Figure 5E), indicating the specific requirement of PI3K in γδT17 development.

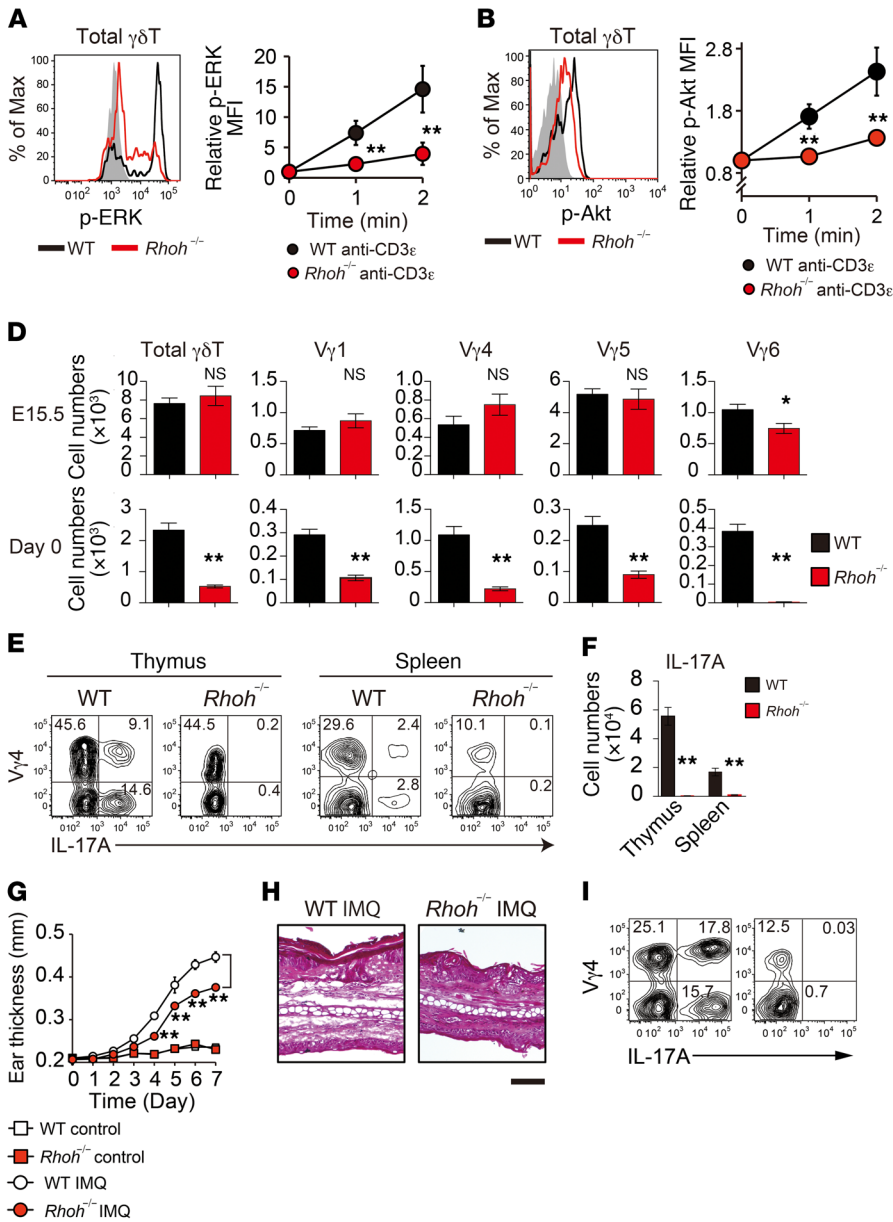


Figure 7. RhoH mediates the $\gamma\delta$ TCR signaling required for $\gamma\delta$ T17 development. (A and B) TCR-induced ERK and Akt phosphorylation in thymic $\gamma\delta$ T cells from WT ($n = 3$) and $RhoH^{-/-}$ mice ($n = 3$). (C) Representative CD5 expression profiles in thymic $\gamma\delta$ T cells ($n = 3$). (D) Number of cells in the indicated thymic $\gamma\delta$ T subsets from WT and $RhoH^{-/-}$ mice at E15.5 (WT, $n = 5$; $RhoH^{-/-}$, $n = 5$) and on day 0 (WT, $n = 8$; $RhoH^{-/-}$, $n = 9$). (E and F) Staining for V $\gamma 4$ and IL-17A in thymic (day 0; WT, $n = 4$; $RhoH^{-/-}$, $n = 4$) and splenic (6-week-old; WT, $n = 8$; $RhoH^{-/-}$, $n = 8$) $\gamma\delta$ T cells after stimulation with PMA and ionomycin. Graph shows the quantification of IL-17A $^+$ $\gamma\delta$ T cells (per mouse). (G–I) WT and $RhoH^{-/-}$ mice were treated daily for 7 days with IMQ cream or control cream on the ear ($n = 3$). Kinetics of IMQ-induced ear swelling (G), representative H&E staining of ear sections on day 7 (H), and flow cytometric analysis of IL-17A $^+$ cells in $\gamma\delta$ T cells from ear-draining lymph nodes on day 7 (I). Scale bar: 100 μ m. All data represent the mean \pm SEM. * $P < 0.05$ and ** $P < 0.01$, by 2-way ANOVA (A, B, and G) and unpaired t test (D and F). Data represent more than 2 independent experiments (A–F) or a single experiment (G–I).

These results indicate that the PI3K/Akt pathway downstream of Syk-mediated $\gamma\delta$ TCR signal controls $\gamma\delta$ T17 development.

Syk mediates Lat-independent, noncanonical signaling to the PI3K/Akt pathway. How does Syk activate the PI3K/Akt pathway in $\gamma\delta$ TCR signaling? Lat is known to be a direct substrate of Zap70 and Syk kinases, acting as a scaffold for downstream signaling molecules. We examined the $\gamma\delta$ T cell signaling and developmental potential of Lat-deficient ($Lat^{-/-}$) mice. As reported previously (33), $Lat^{-/-}$ mice showed a complete arrest of $\gamma\delta$ T cell development at the precursor stage, as characterized by the extremely low number of $\gamma\delta$ TCR $^+$ cells and the absence of CD5 expression (Figure 6, A and B). Anti-CD3 ϵ -induced ERK phosphorylation was also undetectable in $Lat^{-/-}$ $\gamma\delta$ T cells (Figure 6C). Interestingly, we found that Akt phosphorylation levels were normal in anti-CD3-stimulated $Lat^{-/-}$ $\gamma\delta$ T cells (Figure 6D). This Akt activation was inhibited by treatment with IC87114, indicating that the PI3K/Akt signaling axis is independent of the Lat-mediated pathway.

Previous studies have shown that the expression of Zap70 and Syk is inversely regulated during $\alpha\beta$ T cell development in the thymus; Zap70 is hardly detectable at the DN1–3 stages, increases thereafter, and reaches the maximum level in mature $\alpha\beta$ T cells, while Syk is robustly expressed at the DN1–3 stages, gradually decreases thereafter, and reaches an undetectable level at the mature stage (34). In $\gamma\delta$ T cells, Syk protein expression is detectable even at the mature stage (35). In agreement with these previous data, we found that Zap70 expression was almost undetectable in $Lat^{-/-}$ $\gamma\delta$ T cells, which showed developmental arrest at the DN3 stage. Syk expression was almost comparable between WT and $Lat^{-/-}$ $\gamma\delta$ T cells, indicating that $\gamma\delta$ TCR signals solely depended on Syk at this stage (Figure 6E). Notably, pretreatment with BAY61-3606, a specific inhibitor of Syk, significantly reduced $\gamma\delta$ TCR-induced Akt phosphorylation in $Lat^{-/-}$ $\gamma\delta$ T cells (Figure 6F). These results indicate that $\gamma\delta$ TCR-induced PI3K/Akt activation depends on Syk but not Lat. Although the PI3K/Akt pathway was intact,

Lat^{-/-} $\gamma\delta$ T cells had no potential to produce IL-17, indicating that the Lat-independent PI3K/Akt pathway is not sufficient for $\gamma\delta$ T17 differentiation (Figure 6G).

Collectively, our results suggest that $\gamma\delta$ TCR-induced Syk activation stimulates the Lat-dependent canonical pathway, including the Ras/MAPK cascade, and the Lat-independent noncanonical pathway mediated by the PI3K/Akt axis. The former serves as a mainstream signal for $\gamma\delta$ T cell differentiation from precursor cells, whereas the latter induces the additional program toward $\gamma\delta$ T17 differentiation.

The adaptor protein RhoH mediates the $\gamma\delta$ TCR signaling required for $\gamma\delta$ T17 development. Previously, we and other groups have reported that Zap70 and Syk require the receptor proximal adaptor protein RhoH for their recruitment to the $\alpha\beta$ TCR in T cells and the Fc ϵ receptor in mast cells, respectively, and that RhoH is essential for the optimal activation of these receptor signals (36, 37). Subsequently, we investigated whether the $\gamma\delta$ TCR signals also require RhoH-mediated kinase recruitment. $\gamma\delta$ T cells from RhoH-deficient (*RhoH*^{-/-}) mice had a marked reduction in $\gamma\delta$ TCR stimulation-induced ERK and Akt phosphorylation, indicating that RhoH is required for $\gamma\delta$ TCR signal transduction (Figure 7, A and B). Indeed, the expression of CD5 in $\gamma\delta$ T cells was markedly reduced in *RhoH*^{-/-} mice (Figure 7C). We found that the neonatal development of V γ 4⁺ and V γ 6⁺ $\gamma\delta$ T17 cells was also significantly impaired in *RhoH*^{-/-} mice (Figure 7D). These $\gamma\delta$ T cell phenotypes recapitulated those of *Sykb*^{-/-} mice, strongly suggesting that RhoH mediates the $\gamma\delta$ TCR/Syk signaling axis for the induction of $\gamma\delta$ T17 development.

Last, we assessed the *in vivo* significance of RhoH/Syk-mediated $\gamma\delta$ TCR signals using *RhoH*^{-/-} mice and found that V γ 4⁺ $\gamma\delta$ T cell numbers were markedly reduced, while V γ 6⁺ $\gamma\delta$ T cells were barely detectable in the thymus throughout ontogeny (Supplemental Figure 6, A and B). In adult *RhoH*^{-/-} mice, V γ 4⁺ and V γ 6⁺ $\gamma\delta$ T cell numbers were significantly reduced in peripheral tissues, whereas the total numbers of $\gamma\delta$ T cells and V γ 1⁺ (spleen and lung), V γ 5⁺ (skin), and V γ 7 (small intestine) cell subsets were comparable to those in WT mice (Supplemental Figure 6C). In particular, we did not detect $\gamma\delta$ T17 cells in the thymus or periphery in *RhoH*^{-/-} mice (Figure 7, E and F). On the other hand, we found that thymic development of IFN- γ -producing $\gamma\delta$ T cells was unimpaired in *RhoH*^{-/-} mice (Supplemental Figure 3). Previous studies have demonstrated that V γ 4⁺ $\gamma\delta$ T17 cells play a crucial role in psoriasis-like dermatitis induced by imiquimod (IMQ). Upon IMQ treatment, V γ 4⁺ $\gamma\delta$ T17 cells specifically expand in the draining lymph node and recirculate to inflamed skin (4, 38). We observed that IMQ-induced skin inflammation was significantly attenuated and that the induced increase in V γ 4⁺ $\gamma\delta$ T17 cells was completely undetectable in *RhoH*^{-/-} mice (Figure 7, G-I). A similar attenuation of inflammation was also observed in mice reconstituted with Syk-deficient fetal liver cells (Supplemental Figure 2C). These results indicate that a deficiency of RhoH-mediated $\gamma\delta$ TCR signals has a marked impact on the $\gamma\delta$ T17-mediated inflammatory response *in vivo*.

Discussion

In this study, we explored the molecular mechanisms of $\gamma\delta$ TCR signaling pathways for the development and effector fate decision of $\gamma\delta$ T cells during thymic development, focusing on the role of

the receptor proximal tyrosine kinase Syk. Early pioneering studies demonstrated that Syk is required for the development of certain $\gamma\delta$ T cell subsets such as skin- or intestine-resident $\gamma\delta$ T cells (35, 39). However, the functional significance of Syk in the repertoire formation and effector function of $\gamma\delta$ T cells has not been addressed to date. The present study revealed that Syk-dependent $\gamma\delta$ TCR signals are indispensable for the thymic maturation and acquisition of the effector function of $\gamma\delta$ T cells.

It has been demonstrated that the TCR signaling machinery differs between $\alpha\beta$ T and $\gamma\delta$ T cells (17–23, 40), although these 2 cell types derive from common progenitors in the thymus. We showed here that in *ex vivo* $\gamma\delta$ T cells, engagement of the $\gamma\delta$ TCR-CD3 complex leads to the phosphorylation of Syk and Zap70. Experiments using gene-deficient mice proved that Syk plays a dominant role in $\gamma\delta$ TCR signaling. Unexpectedly, it was found that Zap70 has a limited contribution to $\gamma\delta$ TCR signaling and is dispensable for the thymic development of most $\gamma\delta$ T cells. This markedly contrasts $\alpha\beta$ TCR signaling and $\alpha\beta$ T cell development, both of which completely depend on Zap70 but not Syk (25–27). Taken together, these observations indicate that, unlike $\alpha\beta$ T cells that use the $\alpha\beta$ TCR/Lck/Zap70 axis, $\gamma\delta$ T cells use Syk as a dominant $\gamma\delta$ TCR proximal kinase to initiate downstream signaling cascades. This suggests a common feature of antigen receptor signaling machinery between $\gamma\delta$ T and B cells rather than $\alpha\beta$ T cells.

Why do $\gamma\delta$ T cells preferentially rely on Syk to drive $\gamma\delta$ TCR signals? It may be at least partly explained by the differential expression of Syk and Zap70 during T cell development (34). We found high Syk and low Zap70 expression in immature $\gamma\delta$ T cells (such as $\gamma\delta$ T cells from *Lat*^{-/-} mice), which might account for the dominant role of Syk rather than Zap70 in the early phase of $\gamma\delta$ T cell development. While $\alpha\beta$ T cells lose Syk expression during development (34), $\gamma\delta$ T cells maintain Syk expression until the mature stage (35). In addition to the quantitative difference, the qualitative difference between Syk and Zap70 may be the cause of their differential requirement. Indeed, our experiments with FTQC demonstrated that the overexpression of Zap70 in Syk-deficient T progenitor cells did not fully restore $\gamma\delta$ TCR signaling and $\gamma\delta$ T17 development. A previous report also showed that the ectopic expression of Zap70 in Syk-deficient BM macrophages fails to restore the differentiation into normal osteoclasts (41). The functional incompetence of Zap70 compared with Syk may be explained by the differential behavior of these kinases. The kinase domain of Zap70 has been shown to exert lower catalytic activity than that of Syk (42). It is also possible that Syk and Zap70 have different specificities to target proteins, because the ectopic expression of Syk in human $\alpha\beta$ T cells can result in altered gene expression downstream of TCR signaling (43). The Src homology 2 (SH2) domains of Syk may be more structurally flexible than those of Zap70 (44), possibly leading to a higher accessibility of Syk to the immunoreceptor tyrosine-based activation motifs (ITAMs) in $\gamma\delta$ TCR-CD3 complexes. Furthermore, although the activation of Zap70 depends on Lck, Syk functions in an Lck-independent manner (45). These differential properties of the 2 kinases are likely to explain the preferential requirement of Syk in $\gamma\delta$ TCR signaling.

It is likely that the most important target of Syk in $\gamma\delta$ T cells is Lat, which forms a signalosome that provides docking sites for SH2-containing proteins such as PLC γ . This leads to activation of the

Ras/MAPK, Ca/NFAT, and PKC θ /NF- κ B pathways (16). Our results, along with those of a previous study (33), indicate that *Lat*^{-/-} $\gamma\delta$ T cells show a complete loss of MAPK activation, no signs of maturation, and no $\gamma\delta$ T17 induction. However, our finding that Akt phosphorylation upon $\gamma\delta$ TCR stimulation was not altered in *Lat*^{-/-} $\gamma\delta$ T cells clearly indicates that the $\gamma\delta$ TCR/PI3K/Akt axis is independent of the Lat signalosome. A previous study using cell-free experiments showed that Syk directly binds to the p85 α regulatory subunit of PI3K (46). In B cells, upon BCR stimulation, Syk phosphorylates BCAP, an adaptor protein that interacts with and activates PI3K (47). Activation of the PI3K/Akt pathway in $\alpha\beta$ T cells is mediated by the binding of PI3K to the phosphorylated cytoplasmic domain of CD28 upon interaction with its ligands, CD80 or CD86 (48). This mechanism explains the requirement of costimulatory signals from antigen-presenting cells in $\alpha\beta$ T cell activation. Our data indicate that $\gamma\delta$ TCR signals can directly activate the PI3K/Akt pathway, probably through direct interaction between Syk and PI3K proteins or in an indirect manner, mediated by putative adaptor protein(s). Uncovering the molecular links between Syk and PI3K in $\gamma\delta$ T cells still remains a challenge.

Collectively, Syk-mediated $\gamma\delta$ TCR signals can activate the canonical pathway, in which the Lat signalosome acts as a platform for the activation of downstream cascades, as well as the noncanonical accessory pathway mediated by the PI3K/Akt axis. We infer that the latter enables $\gamma\delta$ T cells to efficiently respond to antigen recognition without costimulatory signals.

We further elucidated the essential role of the PI3K/Akt pathway in $\gamma\delta$ T17 development. The induction of $\gamma\delta$ T17 cells was significantly repressed by pharmacological inhibition or genetic ablation of PI3K and enhanced by PTEN inhibition, indicating that the production of PIP3 is a critical determinant of $\gamma\delta$ T17 cell differentiation during thymic development. Inhibition of PI3K reduced the expression of the transcription factors ROR γ t, Sox13, and Sox4 in the developing $\gamma\delta$ T cells. Hence, the PI3K/Akt pathway plays a crucial role in the transcriptional program toward the $\gamma\delta$ T17 lineage. Similarly, the PI3K/Akt pathway directs the differentiation of IL-17-producing Th17 cells (49), suggesting that the PI3K/Akt pathway is a common regulatory system shared by $\alpha\beta$ T and $\gamma\delta$ T lineages to induce the differentiation program toward IL-17-producing subsets. A previous study showed that the genetic deficiency or pharmacological inhibition of PI3K attenuates $\gamma\delta$ T17-dependent inflammation (50), highlighting the physiological importance of this signaling pathway in properly mounting the inflammatory potentials.

In conclusion, we describe the significance of Syk-mediated TCR signaling in the physiological development and effector differentiation of $\gamma\delta$ T cells. Syk acts as a dominant $\gamma\delta$ TCR proximal tyrosine kinase that activates the canonical signaling cascades mediated by the Lat signalosome as well as the Lat-independent noncanonical signal for activation of the PI3K/Akt pathway for $\gamma\delta$ T17 induction (Supplemental Figure 7). Elucidating the functional difference between Syk and Zap70 in terms of T cell function as well as their evolutionary history and contribution to pathogenesis would be intriguing for future studies.

Methods

Mice. C57BL/6 mice were purchased from Japan SLC. *Zap70*^{-/-} (25), *Rag2*^{-/-} (51), *Rhoh*^{-/-} (37), *Tcrb*^{-/-} (52), and *Tcrd*^{-/-} (53) mice were

described previously. *Sykb*^{-/-}, *Lat*^{-/-}, *Zap70*^{-/-} *Sykb*^{-/-}, and *Pik3cg*^{-/-} *Pik3cd*^{-/-} mice were generated by the CRISPR/Cas9-mediated genome editing method. All mice were bred and maintained under specific pathogen-free conditions in our animal facility and were euthanized by overdose of inhalation anesthetics.

Antibodies. Monoclonal antibodies against CD4 (GK1.5), CD5 (53-7.3), CD8 α (53-6.7), CD25 (PC61.5), TCR β (H57-597), and ROR γ t (B2D) were purchased from eBioscience. Monoclonal antibodies against CD3 ϵ (17A2), CD44 (IM7), CD11b (M1/70), CD11c (N418), B220 (RA3-6B2), CD49b (DX5), Gr-1 (RB6-8C5), TER-119 (TER-119), TCR δ (GL3), TCR-V γ 1 (2.11), TCR-V γ 4 (UC3-10A6), TCR-V γ 5 (clone 536), IL-17A (TC11-18H10.1), IFN- γ (XMG1.2), Zap70 (1E7.2), Syk (5F5), and Lat (11B.12) were purchased from BioLegend. Monoclonal antibodies against phosphorylated ERK (p-ERK) (197G2) and p-Akt (D9E) were purchased from Cell Signaling Technology. The monoclonal antibody 17D1, specific for TCR-V γ 6/V δ 1 and TCR-V γ 5/V δ 1, was provided by Robert E. Tigelaar (Yale University, New Haven, Connecticut, USA) and used as described previously (54). Anti-V γ 7 monoclonal antibody (GL1) was provided by the late Leo Lefrançois (University of Connecticut Health Center, Farmington, Connecticut, USA) (55). The $\gamma\delta$ T cell subsets (according to the Heilig and Tonegawa nomenclature) examined in this study are listed in Supplemental Table 1.

Flow cytometry and cell sorting. Flow cytometric analysis and cell sorting were performed with FACSCanto II and FACSaria III systems (BD Biosciences). Prior to cell staining, the Fc blocker (anti-mouse CD16/CD32; clone 2.4G2; TONBO Biosciences) was used. Cells were stained with a mixture of the antibodies at a final concentration of 1 to 2 μ g/ml. 7-Aminoactinomycin D (7AAD) was used to exclude dead cells. For intracellular staining, cells were fixed with IC Fixation Buffer (eBioscience) for 30 minutes and stained with antibodies.

CRISPR/Cas9-mediated genome editing in mice. The preparation of single-guide RNA (sgRNA) and Cas9 mRNA was described previously (56). sgRNA and Cas9 mRNA were injected into the cytoplasm of pronuclear-stage eggs from C57BL/6 mice, and the eggs were transferred into the oviducts of pseudopregnant female ICR mice. The target sequences containing PAM sequences (underlined) were as follows: *Zap70*, GGCACGTACGCCATCGCGGGCGG; *Sykb*-1, CACACCACTACACCATCGAGAGGG; *Sykb*-2, GCCCAAGACCGGACCCTTTGAGGG; *Lat*-1, ACTCACGGCAGCGCACGCACAGGG; *Lat*-2, AGGAAACAGCAGGTGTTCCGGGGGG; *Pik3cg*-1, GTACGTGTCGCTGTACCACGTGG; *Pik3cg*-2, GATCAAAGTGCTTTGGACGTTGG; *Pik3cd*-1, GTGCGGAAGTCGTTTACTTCCGGGG; *Pik3cd*-2, TCTGCTCATCCCGCATAGCAAGGG.

Fetal liver chimeric mice. E15 fetal liver cells were i.v. injected into x-ray-irradiated (4 Gy) *Tcrb*^{-/-} *Tcrd*^{-/-} mice. Mice were analyzed 8 weeks after the transplantation.

Retroviral infection. cDNA fragments encoding Zap70 or Syk were inserted into the retroviral vector pMSCV-IRES-EGFP. Plat-E packaging cells were transfected with the retrovirus plasmid, and its supernatant was used for hematopoietic progenitor cell infection. To obtain hematopoietic progenitor cells, Gr-1⁻ TER119⁻ cells derived from E15.5 fetal livers were cultured in RPMI 1640 complete medium in the presence of IL-7 (25 ng/ml) and stem cell factor (SCF) (50 ng/ml) for 24 hours. The cells were then infected with retrovirus by the spin-infection method as described previously (57).

FTOC. Thymic lobes isolated from E15.5 fetuses were cultured as previously described (57). IC87114 (SYNkinase) or SF1670 (Milli-

poreSigma) were added into culture medium at 1 μ M or 2.5 μ M, respectively. For reconstitution with retrovirally transduced T progenitor cells, E15.5 thymic lobes were cultured with 1.35 mM deoxyguanosine (dGuo) for 5 days. The dGuo-treated thymic lobes were incubated with retrovirus-infected fetal liver cells in hanging-drop culture for 24 hours, rinsed with culture medium, and further cultured in normal FTOC.

Preparation of tissue-resident lymphocytes. To prepare lung- and skin-resident lymphocytes, lung or ear tissue from adult mice was minced into small pieces and digested with 0.2% collagenase D (Roche) and 0.01% DNase I (Roche) at 37°C for 30 minutes. The digested tissues were disrupted by using a syringe and 18-gauge needle, and cells were passed through a 100- μ m nylon mesh to remove tissue debris. The enzymatic reaction was stopped by adding PBS containing 2 mM EDTA and 2% FCS. To prepare the small intestine cell suspension, gut fragments from which Payer's patches were removed were cut open and incubated for 30 minutes at 4°C in PBS containing 30 mM EDTA. After incubation, the gut fragments were washed with PBS and then vigorously shaken to collect the small intestine epithelial fraction. Leukocytes from the intestine epithelial fraction were isolated with a 40%–80% Percoll gradient.

Quantitative mRNA analysis. Total RNA was extracted from isolated cells using the RNeasy Kit (QIAGEN) and reverse transcribed with SuperScript III (Invitrogen, Thermo Fisher Scientific). Quantitative PCR was performed with SYBR Premix ExTaq (TaKaRa) and the StepOne Real-Time PCR System (Life Technologies, Thermo Fisher Scientific). The results were normalized to β -actin expression levels.

Cell stimulation. Total thymocytes or purified $\gamma\delta$ T cells (1×10^6 to 5×10^6) were preincubated in RPMI 1640 complete medium at 37°C for 5 minutes and then added to an equal volume of RPMI 1640 complete medium containing biotinylated anti-CD3 ϵ antibody (60 μ g/ml; 145-2C11; BioLegend) and streptavidin (21 μ g/ml; SouthernBiotech). When necessary, cells were preincubated with IC87114 or BAY61-3603 (MilliporeSigma) at 37°C for 1 hour prior to stimulation. For FACS analysis and Western blotting, an equal volume of 4% paraformaldehyde or 1 ml ice-cold PBS, respectively, was added to stop the stimulation. For cytokine production assay, cells were incubated with complete medium containing PMA (2.5 ng/ml), ionomycin (1 μ g/ml), and brefeldin A (1 μ g/ml) at 37°C for 4 hours.

Immunoprecipitation and Western blot analysis. $\gamma\delta$ T cells were magnetically isolated from the thymus of 1-day-old mice using phycoerythrin-labeled (PE-labeled) anti-TCR δ (GL3) and anti-PE microbeads (Miltenyi Biotec). The purified $\gamma\delta$ T cells were stimulated with an anti-CD3 ϵ antibody as described above. The cells were lysed with lysis buffer containing 50 mM Tris-HCl (pH7.5), 150 mM NaCl, 10 mM MgCl₂, 0.5% Nonidet P-40, 10% glycerol, and protease inhibitor cocktail (MilliporeSigma), as well as phosphatase inhibitor cocktail (Thermo Fisher Scientific). Cell lysates were incubated with anti-phosphotyrosine antibody (4G10) conjugated to Protein G Sepharose (GE Healthcare) at 4°C for 1 hour. Subsequently, the precipitates were washed and boiled in Laemmli gel-loading buffer. The proteins were subjected to SDS-PAGE and transferred onto a PVDF membrane.

IMQ-inducible psoriasis. For testing psoriasis-like dermatitis, a daily dose of 5 mg Beselna cream (5% IMQ; Mochida Pharmaceutical) or control vaseline cream (Wako) was applied to each ear for 6 days. Ear thickness was measured using a micrometer. On day 7, the ears were embedded in OCT compound (Sakura Finetek), sliced into 5- μ m-thick sections with a Cryostat (Leica), air dried, fixed with acetone, and stained with H&E. The images were obtained with a Keyence BZ-9000 fluorescence microscope.

Statistics. All data are presented as the mean \pm SEM. For statistical analysis, GraphPad Prism 6 (GraphPad Software) was used. A *P* value of less than 0.05 was considered statistically significant. A 2-tailed, unpaired *t* test was used for comparisons of 2 groups. A 1-way or 2-way ANOVA was used to compare 3 or more groups.

Study approval. All animal experiments were approved by the IRB of The University of Tokyo (approval I-H17-010) and the IACUC of the Research Institute of the National Center for Global Health and Medicine Research Institute (approvals 17024 and 17043) and were conducted in accordance with institutional protocols.

Author contributions

RM and TN performed most of the experiments, interpreted the results, and prepared the manuscript. KN and TO generated the genetically modified mice. HT provided advice on the project design and data interpretation and prepared the manuscript. HS supervised the project and wrote the manuscript.

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Address correspondence to: Takeshi Nitta, Graduate School of Medicine and Faculty of Medicine, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan. Phone: 81.3.5841.3377; Email: nit-im@m.u-tokyo.ac.jp. Or to: Hiroshi Takayanagi, Graduate School of Medicine and Faculty of Medicine, The University of Tokyo, 7-3-1, Hongo, Bunkyo-ku, Tokyo, 113-0033, Japan. Phone: 81.3.5841.3373; Email: takayana@m.u-tokyo.ac.jp. Or to: Harumi Suzuki, Department of Immunology and Pathology, Research Institute, National Center for Global Health and Medicine, 1-7-1, Kounodai, Ichikawa-shi, Chiba, 272-8516, Japan. Phone: 81.47.375.4764; Email: lbhsuzuki@hospk.ncgm.go.jp.

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