After development in the BM, NK cells are released into circulation and are found in large numbers in the spleen and liver. Recent studies have also highlighted the presence of NK cells within LNs (Martín-Fontecha et al., 2004; Chen et al., 2005; Bajénoff et al., 2006; Garrod et al., 2007; Walzer et al., 2007a), accounting for \( \geq 0.5\% \) of cells in mouse LNs and \( \sim 5\% \) in human LNs (Grégoire et al., 2007). After immunization or infection, NK cell numbers can increase rapidly within draining LNs (Martín-Fontecha et al., 2004; Lucas et al., 2007; Gustafsson et al., 2008; Watt et al., 2008). Accumulating evidence suggests that NK cells help shape the adaptive immune response emerging within a responding lymphoid tissue (Martin–Fontecha et al., 2004; Bajénoff et al., 2006; Kassim et al., 2009). LNs and spleen are also likely to be early sites of NK encounter with inflammatory stimuli presented, for example, by dendritic cells. A recent study has provided evidence that NK cells can be primed in draining LNs before returning to the circulation with enhanced effector function (Lucas et al., 2007). Moreover, several recent studies have identified requirements for NK cell entry into LNs (Martín-Fontecha et al., 2004; Chen et al., 2005; A. Enders and R. Rivera contributed equally to this paper.

### T-bet–dependent S1P5 expression in NK cells promotes egress from lymph nodes and bone marrow

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During a screen for ethylnitrosourea–induced mutations in mice affecting blood natural killer (NK) cells, we identified a strain, designated Duane, in which NK cells were reduced in blood and spleen but increased in lymph nodes (LNs) and bone marrow (BM). The accumulation of NK cells in LNs reflected a decreased ability to exit into lymph. This strain carries a point mutation within Tbx21 (T-bet), which generates a defective protein. Duane NK cells have a 30–fold deficiency in sphingosine-1-phosphate receptor 5 (S1P₅) transcript levels, and S1P₅-deficient mice exhibit an egress defect similar to Duane. Chromatin immunoprecipitation confirms binding of T-bet to the S1pr5 locus. S1P₅-deficient mice exhibit a more severe NK cell egress block, and the FTY720–sensitive S1P₅ also plays a role in NK cell egress from LNs. S1P₅ is not inhibited by CD69, a property that may facilitate trafficking of activated NK cells to effector sites. Finally, the accumulation of NK cells within BM of S1P₅-deficient mice was associated with reduced numbers in BM sinusoids, suggesting a role for S1P in BM egress. In summary, these findings identify S1P₅ as a T-bet–induced gene that is required for NK cell egress from LNs and BM.

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Bajénoff et al., 2006; Lucas et al., 2007); however, less is understood about how they return to circulation.

T cell egress from thymus, and T and B cell egress from peripheral lymphoid organs depends on sphingosine-1-phosphate (S1P) and S1P receptor 1 (S1P1; Allende et al., 2004; Matloubian et al., 2004; Pappu et al., 2007). In contrast, S1P1, and S1P deficiency have not been found to block B cell egress from BM (Matloubian et al., 2004; Pappu et al., 2007). FTY720, a small molecule that can down-modulate S1P1, is also effective in preventing T and B cell egress from thymus and LNs (Mandala et al., 2002; Grüler and Goetzl, 2004; Matloubian et al., 2004). However, FTY720 treatment does not deplete NK cells from circulation in mice or humans (Vaessen et al., 2006; Walzer et al., 2007b). NK cells selectively express S1P1, and in mice deficient in this receptor, NK cell distribution was altered, with reduced NK cell numbers in blood and spleen and increased numbers in LNs and BM (Walzer et al., 2007b). This work established a role for S1P1 in NK cell recirculation; however, S1P1’s role in egress was not defined.

T-bet is a T-box–containing transcription factor that is required for Th1 cell development and also functions in the generation of effector CD8+ T cells and in B cells for switch- required for Th1 cell development and also functions in the role for S1P5 in NK cell recirculation; however, S1P5’s role in LNs and BM (Walzer et al., 2007b). This work established a role for S1P5 in NK cell recirculation; however, S1P5’s role in egress was not defined.

T-bet is a T-box–containing transcription factor that is required for Th1 cell development and also functions in the generation of effector CD8+ T cells and in B cells for switching to IgG2a (Shiow et al., 2006; Peng et al., 2002; Lugo-Villarino et al., 2003; Xu and Zhang, 2005; Joshi et al., 2007; Intlekofer et al., 2008). T-bet is also required for the final maturation of NK cells and for the development of invariant NKT cells (Townsend et al., 2004). T-bet has been shown to mediate direct effects on various promoters, to bind and modify the effects of other transcription factors, and to facilitate chromatin remodeling through the regulation of histone methyltransferase activity (Hwang et al., 2005; Mehta et al., 2005; Beima et al., 2006; Chen et al., 2006; Djuretic et al., 2007; Lewis et al., 2007). The key genes regulated by T-bet in NK cell development and maturation are not well defined.

In an effort to identify genes involved in NK cell development or trafficking, we screened mice carrying ethynitrosourea (ENU)-induced mutations for altered blood NK cell numbers or surface phenotypes. Our characterization of a strain with low circulating NK cells led us to identify a role for T-bet in promoting S1P3 expression in several cell types and to establish a role for S1P3 in NK cell egress from LNs and BM.

RESULTS
Characterization of the ENU strain Duane
Screening peripheral blood for lymphocyte phenotypes resulting from ENU-induced mutations identified a strain, Duane, with a low percentage of NK cells in the blood, spleen, and liver, but a significantly elevated frequency of NK cells in peripheral LNs and BM (Fig. 1 A; and Fig. S1, A and B). The blood samples were also screened for CD69, with the intent of detecting mutations that altered the ability of CD69 to regulate lymphocyte egress (Shiow et al., 2006). An increased fraction of Duane NK cells was found to express CD69 (Fig. 1 B). Through further flow cytometric analysis of various developmental markers, Duane NK cells were found to have the CD27hiKLRII- phenotype typical of immature NK cells (Fig. 1 B). Duane had a near complete absence of mature iNKT cells (Fig. S1 A).

To determine if the NK cell accumulation in peripheral LNs was cell intrinsic, mixed BM chimeras were generated. In these mice, a lower percentage of Duane NK cells was observed in blood and spleen as compared with wild-type NK cells, whereas there was a relative accumulation of Duane NK cells in peripheral LNs (Fig. 2 A). The distribution of Duane and wild-type B cells was examined as a control and was equivalent in all sites (Fig. 2 A). Analysis of the lymph from these mice revealed an underrepresentation of Duane NK cells, suggesting that the LN accumulation was caused by a failure of these cells to egress (Fig. 2 A). When mixed BM chimeras were treated with α4 integrin, αL integrin, and L-selectin blocking antibodies to prevent NK cell and lymphocyte entry into LNs (von Andrian and Mempel, 2003; Bajénoff et al., 2006; Pham et al., 2008), and the extent of decay in LN cell numbers was measured after 40 h, an increase in the percentage of Duane NK cells was observed (Fig. 2 A). This finding was consistent with a reduction in the ability of Duane NK cells to exit LNs. In another test of trafficking behavior, wild-type and Duane splenocytes were each transferred into wild-type B6 recipients, and 24 h later the ratio of donor NK cells in the LN versus spleen was calculated. A greater fraction of Duane NK cells was found in the LNs as compared with wild-type NK cells, consistent with a defect in Duane NK cell egress from peripheral LNs (Fig. 2 B).

Identification of the Duane mutation
Mapping the causative genetic lesion in Duane was achieved by crossing an affected Duane mouse onto a wild-type C57BL/10 mouse, followed by intercrossing these F1 offspring and screening for the Duane phenotype. The seven most clearly affected and eight clearly unaffected mice were selected for the initial genome scan. Mapping was performed as previously described (Nelms and Goodnow, 2001) by using a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11, and all mice were typed for a panel of 80 Amplifluor assays that can distinguish single nucleotide polymorphisms (SNPs) between C57BL/6 and C57BL/10. The only clear linkage was for markers on the distal part of chromosome 11.
encoding T-bet, *Tbx21*, identified a point mutation resulting in the replacement of a single nucleotide in the second intron (Fig. S2, C and D). This mutation disrupts an intronic splice acceptor site, thereby preventing the normal splicing of the T-bet mRNA (Fig. S2, E and F). PCR amplification and sequencing of T-bet mRNA isolated from Duane splenocytes revealed the use of a cryptic intronic splice acceptor site located 24 nucleotides into exon 3 (Fig. S2, F and G). This results in a predicted, in-frame, eight–amino acid deletion in the deduced protein sequence of Duane T-bet (Fig. S2 G). Comparison of the predicted protein structure of Duane T-bet to the known structure of the T-box domain of *Xenopus laevis* T protein and the predicted structures of other mammalian T-box proteins indicates that this deletion corresponds to a region adjacent to and including one of the residues involved in known protein–protein interactions (Fig. S2 H).

**Expression of T-bet in Duane**

PCR analysis of T-bet mRNA levels using primers spanning exons 1 and 2 indicated little difference between Duane and wild-type NK cells (Fig. S2 I). To assay T-bet protein levels, splenocytes were cultured for 48 h in conditions conducive to polyclonal T cell activation. Although both Duane and wild-type splenocytes activated to the same degree (Fig. S2 J), the amount of T-bet protein in Duane cell lysates were three- to fourfold lower than those of wild-type mice (Fig. S2 K). Interestingly, although some T-bet protein was detected in Duane, the NK phenotype of this strain was indistinguishable from that of T-bet–null mice (Fig. 1 B), and both strains exhibit a severe deficiency in iNKT cells (Fig. S1; Townsend et al., 2004).

**T-bet function in Duane**

To determine if the Duane mutation affected the function of T-bet, cells were transfected with an empty vector or a vector encoding wild-type or Duane T-bet, and the transcription of various gene targets was assayed. Overexpression of wild-type T-bet resulted in greater than fivefold induction in the transcription of IFN-γ, CCL3, and CXCR3 (Fig. S3 A). In contrast, overexpression of Duane T-bet did not result in the increased transcription of any of these known T-bet target genes, suggesting that the Duane mutation has rendered T-bet functionally inactive.

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**Figure 1. Identification of the ENU mutant Duane.** (A) NK cell frequencies within the indicated tissues of Duane and wild-type B6 mice. Bars represent mean values, and circles represent individual animals. Data are representative of at least two Duane and two wild-type mice in each of three independent experiments. (B) Representative flow cytometric analysis of NK cells from Duane, *Tbx21*<sup>−/−</sup>, and wild-type B6 mice for cell-surface markers. Plots are representative of at least three independent experiments, each analyzing at least two Duane and two wild-type mice. PLN, peripheral LN. *, *P < 0.005; **, *P < 0.0001.
T-bet nonfunctional. Additionally, cotransfection of cells with a vector containing Duane T-bet and a luciferase reporter coupled to the mouse IFN-γ promoter region failed to result in an increase in luciferase activity, whereas transfection of a wild-type T-bet vector together with the reporter construct resulted in robust luciferase activity (Fig. S3 B).

To further test if any T-bet function remained in Duane, we analyzed both T and B cell differentiation in assays previously demonstrated to be T-bet dependent. Mixed cultures of wild-type and Duane T cells under Th1-inducing conditions failed to result in the expression of IFN-γ within the Duane cells despite robust expression in the co-cultured wild-type cells (Fig. S3 C). This result was similar to that observed in a wild-type and T-bet–deficient cell co-culture (Fig. S3 C). Likewise, co-culture of wild-type and Duane B cells under IgG2a-inducing conditions resulted in expression of IgG2a by the CD45.1+ wild-type cells but not the Duane B cells (Fig. S3 D). From these assays, the Duane mutation appears to result in a functionally null T-bet phenotype.

**Figure 2.** Peripheral lymph node NK cell accumulation in Duane results from a cell-intrinsic egress defect. (A) Analysis of wild-type mice reconstituted with a mix of wild-type and Duane BM. Some mice (PLN+Block) received integrin and selectin blocking antibodies 40 h before analysis. Values are reported as a ratio of Duane (CD45.2) to wild-type (CD45.1) mice. At least two untreated and two treated chimeras were analyzed in each of two independent experiments. (B) Analysis of wild-type B6 mice 24 h after adoptive transfer of either Duane or wild-type splenocytes. Values are reported as a ratio of transferred NK cells recovered from the spleen (as a percentage of transferred B cells) to transferred NK cells in the peripheral LNs (as a percentage of transferred B cells). Data were obtained from two independent experiments, each composed of two recipients receiving Duane splenocytes and two recipients receiving wild-type splenocytes. Bars represent mean values, and circles represent individual animals. PLN, peripheral lymph node. *, P < 0.005; **, P < 0.001.

**T-bet regulation of S1P5**

In an effort to understand the mechanism behind the NK cell accumulation in Duane LNs, we analyzed the expression of S1P receptors in NK cells. NK cells were notable in their abundant expression of S1P5 (Fig. 3 A; Barrett et al., 2007), as reported previously (Walzer et al., 2007b), but they also expressed S1P1 (Fig. 3 A). A comparison of Duane and wild-type NK cells revealed markedly reduced amounts of S1P1 in Duane NK cells but comparable amounts of S1P1 between the two groups (Fig. 3 B).

To explore the possibility that T-bet was a regulator of S1P5 expression, T-bet was overexpressed in WEHI-231 cells and in primary CD4+ and CD8+ T cells (Fig. 3 C). In each case, transduction of cells with a vector containing T-bet was sufficient to induce S1P5 expression. Although only low levels of S1P5 expression were achieved in WEHI-231 cells, the magnitude of this induction was similar to that of the known T-bet target IFN-γ (Fig. 3 C). To determine if T-bet acted directly on the S1pr5 locus, binding to conserved 5′ and 3′ regions of the gene was examined. T-bet chromatin immunoprecipitation (ChIP) using lysates from cell types known to abundantly express T-bet (Th1 cells and effector CD8+ T cells) demonstrated an interaction of T-bet with a 3′ site (Fig. 3 D).

We addressed whether other cell types that express T-bet show S1P5 expression. iNKT cells were found to have high S1P5 expression (Fig. 3 E). The failure of iNKT cells to develop in the absence of T-bet prevented us from further testing the connection between T-bet and S1P5 expression in these cells. Sorted CD44hiCD4+ and CD8+ T cells, representing memory and/or effector T cell populations, freshly isolated from adult mice showed low but measurable S1P5 expression as well as T-bet, and the S1P5 transcripts were reduced by >50-fold in cells sorted from T-bet–deficient mice (Fig. 3 E). Finally, when CD8+ T cells were stimulated with antigen under culture conditions that promote development of T-bet–expressing effector cells (Intlekofer et al., 2008), there was marked up-regulation of S1P5 and this was dependent on intrinsic T-bet expression (Fig. 3 F). Thus, T-bet promotes the expression of the egress receptor S1P5 in NK cells and CD8+ effector T cells, and likely also in iNKT cells.

**S1P and S1P receptor requirement for NK cell egress from LNs**

In initial experiments to elucidate the contribution of S1P receptors to NK cell egress from secondary lymphoid tissues, mice were treated for 20 h with FTY720, and analyzed for NK cell and T and B cell numbers in lymph. As previously reported, FTY720 treatment resulted in a near complete absence of T or B cells from the lymph (Fig. 4 A; Mandala et al., 2002; Matloubian et al., 2004). NK cells, however, were present in the lymph but were reduced in number as compared with saline-treated animals (Fig. 4 A). When mice were treated with integrin and selectin blocking antibodies to prevent NK cell and lymphocyte entry into lymph nodes, additional treatment with FTY720 prevented the egress-mediated...
Figure 3. Reduced S1P5 but not S1P1 expression in Duane cells and T-bet–mediated induction of S1P5 expression. (A–C) Quantitative PCR analysis of S1PR or IFN-γ transcript expression in (A) total splenocytes and sorted splenic NK cells from a wild-type mouse, (B) wild-type and Duane splenic NK cells (bars represent mean values, and circles represent sorted NK samples from individual animals), and (C) either vector- or T-bet–transduced WEHI-231 cells (left; bars represent mean values, and circles represent individual transductions) or primary T cells (right; bars represent individual transductions). (D) T-bet associates with the region 3′ of the S1pr5 gene. Primary CD4+ T cells were isolated from either Tbx21−/− (lanes 1–3) or wild-type (lanes 4–6) mice, and were polarized in Th1 conditions for 6 d (results are representative of two independent experiments, each using cells pooled from two individual animals). CD8+ T cells were isolated from mice infected with LCMV (lanes 7–9; results are representative of two independent immunoprecipitations using cells pooled from three individual animals). A standard ChIP analysis was then performed with a T-bet–specific antibody (lanes 1, 4, and 7) or an IgG control (lanes 3, 6, and 9). A standardized aliquot of the input chromatin was also examined as a control. Gene-specific primers were used to amplify the ChIP samples, as indicated to the left of the gel images. (E and F) Quantitative PCR analysis of T-bet or S1P5 transcript expression in (E) various lymphocyte subsets sorted from naive wild-type or T-bet–deficient mice (bars represent mean values, and circles represent sorted cell samples from individual animals; data were obtained from three independent experiments), and (F) in vitro–generated, sorted, polyclonal-activated (CD44hi) or LCMV antigen–specific (GP33+) CD8+ effector T cells (bars represent samples sorted from cells pooled from at least three individual animals). ▲, PCR signal < 0.001; ◆, PCR signal below detection threshold.
decay of T cell numbers, but NK cell numbers continued to decline (Fig. S4 A), indicating the presence of an FTY720-insensitive egress mechanism. Thus, FTY720 treatment appears to reduce but not block NK cell egress from LNs into lymph. To determine the impact of FTY720 exposure on S1P receptor expression, we examined the surface abundance of FLAG-tagged S1P1 and S1P5 in transduced WEHI-231 B lymphoma cells in the presence of either S1P or FTY720-P. As previously reported (Gonzalez-Cabrera et al., 2007; Oo et al., 2007), exposure to either S1P or FTY720-P, even in small quantities, was sufficient to induce loss of cell-surface S1P1. Neither compound was able to affect the surface expression of S1P5 (Fig. S4 B). The resistance of S1P5 to down-modulation is unlikely to be caused by overexpression because the surface abundance of the receptor was lower than for S1P1 (Fig. S4 B). These observations suggest that S1P5 on lymphoid cells may be less sensitive than S1P1 to agonist-mediated down-modulation.

The effects of FTY720 on T and B cell trafficking have been associated with intrinsic S1P1 function in these cells (Matloubian et al., 2004). To determine if S1P1 played a role in NK cell trafficking, mixed S1P1-deficient and wild-type BM chimeras were examined (Fig. 4 B). Compared with control mixed chimeras, there was a small but significant accumulation of S1P1-deficient NK cells in LNs compared with blood and spleen, and lower numbers of S1P1-deficient NK cells in lymph (Fig. 4 B). There was also a mild accumulation of S1P1-deficient cells in the BM. Thus, like FTY720 treatment, hematopoietic S1P1 deficiency reduces but does not block NK cell egress from LNs into lymph.

To understand the role of S1P5 in NK cell egress from lymphoid tissues, we generated S1P5-deficient mice (Fig. S5). The S1P5-deficient founders were backcrossed three times to B6 mice, and BM from either these mice or their S1P5+/+ littermate control BM was used to generate mixed BM chimeras. These chimeras demonstrated a significant accumulation of S1P5-deficient NK cells in the BM and in the LNs, together with a deficit of S1P5-deficient NK cells in the blood and the spleen relative to wild-type NK cells (Fig. 4 C),

Figure 4. NK cell egress requires S1P, and uses both S1P1 and an FTY720-sensitive receptor. (A) Cellular composition of lymph collected from wild-type mice treated for 20 h with 1 mg/kg FTY720. Values are reported as the number of cells in the lymph of FTY720-treated animals as a percentage of lymph cell numbers in saline-treated animals. Data are derived from at least three independent experiments. (B) Examination of wild-type B6 mice reconstituted with a mix of CD45.1 wild-type and CD45.2 S1pr5−/− or CD45.2 S1pr5+/− littermate control BM. Some mice (Lymph+FTY) received 1 mg/kg FTY720 i.p. 20 h before analysis. Values are reported as a ratio of S1P5-deficient or control (CD45.2) to wild-type (CD45.1) cells. NK cell ratios were normalized to BM CD19+ B cell ratios for each mouse. Data are derived from two independent experiments. (D) Analysis of NK cell distribution in Sphk-deficient and littermate control mice. Values for BM, spleen, and peripheral LNs (six nodes) represent absolute NK cell numbers; values for lymph represent cells per microliter of lymph. Sphk Δ represents mice that were Sphk2 null, were deficient for one allele of Sphk1, and had the second allele of Sphk1 excised. Control represents Sphk2-null mice with at least one functional allele of Sphk1. Data are derived from at least three independent experiments. Bars represent mean values, and circles represent individual animals. n.s., not significant; PLN, peripheral LN. *, P ≤ 0.05; **, P < 0.005.
in agreement with previous findings (Walzer et al., 2007b). In addition, there was a lower ratio of S1P5-deficient NK cells to wild-type NK cells in the lymph as compared with the peripheral LNs, indicating a reduced capacity of the S1P5-deficient NK cells to egress from LNs into lymph. This ratio skewed further in favor of the wild-type NK cells if the mice were treated with FTY720 for 20 h before analysis (Fig. 4 C). These results indicate that S1P5 is important for the egress of NK cells from LNs, while also indicating that some NK cell exit from LNs is S1P3 independent and can be attributed to a receptor that is modulated by FTY720, most likely S1P1.

To address the role of S1P in NK cell egress, we analyzed mice deficient in Sphk2 and conditionally ablated for Sphk1, and that lacked detectable circulating S1P (Pappu et al., 2007). In these mice, we observed a significant reduction in the number of NK cells in the spleen but found these mice to have a normal or slightly elevated number of NK cells in peripheral LNs (Fig. 4 D). These mice also demonstrated a significant accumulation of NK cells in the BM. Analysis of lymph from these animals revealed a significant reduction in the number of NK cells, indicating a failure to egress from the peripheral lymphoid tissues in the absence of S1P (Fig. 4 D).

Reduced NK cell numbers in BM sinusoids of S1P-deficient mice

Cellular egress from the BM occurs via BM sinusoids. Recent work has shown that a 2-min in vivo exposure to PE-coupled anti-CD45 antibody selectively labels sinusoidal cells among BM cells (Pereira et al., 2009). Using this labeling procedure, we found that ~14% of BM NK cells were situated inside sinusoids (Fig. 5 A). In S1P-deficient mice, this frequency fell to <6% (Fig. 5 A). Previous studies have shown a tight relationship between S1P, surface abundance on T cells and local S1P concentrations (Lo et al., 2005; Schwab et al., 2005; Pappu et al., 2007). Analysis of T cells in the BM showed that S1P1 was present in higher amounts on parenchymal compared with sinusoidal cells (Fig. 5 B), suggesting the existence of an increasing S1P gradient between parenchyma and sinusoid. These observations, coupled with the lower total NK cell numbers in the periphery, suggest that the ability of NK cells to exit from BM parenchyma to sinusoid is diminished in the absence of S1P.

S1P5 mediates the egress of activated NK cells

CD69 is rapidly expressed at high levels on activated NK cells and may have a role in NK cell-mediated cytotoxicity (Karlhofer and Yokoyama, 1991). CD69 has also been shown to bind and inhibit the function of S1P1 in T cell egress (Shiow et al., 2006). To test whether CD69 interacts with S1P5, we used a coexpression system whereby a FLAG-tagged S1P receptor was coexpressed with a fusion molecule consisting of the extracellular and transmembrane domains of CD69 coupled to the intracellular domain of CD3ζ (Fig. S6). CD69 is known to physically associate with S1P1, and cross-linking of FLAG-tagged S1P1 results in the induction of CD3ζ signaling, as evident by the expression of an NFAT-regulated GFP reporter (Fig. 6 A). When FLAG-S1P1 was cross-linked, no expression of GFP was detected, indicating a failure of CD69 to associate with S1P5. Further, as previously reported (Shiow et al., 2006), immunoprecipitation of FLAG-S1P1 resulted in the pull down of hemagglutinin (HA)-tagged CD69 (Fig. 6 B). Immunoprecipitation of FLAG-S1P5, however, even from cells expressing higher amounts of the S1P receptor (S1P1 +/+ vs. S1P1 +), failed to pull down any detectable HA-CD69 (Fig. 6 B). In agreement with the lack of interaction between CD69 and S1P5, CD69 showed no ability to inhibit S1P-dependent S1P chemotaxis in Transwell assays with transduced cells (Fig. 6 C).

These observations suggested that, compared with T cells, NK cells may be resistant to LN egress inhibition caused by CD69 up-regulation. To assess the ability of CD69 to block NK egress in vivo, we analyzed the cellular composition of lymph from animals treated with the type I IFN–inducing agent poly I:C for 6 h. Treatment of mice with poly I:C has been previously demonstrated to efficiently block T cell egress
metric analysis confirmed that all NK cells in the lymph appeared activated and expressed high amounts of CD69 (Fig. 6 E), indicating that S1P₅ is able to mediate egress of activated NK cells even in the presence of CD69.

Figure 6. CD69 neither associates with nor inhibits S1P₅ function. (A) NFAT-GFP reporter expression in 2B4 cells transduced with the indicated constructs and treated with anti-CD69 antibody (top) or anti-FLAG antibody (bottom). Numbers indicate percentages of cells expressing the reporter. Data are representative of six independent experiments. (B) Western blot analysis of total lysates or anti-FLAG immunoprecipitates from WEHI-231 cells transduced with the indicated transgenes and sorted for CD69 and FLAG expression (+, low; ++, high). WB indicates the antibody used for Western blotting, and IP indicates the antibody used for immunoprecipitation. Data are representative of two independent experiments. (C) Transwell migration assay of untransduced WEHI-231 cells (control) or cells expressing S1PR transgenes alone or together with a CD69 transgene. Values are reported as the percentage of input cells migrating to the lower chamber during the 3-h assay. Columns represent the means of duplicate wells, and the bars represent the range within a single experiment. Data are representative of three independent experiments. (D) Cellular composition of lymph from animals treated with poly I:C for 6 h before analysis. Values are reported as the number of cells in the lymph of poly I:C-treated animals as the percentage of cells in the lymph of the PBS-treated animals. Data are representative of at least three independent experiments. Bars represent mean values, and circles represent individual animals. (E) Representative flow cytometric analysis of lymph and LN NK cells from saline- or poly I:C-treated mice. Data are representative of at least three independent experiments. PLN, peripheral LN. **, P < 0.005.
T-bet has been previously demonstrated to be important for normal NK cell development and survival (Townsend et al., 2004). NK cells from T-bet−/− deficient mice appear phenotypically immature and hyperactivated, and undergo increased rates of cell death. Although these observations may partly explain the observed deficit of NK cells in some peripheral sites of T-bet−/− deficient mice (blood, spleen, and liver), they do not explain the observed increase in NK cell number within the BM and peripheral LNs. Our findings indicate that S1P5 is likely the key gene acting downstream of T-bet to allow the normal LN and BM egress of NK cells, and thus, recirculation to other sites. T-bet also promotes expression of CXCR3, a receptor involved in NK cell entry to inflamed LNs (Martin-Fontecha et al., 2004), indicating that part of the T-bet−/− induced gene expression program acts to coordinate NK cell trafficking. ChIP analysis identified the ability of T-bet to bind a conserved element 3′ of the S1pr5 gene. This finding, together with our observation of T-bet−/− induced expression of S1P5 in three different transduced cell types, as well as the T-bet dependence of S1P5 expression in NK and CD8+ T cells, establishes that S1P5 is a common component of the T-bet gene expression program.

Within a day after activation in peripheral LNs, “primed” NK cells can be detected at distal sites such as the spleen, lungs, and liver (Lucas et al., 2007). This apparent ability of acutely activated NK cells to traffic from LNs seemed contrary to what has been observed for activated T cells, where CD69 inhibits S1P1-mediated egress (Shiow et al., 2006). Our findings suggest that this is likely a consequence of S1P5 being resistant to CD69-mediated inhibition. The expression of S1P5 by effector CD8+ T cells suggests that these cells may also be competent to egress while in an activated state. Similar trafficking patterns of NK cells and effector CD8+ T cells have been noted (Grégoire et al., 2007). In this regard, it is notable that CD69 is a member of the NK receptor C-type lectin-like family, and some studies have suggested that it has an effector role (Karlhofer and Yokoyama, 1991), although no extrinsic ligand has yet been identified. By facilitating egress of CD69+ cells, S1P5 may allow this CD69 effector function to occur. Many iNKT cells express CD69 (Matsuda et al., 2000), and we propose that T-bet−/− induced S1P5 also functions to facilitate egress and recirculation of these cells.

FTY720, in the active phosphorylated form, is a receptor agonist that is also a functional antagonist of S1P1, and FTY720 treatment causes rapid down-modulation of S1P1 on T cells, an effect that has correlated tightly with FTY720-mediated inhibition of T cell egress (Matloubian et al., 2004; Pham et al., 2008). In vitro studies have shown that FTY720-P causes internalization, ubiquitination, and degradation of S1P1 (Gonzalez-Cabrera et al., 2007; Oo et al., 2007). In our studies, we found that in contrast to S1P1, S1P5 was resistant to FTY720-induced down-modulation, and our data suggest that this receptor continues to support NK cell egress in FTY720-treated hosts. The finding that NK cell egress is relatively, albeit not completely, resistant to FTY720 treatment is consistent with studies showing minimal changes in blood NK cell numbers in FTY720-treated humans (Vaessen et al., 2006) and mice (Walzer et al., 2007b). The ability of many NK cells to egress from LNs after FTY720 treatment provides further evidence against models arguing that FTY720 inhibits egress by acting on endothelial or stromal S1P receptors to close LN egress portals (Rosen and Goetzl, 2005). iNKT cell recirculation is also relatively resistant to FTY720 treatment (Allende et al., 2008). Our finding of S1P3 expression in these T-bet−/− dependent cells provides a possible explanation for this finding, and it will be important in future studies to track the impact of S1P3 deficiency on iNKT cell as well as NK cell and effector CD8+ T cell function.

Although S1P5 appears to be the dominant S1P receptor in NK cells, we did observe S1P expression in these cells, and S1P deficiency caused a measurable decrease in NK cell representation in lymph. Although a previous study suggested S1P1 may not be present in NK cells (Walzer et al., 2007b), S1P1 transcripts were within ∼10-fold of the amounts present in T and B cells in that study, as observed in the present work. The greater effect of S1P deficiency than S1P5 deficiency on NK cell numbers in lymph also supports the view that S1P1 plays a role in these cells, as does the finding that FTY720 treatment is able to further reduce the egress of S1P5-deficient NK cells. It remains to be determined whether these receptors are coexpressed in all NK cells or expressed in separate subsets.

Within the spleen, NK cells are largely excluded from the white pulp and are localized in the red pulp (Walzer et al., 2007a). S1P1 deficiency or FTY720 treatment depletes T and B cells from red pulp while leaving cells within the white pulp. This likely reflects a role for S1P and S1P1 in overcoming chemokine-mediated retention in the white pulp (Pham et al., 2008). The general NK cell deficiency in the spleen of T-bet−/−, S1P5−/−, and S1P1−/− deficient mice is consistent with observations that few splenic NK cells are present within the white pulp, and with evidence that positioning in the red pulp is Gαi independent and, thus, most likely not chemokine mediated (Grégoire et al., 2007). The lack of a Gαi-mediated retention mechanism may well obviate the need for S1P1 receptor signaling during splenic egress (Pham et al., 2008). We suspect that in the absence of S1P5 or S1P, NK cells become trapped in LNs and BM at the expense of representation in blood and the splenic red pulp. We note that the reduction in NK cell numbers in the spleens and livers of T-bet−/− deficient mice exceeds their numerical accumulation in LNs and BM, likely reflecting a requirement for T-bet in the maturation or maintenance of NK cells. Although T-bet has a large number of target genes, there may be a similar deficiency in the total peripheral NK cell pool in S1P5−/− deficient mice (Walzer et al., 2007b), raising the possibility that T-bet−/− driven S1P5 expression is required for normal NK cell maturation or homeostasis, a topic that will need further assessment in future studies.

The requirements for cell egress from the BM are poorly understood. CXCR4 has an established role in mediating precursor retention in the BM and there is evidence that

DISCUSSION
NK cells are retained by CXCR4, and down-regulation of this receptor coincides with maturation and exit from the BM (Beider et al., 2003; Bernardini et al., 2008). However, mature NK cells retain substantial amounts of CXCR4 and are highly responsive to CXCL12 (Bernardini et al., 2008). We suggest that the requirement for S1P for efficient egress of NK cells from BM parenchyma into sinusoids reflects a role for S1P, together with S1P1 and S1P5, in overcoming CXCR4–CXCL12–mediated retention, analogously to S1P–S1P, overcoming the CCR7–CCL21–mediated retention of T cells in lymph nodes (Pham et al., 2008). These findings point to the possibility that S1P and S1P receptors function in the BM egress of additional cell types. This has important implications for the application of therapies that interrupt S1P receptor function.

In summary, our findings establish that T-bet promotes S1P1 expression and that S1P5 and its ligand S1P are required for NK cell egress from LNs and BM. T-bet–dependent S1P1 expression also occurs in effector CD8+ T cells. These findings extend the paradigm that S1P promotes egress through actions on migrating S1P1+ cells by showing that a second leukocyte S1P receptor is involved in egress. We propose that the differential use of S1P5 by NK and effector CD8+ T cells facilitates their egress in a CD69+ effector state. Finally, our study adds to recent findings (Walzer et al., 2007b) to suggest strongly that S1P and S1P receptors are required for efficient NK cell egress from the BM.

**MATERIALS AND METHODS**

**Mice, ENU mutagenesis, chimeras, lymphocyte transfers, and treatments.** C57BL/6 (B6) and CD45.1 congenic B6 mice were obtained from the National Cancer Institute (NCI). C57BL/10 and CBA/J mice were obtained from the Australian Phenomics Facility, Australian National University (ANU). B6.2T11/2 mice were obtained from the Jackson Laboratory. All experiments conformed to ethical principles and guidelines approved by the University of California, San Francisco Institutional Animal Care and Use Committee, the ANU Animal Experimentation Ethics Committee, and the Scripps Research Institute Animal Research Committee. The generation of S1P1−/− mice is described in detail in the following section. S1P1−/− mice were crossed three times to B6 mice. The generation of S1P1−/− mice, S1P1-deficient fetal liver chimeras, and Spkh-deficient mice have been previously described (Liu et al., 2000; Matloubian et al., 2004; Pappu et al., 2007). S1P1+/− mice were provided by S. Proia (University of California, San Francisco, San Francisco, CA). The Duane strain was established through ENU-mediated mutagenesis of B6 mice, as previously described (Nelms and Goodnow, 2001; Shio et al., 2008). Mapping and sequencing of the Duane mutation was performed at the Australian Cancer Research Foundation (ACRF) Biomolecular Resource Facility (John Curtin School of Medical Research [JCSMR], ANU) and is described in Genetic mapping of the Duane mutation.

**Protein modeling.** T-bet protein models were generated by using the Geno3D server (available at http://geno3d-pbil.ibcp.fr; Combet et al., 2002).
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ARTICLE

Immunoprecipitation and Western blotting. Immunoprecipitation was performed as previously described (Shaw et al., 2006). For immunoblot analysis, cell pellets were lysed in 0.875% BriJ77, 0.125% NP-40, 150 mM NaCl, 10 mM Tris-HCl (pH 7.4), and 0.02% Na2O, buffer containing protease inhibitors (Sigma-Aldrich). Samples were resolved by 10% SDS-PAGE (NuPAGE; Invitrogen) and transferred to Immobilon-FL membranes (Millipore). Membranes were blocked with buffer (LI-COR, Biosciences) and stained with anti-T-bet (clone 39D raised against full-length mouse T-bet; Santa Cruz Biotechnology, Inc.), rabbit anti-actin (Sigma-Aldrich), anti-FLAG (clone M1; Sigma-Aldrich), and biotin-conjugated anti-HA (clone 3F10; Roche). Products were detected with IRDye 680–conjugated goat anti–mouse Ig, IRDye 800CW–conjugated streptavidin (LI-COR Biosciences), or IRDye 700DX–conjugated donkey anti–rabbit Ig (Rockland), and imaged on an infrared imager (Odyssy; LI-COR Biosciences).

ChIP. ChIP was performed as previously described (Miller et al., 2008). Primers specific to the 3′ region of the Sipr5 gene were as follows: forward, 5′-CACCTTGCAAGTCTCCTGAG-3′, and reverse, 5′-GAGGCGACCAGACTGATTC-3′.

Luciferase reporter and endogenous T-bet target transcription analyses. Luciferase and endogenous gene quantitative RT-PCR analyses were performed as previously described (Miller et al., 2008).

NFAT-GFP reporter assay. SIP receptor and CD69-hCD43 fusion proteins were cotransduced into mouse 2B4 hybridoma cells with an NFAT-GFP reporter construct and were assayed as previously described (Arase et al., 2002; Rosen et al., 2005; Show et al., 2006).

SIPR down-modulation assay. WEHI-231 cells stably expressing FLAG-tagged SIPR were washed twice in RPMI 1640 medium with 10 mM Hepes and 0.5% fatty acid–free BSA (EMD; BSA-RPMI), and then incubated in BSA-RPMI for 30 min at 37°C. SIPR ligands indicated in the figures (SIP or FTY720) were titrated into BSA-RPMI in a 96-well U-bottom plate. Cells were added to each well, and the plate was incubated for 40 min at 37°C. The resulting surface SIPR levels were measured by flow cytometry using the anti-FLAG antibody (clone M2; Sigma-Aldrich).

Transwell migration. Transwell migrations were performed as previously described (Matloubian et al., 2004; Lo et al., 2005). In brief, transduced WEHI-231 cells were harvested, washed, and incubated for 30 min at 37°C in migration media (RPMI 1640 supplemented with 10 mM Hepes, 100 U/ml penicillin–streptomycin, and 0.5% fatty acid–free BSA). 106 cells were loaded into 5-µm Transwells and cultured for 3 h in response to media alone, stromal cell–derived factor 1 (PeproTech), or SIP (Sigma-Aldrich). Contents from the bottom of each well were harvested and enumerated by flow cytometry.

Online supplemental material. Table S1 lists nucleotide sequences for PCR primer and probe sets. Fig. S1 contains representative flow cytometric analysis and NK cell counts from various tissues from Duane and wild-type mice. Fig. S2 presents mapping and nucleotide sequencing of the causative genetic lesion within the Duane Tbc21 gene, amplification and sequencing of Duane and wild-type T-bet cDNA, and quantitative PCR and Western blot analysis of T-bet expression in Duane and wild-type mice. Fig. S3 presents assays demonstrating that the Duane T-bet mutation results in a functionally null phenotype. Fig. S4 contains analysis of NK cell numbers in peripheral LN from mice after blocking lymphocyte entry in the presence or absence of FTY720, and representative flow cytometric analysis of untreated and SIP-treated 2B4 hybridoma cells transduced with either FLAG-SIP or FLAG-SIP. Fig. S5 illustrates the generation of SIP-deficient mice. Fig. S6 presents representative cell-surface staining for CD69 and FLAG on transduced 2B4 hybridoma cells used for NFAT-GFP reporter assays. Online supplemental material is available at http://www.jem.org/cgi/content/full/jem.20090525/DC1.
We thank S. Coughlin and R. Proia for mice; A. Intlekofer for the CD8+ effector T cells; A. Yang for generation of the S1pr1 targeting construct; J. Green, T. Pham, and B. Whittle for technical advice; and J. An for expert animal husbandry.

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The authors have no financial conflicts of interest.

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Figure S1. Identification of the ENU mutant Duane. (A) Representative flow cytometric analysis of various tissues from Duane and wild-type mice. Cells were gated on size. Numbers indicate the frequency of gated cells. Data are representative of at least two Duane and two wild-type mice in each of three independent experiments. (B) Absolute NK cell numbers in spleens, peripheral LNs (three nodes), BM (one femur and one tibia), and livers of Duane and wild-type mice. Data are derived from at least two independent experiments, each composed of at least two Duane and two wild-type mice. Bars represent mean values, and circles represent individual animals. PLN, peripheral LN. *, P < 0.05; **, P < 0.001.
Figure S2. Mapping and Identification of a splice site mutation in Duane T-bet resulting in an eight–amino acid deletion and reduced T-bet protein expression. (A and B) The critical interval on chromosome 11 containing the causative mutation in Duane as defined by mapping SNPs that are polymorphic between Duane and either C57BL/10 (A) or CBA/J (B) mice. (C) Dideoxy sequencing chromatograph of genomic DNA from Duane and wild-type B6 mice revealing a T-to-A point mutation. (D) Schematic of the intron and exon organization of the \( \text{Tbx21} \) gene locus indicating the location of the Duane mutation. (E) Alignment of nucleotide sequences obtained from Duane and wild-type B6 genomic DNA. The Duane point mutation and the 5’ borders of exon 3 in each sequence are as indicated. (F) Amplification of T-bet transcripts from splenocyte cDNA generated from wild type, mice heterozygous for the Duane mutation (Het), and mice homozygous for the Duane mutation (Duane). Transcripts were amplified from at least two mice in two independent experiments. (G) Nucleotide alignment of cDNA sequences derived from Duane and wild-type B6 splenocytes. Boundaries of exon 2 and 3 are as indicated. Dashes indicate gaps corresponding to 24 nucleotides inserted into the Duane sequence to maximize alignment. Predicted amino acid sequences are included above and below the nucleotide alignment. (H) Predicted structure of the Duane T-bet protein derived from comparative protein analysis. Both ribbon and space filling models are displayed. Residues identified as responsible for DNA binding are colored green, those for protein dimerization are colored blue, and those predicted to be deleted by the Duane mutation are colored yellow. The single red residue corresponds to an amino acid known both to be important for dimerization and predicted to be deleted in Duane T-bet. (I) Quantitative PCR analysis of the expression of T-bet transcripts from wild-type and Duane splenic NK cells. Bars represent mean values, and circles represent individual PCR reactions. (J) Flow cytometric analysis of splenocytes cultured for 48 h under polyclonal T cell stimulation conditions (plate-bound anti-CD3 + anti-CD28). Populations were gated on CD4+ NK1.1− cells. Data are representative of at least two individual animals in two independent experiments. (K) Western blot analysis of total cell lysates from the T cell splenocyte cultures in J. Samples were loaded in serial threefold dilutions. Data are representative of at least two individual animals in two independent experiments.
Figure S3. Duane T-bet appears to be functionally null. (A) The ENU mutation abolishes T-bet's ability to activate endogenous target genes. EL4 T lymphoma cells were transfected with constructs expressing either wild type T-bet (T-bet), the ENU mutant T-bet (Duane), or a pcDNA vector control (Vector). RNA was harvested from each transfection, and quantitative RT-PCR reactions were performed to monitor the endogenous gene expression of IFN-γ, CCL3, or CXCR3. All samples were first normalized to actin expression. Values are reported as the expression level for each target gene in the transfected sample relative to the level in the wild-type T-bet transduction. Bars represent means ± SD of two independent experiments. (B) The ENU mutation abolishes T-bet's ability to transactivate an IFN-γ promoter–reporter construct. EL4 T cells were transfected with an IFN-γ promoter–luciferase reporter construct, thymidine kinase–renilla control, and wild-type T-bet (T-bet), the ENU mutant T-bet (Duane), or a pcDNA vector control (Vector). Values are reported as relative luciferase light units (RLU) normalized to the control renilla expression for each transfected sample. Bars represent means ± SD of three independent experiments. (C) Duane or T-bet–deficient splenocytes were mixed with wild-type CD45.1 splenocytes and cultured for 5 d under Th1-inducing conditions (IL-2, IFN-γ, and anti–IL-12). Populations are gated on CD4+ NK1.1+ cells. Numbers indicate the frequency of gated cells. Data are representative of at least two independent experiments. (D) Duane or T-bet–deficient splenocytes were mixed with wild-type CD45.1 splenocytes and cultured for 4 d under conditions known to induce IgG2a Ig isotype switching (LPS, IFN-γ, and anti-IgM). Populations were gated B220+ cells. Numbers indicate the frequency of gated cells. Data are representative of at least two independent experiments.
Figure S4. NK cell egress from LNs is FTY720 resistant. (A) Analysis of NK cell numbers in peripheral LNs from mice after 40 h of lymphocyte entry blockade. Mice were treated with integrin and L-selectin blocking antibody, 1 mg/kg FTY720, or a combination of blocking antibody and FTY720 for 40 h before analysis. Values are normalized to saline-treated controls. Bars represent mean values, and circles represent individual animals. Data are derived from more than three independent experiments. (B) Modulation of S1PR cell-surface expression. NFAT-GFP 2B4 hybridoma cells transduced with either FLAG-S1P₁ or FLAG-S1P₅ were left untreated (shaded) or incubated in the presence of the indicated concentrations of either S1P or FTY720-P (continuous line), and cell-surface expression of S1PR was detected by flow cytometry. Plots are representative of at least three experiments.
Figure S5. Generation of S1P$_5$-deficient mice. (A) Schematic diagram of the S1pr5 genomic locus, targeting vector, and targeted allele. A portion of the S1P$_5$ coding region was removed, and Ds-Red (DsR) was inserted in frame into the deleted region. A neomycin resistance gene (Neo) under the control of the phosphoglycerate kinase promoter was also introduced into the targeting vector in an orientation reverse to that of the S1pr5 genomic locus. Relevant restriction enzyme sites are shown. (B) BamHI-digested genomic DNA from one wild-type, two heterozygous, and one S1P$_5$-null mutant mice Southern blotted and probed with the indicated external probe. Resultant bands for wild-type alleles are 7.6 kb, whereas bands from recombined alleles are ~5 kb. (C) PCR products from wild-type, heterozygous, and null mutant mice are shown. Primers used to amplify wild-type and mutant DNA elements are shown as arrows in the targeting schematic. Wild-type PCR products are ~575 bp and products from mutant mice are ~400 bp in length. Genotypes are indicated. (D) An absence of S1P$_5$ transcripts from the spinal cords of adult mice confirms the generation of null mutant mice. Spinal cord RNA from wild-type (+/+) and S1P$_5$-deficient (−/−) mice was reverse transcribed, and the presence of β-actin and S1P$_5$ transcripts was assayed for by PCR. PCR product sizes for β-actin and S1P$_5$ were ~350 and 200 bp, respectively.

Figure S6. Cell-surface staining of transduced 2B4 hybridoma cells used for NFAT-GFP reporter assays. Representative flow cytometric analysis of transduced NFAT-GFP 2B4 cells stained for cell-surface expression of CD3ζ-CD69 and either FLAG-S1P$_1$ or FLAG-S1P$_5$. Data are representative of at least two independent experiments.
Table S1. PCR primer and probe sets used

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</table>

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Table S1.  PCR primer and probe sets used (Continued)

<table>
<thead>
<tr>
<th>Name</th>
<th>Type</th>
<th>Sequence (5’ to 3’)</th>
</tr>
</thead>
<tbody>
<tr>
<td>DsRed Rev</td>
<td>Antisense</td>
<td>TTGGTCACCTTCAGCTTCACG</td>
</tr>
<tr>
<td>S1P, KO Rev Gen</td>
<td>Antisense</td>
<td>CTCATAAGCAATGGCCAAGAG</td>
</tr>
</tbody>
</table>