The requirements for natural Th17 cell development are distinct from those of conventional Th17 cells

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CD4+ T helper 17 (Th17) cells play a critical role in the adaptive immune response against extracellular pathogens. Most studies to date have focused on understanding the differentiation of Th17 cells from naive CD4+ T cells in peripheral effector sites. However, Th17 cells are present in the thymus. In this study, we demonstrate that a population of Th17 cells, natural Th17 cells (nTh17 cells), which acquire effector function during development in the thymus before peripheral antigen exposure, shows preferential usage of T cell receptor Vβ3. nTh17 cells are dependent on major histocompatibility complex (MHC) class II for thymic selection, yet unlike conventional CD4+ T cells, MHC class II expression on thymic cortical epithelium is not sufficient for their development, rather expression on medullary epithelium is necessary. Differential signaling requirements for IL-17 priming further distinguish nTh17 from conventional Th17 cells. Collectively, our findings define a Th17 population, poised to rapidly produce cytokines, that is developmentally distinct from conventional Th17 cells and that potentially functions at the interface of innate and adaptive immunity.

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Abbreviations used: ANOVA, analysis of variance; cTEC, cortical TEC; FTOC, fetal thymic organ culture; LP, lamina propria; mTEC, medullary TEC; SP, single positive; TEC, thymic epithelial cell.

CD4+ T cells are an essential component of the adaptive immune system. Upon activation by APCs in the periphery, naive CD4+ T cells differentiate into effector Th cells that are specialized to produce specific cytokines and/or exhibit specific effector functions. In addition to the Th1 and Th2 cell lineages, a third subset of CD4+ T cells has been characterized by its expression of IL-17, hence the designation Th17 cells (Harrington et al., 2005; Park et al., 2005). The essential role of Th17 cells in mucosal and epithelial host defense has been demonstrated in many studies using various infection and disease models (Korn et al., 2009). Th17 cells have also been shown to be critical in the pathogenesis of several inflammatory diseases, leading to successful clinical trials targeting Th17 cells in psoriasis and Crohn's disease (Steinman, 2010).

Th17 cells produce IL-17F and IL-22, in addition to IL-17 (also known as IL-17A), and are identified by the lineage-specific transcription factors, ROR-γt (retinoid-related orphan receptor γt) and ROR-α (Ivanov et al., 2006; Yang et al., 2008). IL-6 and TGF-β were initially shown to be indispensible for in vitro Th17 cell differentiation from naive CD4+ T cells, whereas IL-23 is important for the maintenance and survival of the lineage in vivo (McGeachy and Cua, 2008). However, a TGF-β–independent alternative pathway of Th17 cell generation has recently been identified, suggesting heterogeneity in Th17 cells (Ghoreschi et al., 2010).

In addition to its production by Th17 cells, IL-17 is a proinflammatory cytokine also produced by many innate immune cells (Cua and Tato, 2010), including NKT cells (Michel et al., 2007) and γδ T cells (Martin et al., 2009), that gain IL-17 competency during thymic development. Recently, a population of CD4 single-positive (SP) thymocytes was shown to produce IL-17, and it was suggested that these cells are generated in the thymus (Marks et al., 2009; Tanaka et al., 2009). However, the developmental

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requirements and characteristics that distinguish this population from peripherally induced conventional Th17 cells are not well defined.

The present study utilizes fetal thymic organ culture (FTOC) to demonstrate definitively that a population of Th17 cells indeed develops in the thymus. These cells show unique characteristics in TCR gene usage and MHC class II requirements compared with those of conventional Th17 cells. Finally, a TCR signaling mutant reveals differential signaling requirements for the generation of these two distinct Th17 cell populations. Thus, our data define these natural Th17 cells (nTh17 cells) as a Th17 cell population that is distinct from conventional Th17 cells.

RESULTS AND DISCUSSION

We confirmed an earlier report (Marks et al., 2009) of an IL-17–expressing population within the $CD4^{SP}$ thymocyte compartment in WT mice (Fig. 1 A). The thymic IL-17$^+$ $CD4^{SP}$ population is distinct from NKT and γδ T cells, as this population is still present in SAP (SLAM-associated protein)-deficient (Fig. S1 A; Nichols et al., 2005) and γδ TCR KO mice (Fig. S1 B), which lack NKT and γδ T cells, respectively. We demonstrate that a significant proportion of these IL-17–producing $CD4^{SP}$ thymocytes coexpress IL-17F, and, as reported (Marks et al., 2009), have other characteristic Th17 lineage properties including IL-22 message, expression of the transcription factor ROR-γt, CCR6 (chemokine receptor 6), IL-23R, and CD44, a marker present on activated/memory cells and innate immune cells (Fig. 1, A and B). Moreover, thymic Th17 cells do not express Foxp3 (forkhead box p3) or IFN-γ (key features of $CD4^+$ regulatory T cells [Treg cells] or Th1 cells, respectively), indicating that their transcriptional and cytokine program is specific to the Th17 lineage. Similarly, we found that in young RAG2-GFP mice, in which GFP marks newly generated thymocytes, virtually all thymic IL-17–producing $CD4^{SP}$ T cells are GFP^{hi}, indicating that they are newly generated in the thymus (discussed further below; Fig. 2 D). As a more rigorous approach to analyze the ontogeny of thymic Th17 cells, we used FTOC, which revealed significant numbers of these cells at day 8 (Fig. 1 C), when the $CD4^{SP}$ population was clearly definable. These experiments demonstrate that a population of nTh17 cells develops in the thymus with the inherent ability to produce cytokines without the need for peripheral TCR-induced differentiation, thus sharing properties with other lymphocytes with innate-like characteristics.

Innate lymphocyte lineages that arise in the thymus often have a unique or skewed TCR repertoire (Lantz and Bendelac, 1994; Azuara et al., 1997). We examined the TCR repertoire of nTh17 cells by analyzing their TCR β chain variable region (TCR Vβ) usage. nTh17 cells showed preferential usage of TCR Vβ3 compared with non-Th17 $CD4^{SP}$ thymocytes (11.5 ± 0.9% vs. 2.55 ± 0.10%), whereas expression of other Vβ genes was similar or slightly decreased in a complementary manner (e.g., Vβ6; Fig. 2 A). This pattern was also observed in nTh17 cells that developed in FTOC, thus verifying the thymic origin of cells preferentially expressing this TCR Vβ family member (Fig. 2 B). In contrast, Th17 cells isolated from the small intestinal lamina propria (LP), a physiological site enriched with Th17 cells, did not show skewing toward TCR Vβ3 (Fig. 2 C). Moreover, among the TCR Vβs that were analyzed, splenic and small intestinal LP Th17 cells showed no difference in TCR Vβ usage compared with non-Th17 $CD4^+$ T cells from the same sites (Fig. 2 C and Fig. S2). Further analysis of RAG2-GFP mice revealed that, with age, a significant population of IL-17$^+$ GFP^{lo} cells emerged and that this population had even more highly skewed Vβ3 usage than their

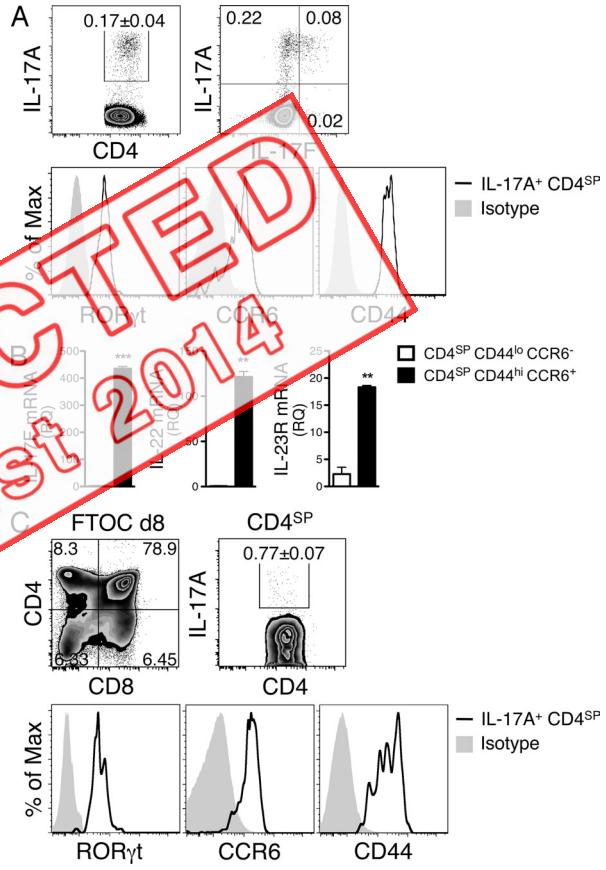

Figure 1. A population of Th17 cells develops in the thymus. (A) Thymocytes from C57BL/6 WT mice were stimulated ex vivo with PMA/ionomycin in the presence of brefeldin A and stained for surface markers and intracellular expression of IL-17A, IL-17F, and ROR-γt. Flow cytometry plots are gated on $CD4^{SP}$TCR-β$^+$TCR-γδ$^-$CD1d-tetramer$^-$ cells (first row). Histograms show the expression of the indicated transcription factor or surface marker on $CD4^{SP}$TCR-β$^+$TCR-γδ$^-$CD1d-tetramer$^-$IL-17A$^+$ thymocytes (solid black line). (B) Quantitative RT-PCR analysis of messenger RNA (mRNA) transcripts in thymocyte populations (key) sorted from WT mice, relative to GAPDH. Error bars represent SEM. **, P ≤ 0.01; ***, P ≤ 0.001 (two-tailed Student's *t* test). (C) Cells from day 8 culture of WT E15 FTOC were stimulated and stained for flow cytometry. Flow cytometry plots are gated on whole thymocytes (left) and $CD4^{SP}$TCR-β$^+$TCR-γδ$^-$CD1d-tetramer$^-$ cells (right). Histograms are as in A. Data are representative of at least three independent experiments with $n \geq 3$ mice (or FT lobe [C]) per experiment.

IL-17$^+$ GFP^{hi} counterparts (Fig. 2 D). These data indicate preferential recirculation of Vβ3$^+$ nTh17 cells to the thymus and/or preferential retention of this subset. The lack of Vβ3 skewing among Th17 cells in the periphery could be caused by differential homing of nTh17 versus conventional Th17 cells and/or differences in the expansion of these populations at particular organ sites. It has been suggested that nTh17 cells preferentially home to the small intestinal LP (Marks et al., 2009), but whether these cells represented nTh17 cells or a combination of natural and conventional Th17 cells was unclear.

The innate-like properties and skewed Vβ usage prompted us to explore the requirements for nTh17 cell development. Thymic selection occurs via interactions between the TCR and MHC molecules expressed on thymic epithelial cells (TECs) and hematopoietic APCs (Klein et al., 2009). Because conventional CD4$^+$ T cells are selected on MHC class II, we investigated the role for this restricting element in nTh17 cell development using MHC class II–deficient mice. No nTh17 cells were present in these mice, indicating that selection of nTh17 cells is MHC class II dependent (not depicted). In addition to the identity of the selecting ligand, determining the specific thymic compartment (cortex vs. medulla) and cell type (epithelium vs. hematopoietic cells) presenting the ligand has provided insight into understanding the development of various lymphocyte lineages. To determine the role of radioresistant TECs versus radiosensitive hematopoietic cells in nTh17 cell selection, we generated radiation BM chimeras with MHC class II–deficient mice either as BM donors or hosts. In BM chimeras in which MHC class II–deficient BM cells (CD45.2$^+$) were transplanted into lethally irradiated WT hosts (CD45.1$^+$), creating a thymic environment in which only the TECs express MHC class II, the percentage and number of nTh17 cells were similar to control WT BM chimeras (Fig. 3, A and B). These data indicate that MHC class II expression on cortical TECs (cTECs) and medullary TECs (mTECs) is sufficient to support nTh17 cell development and that there is not an absolute requirement for MHC class II expression on hematopoietic APCs for the generation of this population. Chimeras in which WT BM cells (CD45.1$^+$) were transplanted into MHC class II–deficient hosts (CD45.2$^+$) were nearly devoid of nTh17 cells (Fig. 3 C), indicating that MHC class II expression on hematopoietic cells alone is not sufficient for normal nTh17 cell selection.

To define the contribution of cTECs versus mTECs in nTh17 cell development, we first used K14-A$_\beta^b$ mice that express MHC class II only on cTECs, whereas mTECs and hematopoietic APCs are MHC class II deficient (Laufer et al., 1996). nTh17 cells were not found in the thymi of K14-A$_\beta^b$ mice (Fig. 3 D), despite the presence of abundant CD4^{SP} thymocytes and the ability of peripheral CD4$^+$ T cells from these mice to differentiate into Th17 cells under in vitro Th17-polarizing conditions (not depicted). These data suggest that expression of MHC class II on thymic cortical epithelium, as defined in K14-A$_\beta^b$ mice, is not sufficient for selection of nTh17 cells. This finding is in contrast to nT$_{reg}$ and conventional CD4$^+$ T cell development for which cortical MHC class II expression is sufficient for positive selection (Laufer et al., 1996; Bensinger et al., 2001; Liston et al., 2008).

To investigate the role of mTECs in MHC class II–mediated nTh17 selection, we analyzed thymocytes from C2TAkd mice, which have greatly diminished MHC class II expression specifically on mTECs because of targeted knockdown of the MHC class II transactivator, CIITA (Hinterberger

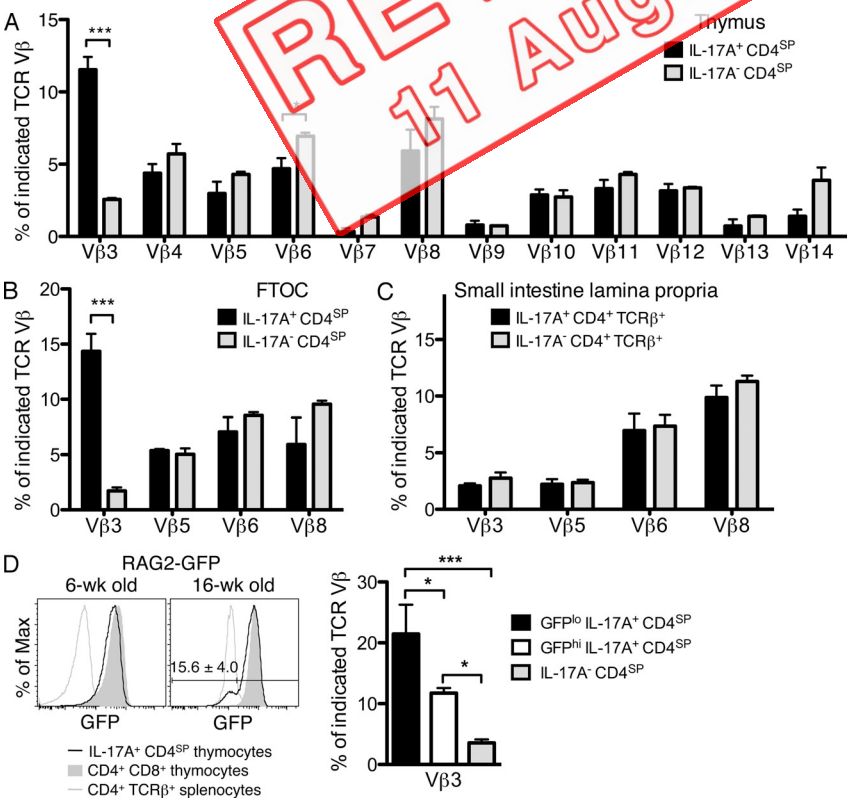

Figure 2. nTh17 cells show preferential usage of TCR Vβ3. (A–C) CD4^{SP} thymocytes (6–8-wk-old mice [A] or E15 FTOC d8 [B]) or CD4$^+$ T cells isolated from the small intestinal LP (C) of WT (B6) mice were assessed for the proportion of cells expressing the indicated TCR Vβ chain in IL-17A$^+$ versus IL-17A$^-$ cells. Pooled data from three independent experiments with $n \geq 3$ mice (or FT lobe [B]) per experiment; bars and error bars represent mean ± SEM. *, $P \leq 0.05$; ***, $P \leq 0.001$ (two-way ANOVA followed by Bonferroni post-tests). (D) GFP expression of indicated populations from 6- and 16-wk-old RAG2-GFP mice. Percentage (mean ± SEM) of GFP^{lo} cells among nTh17 cells in 16-wk-old mice is shown. Graph represents the proportion of Vβ3$^+$ cells in the indicated thymocyte populations (key) in 16-wk-old mice. Data are from three independent experiments with $n \geq 9$ mice per group. Bars and error bars represent mean ± SEM. *, $P \leq 0.05$; ***, $P \leq 0.001$ (one-way ANOVA followed by Tukey's post-tests).

et al., 2010). nTh17 cells were nearly absent from thymi of C2TAkd mice, demonstrating that MHC class II expression on mTECs is necessary for nTh17 cell development and that combined MHC class II expression on cTECs and hematopoietic APCs cannot compensate for loss of MHC class II on mTECs. This observation is again in contrast to the requirements for selection of conventional $CD4^+$ and nT_{reg} cells, as these cell types are present in elevated frequencies in C2TAkd mice (Hinterberger et al., 2010). Expression of MHC class II in K14-A_β^b mice is diminished compared with WT mice, presenting the possibility that lack of nTh17 cell generation could be the result of low MHC class II expression. However, C2TAkd mice have WT levels of MHC class II on cTECs, yet this pattern of expression is not sufficient for nTh17 cell selection. Collectively, these data show that MHC class II expression on cTECs, while sufficient for nT_{reg} and conventional $CD4^+$ T cell selection, is not sufficient for nTh17 cell development; rather, MHC class II expression on mTECs appears to play a critical role in nTh17 cell development. Further studies are required to determine whether mTECs are sufficient for the generation of nTh17 cells and to dissect how MHC class II:peptide presentation, alone or in concert with soluble factors and/or co-stimulatory molecules, dictates nTh17 lineage commitment.

The strength of TCR signaling is known to affect the development of many lymphocyte lineages, including γδ T cells (Hayes et al., 2005) and $CD4^+$ nT_{reg} cells (Jordan et al., 2001). SLP-76 (SH2 domain–containing leukocyte protein of 76 kD) is a critical adaptor protein for thymocyte selection and TCR signaling (Koretzky et al., 2006). Recently, we showed that mutation of tyrosine 145 of SLP-76 (Y145F) diminished TCR signal strength, resulting in altered thymocyte selection (Jordan et al., 2008). To test whether diminished TCR signaling affects the development of nTh17 cells, we examined thymi of mice harboring the SLP-76 Y145F mutation (Y145F mice). Interestingly, these mice had a marked increase in the proportion and absolute number of nTh17 cells compared with WT mice (Fig. 4, A and B). nTh17 cells in Y145F mice were phenotypically similar to nTh17 cells from WT mice with respect to cytokine potential and expression of cell surface markers (Fig. S3, A and B). They developed in FTOC with an increased frequency and number compared with WT (Fig. S3, C and D) and displayed preferential usage of TCR Vβ3 (Fig. S3 E). It is unclear why Y145F mice are enriched for nTh17 cells because agonist peptides have been implicated in their development (Marks et al., 2009). We speculate that the altered responsiveness of Y145F thymocytes results in selection of $CD4^{SP}$ cells that would otherwise largely be negatively selected. However, to rule out the possibility that contribution of cell-extrinsic factors drive enhanced nTh17 development in Y145F mice, we generated radiation mixed BM chimeras in which WT ($Thy1.1^+$) and Y145F or WT ($CD45.2^+$) BM cells were mixed and transplanted into lethally irradiated WT ($CD45.1^+Thy1.2^+$) host mice. Regardless of the chimerism, which can affect the degree of potential extrinsic factors, thymocytes derived from Y145F BM had an increased proportion of nTh17 cells compared with WT donor BM–derived thymocytes that had developed in the same thymic environment (Fig. 4, C and D). These data indicate that the enrichment of nTh17 cells in Y145F thymus is a cell-intrinsic property. This finding is in contrast to a $CD8^+$ innate-like lymphocyte population that has recently been shown to be increased in these mice via a cell-extrinsic mechanism (Gordon et al., 2011).

Despite the enrichment of thymic nTh17 cells, surprisingly, $CD4^+$ T cells from the small intestinal LP of Y145F mice showed greatly reduced IL-17 production and ROR-γt expression compared with WT LP cells (Fig. 5, A and B). Lack of Th17 cells in the Y145F

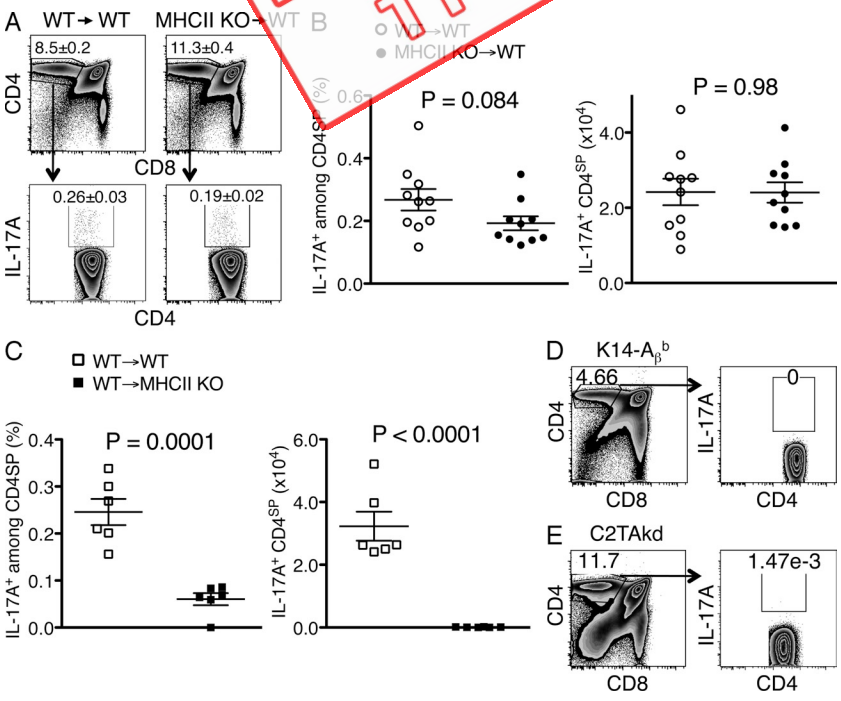

Figure 3. MHC class II expression on thymic medullary epithelium is necessary for selection of nTh17 cells. (A) Thymocytes from BM chimeras were stimulated and analyzed. Representative flow cytometry plots gated on live thymocytes (top) or $CD4^{SP}TCR\text{-}\beta^+TCR\text{-}\gamma\delta^-NK1.1^-$ cells (bottom) from donor BM-derived cells ($CD45.2^+$) are shown. (B and C) The proportion (left) or number (right) of nTh17 cells of BM donor origin in indicated chimeras is shown (mean ± SEM; p-values are from two-tailed Student's *t* test). Data are from two independent experiments with a total of $n = 6$–10 mice per group. (D and E) Thymocytes from K14-A_β^b (D) and C2TAkd mice (E) were stimulated and analyzed. Flow cytometry plots are gated on live thymocytes (left) and $CD4^{SP}TCR\text{-}\beta^+TCR\text{-}\gamma\delta^-NK1.1^-$ cells (right). Data are representative of at least two independent experiments with a total of $n \geq 4$ mice per group.

LP could be caused by the inability of Y145F peripheral CD4$^+$ T cells to differentiate into Th17 cells, a defect in Y145F CD4$^+$ T cells homing to peripheral sites, or an altered gut environment resulting from an unappreciated effect of the Y145F mutation. Naive (CD44^{lo}CD62L^{hi}) Y145F peripheral CD4$^+$ T cells showed a severe defect in IL-17 production compared with WT cells when cultured in vitro under conditions that promote Th17 cell differentiation (Fig. 5 C), similar to T cells deficient in the SLP-76 binding partner Itk (IL-2–inducible T cell kinase; Gomez-Rodriguez et al., 2009). In contrast, in vitro differentiation to Th1 or Th2 lineages was intact (Fig. S4, A and B), indicating that Y145F CD4$^+$ T cells are not globally defective in cytokine production or differentiation into effector subsets. Consistent with these findings, Y145F BM-derived CD4$^+$ T cells showed defective IL-17 production in mixed BM chimeras in the presence of WT BM-derived APCs and a WT gut environment, indicating that the Y145F peripheral CD4$^+$ LP T cells have an intrinsic defect in Th17 lineage commitment (Fig. 5 D). Because the number of CD4$^+$ T cells in the small intestinal LP of Y145F mice is comparable with that of WT mice and splenic CD4$^+$ IL-17$^+$ T cells are present in these mice, we speculate that defective trafficking is unlikely (not depicted). To address the permissiveness of the Y145F intestinal environment, we generated BM chimeras in which WT BM was transplanted into irradiated Y145F host. WT donor BM-derived LP CD4$^+$ T cells showed intact IL-17 production in Y145F host, thus again supporting the idea that the defective peripheral Th17 phenotype in Y145F mice is via a cell-intrinsic mechanism (Fig. 5 E).

Collectively, these data demonstrate that nTh17 development and peripheral Th17 conversion have different signaling requirements. The biochemical mechanism underlying preserved nTh17 generation in the face of defective conventional Th17 cell differentiation in Y145F mice is not known. It is possible that IL-17–producing cells are present among Y145F thymocytes because high affinity T cells are still represented within the developing Y145F repertoire, allowing for compensation of defective TCR signal transduction. Alternatively, the differences in signaling pathways between thymocytes and

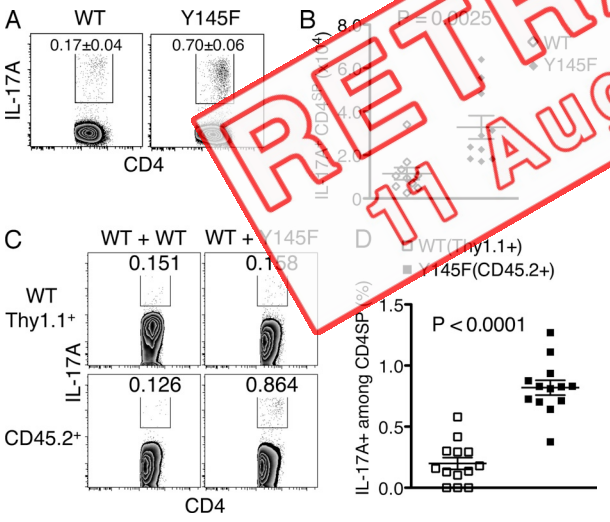

Figure 4. Y145F mice show enrichment of thymic nTh17 cells via a cell-intrinsic mechanism. (A and B) Thymocytes from WT and Y145F mice were stimulated with PMA/ionomycin and analyzed. Representative flow cytometry plots gated on CD4^{SP}TCR-β$^+$TCR-γδ$^-$NK1.1$^-$ cells (A) and pooled data (B) from at least three independent experiments with $n \geq 3$ per experiment are shown. Error bars represent SEM. (C) Thymocytes from mixed BM chimeras were stimulated and analyzed. Representative flow cytometry plots gated on CD4^{SP} TCR-β$^+$TCR-γδ$^-$NK1.1$^-$ cells showing the percentage of IL-17A$^+$ cells among Thy1.1$^+$ or CD45.2$^+$ populations. (D) Pooled data representing the proportion of nTh17 cells among CD4^{SP} cells in either WT (Thy1.1$^+$)- or Y145F (CD45.2$^+$)-derived thymocytes from WT + Y145F mixed BM chimeras (mean ± SEM; p-value from two-tailed Student's *t* test). Data are from two independent experiments with $n \geq 6$ mice per group.

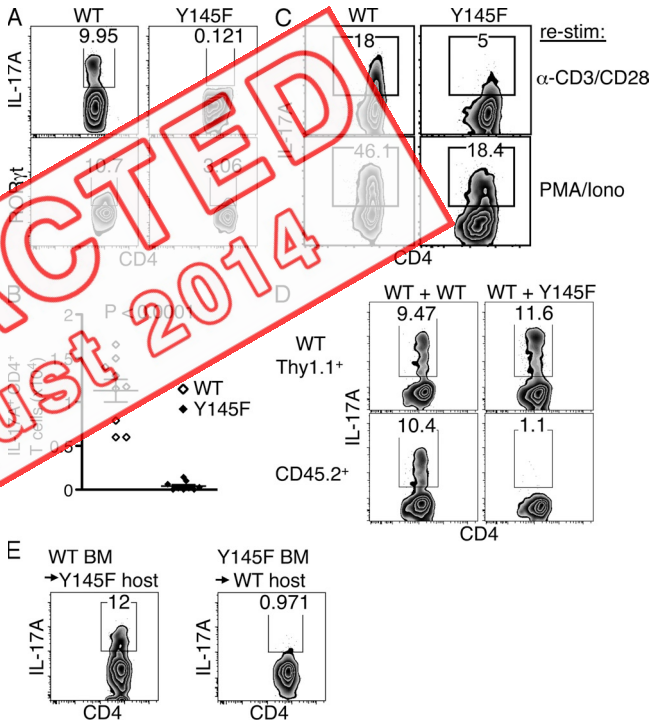

Figure 5. Y145F CD4$^+$ T cells have an intrinsic defect in peripheral Th17 cell differentiation. (A and B) Small intestinal LP cells were isolated from WT and Y145F mice, stimulated, and analyzed. Representative flow plots gated on CD4$^+$CD3$^+$TCR-β$^+$ cells (A) and pooled data (B) from at least three independent experiments with $n \geq 3$ per group in each experiment (mean ± SEM; p-value from two-tailed Student's *t* test) are shown. (C) Naive CD4$^+$ T cells from WT and Y145F mice were isolated by cell sorting and cultured with plate-bound anti-CD3/CD28 and TGF-β, IL-6, IL-23, anti–IL-4, and anti–IFN-γ for 3 d. Cells were restimulated with either anti-CD3/CD28 or PMA/ionomycin with brefeldin A followed by intracellular staining for IL-17A. Data are representative of at least three independent experiments. (D and E) Small intestinal LP cells from mixed BM chimeras (D) or BM chimeras with the indicated hosts (E) were stimulated and analyzed. Representative flow cytometry plots gated on CD4$^+$CD3$^+$TCR-β$^+$ cells showing the percentage of IL-17A$^+$ cells among Thy1.1$^+$ or CD45.2$^+$ populations (or donor BM-derived cells [E]) are shown. Data are from two independent experiments with $n \geq 6$ mice per group (D) or one independent experiment with $n = 5$ mice per group (E).

naive peripheral T cells and/or the requirements for IL-17 induction in these cell populations may be fundamentally different. Indeed, recent publications suggest that different IL-17–producing T cell populations have differential requirements for TCR and/or cytokine-initiated signal transduction for Th17 lineage differentiation (Tanaka et al., 2009; Ghoreschi et al., 2010; Powolny-Budnicka et al., 2011).

We have described a population of Th17 cells with innate immune cell characteristics. These cells acquire effector function during thymic development, show a skewed TCR gene usage, and have positive selection requirements distinct from that of conventional T cells. Using a TCR signaling mutant, we further demonstrate that the nTh17 cells constitute a population distinct from conventional Th17 cells, as these mice have enriched nTh17 cells in the thymus but show markedly defective conventional Th17 cell differentiation in the periphery because of cell-intrinsic mechanisms. Understanding the biology of nTh17 cells will provide insight into recently identified Th17 cells in human thymi and umbilical cord blood (Cosmi et al., 2008; Kleinschek et al., 2009) and may also shed light on the role of IL-17 in bridging innate and adaptive immune responses.

MATERIALS AND METHODS

Mice. C57BL/6J, B6.PL-Thy1^{a}/CyJ, FVB-Tg(Rag2-EGFP)1Mnz/J, and B6.129P2-Tcrd^{tm1Mom}/J (γδ TCR KO) mice were purchased from the Jackson Laboratory. B6 CD45.1, Ab1^{tm1Gru} (MHC class II KO, I-A$^{-/-}$) mice were purchased from Taconic. SLP-76 Y145F (Jordan et al., 2008), SAP$^{-/-}$ (provided by K. Nichols, Children's Hospital of Philadelphia, Philadelphia, PA; Yin et al., 2003), K14-A$_{\beta}^{b}$ (provided by T. Laufer, University of Pennsylvania, Philadelphia, PA; Laufer et al., 1996), and C2TAkd (provided by L. Klein, Ludwig-Maximilians-University, Munich, Germany; Hinterberger et al., 2010) mice were previously described. Animals were housed at the University of Pennsylvania, and experiments were performed in accordance with protocols approved by the Institutional Animal Care and Use Committee.

FTOC. Fetal thymic lobes were dissected from embryonic day (E) 15 embryos and cultured on sponge-supported filter membranes (Gelfoam absorbable gelatin sponge, USP 7 mm [Pfizer]; Nuclepore track-etched membranes, 0.8 μm–13 mm round [GE Healthcare]) at an interphase between 5% CO_2-humidified air and IMDM (10% FCS/50 μM 2-mercaptoethanol/2 mM L-glutamine/penicillin/streptomycin). Medium was changed after 3 d of culture.

TCR Vβ analysis. Proportion of the indicated TCR Vβ among the analyzed populations was assessed using TCR Vβ screening panel (BD) and flow cytometry.

Radiation BM chimeras. Recipient mice were irradiated with 950 rads and injected i.v. with a mixture of T cell–depleted (magnetic bead depletion; QIAGEN) BM from the indicated donor mice. Recipients were reconstituted with 2 × 10^6 BM cells and maintained on sterile water with sulfamethoxazole/trimethoprim for 2–3 wk. Chimeras were analyzed at 5–6 wk (MHC class II KO BM into WT hosts) or 8 wk (all other BM chimeras) after transplantation.

Isolation of LP lymphocytes. The small intestine was dissected, cleared from mesentery, fat, and Peyer's patches, washed in PBS, and cut into pieces. After incubation in RPMI 1640 with EDTA, epithelial cells were separated, and the tissue was digested with Liberase TM and DNase I (both from Roche) at 37°C. LP lymphocytes were recovered after filtering the digested tissue through a 70-μm cell strainer and washed in media.

Ex vivo stimulation. Freshly isolated or cultured lymphocytes were stimulated ex vivo for 5 h with 50 ng/ml PMA and 500 ng/ml ionomycin in the presence of 1 μg/ml brefeldin A. Cells were then assayed for cytokine production by intracellular flow staining.

T cell isolation and differentiation. CD4^{+} T cells from spleens and lymph nodes of the indicated mice were purified by negative selection and magnetic separation (Miltenyi Biotec) followed by sorting of naive CD4^{+}CD25^{-}CD44^{lo}CD62L^{hi} population using the FACSAria II (BD). Cells were activated by 1 μg/ml plate-bound anti-CD3 and 5 μg/ml anti-CD28 (both from eBioscience) in the presence of 5 ng/ml TGF-β, 20 ng/ml IL-6, 10 ng/ml IL-23, 10 μg/ml anti–IL-4, and 10 μg/ml anti–IFN-γ for Th17 polarization; 50 U/ml IL-12 and 10 μg/ml anti–IL-4 for Th1 polarization; and 2,000 U/ml IL-4, 10 μg/ml anti–IL-12, and 10 μg/ml anti–IFN-γ for Th2 polarization.

Flow cytometry. The following antibodies were used for surface stain (from BD unless noted): anti-CD3-PE-Cy5 or -PB (BioLegend), anti-CD4-PE-Cy7 or -FITC, anti-CD8-PETR (Invitrogen) or -APC-Cy7, anti-CD44-AF700 (BioLegend) or -PE, anti-CD45.1-PE, anti-CD45.2-FITC or -PE-Cy7, anti-CD62L-APC, anti-Thy1.1-PE-Cy5 or -PE, anti–TCR-β–APCe780 (eBioscience), anti-TCR-γ/δ-PE-Cy5, anti-NK1.1-PE-Cy7, anti-CCR6-AF647 (eBioscience), and PBS57-CD1d-tetramer-APC (National Institutes of Health Tetramer Core Facility). For intracellular cytokine or transcription factor expression staining was performed using Foxp3 staining buffer (eBioscience) according to the manufacturer's instructions. The following antibodies were used (from eBioscience unless noted): anti–ROR-γt–PE, anti-Foxp3-FITC, anti–IL-17A–AF647 or –PE, anti–IL-17F–FITC, anti–IFN-γ–PB (BioLegend), and anti–IL-4–PE-Cy7. Data were acquired using the FACS LSR II (BD) and analyzed with FlowJo software (Tree Star).

Real-time PCR. Total RNA was isolated from FACS-purified thymocytes using the RNeasy Mini kit (QIAGEN), and cDNA was synthesized with the Superscript III First Strand kit (Invitrogen). RT-PCR was performed with gene-specific primers and probes (Applied Biosystems) with Fast Taq Master Mix (Applied Biosystems) on a 7500 Fast Real-Time PCR system (Applied Biosystems). For analysis, samples were normalized to GAPDH levels and then set relative to the CD4^{SP}CD44^{lo}CCR6^{-} population by the relative quantification method (ΔΔCT). The following primers and probes (Applied Biosystems) were used: Gapdh, Mm03302249_g1; Il-17f, Mm00521423_m1; Il-22, Mm00444241_m1; and Il23r, Mm00519943_m1.

Statistical analysis. P-values were analyzed from Student's *t* test, one-way analysis of variance (ANOVA) followed by Tukey's post-test, or two-way ANOVA followed by the Bonferroni post-test using Prism (GraphPad Software).

Online supplemental material. Fig. S1 shows that thymic Th17 cells are not NKT cells or γδ T cells and do not express Foxp3 or IFN-γ. Fig. S2 shows the TCR Vβ usage of peripheral Th17 cells. Fig. S3 shows that Y145F nTh17 cells are phenotypically similar to WT nTh17 cells. Fig. S4 shows that Y145F peripheral CD4^{+} T cells show intact Th1 and Th2 cell differentiation. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20110680/DC1.

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