Extrathymic development of murine T cells after bone marrow transplantation

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Restoring T cell competence is a significant clinical challenge in patients whose thymic function is severely compromised due to age or cytoreductive conditioning. Here, we demonstrate in mice that mesenteric LNs (MLNs) support extrathymic T cell development in euthymic and athymic recipients of bone marrow transplantation (BMT). Furthermore, in aged murine BMT recipients, the contribution of the MLNs to the generation of T cells was maintained, while the contribution of the thymus was significantly impaired. Thymic impairment resulted in a proportional increase in extrathymic-derived T cell progenitors. Extrathymic development in athymic recipients generated conventional naive TCRαβ T cells with a broad Vβ repertoire and intact functional and proliferative potential. Moreover, in the absence of a functional thymus, immunity against known pathogens could be augmented using engineered precursor T cells with viral specificity. These findings demonstrate the potential of extrathymic T cell development for T cell reconstitution in patients with limited thymic function.

Introduction

The scarcity of T cells in recipients of BM transplantation (BMT) leads to a devastating susceptibility to pathogens and is associated with increased malignant relapse (1–4). Moreover, age-related thymic involution leads to inefficient thymopoiesis and T cell regeneration in adult BMT patients, who are often decades into the process of thymic involution (5). Thymic involution results in the dramatic diminution of thymic function over time, with a loss of thymic epithelial cells as early as 1 year after birth and the decline of thymopoiesis hastened by hormones during puberty (6–9). Recent evidence suggests that naive T cell export from the thymus is completely absent in aging humans, where the primary source of T cell repopulation is homeostatic proliferation (10). Expansion of peripheral T cells after BMT can lead to a pool of memory phenotype T cells with limited T cell receptor diversity (11, 12), leading to decreased immune function as well as poorer prognosis for older BMT patients (13–15). Consequently, mechanisms to circumvent the thymus to generate functional T cells could drastically improve not only BMT outcomes, but outcomes for all immunodeficient patients.

We have previously demonstrated that adoptive transfer of T cell precursors (preTs) generated ex vivo on the OP9-DL1 system into BMT recipients significantly increased thymopoiesis, circulating T cell numbers, and protection against bacterial infection (16, 17). While this is primarily dependent on improved thymopoiesis, based on studies in thoracically thymectomized BMT recipients, we hypothesized that extrathymic T cell development could contribute to the regeneration of the posttransplant T cell pool (16).

Extrathymic development of conventional TCRαβ⁺CD4⁺ and CD8α⁺ T cells in physiologic settings is controversial, though recent evidence indicates that extrathymic T cell development occurs in human tonsil (18). In oncostatin-M (OM) transgenic mice, which

have no thymic function, LNs support T cell development of largely dysfunctional mature T cells with a premature activation phenotype and limited antiviral function (19–32). Following BMT, early T lineage cells including CD4⁺CD8⁺ (double positive [DP]) cells have been identified in extrathymic sites, including LNs, spleen, and BM (19, 27, 29, 30, 32). While thymic function is important for restoring T cell immunity after transplant, the potential for extrathymic development to support the reconstitution of functional T cells is unknown. Further study could offer clinically feasible strategies to support T cell regeneration through stimulation of extrathymic T cell development.

We therefore sought to determine whether extrathymic T cell development produces functional T cells during regeneration following BMT and whether adoptive transfer of ex vivo–generated preTs enhance T cell function in athymic recipients.

Results

Gut-associated tissues support extrathymic T cell differentiation after BMT. To determine the role of extrathymic T cell development after BMT, we performed a kinetic analysis of DP cells from donor BM origin in the lymphoid organs of BMT recipients for 8 weeks (CD45.2⁺ BALB/c→CD45.2⁺ BALB/c). As expected, the number of DP cells in the thymus increased early after BMT, reaching a plateau after 2 to 3 weeks (Figure 1A). Although the spleen, peripheral LNs (PLNs), and BM had previously been reported to support early lineage-negative or DP T cell progenitors after BMT (30), we did not detect extrathymic T cell development in these sites (Figure 1, A and B, and Supplemental Figure 1A; supplemental material available online with this article; doi:10.1172/JCI60630DS1). Moreover, the intestinal environment appeared to be critical for extrathymic development, as mesenteric LNs (MLNs), Peyer's patches, intraepithelial sites, and lamina propria supported DP cells (Figure 1, A and B, and Supplemental Figure 1B). MLN DP cells expressed CD8β, CD3, TCRβ, Thy1, and CD69 at levels equivalent to thymic DP cells, with lower expression of CD24 (Figure 1C).
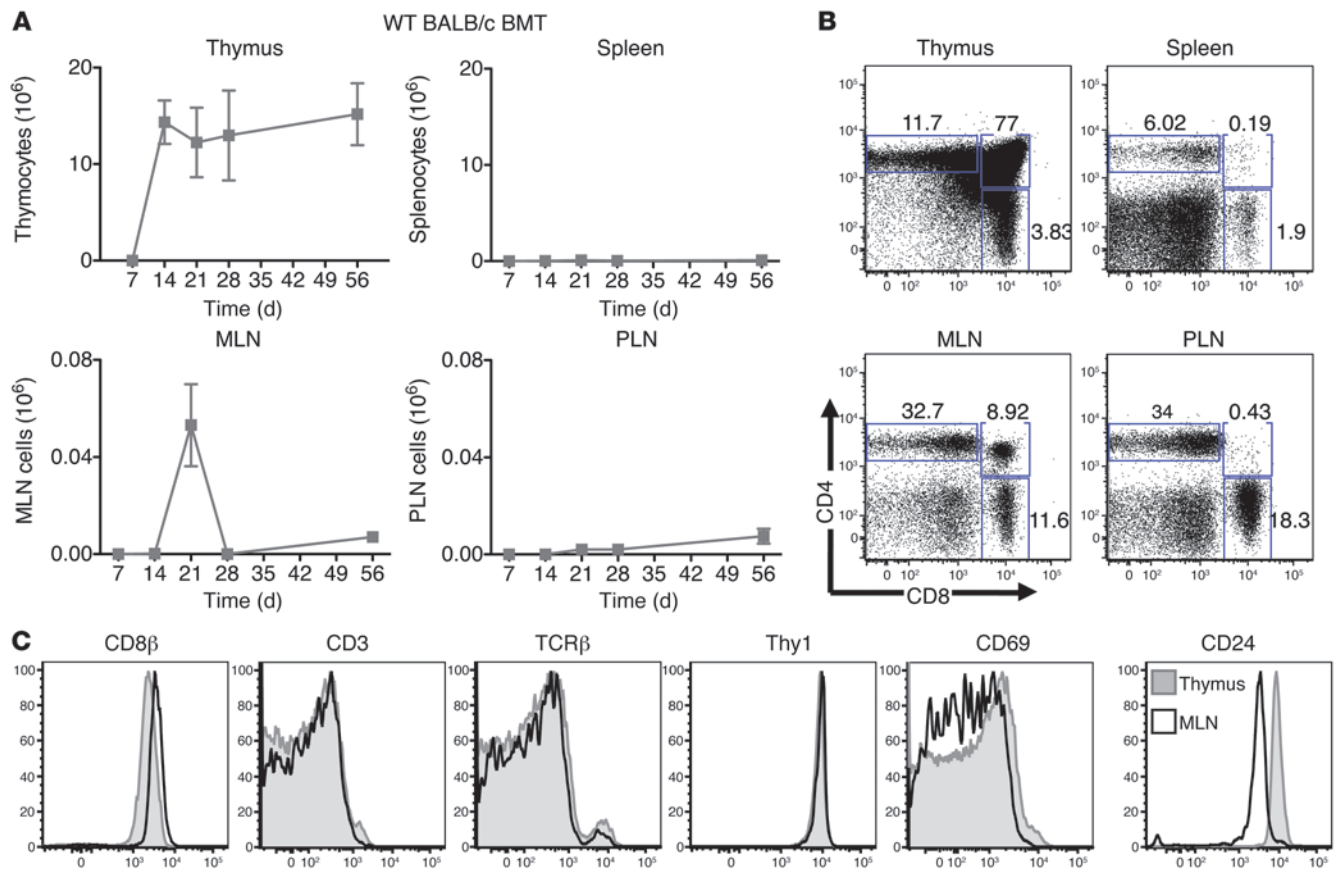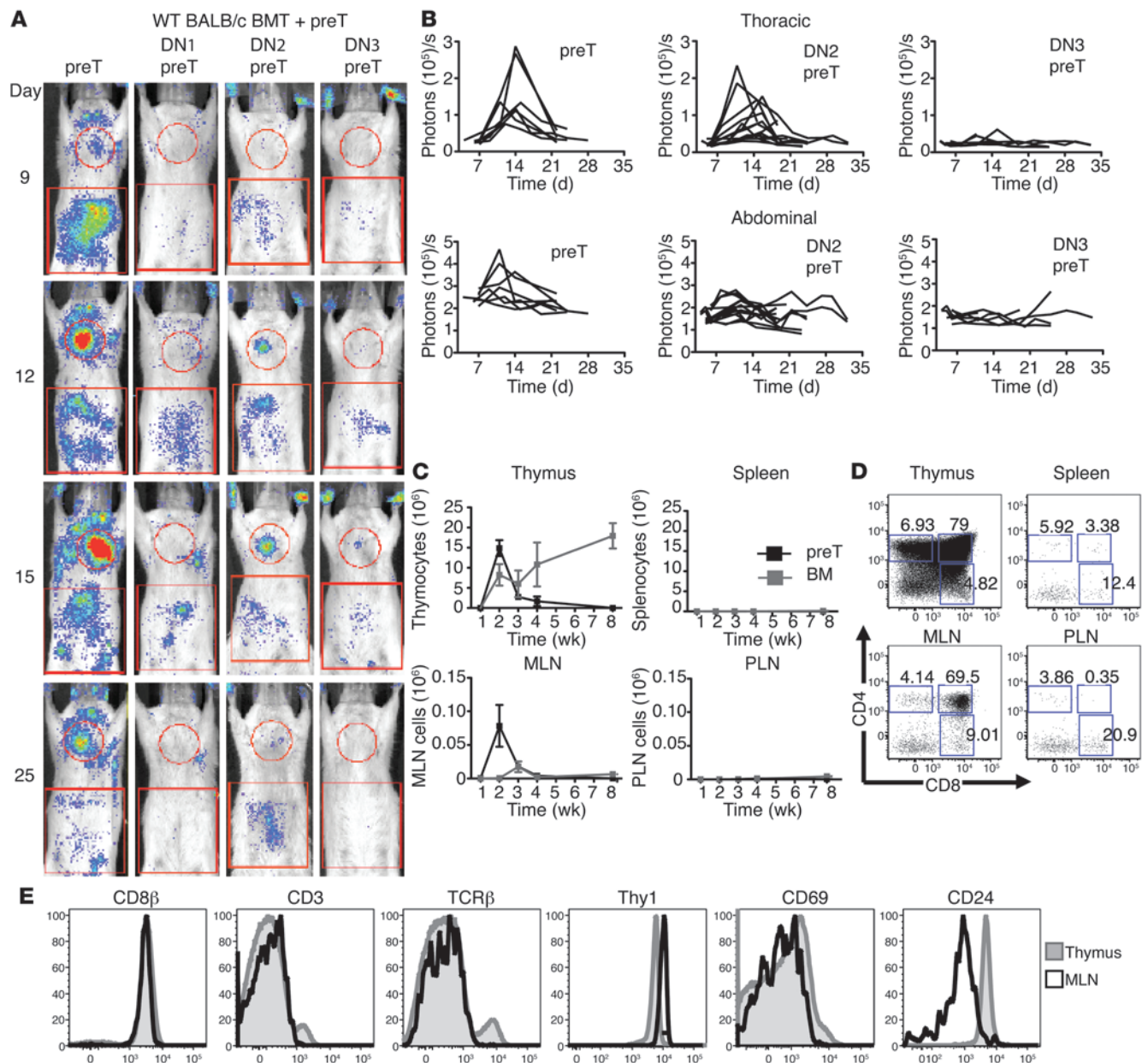
Figure 1
MLNs support DP T cell progenitors after BMT. Analysis of CD4+CD8+ BM–derived cells after syngeneic (BALB/c→BALB/c) BMT alone by flow cytometry. (**A**) Kinetics of CD4+CD8+ cells in thymus, spleen, MLNs, and PLNs. Data represent 5 to 15 mice per time point, combined from 1 to 3 experiments. (**B**) Representative dot plot showing CD4+CD8+ cells at day 21 after BMT in **A**. (**C**) Representative histograms comparing cell-surface markers on CD4+CD8+ cells from thymus (gray shaded histogram) and MLNs (black line). Data represent 5 mice from 1 experiment.

Taken together, these data demonstrate that gut-associated tissues can support extrathymic T cell progenitors following BMT.

Adoptively transferred preTs undergo T cell development in MLNs. Having observed extrathymic development of BM-derived T cell progenitors after BMT, we sought to determine whether preTs also underwent extrathymic development (16, 17). We generated preTs by coculturing lineage−c-kit+Sca-1+ hematopoietic progenitors on the OP9-DL1 stromal cell layer for up to 26 days in the presence of IL-7 and Flt3L. We have previously determined that preT incubated for this period primarily share a phenotype with double-negative (DN) CD4−CD8− DN2 (CD44+CD25+) or DN3 (CD44−CD25+) cells and engraft in the thymus, generating mature peripheral T cells after BMT (16). We used luciferase+ preTs for in vivo bioluminescence imaging (BLI) to analyze the kinetics and sites of preT engraftment after transplant (BMT+preT, luciferase+H2-Kb+ C57BL/6 [B6] preTs in CD45.2+ BALB/c→CD45.2+ BALB/c recipients). Consistent with our previous findings, thymic engraftment of preTs peaked 2 weeks after BMT (Figure 2, A and B). Additionally, we confirmed that DN2 preTs, but not DN1 (CD44+CD25−) or DN3, recapitulated the thymic engraftment phenotype of the whole cell milieu resulting from preT culture (referred to throughout simply as preT) (Figure 2, A and B). Strikingly, we found engraftment of preTs and DN2 preTs in the abdomen of recipients prior to the peak of thymic engraftment (Figure 2, A and B).

We then investigated whether preT engraftment in the abdomen corresponded to extrathymic T cell development. Consistent with our findings with BM-derived cells, we found that MLNs supported a wave of preT-derived (CD45.1+) DP cell development (Figure 2, C and D) with moderately lower CD24 expression, but comparable expression of CD8β, CD3, TCRβ, Thy1, and CD69 to thymic DP cells (Figure 2E). These findings confirm that extrathymic T cell development occurs in the first 3 weeks after BMT. Additionally, they indicate that preTs can be used both therapeutically and as a tool to study the development and function of extrathymic-derived T cells.

In order to assess their ultimate fate, we examined the lineage potential of preTs in BMT recipients. In euthymic BMT+preT recipients (CD45.1+CD45.2+ B6→CD45.2+ WT B6 or B6 nude), preTs and DN2 preTs (CD45.1+ B6) gave rise to many hematopoietic lineages, including B, NK, and dendritic cells and macrophages, though they were primarily restricted to a T cell fate (Supplemental Figure 2, A–F). Even without the strong signals of the thymic environment where 70% of preTs became T cells (Supplemental Figure 2, A and B), greater than 30% of preT and DN2 preT progeny in athymic recipients gave rise to T lineage cells (Supplemental Figure 2, C and D). After transfer across MHC barriers into allogeneic recipients, preTs also gave rise to T cells (data not shown), indicating that extrathymic T cell development is not strain specific and preTs can be used as a universal therapy.

Figure 2

Adoptively transferred preTs undergo extrathymic T cell development in BMT recipients. (**A**) BLI of BALB/c→BALB/c recipients+luciferase⁺ B6 unsorted preTs (*n* = 7), DN1 preTs (*n* = 2), DN2 preTs (*n* = 13), DN3 preTs (*n* = 6). Combined from 1–3 experiments. Circular regions measure thoracic signal, and rectangular regions measure abdominal signal. (**B**) Thoracic and abdominal signal from **A**. (**C**) CD4⁺CD8⁺ cells of BM (CD45.2⁺, gray) and preT origin (CD45.1⁺ B6, black) in thymus, spleen, MLNs, and PLNs of BALB/c→BALB/c recipients. *n* = 5–15 mice per time point, combined from 1–3 experiments. (**D**) Representative plot showing preT-derived cells at day 14 after BMT in **C**. (**E**) Representative histograms of CD4⁺CD8⁺ cells from preT origin in thymus (gray shaded histogram) and MLNs (black line). *n* = 5 mice, 1 experiment.

We previously demonstrated that preTs undergo nuclear factor of activated T cell (NFAT) activation in the thymus, consistent with thymic positive selection (33–35). We administered NFAT vector⁺ preTs (CD45.1⁺ B6) into WT or nude BMT recipients (CD45.2⁺ BALB/c→CD45.2⁺ BALB/c) (Figure 3, A–D). NFAT activation was restricted to the abdominal region in all recipients and the thoracic region in WT recipients (Figure 3, A and B). Upon ex vivo analysis of the abdominal area, we found that NFAT activation occurred primarily in MLNs, where a large proportion of

preTs gave rise to DP cells (Figure 3, C and D), indicating that extrathymic developing T cells in BMT recipients employ signaling mechanisms similar to those of thymocytes.

We next sought to determine if extrathymic T cell development was regulated similarly to thymopoiesis at the level of progenitor trafficking. We detected direct engraftment of preTs (CD45.1⁺ B6) in the spleen, MLNs, and PLNs of WT and nude recipients (CD45.2⁺) one day post-transfer, as well as engraftment in WT thymus (Figure 3E). We confirmed our prior observation that DN2
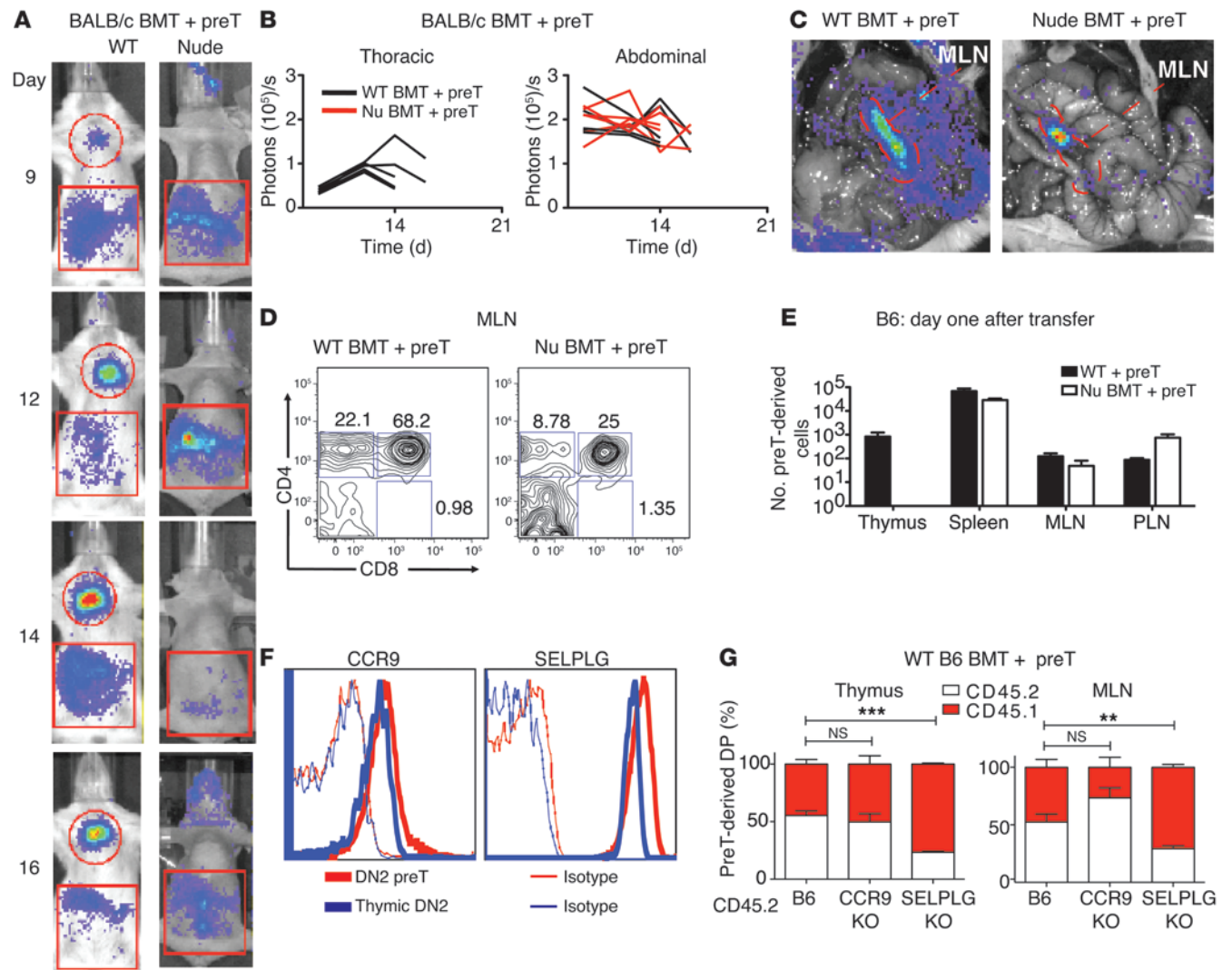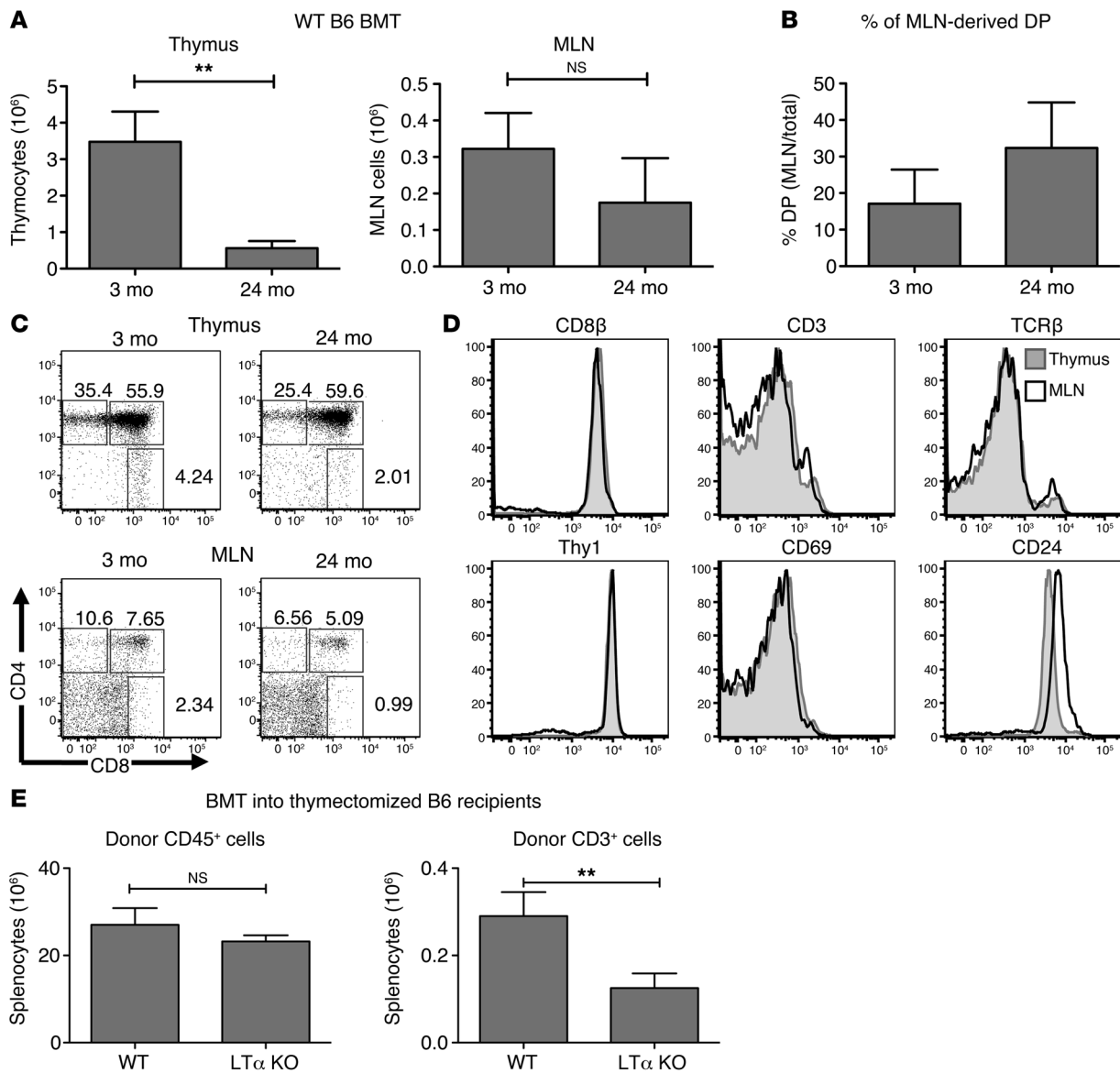
Figure 3
Extrathymic progenitors undergo NFAT signaling, engraft directly in extrathymic sites, and require PSGL-1 for repopulation. (**A–D**) BLI of BALB/c→ BALB/c WT or nude+NFAT vector⁺CD45.1⁺ preTs. $n = 5$ mice per group, combined from 2 experiments. Pseudocolor overlay represents NFAT activation. Circular regions measure thoracic signal, and rectangular regions measure abdominal signal. (**B**) Thoracic and abdominal signals from **A**. Black, WT; red, nude. (**C**) Representative ex vivo abdominal images at day 16 from **A**. (**D**) Representative plots of preT-derived CD4⁺CD8⁺ cells in MLNs at day 16 from **A**. (**E**) CD45.1⁺ B6 preT engraftment 18 hours after transfer into lethally irradiated CD45.2⁺ B6 WT (black, $n = 10$) or nude recipients (white, $n = 6$). Data combined from 2–3 experiments. (**F**) DN2 CD45.1⁺ B6 preTs at day 21 of culture ($n = 5$) with freshly isolated B6 DN2 thymocytes ($n = 3$ preparations). Heavy red line, DN2 preTs; heavy blue line, thymic DN2; thin red line, isotype on preTs; thin blue line, isotype on thymic DN2. (**G**) Competitive reconstitution at day 14 after CD45.1⁺CD45.2⁺ B6→CD45.1⁺CD45.2⁺ B6 BMT. CD4⁺CD8⁺ cells in thymus and MLNs of recipients of CD45.1⁺ (red) preTs and CD45.2⁺ (white) B6 ($n = 10–12$), *Ccr9* KO ($n = 7$), or *Selplg* KO ($n = 16$) preTs. Combined from 3 to 4 experiments. **$P < 0.01$; ***$P < 0.001$.

preTs express high levels of the trafficking molecules SELPLG (or PSGL-1) and CCR9 (Figure 3F), which are known to mediate entry into thymus and intestinal sites (36–38). Using competitive reconstitution assays (CD45.1⁺CD45.2⁺ B6→CD45.1⁺CD45.2⁺ B6), we observed that preTs require PSGL-1 but not CCR9 (CD45.2⁺ KO B6 preT vs. CD45.1⁺ WT B6 preT) for thymic and MLN DP cell reconstitution after BMT (Figure 3G). We detected P-selectin and ICAM expression in the MLNs, but not VCAM, with similar expression patterns in the PLNs (Supplemental Figure 3, C and D). However, there was no change in expression after transplant, nor a reorganization in the stromal compartment, to account for amplified

extrathymic T cell development after BMT (Supplemental Figure 3, A and B). Taken together, these studies indicate that preTs engraft directly in extrathymic sites after BMT and require the trafficking molecule PSGL-1 for reconstitution.

The relative contribution of extrathymic T cell development increases in aging BMT recipients. Given that we observed extrathymic T cell development after transplant into healthy young recipients, we next investigated its role in a clinically relevant model of impaired thymic function by using aging recipients. In 24-month-old recipients (CD45.1⁺CD45.2⁺ B6→CD45.2⁺ B6), we found significantly fewer thymic DP cells than in 3-month-old controls at day 21 after

Figure 4
Extrathymic T cell development increases in aging BMT recipients. (**A**) BM-derived CD4+CD8+ cells in the thymus and MLNs of 3-month-old (*n* = 10) and 24-month-old (*n* = 8) recipients at day 21 after BMT (CD45.1+CD45.2+ B6→CD45.2+ WT B6). Data combined from 2 experiments. (**B**) Percentage of total BM-derived CD4+CD8+ cells derived from MLNs in **A**. (**C**) Representative plots showing BM-derived cells from the thymus and MLNs at day 21 after BMT in **A**. (**D**) Representative histograms of CD4+CD8+ cells from BM origin in the thymus (gray shaded histogram) and MLNs (black line) of 24-month-old recipients. (**E**) BM-derived CD45+ and CD3+ cells in thymectomized WT (*n* = 10) and LTα KO recipients (*n* = 10) (CD45.1+CD45.2+ B6→CD45.2+ B6) on day 28 after BMT. Data combined from 2 experiments. **P < 0.01.

BMT (Figure 4, A and C). Importantly, although nontransplanted old mice did not have MLN DP cells (Supplemental Figure 4E), we found that the MLNs in 24-month-old mice maintained their capacity to support DP cells (Figure 4, A and C). MLNs contributed more than 30% of DP cells in aged BMT recipients (Figure 4B), indicating that extrathymic T cell development plays an increasingly important role in T cell reconstitution in patients with severe thymic impairment. We confirmed these findings in young and aged CBF1 (H2-b/d) syngeneic BMT recipients, which suggests these findings are not strain or MHC specific (Supplemental Figure 4). DP cells found in aging MLNs were phenotypically compa-

rable to thymic DP cells (Figure 4D). These studies demonstrate for what we believe is the first time that extrathymic T cell differentiation plays a greater role in restoring the T cell pool after BMT when thymic function is compromised.

Given the maintenance of T cell generation in MLNs when there is considerable thymic atrophy, we then investigated whether LNs themselves are critical for extrathymic T lineage generation. We performed congenic transplants (CD45.1+ CD45.2+ B6→CD45.2+ B6) into thymectomized WT or LTα KO recipients, which lack LNs and Peyer's patches (39, 40). Although total engraftment was unaffected, mice lacking LNs exhibited significantly reduced de
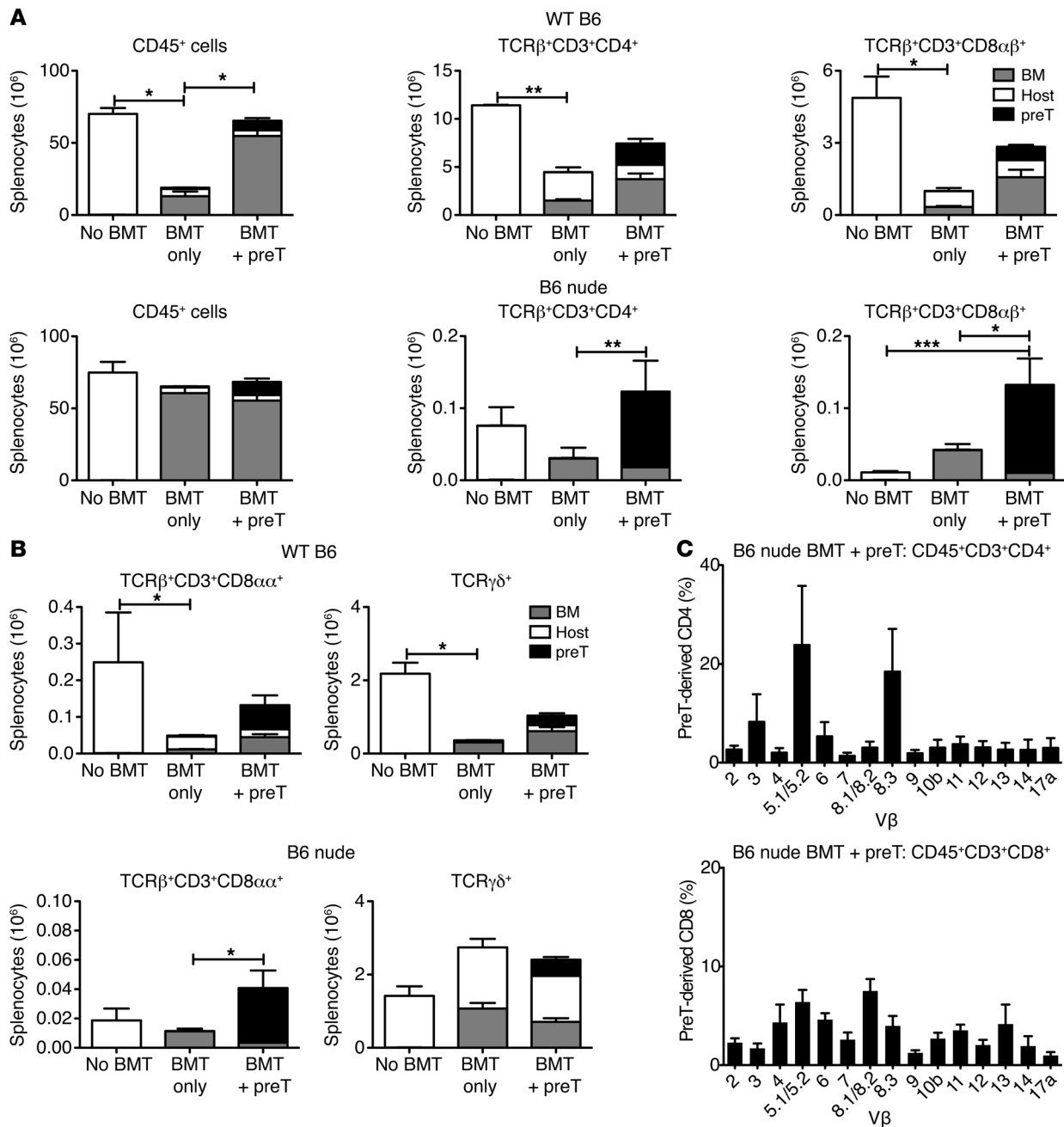
A

B

C

Figure 5
Extrathymic T cell development yields a broad repertoire of TCRαβ+ CD4+ and CD8αβ+ T cells after BMT. Analysis of mature T cells at day 42 after congenic (CD45.1+CD45.2+ B6→CD45.2+ WT B6 or B6 nude) BMT. Analyzed by nonparametric Mann-Whitney test. White bars, host; gray bars, BM; black bars, preT. Quantification of mature T cells in WT (nontransplanted, $n = 2$; BMT only, $n = 2$; BMT+preT, $n = 10$) and nude (nontransplanted, $n = 6$; BMT only, $n = 29$; BMT+preT, $n = 18$) mice. Data combined from 1 to 7 experiments. (**A**) CD45+ cells, CD4+ and CD8αβ+ T cells in WT and nude recipients. (**B**) CD8αα+ and TCRγδ+ T cells in WT and nude recipients. (**C**) Percentage of Vβ usage measured by flow cytometry in CD4+ and CD8+ T cells from preT origin in nude BMT+preT recipients ($n = 6$). *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

novo T cell production 28 days after BMT (Figure 4E), suggesting that LNs and Peyer's patches play an important role in supporting extrathymic T cell development after transplant.

Extrathymic development generates a diverse pool of T cells after BMT. Considering our evidence demonstrating extrathymic T cell differentiation in euthymic and athymic BMT recipients, we next investigated the generation of mature extrathymic-derived T cells. We found that BM (CD45.1+CD45.2+ B6) and preT (CD45.1+ B6) cells generated mature TCRαβ+CD4+ and CD8αβ+ T cells in WT B6 and B6 nude (CD45.2+) recipients at day 42 after BMT (Figure 5A). In addition, they generated TCRγδ+ T cells and CD8αα+ T cells, which are typically intraepithelial lymphocytes of extrathymic origin
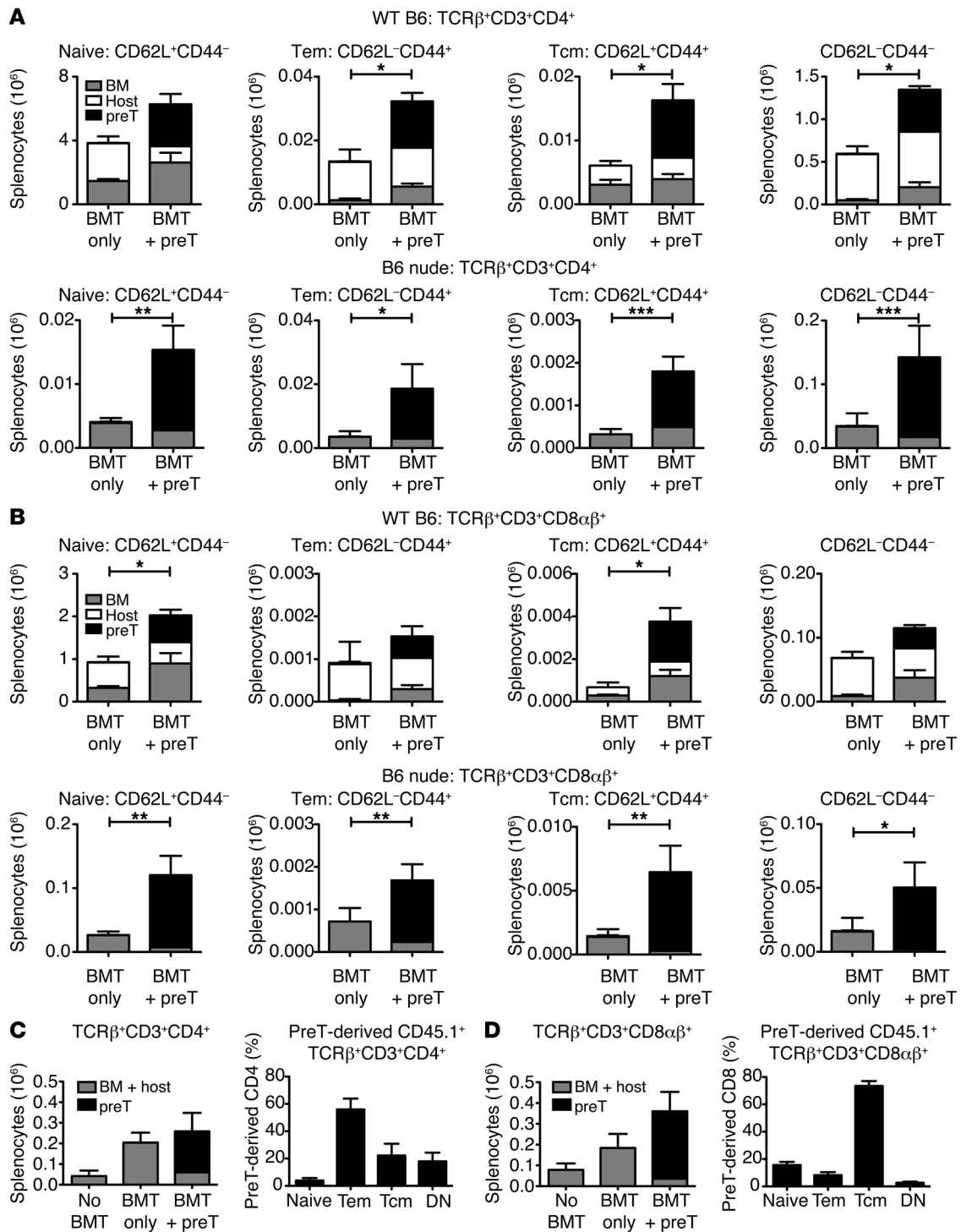
Figure 6
Thymus-independent development yields naive T cells. (**A** and **B**) Naive (CD62L+CD44−), effector memory (CD62L−CD44+), central memory (CD62L+CD44+), and CD62L−CD44− T cells. WT: BMT only, *n* = 3; BMT+preT, *n* = 6. Data combined from 2 to 3 experiments. Nude: BMT only, *n* = 19; BMT+preT, *n* = 12. Data combined from 4 to 5 experiments. (**C** and **D**) CD45.1+CD45.2+ B6 or CD45.2+ B6→ CD45.2+ B6 nude BMT recipients ± CD45.1+ preTs on day 90 after transplant. Black bars, preTs; gray bars: BMT+host. Nontransplanted, *n* = 5; BMT only, *n* = 11; BMT+preT, *n* = 13. Data combined from 1 to 3 experiments. (**C**) CD4+ T cells and (**D**) CD8+ T cells. *P < 0.05; **P < 0.01; ***P < 0.001.
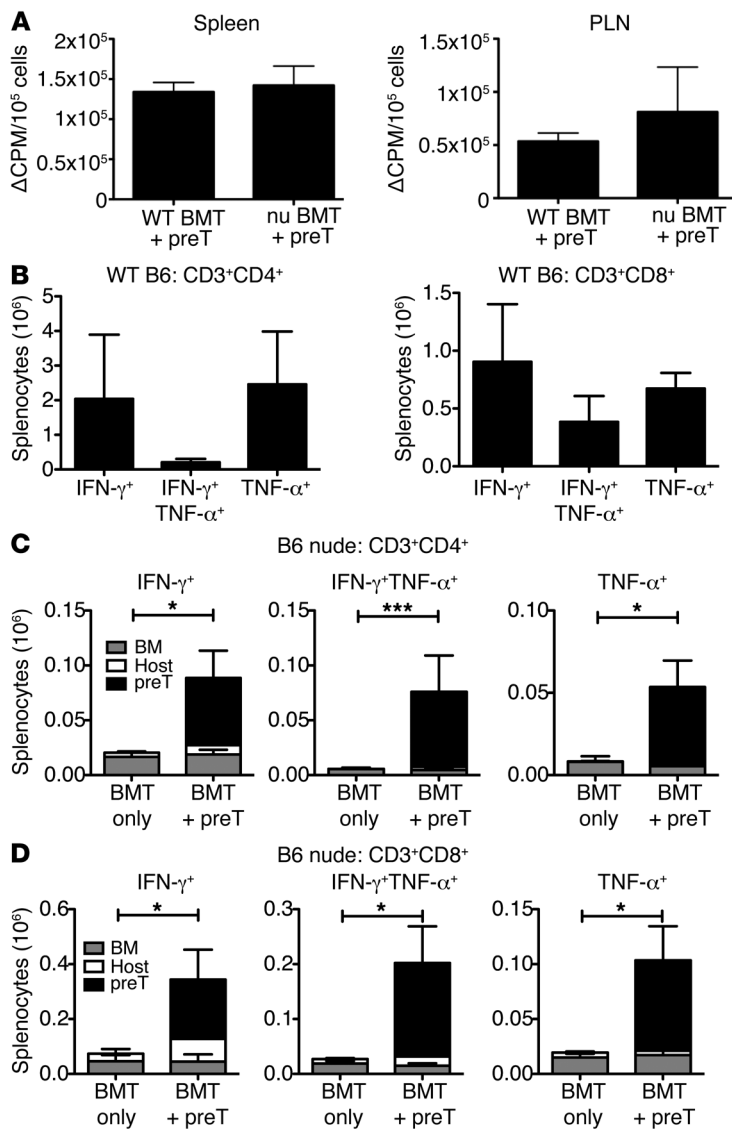
Figure 7
Extrathymic T cells generated after BMT are functional in vitro. Analysis of T cells after congenic (CD45.1+CD45.2+ B6→CD45.2+ WT B6 or B6 nude) BMT. Analyzed by Mann-Whitney test. White: host; gray: BM; black: preT. (**A**) Stimulation index after αCD3/CD28 activation in vitro of splenic and PLN T cells from WT and nude BMT+preT recipients at day 42. One representative experiment of 2; $n = 3$ for each condition, in triplicate. (**B–D**) Quantification of TNF-α– and IFN-γ–producing splenic T cells from WT ($n = 2$) (**B**) and nude BMT alone ($n = 6$) and nude BMT+preT ($n = 10$) (**C** and **D**) recipients at day 42 following PMA/ionomycin stimulation. Data combined from 2 to 3 experiments. (**C**) CD4+ T cells. (**D**) CD8+ T cells. *$P < 0.05$; ***$P < 0.001$.

(Figure 5B). Interestingly, BMT alone tended to enhance predominantly CD8+ T cells, and BMT+preT significantly enhanced splenic CD4+, CD8αβ+, and CD8αα+ T cells (Figure 5, A and B), as well as enhancing T cell counts in MLNs, Peyer's patches, and PLNs (Supplemental Figure 5, A–C). The TCRγδ+ T cell pool was not significantly affected (Figure 5B), indicating that this niche is sufficiently filled in athymic mice. Interestingly, TCRαβ+ intraepithelial lymphocytes were reduced by 2-log–fold in athymic versus euthymic BMT recipients (Supplemental Figure 5D), emphasizing the impor-

tance of the early thymic development of gut-associated T cells. Both CD4+ and CD8+ T cells in nude BMT+preT recipients had a polyclonal Vβ repertoire (Figure 5C), demonstrating that BMT into recipients lacking thymic function can result in a broad pool of T cells, which is significantly enhanced by administration of preTs.

Extrathymic-derived T cells have been reported to express an activated, memory-like phenotype (CD4+CD44+CD62L^{lo} effector memory and CD8+CD44+CD62L+ central memory), which may result in an inability to respond to immune challenges (22). We therefore sought to determine whether preT-derived T cells in athymic BMT recipients were naive T lineage cells. At day 42 after transplant, 2 weeks after the first appearance of mature T cells (Figure 2), splenic preT-derived CD4+ T cells in nude BMT+preT recipients displayed an atypical CD44^{lo}CD62L^{lo}, unlike CD4+ in WT BMT+preT recipients, which may be attributable to homeostatic proliferation (Figure 6A). CD8+ T cells in nude BMT+preT recipients were primarily naive, as in WT BMT+preT recipients (Figure 6B).

We next examined the long-term effects of preTs on T cell reconstitution in athymic recipients. We found that extrathymic-derived T cells persisted up to 90 days after transplant, at which point they displayed CD4 effector and CD8 central memory phenotypes (Figure 6, C and D). In addition to aiding reconstitution by generating preT-derived T cells, transfer of allogeneic preTs (CD45.1+ B6) enhanced BM-derived T cell numbers in athymic recipients (CD45.2+ BALB/c→CD45.2+ BALB/c nude) even after 4.5 months when there were no remaining preT-derived cells (Supplemental Figure 6). Together, these data demonstrate that extrathymic T cell development can generate a pool of diverse T cells either directly or by enhancing the extrathymic development of BM-derived T cells.

Extrathymic-derived T cells generated after BMT are functional. As we observed an increased contribution of extrathymic T cell development in aging BMT recipients, we hypothesized that recipients with limited to no thymic function will increasingly rely on extrathymic-derived T cells for protective immunity. We therefore assessed the function of extrathymic-derived cells. In contrast with previous reports, we found similar proliferation on a per T cell basis in splenocytes and PLN cells from euthymic and athymic recipients at day 42 after BMT (Figure 7A). After in vitro stimulation with PMA and ionomycin, nude BMT+preT recipients secreted more TNF-α and IFN-γ, factors essential for T cell responses against pathogens and tumors than nude BMT alone controls (Figure 7, C and D). While athymic recipients tended to produce less TNF-α than WT controls, they were efficient at producing IFN-γ (Figure 7, B–D).

In order to assess the functional capacity of extrathymic-derived T cells in vivo, we selected the lymphocytic choriomeningitis virus (LCMV) model, which induces potent CD8+ T cell responses. At the peak of LCMV-specific T cell responses on day 8 after challenge, we found an increased number of IFN-γ–producing CD4+ T cells in LCMV-infected nude BMT+preT recipients (Figure 8B), though less than WT controls (Figure 8A). We also found an increased number of TNF-α– and IFN-γ–producing CD8+ T cells in LCMV-infected nude BMT+preT recipients (Figure 8D), albeit 1 to 2 logs lower
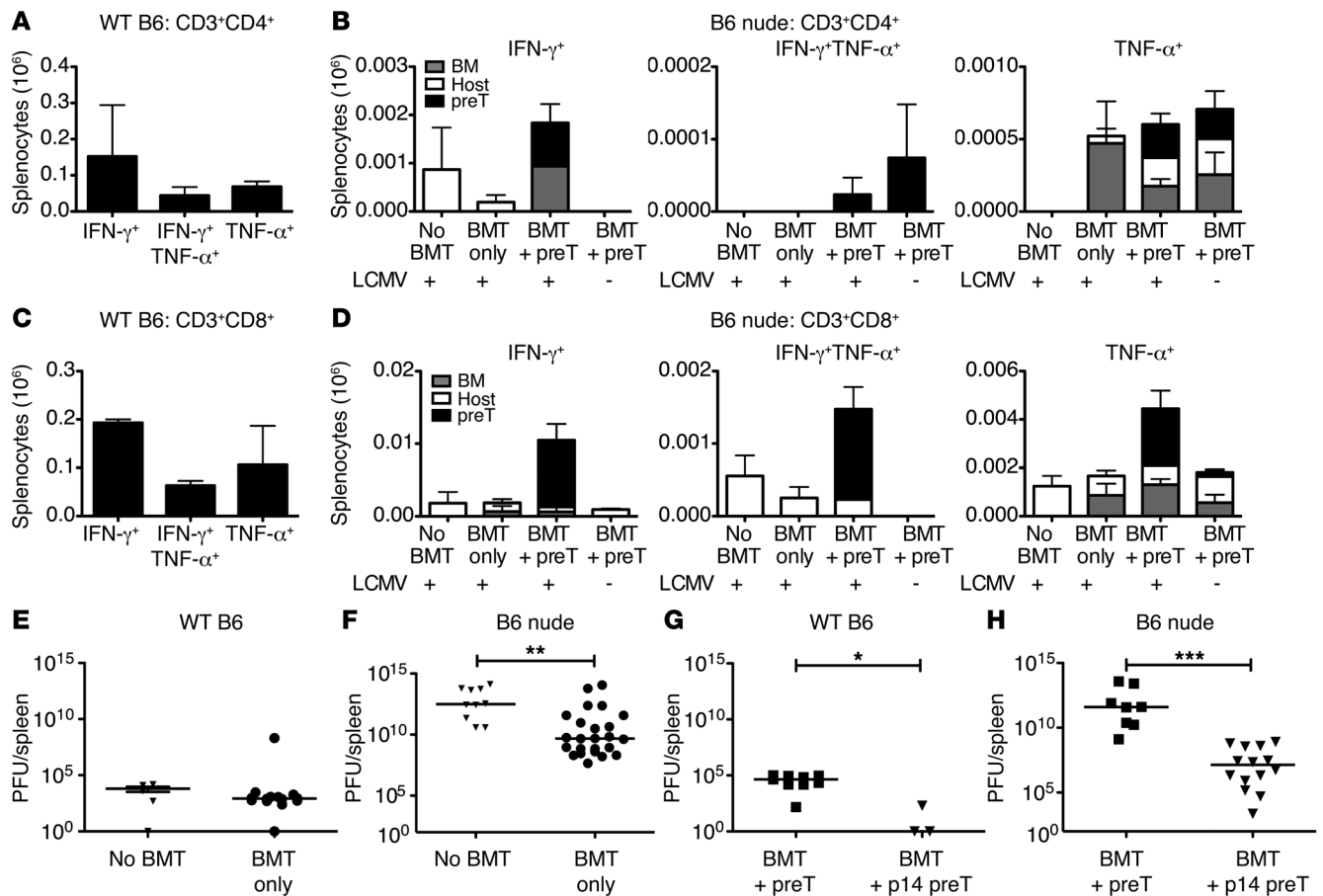
Figure 8
PreT-derived extrathymic T cells mount protective antiviral responses in vivo. (**A–D**) Quantification of cytokine-producing T cells from nontransplanted WT and nude mice ($n = 2$ each), and nude BMT only ($n = 5$) and BMT+preT ($n = 9$ +LCMV challenge and $n = 3$ –LCMV) recipients 8 days after LCMV challenge at day 28 after BMT. TNF-α– and IFN-γ–producing splenic CD4^{+} T cells from WT mice (**A**) and nude mice (**B**), and CD8^{+} T cells from WT mice (**C**) and nude mice (**D**). (**E–H**) PFU in day 42 after BMT recipients challenged with LCMV and harvested 8 days after infection. (**E**) Nontransplanted ($n = 5$) and BMT only ($n = 14$) WT mice. (**F**) Nontransplanted ($n = 10$) and BMT only ($n = 24$) nude mice. (**G**) BMT+CD45.1[+] B6 preT ($n = 9$) and BMT+p14 preT ($n = 3$) WT mice. (**H**) BMT+CD45.1[+] B6 preT ($n = 8$) and BMT+p14 preT ($n = 14$) nude mice. *$P < 0.05$; **$P < 0.01$; ***$P < 0.001$.

than in WT controls (Figure 8C), indicating enhanced antiviral responses conferred by preT-derived T cells in athymic mice.

Finally, we assessed viral burden after LCMV infection in WT and nude mice. As expected, WT mice effectively clear the virus due to thymic T cell development (Figure 8, E and G). Nontransplanted athymic mice, however, are persistently infected with LCMV (Figure 8F). Importantly, nude recipients of BMT have significantly lower viral burden (Figure 8F), suggesting the extrathymic generation of a functional T cell receptor repertoire from the polyclonal BM progenitor pool. Despite a trend in individual experiments toward lower viral burden, we did not detect a significant enhancement of antiviral immunity in nude recipients of WT preTs compared with nontransplanted nude controls (Figure 8, F and H). However, athymic BMT recipients that received p14 transgenic preTs, which express the LCMV-specific T cell receptor p14, had several logs lower viral burden than nude recipients of WT preTs, indicating a significant improvement in pathogen clearance (Figure 8H). These findings indicate that extrathymic T cell development after BMT generates fully functional T cells from BM and preT origin. Importantly, genetically engineered preTs can further enhance antiviral immunity in athymic recipients.

Discussion

The ability of extrathymic sites to support the generation of functional T cells of the TCRαβ lineage has been a subject of debate owing to conflicting data in disparate model systems. Conventional CD4^{+} and CD8αβ^{+} T cells have routinely only been found to be of thymic origin, though in select systems, such as the overexpression of OM, LNs can support conventional T cell development, resulting in functionally inferior T cells (20–23). In the context of BMT, the potential for extrathymic T cell development appears to be significantly enhanced, with several groups describing early T cell precursor cells in BM, spleen, and LNs of BMT recipients (19, 27, 29, 30, 32). However, the ability of these extrathymic progenitors to generate functional T cells was poorly defined. In this study, we demonstrate that extrathymic T cell development after BMT generates a broad pool of functional T cells that, importantly, can contribute toward restoring immune competence in patients with limited thymic function.

LNs express many of the critical factors required for T cell development, including Notch ligands, IL-7, and peripheral tissue antigens required for T lineage cell commitment and selection (26, 41, 42). However, the intestinal environment was critical to extrathymic T cell

development, as anatomically distant PLNs failed to support DP cell development in multiple mouse strains. The unique signals provided by the intestinal environment that allow MLNs to support T cell development, along with the intra-nodal conditions that actually support that development, are an exciting area for future investigation. While MLNs in aging euthymic and athymic mice do not support appreciable numbers of DP cells, extrathymic T cell development is documented in athymic mice (19). However, this process is inhibited by the presence of mature T cells in the LNs (19). The posttransplant setting, with its extreme lymphopenia and depletion of T cells from the periphery, may condition the LNs for extrathymic T cell development until such time as mature T cells recolonize the organ (19, 20). It will be interesting to investigate the roles of lymphopenia, tissue damage, and the abundance of circulating progenitor cells in transiently amplified extrathymic T cell development after transplant.

Limited thymic function in aged BMT patients leads to slow and often incomplete T cell recovery, causing susceptibility to opportunistic pathogens and tumor relapse. In fact, aging takes an even greater toll on the thymus in humans than in mice (10), and it has been suggested that athymic mice would potentially serve as more appropriate BMT recipients than aged mice in modeling transplant into older patients (12). As such, it is therefore likely that extrathymic T cell differentiation plays an even more prominent role in T cell reconstitution in BMT patients than we have been able to demonstrate in our models. Here we show that *Foxn1*-deficient, genetically athymic mice can generate significant numbers of conventional TCRαβ^{+} T cells following BMT. Neither CD4^{+} nor CD8^{+} T cells displayed the premature activation or memory phenotype reported in previous studies of extrathymic-derived T cells (22). While the number of TCRαβ^{+} T cells in athymic BMT recipients is approximately 2 logs lower than in euthymic recipients, the successful generation of functional extrathymic T cells constitutes an attractive target for therapeutic optimization. The extrathymic microenvironmental cues provided to either polyclonal BM or preT cells are adequate to produce a qualitatively functional extrathymic-derived T cell pool, as extrathymic-derived T cells in our system proliferate after TCR ligation and mount antiviral cytokine responses. We also demonstrate that, in the absence of a functional thymus, rapid immune competence can be conferred against previously unseen pathogen suggesting the generation of a diverse receptor repertoire. The inability of polyclonal preTs to enhance antiviral immunity compared with BM alone indicates that the increased size of the T cell pool does not result in increased LCMV-specific T cell frequency. In addition, several factors may have masked any potential effects of the WT preTs, including administration of the standard infection dose despite 2-log lower T cell numbers and assessment of PFU at the standard time point despite persistent infection. Importantly, using genetically engineered preT cells with viral specificity, we could substantially enhance viral clearance in both euthymic and athymic recipients.

These findings indicate that patients with limited thymic function due to genetics, aging, or prolonged cytoreductive therapies may yet have the requisite machinery to generate a diverse repertoire of functional T cells. Moreover, these extrathymic pathways of T cell development can be harnessed to provide rapid specific antimicrobial and antitumor immune competence.

Methods

Mice. B6 (CD45.2[+] B6), B6.SJL-*Ptprc[a] Pep3[b]*/BoyJ (CD45.1[+] B6), BALB/c (CD45.2[+]), and CB6F1 mice were obtained from the Jackson Laboratory. B6 and BALB/c background *Foxn1*-deficient nude mice (CD45.2[+]) were obtained from Taconic Farms. *Ccr9* KO, *Selplg* (PSGL-1) KO, F1 CD45.1[+] CD45.2[+] B6, luciferase[+] B6 maintained at Memorial Sloan-Kettering Cancer Center in accordance with Institutional Animal Care and Use Committee standards.

BMT. Transplants were performed as previously described (33, 43). Briefly, mice received split-dose lethal total body irradiation (B6 background mice: 1100 cGy; BALB/c background mice: 850 cGy; CB6F1 background mice: 1300 cGy). BM, prepared by aseptic preparation of femoral BM using MACS lineage cell depletion kit (Miltenyi Biotec), was administered i.v. at a dose of 10^5 lineage-depleted BM cells per mouse. Where indicated, preTs (4–8×10^6 cells) or sorted preTs (1–2×10^6 cells) were coadministered with BM.

Culture. Femoral BM was harvested aseptically and processed using a MACS lineage cell depletion kit to deplete mature hematopoietic cells expressing CD5, CD45R (B220), CD11b, Gr-1 (Ly-6G/C), 7-4, and Ter-119 (Miltenyi Biotec). Following lineage depletion, the cells were stained for a lineage panel (CD3, CD4, CD8, CD19, CD11b, NK1.1, and Gr-1), Sca-1, and c-kit. Lineage[–] Sca-1^{+}c-kit^{+} cells were isolated on MoFlo (BeckmanCoulter) or Aria (BD Biosciences) cell sorters, then plated on OP9-DL1. Cells were maintained in MEM-α + 20% FCS +1% penicillin/streptomycin (P/S) with 10 ng/ml murine IL-7 and 10 ng/ml murine Flt3 ligand. Cultures were passaged every 4 days and used for analysis or transplant between days 14 and 28 of coculture.

Antibodies and flow cytometry. All antibodies were obtained from BD Biosciences — Pharmingen other than CD62L PE–Texas Red (Caltag Laboratories), CD44 Alexa Fluor 700 (BioLegend), CD25 PE–Texas Red (Caltag Laboratories), and CCR9 PE (R&D Systems). For cell-surface markers, cells were stained for 15 minutes at 4°C in PBS with 0.5% BSA (PBS/BSA), washed, and resuspended in DAPI in PBS/BSA. For intracellular cytokine staining, cells were stimulated for 5 hours with 50 ng/ml PMA and 500 ng/ml ionomycin. Cell-surface staining was as above, followed by intracellular staining with the eBioscience kit per the manufacturer's instructions. All flow cytometry was performed on an LSR II (BD Biosciences) and analyzed with FlowJo (TreeStar Software).

BLI. PreTs generated from mice expressing firefly luciferase were adoptively transferred into BMT recipients as described above. Engraftment of preTs was monitored several times per week by in vivo bioluminescence. Mice received D-luciferin (6 mg/mouse; Caliper Life Sciences) i.p., were anesthetized by isoflurane, and imaged 10 minutes after injection. Mice were placed in the light-tight chamber of an IVIS-200 imaging system (Caliper Life Sciences), and 5 minute exposures were acquired. Bioluminescence data were analyzed using Living Image 2.5 (Caliper Life Sciences).

Proliferation assay. Spleens and PLNs were harvested at day 42 following BMT and aseptically processed to single-cell suspension; then 5×10^5 cells each were plated in a volume of 200 μl of RPMI + 10% FCS + 1% P/S + 1% β-mercaptoethanol in a 96-well U-bottom plated coated with αCD3 (10 μg/ml) and αCD28 (1 μg/ml). Each sample was plated in triplicate. Cells were stimulated for 72 hours at 37°C in a humidified atmosphere with 5% CO_2 content. ^{3}H-thymidine was added 72 hours into stimulation, and cells were harvested 16 hours later.

LCMV challenge. At day 28 after BMT, mice were challenged i.p. with 2×10^5 LCMV-Armstrong PFUs. Splenocytes were harvested 8 days after challenge and plated with either CD4 epitope gp61 or CD8 epitope gp33 peptides. After 5 hours, cells were harvested and processed for intracellular cytokine (ICC) as above. PFU assays were performed as previously described (44). Briefly, 7.5×10^5 Vero cells were plated per well in a 6-well plate on day –1 of assay. On day 8 after infection, spleens were harvested. Spleens were sonicated in 1 ml of RPMI and medium was aspirated from Vero cells; then 0.2 ml of sonicate was plated in serial dilution (10^{-1} through 10^{-11}) and covered with a 1:1 complete Medium 199:1% agarose mixture following 60 minutes of adsorption on day 0 of assay. Plates were kept at 37 degrees in a CO_2 incubation and after 4 days, additional 1:1 complete 199 medium (1% agarose containing neutral red dye) was added to wells. The following day, plaques were read.

1. Cook MC, Tangye SG. Primary immune deficiencies affecting lymphocyte differentiation: lessons from the spectrum of resulting infections. *Int Immunol*. 2009;21(9):1003–1011.
2. Edgar JD. T cell immunodeficiency. *J Clin Pathol*. 2008; 61(9):988–993.
3. Appelbaum FR. The current status of hematopoietic cell transplantation. *Annu Rev Med*. 2003;54:491–512.
4. Wils EJ, et al. Insufficient recovery of thymopoiesis predicts for opportunistic infections in allogeneic hematopoietic stem cell transplant recipients. *Haematologica*. 2011;96(12):1846–1854.
5. Parkman R, Weinberg KI. Immunological reconstitution following bone marrow transplantation. *Immunol Rev*. 1997;157:73–78.
6. Steinmann GG. Changes in the human thymus during aging. *Curr Top Pathol*. 1986;75:43–88.
7. Appay V, Sauce D, Prelog M. The role of the thymus in immunosenescence: lessons from the study of thymectomized individuals. *Aging (Albany NY)*. 2010;2(2):78–81.
8. Holland AM, van den Brink MR. Rejuvenation of the aging T cell compartment. *Curr Opin Immunol*. 2009; 21(4):454–459.
9. Haynes L, Maue AC. Effects of aging on T cell function. *Curr Opin Immunol*. 2009;21(4):414–417.
10. den Braber I, et al. Maintenance of peripheral naive T cells is sustained by thymus output in mice but not humans. *Immunity*. 2012;36(2):288–297.
11. Mackall CL, Granger L, Sheard MA, Cepeda R, Gress RE. T-cell regeneration after bone marrow transplantation: differential CD45 isoform expression on thymic-derived versus thymic-independent progeny. *Blood*. 1993;82(8):2585–2594.
12. Mackall CL, Gress RE. Pathways of T-cell regeneration in mice and humans: implications for bone marrow transplantation and immunotherapy. *Immunol Rev*. 1997;157:61–72.
13. McElhaney JE, Dutz JP. Better influenza vaccines for older people: what will it take? *J Infect Dis*. 2008; 198(5):632–634.
14. Litzow MR. Acute lymphoblastic leukemia in adults. *Curr Treat Options Oncol*. 2000;1(1):19–29.
15. Small TN, et al. Immune reconstitution following T-cell depleted bone marrow transplantation: effect of age and posttransplant graft rejection prophylaxis. *Biol Blood Marrow Transplant*. 1997; 3(2):65–75.
16. Zakrzewski JL, et al. Adoptive transfer of T-cell precursors enhances T-cell reconstitution after allogeneic hematopoietic stem cell transplantation. *Nat Med*. 2006;12(9):1039–1047.
17. Zakrzewski JL, et al. Tumor immunotherapy across MHC barriers using allogeneic T-cell precursors. *Nat Biotechnol*. 2008;26(4):453–461.
18. McClory S, et al. Evidence for a stepwise program of extrathymic T cell development within the human tonsil. *J Clin Invest*. 2012;122(4):1403–1415.
19. Guy-Grand D, et al. Extrathymic T cell lymphopoiesis: ontogeny and contribution to gut intraepithelial lymphocytes in athymic and euthymic mice. *J Exp Med*. 2003;197(3):333–341.
20. Blais ME, et al. Why T cells of thymic versus extrathymic origin are functionally different. *J Immunol*. 2008;180(4):2299–2312.
21. Blais ME, Gerard G, Martinic MM, Roy-Proulx G, Zinkernagel RM, Perreault C. Do thymically and strictly extrathymically developing T cells generate similar immune responses? *Blood*. 2004; 103(8):3102–3110.
22. Boileau C, Houde M, Dulude G, Clegg CH, Perreault C. Regulation of extrathymic T cell development and turnover by oncostatin M. *J Immunol*. 2000; 164(11):5713–5720.
23. Dulude G, et al. Thymic and extrathymic differentiation and expansion of T lymphocytes following bone marrow transplantation in irradiated recipients. *Exp Hematol*. 1997;25(9):992–1004.
24. Louis I, et al. Changes in the lymph node microenvironment induced by oncostatin M. *Blood*. 2003; 102(4):1397–1404.
25. Terra R, Labrecque N, Perreault C. Thymic and extrathymic T cell development pathways follow different rules. *J Immunol*. 2002;169(2):684–692.
26. Terra R, Louis I, Le Blanc R, Ouellet S, Zuniga-Pflucker JC, Perreault C. T-cell generation by lymph node resident progenitor cells. *Blood*. 2005; 106(1):193–200.
27. Dejbakhsh-Jones S, Jerabek L, Weissman IL, Strober S. Extrathymic maturation of alpha beta T cells from hemopoietic stem cells. *J Immunol*. 1995; 155(7):3338–3344.
28. Dejbakhsh-Jones S, Garcia-Ojeda ME, Chatterjea-Matthes D, Zeng D, Strober S. Clonable progenitors committed to the T lymphocyte lineage in the mouse bone marrow; use of an extrathymic pathway. *Proc Natl Acad Sci U S A*. 2001;98(13):7455–7460.
29. Garcia-Ojeda ME, et al. Stepwise development of committed progenitors in the bone marrow that generate functional T cells in the absence of the thymus. *J Immunol*. 2005;175(7):4363–4373.
30. Arcangeli ML, et al. Extrathymic hemopoietic progenitors committed to T cell differentiation in the adult mouse. *J Immunol*. 2005;174(4):1980–1988.
31. Gautreau L, et al. Identification of an IL-7-dependent pre-T committed population in the spleen. *J Immunol*. 2007;179(5):2925–2935.
32. Maillard I, et al. Notch-dependent T-lineage commitment occurs at extrathymic sites following bone marrow transplantation. *Blood*. 2006;107(9):3511–3519.
33. Na IK, et al. Concurrent visualization of trafficking, expansion, and activation of T lymphocytes and T-cell precursors in vivo. *Blood*. 2010; 116(11):e18–e25.
34. Rincon M, Flavell RA. Regulation of AP-1 and NFAT transcription factors during thymic selection of T cells. *Mol Cell Biol*. 1996;16(3):1074–1084.
35. Cante-Barrett K, Winslow MM, Crabtree GR. Selective role of NFATc3 in positive selection of thymocytes. *J Immunol*. 2007;179(1):103–110.
36. Rossi FM, et al. Recruitment of adult thymic progenitors is regulated by P-selectin and its ligand PSGL-1. *Nat Immunol*. 2005;6(6):626–634.
37. Veerman KM, et al. Interaction of the selectin ligand PSGL-1 with chemokines CCL21 and CCL19 facilitates efficient homing of T cells to secondary lymphoid organs. *Nat Immunol*. 2007; 8(5):532–539.
38. Uehara S, Grinberg A, Farber JM, Love PE. A role for CCR9 in T lymphocyte development and migration. *J Immunol*. 2002;168(6):2811–2819.
39. De Togni P, et al. Abnormal development of peripheral lymphoid organs in mice deficient in lymphotoxin. *Science*. 1994;264(5159):703–707.
40. Mariathasan S, Matsumoto M, Baranyay F, Nahm MH, Kanagawa O, Chaplin DD. Absence of lymph nodes in lymphotoxin-alpha(LT alpha)-deficient mice is due to abnormal organ development, not defective lymphocyte migration. *J Inflamm*. 1995; 45(1):72–78.
41. Fletcher AL, et al. Lymph node fibroblastic reticular cells directly present peripheral tissue antigen under steady-state and inflammatory conditions. *J Exp Med*. 2010;207(4):689–697.
42. Link A, et al. Fibroblastic reticular cells in lymph nodes regulate the homeostasis of naive T cells. *Nat Immunol*. 2007;8(11):1255–1265.
43. Alpdogan O, et al. Keratinocyte growth factor (KGF) is required for postnatal thymic regeneration. *Blood*. 2006;107(6):2453–2460.
44. Ahmed R, Salmi A, Butler LD, Chiller JM, Oldstone MB. Selection of genetic variants of lymphocytic choriomeningitis virus in spleens of persistently infected mice. Role in suppression of cytotoxic T lymphocyte response and viral persistence. *J Exp Med*. 1984;160(2):521–540.