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Peyer’s Patch Inducer Cells Play a Leading Role in the Formation of B and T Cell Zone Architecture

Reiko Nakagawa,*1 Atsushi Togawa,*,†1 Takashi Nagasawa,‡ and Shin-ichi Nishikawa*1

Peripheral lymphoid tissues, such as lymph nodes and Peyer’s patches (PPs), are organs required for mounting highly efficient immune responses to small quantities of Ag. The compartmentalization of the cellular components involved in the immune response into distinct zones supports the function of these tissues; however, little is known about how this compartmentalization is achieved. In this study, we analyzed neonatal PP development and present evidence that the CD3+IL-7Ra+ PP inducer cells that initially play a pivotal role in the formation of the PP anlagen are involved in the formation of B and T cell zones in neonatal mice. PP inducer cells migrate between these zones by undergoing chemokine receptor switching. The Journal of Immunology, 2013, 190: 000–000.

In comparison with the neonatal process of establishing initial compartmentalization, the earliest processes that take place in PLT anlage formation are understood to a considerable extent for both LNs and PPs (10–13). Although LNs and PPs differ in their molecular requirements for initiating organogenesis, LTαβ and LTi cells that express LTαβ are key components regulating anlage formation, the former at the molecular level and the latter at the cellular level (13–17). LTi cells are known to divide in the lymphocyte differentiation pathway in the fetal liver (15, 18), and two transcriptional regulators, Id2 and RORγt, have been identified as essential for the lineage commitment of LTi cells (19–23). Although LTi cells share many common molecules, such as IL-7Ra and c-Kit, with lymphocyte progenitors, they do not undergo rearrangement of the Ig or TCR genes (24, 25). After the emergence of LTi cells in the fetal liver, the cells migrate to regions where the PLTs are formed; however, this process is poorly understood (12, 16, 21, 26, 27). Once LTi cells reach the appropriate PLT anlage, interactions between lymphotixin (LTαβ), which is present on the cell surface, and the surrounding stromal cells induce the generation of lymphoid tissue organizer (LTo) cells (28, 29). LTo and LTo cells express an array of interacting molecules (10, 11, 13, 30), such as LToαβ and the LToβ receptor (14, 24, 27, 31–38), IL-7Ra and IL-7 (16, 17, 25, 28, 39, 40), integrin αββ and MadCAM1 (15, 23, 24), and CXCR5 and CXCL13 (41–45). The complementarity of LTo and LTo cells allows for their interaction, thereby expanding the realm of the PLT anlagen by recruiting more LTi cells. When LTi cells were first defined, their role was thought to be restricted to PPs and LNs, but subsequent work has shown that LTi cells are involved in the organogenesis of other PLTs in similar contexts (40, 46). Accordingly, the more general term LTi is used, rather than PPI or LNI.

The fate of LTi cells after PLT anlage formation remains another important topic of research (47). Lane and colleagues (7–9, 48–50) suggested that LTi cells have distinct roles after the completion of PLT organogenesis that affect cellular compartmentalization and the adaptive T cell response. One line of evidence also suggests that in vitro, LTi cells further differentiate into other cell lineages, including NK cells and dendritic cells, when provided with the appropriate signals (15, 18). Recently, Vonarbourg et al. (51) reported that the transition from LTi to NK cells occurs in vivo because of the downregulation of the molecular signatures specific to LTi cells. This phenotypic shift led to use of the term “immunological chameleon” to describe LTi cells (52). Because

*1Center for Developmental Biology, RIKEN, Kobe 650-0047, Japan; †Hematology, Oncology, Endocrinology and Infectious Disease, Faculty of Medicine, Fukuoka University, Fukuoka 814-0180, Japan; and ‡Institute for Frontier Medical Sciences, Kyoto University, Kyoto 606-8507, Japan

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Address correspondence and reprint requests to Dr. Shin-Ichi Nishikawa, Center for Developmental Biology, RIKEN, 2-2-3 Minatojima-miraihama, Chuo-ku, Kobe 650-0047, Hyogo, Japan. E-mail address: nishikawa@cdb.riken.jp

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Abbreviations used in this article: E, embryonic (day); FDC, follicular dendritic cell; FZ, follicular zone; HEV, high endothelial venule; IFZ, interfollicular zone; LN, lymph node; LT, lymphotixin; LTo, lymphoid tissue inducer; LToαβ, lymphotixin αββ; P, postpartum (day); PF, parafollicular zone; PLT, peripheral lymphoid tissue; PP, Peyer’s patch; PPI, PPI inducer; PPs, PLT/PPI organizer.

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TTi cells are thought to have multiple functions, it is possible that these cells are involved in the initial compartmentalization of LTs. Thus, we addressed this question in PPs and present evidence that CD3+IL-7Ra+PPi plays a role in the formation of B/T zones.

Materials and Methods

**Mice**

C57BL/6, C.B17/cge-SCID Jcl, and BALB/cA Jcl-Nude mouse strains were purchased from Japan CLEA. JH-2/8 mice were prepared from Quasi mice (53). BAC-transgenic RORγt-Cre mice were generated as described previously (54). CXCR4b/3 mice (55), CXCR4b/3 mice (56), CXCL12-GFP knockin mice (57), ROSA26A-EYFP mice (58), and Tie2-Cre mice (59) have been described previously. Female and male mice were mated overnight, and females with a vaginal plug were considered pregnant; thus, noon on the day when the vaginal plug was found was calculated as 0.5 d post coitum. All animal experiments were carried out in accordance with the RIKEN guidelines for animal and recombinant DNA experiments.

**Abs**

Pacific Orange-conjugated anti-CD45 (30-F11), Alexa Fluor 488-conjugated purified donkey polyclonal anti-goat IgG(H+L), Alexa Fluor 594-conjugated purified donkey polyclonal anti-rat IgG(H+L), Alexa Fluor 647-conjugated purified chicken polyclonal anti-rat IgG(H+L), Alexa Fluor 488-conjugated purified rabbit polyclonal anti-GFP, and Alexa Fluor 594-conjugated streptavidin were purchased from Invitrogen. eFluor 450-conjugated anti-CD3 (17A2), APC-conjugated, Alexa Fluor 700-conjugated, and biotin-conjugated anti-IL-7Ra (A7R34), biotin-conjugated anti-CXCR4 (2B11), biotin-conjugated anti-CCR7 (3D12), biotin-conjugated IgG2a (eB2a), biotin-conjugated anti-CR1CR2 (eB1015D9), biotin-conjugated anti-CD19 (eB101D3), biotin-conjugated anti-human IgG Fe, and purified rat monoclonal anti-ROSYt (AFKS-9) were purchased from Biotec. APC Cy7-conjugated anti-CD4 (GK1.5), PE-conjugated anti–integrin α4β7 (DATK32), APC-conjugated anti–NK1.1 (PK136), biotin-conjugated anti–ICAM1 (3D2), biotin-conjugated anti–CXCR5 (3G8), biotin-conjugated anti–CD3 (145-2C11), biotin-conjugated or PE-conjugated anti–CD11c (HL3), APC-conjugated anti–CD19 (6D5), purified rat monoclonal anti–CD16/32 (2.4G2), purified rat monoclonal anti–VCAM1 (429[MVCAM.A]), purified goat monoclonal anti–IL-7Ra, biotin-conjugated goat polyclonal anti–mouse CXCL13, and mouse monoclonal anti–TGF-β1/β2/β3 (1D11) were purchased from R&D Systems.

Preparation of single-cell suspensions for flow cytometry and cell sorting

Single-cell suspensions of the whole gut from embryonic mice and the PP from neonatal mice were prepared as described previously (6). Cells were stained with anti–CD45, anti–CD3, anti–CD4, anti–integrin α4β7, anti–IL-7Ra, anti–VCAM1, anti–ICAM1, and anti–chemokine receptor (CXCR4, CXCR5, CCR7, or control IgG2a) Abs with 7-aminocoumarin C (BD Biosciences). After staining for cell surface Args, fixation and permeabilization were performed using the BD Cytofix/Cytoperm Kit (BD Biosciences Pharmingen), and the cells were then stained with anti–ROSYt. Stained cells were analyzed or sorted using a FACSCanto II or FACSAria II (BD Biosciences), respectively. The culture conditions for the sorted inductor cells on OP9 stromal cells were described previously (16). A concentration of 10 μg/ml was used for all of the recombinant cytokines in this study (murine stem cell factor, murine IL-7, human TGF-β1, and human/mouse/atacin A).

Immunohistochemistry

Whole-mount immunostaining was performed as previously described, with slight modifications (6). Briefly, samples were fixed with 4% paraformaldehyde in PBS, dehydrated, and then blocked with endogenous peroxidase with 30% H2O2 in methanol. The small-intestine specimens were then blocked in 1% BSA in PBS for 1 h at 4°C and then incubated with PBST-BSA containing 1 mg/ml of the biotinylated anti–IL-7Ra, anti–VCAM1, anti–CD3, anti–CD19, anti–B220, or anti–CR1CR2 Abs overnight at 4°C. After washing five times in PBST-BSA for 1 h at 4°C, the primary Ab was detected using the R.T.U Streptavidin-HRP and DAB Peroxidase Substrate Kit (Vector Laboratories) and then observed by microscopic microscopy (Leica).

For whole-mount immunofluorescence, the dehydrated small intestines were first blocked by incubating twice in PBST-BSA for 1 h at 4°C and then incubated with PBST-BSA containing 1 mg/ml of the anti–IL-7Ra goat polyclonal Ab, anti–VCAM1 rat mAb, biotinylated anti–CD3 mAb, anti–CD19 rat mAb, anti–ROSYt rat mAb, biotinylated anti–CXCL13 goat polyclonal Ab, or anti–MadCAM1 rat Ab. As we could not find any appropriate Abs for CXCL12 staining, we used CXCL12-GFP knockin mice (57) and the Alexa Fluor 488-conjugated purified anti-GFP rabbit polyclonal Ab. After washing five times in PBST-BSA for 1 h at 4°C, the primary Ab was detected with Alexa Fluor 488-conjugated purified donkey polyclonal anti–goat IgG(H+L), Alexa Fluor 594-conjugated purified donkey polyclonal anti–rat IgG(H+L), Alexa Fluor 647-conjugated purified chicken polyclonal anti–IgG(H+L), or Alexa Fluor 594-conjugated streptavidin. For the immunostaining of cryosections, samples were fixed with 4% paraformaldehyde in PBS for 1 min. After a brief wash, the sections were blocked by incubating twice in PBST-BSA for 1 h at room temperature and then incubated with PBST-BSA containing 1 mg/ml anti–B220 and biotinylated anti–CD3 Abs overnight at 4°C. After washing three times in PBST-BSA for 10 min at room temperature, the primary Ab was detected with Alexa Fluor 488-conjugated purified donkey polyclonal anti–rat IgG(H+L) and Alexa Fluor 594-conjugated streptavidin. Fluorescent signals were detected by confocal microscopy using the LSM710 microscope (Carl Zeiss).

Preparation of LTβR-Fc

Mouse monoclonal anti–TGF-β1/β2/β3 (1D11) (10 mg/kg) was i.p. injected at days P1, P2, and P3 after birth. FACS analysis was performed at P4 (60, 61).

Results

The neonatal process of cell compartmentalization establishment in PPs

The first PP primordium formed during embryonic development is composed of simple cell aggregates, and we have previously shown that this structurally simple PP anlage gains complexity and eventually develops into an organ with distinctive zones comprising different cell types (6). This process involves the intrinsic regulation of cell distribution but is independent of Ag stimulation. As shown in Fig. 1A, PPs at P7 consist of the following: 1) the follicular zone (FZ), where CXCL13 is expressed and B cells and follicular dendritic cells (FDCs) are concentrated; 2) the parafollicular zone (PFZ), where MadCAM+ high endothelial venule (HEV) and PPi cells are evenly distributed in the PP anlagen in embryonic day (E) 17.5 embryos. Thus, the basic tissue organization of PPs is achieved during the first 7 d of the neonatal period.

We next determined which cell types play a leading role in this neonatal process by analyzing the expression of molecular markers during the first 7 neonatal days (Fig. 1B). During this period, B cells accumulated in and were distributed throughout the FZ, CRI/CRI* FDCs emerged in the FZ, and T cells accumulated in and were distributed throughout the PFZ and IFZ. In addition, we detected events that were previously unreported. The most notable obser-
vation involved the behavior of IL-7Rα+ PPi cells. In the embryo, these cells are homogeneously distributed throughout the entire PP anlage, and these cells then segregate into multiple clusters corresponding to their prospective FZs and relocate to the outer zone of the FZ (6, 25, 28, 39, 43). Notably, IL-7Rα+ PPi cell migration to these two zones preceded the accumulation of lymphocytes into the same regions. Thus, we hypothesized that PPi cells are involved in the establishment of both B and T cell zones.

IL-7Rα+ cells in neonatal PPs correspond to PPi cells

To determine whether PPi cells play a leading role in the formation of the B and T cell zones, we first confirmed that the IL-7Rα+ cell population shown in Fig. 1 represented PPi cells, as IL-7Rα is widely expressed on immature lymphocyte precursors (62). To do so, we performed flow cytometry on cells from PPs to evaluate the expression of IL-7Rα and RORγ; the expression of RORγ has been used to distinguish PPi cells from T cells, which are also known to express IL-7Rα (21, 47, 62). The PP regions of P7 mice were isolated, dissociated, and analyzed by flow cytometry (Fig. 2), and the results indicate that most, if not all, of the CD3− integrin αβ7+ cells in the PP express RORγ, thus confirming the identity of these cells as PPi cells. In contrast, all of the CD3+ cells were RORγ negative. Thus, PPi cells could be distinguished from T cells by the expression of these markers. Although both CD3+ and CD3− cells express IL-7Rα, the expression levels of IL-7Rα were 5-fold higher among CD3− integrin αβ7+ RORγ+ cells compared with CD3+ cells (mean ± SD: 278 ± 27.5 and 1619 ± 151.3, respectively) (Fig. 2). Therefore, we concluded that the IL-7Rα+ cells shown in Fig. 1 correspond to PPi cells.

The PPi cell cluster in the FZ is involved in B cell zone formation

As shown in Fig. 1B, PPi cell clusters spread throughout the entire PP anlage, break off into segregated small clusters, and eventually

FIGURE 1. Histological architecture of PP at postnatal day 7. PPs were immunostained with the Abs indicated. (A) In E17.5 embryo, expression of the markers used in this analysis is distributed homogeneously. At this stage, PP thus appears reminiscent of a simple inflammatory region that is basically an accumulation of a set of cells attracted to the inflammatory region. Neither B nor T cells are detected in the neonatal PP. Ag-independent process of PP organogenesis completes about P7, resulting in a more complex organ with distinct zonings. Three zones are recognized at this stage. The FZ is characterized by accumulation of B cells (CD19+) and expression of the CXCL13 chemokine. The PFZ is the area where MadCAM+ HEV is present. In addition, IL-7Rα+ RORγ+ PPi are concentrated in this region. The remaining area is the IFZ, in which T cells are distributed. PPi are also distributed in this area, albeit to a lesser extent than PFZ. Left, Green: IL-7Rα, red: RORγ. Middle, Green: IL-7Rα, red: CD3, blue: CD19. Right, Green: CXCL12, red: CXCL13, blue: MadCAM1. Scale bars, 100 μm. F, Follicular zone; P, parafollicular zone; I, interfollicular zone. (B) IL-7Rα, VCAM1, CD3, CD19, and CR1CR2 represent PPi, PPo, T cells, B cells, and FDCs, respectively. Although the MadCAM1 is expressed by PPo, its expression in postnatal life is confined to HEV. Accumulation of B and T cells in PPs occurs only after birth. At P7, B and T cell zones are completely segregated into FZ and IFZ, respectively. Disturbance of the homogeneity in the cellular distribution of PP anlage is first discerned as formation of clusters in which PPi accumulate. These clusters develop rapidly to FZ in which B and FDCs are concentrated. At P4, distribution of B and FDCs remains in FZ, whereas PPi disappears from FZ and is concentrated in PFZ. VCAM1 expression coincides with the distribution of PPi, suggesting that the PPi is the main inducer of VCAM1. T cells are distributed from PFZ to IFZ. Each picture is a representative result confirmed by at least two independent experiments. Original magnification ×25.
Chemokine receptor switching in PPi cells is essential for PPi cell relocation to the outer zone of the FZ

One intriguing finding was the relocation of PPi cells from the FZ to the outer zone (Fig. 1). Because PPi cells are CXCR5+, as reported in our previous studies (43), this relocation would be inconsistent with the observation that the chemokine CXCL13 is expressed in the FZ (Fig. 1A). To better understand the mechanism underlying the behavior of PPi cells, we analyzed chemokine receptor expression on PPi cells during neonatal development. As shown in Fig. 4, the expression of CXCR4, CXCR5, and CCR7 among the CD3+ IL-7Rα+ cell population was examined, and CXCR4 expression could be detected at P4 after CXCR5 downregulation. This CXCR5 downregulation occurred soon after birth, whereas CXCR4 expression was induced 1 d later (Supplemental Fig. 1B). Of interest, CXCR4 expression was detected in LTi cells in the LNs during the embryonic stage, whereas the downregulation of CXCR5 occurred during the neonatal stage, as is the case for PPi cells (Supplemental Fig. 1A). Thus, the expression of CXCR4 and CXCR5 is regulated independently in a tissue-specific manner. Nonetheless, as CXCL12 expression was observed in the IFZ (Fig. 1A), the relocation of PPi cells during the neonatal stage is consistent with the differential expression of chemokine receptors.

The molecular mechanism of chemokine receptor switching in PPi cells

Severe suppression of PP organogenesis during the neonatal stage (Fig. 3A) suggests that LTαβ signaling plays a role in chemokine receptor expression in PPi cells. To investigate this possibility, we analyzed chemokine receptor expression and distribution on PPi cells on days 1 and 2 after the injection of LTβR-Fc on P4, which is when chemokine receptor switching in PPi cells begins. LTβR-Fc injection reduced the increased expression of CXCR4 on P4 (Fig. 3D). However, CXCR5 expression remained negative, suggesting that the expression of CXCR4 and CXCR5 is regulated independently. In addition to the suppression of CXCR4 expression, the PPi cells located at the rim of the FZ at P4 do not migrate to the IFZ but rather return to the central part of the FZ (Fig. 3C). Thus, LTαβ signaling appears to be involved in the switching of chemokine receptor expression. Nevertheless, the block in LT signaling resulted in the disappearance of PPi cells from the PP the following day (Fig. 3C). However, as shown in Fig. 3B, this block in LT signaling did not have a substantial effect on CXCL12 expression, which suggests that the expression pattern of CXCL12 may be regulated independently of LTαβ.

PPi cells do not respond to LTαβ, as these cells express LTαβ, but not the LTαβ receptor. Hence, the inhibition of CXCR4 expression on PPi cells via the block in LT signaling was most likely indirect, presumably through the suppression of PPo cells or other cells that are reactive to LTαβ. In addition, as shown in Supplemental Fig. 2, all of the major cell types in the PP express LTαβ, so the effect of LTαβ on PPi cells remains unclear. However, because receptor switching occurred in scid/scid mice and JH+ mice (Supplemental Fig. 4A), it is unlikely that lymphocytes are involved in this process.

Next, we investigated which factors induce CXCR4 expression on PPi cells. To do so, we tested the effects of various cytokines on PPi cells in vitro. TGF-β treatment resulted in the expression of CXCR4 in our cell culture system (Fig. 5A). Similarly, a previous study showed that TGF-β can induce CXCR4 expression in monocyte-derived dendritic cells (64). Of Interest, CXCR5 was also expressed on the PPi cells expressing CXCR4, which suggests that these two chemokine receptors are differentially regulated. However, activin A, which is a member of the TGF-β family, did not affect its expression (Fig. 5A), and daily injections of an anti–TGF-β mAb (100 μg per neonate) (60) between P0 and P2 failed to inhibit receptor switching (Fig. 5B). These data indicate that the signals involved in chemokine receptor switching in the embryo warrant further investigation.

Chemokine receptor switching on PPi cells is essential for relocation

To confirm that chemokine receptor switching was involved in the relocation of PPi cells, we conditionally deleted the ccr4+ gene in RORγt+ cells by generating ccr4floxFloxFt+ × rorgcre/+ mice (54, 56) (Supplemental Fig. 3A, 3B). The expression of the ccr4+ gene was almost completely disrupted in RORγt+ cells from these mice (Fig. 6). As expected, CXCR5 and CCR7 downregulation was observed.
We then analyzed the localization of IL-7Rα+ cells in the PP strain, and the results shown in Fig. 7 indicate that IL-7Rα+ PPi cells remained in the FZ and failed to relocate to the PFZ in the neonatal PP in the absence of CXCR4. Thus, chemokine receptor switching is required for the relocation of PPi cells from the FZ to the outer zones.

PPi cell relocation is required for the formation of the T cell zone

Lane and colleagues (7, 8) suggested that LTi cells play a role in the segregation of the T and B cell zones in the spleen. Thus, we used the mouse strain described above to evaluate the role of PPi cells in the formation of T cell zones while leaving other processes intact. By comparing the PP structures in normal mice with those in conditional knockout mice, we observed that T cell distribution in the mutant mice was markedly different from that in control mice (Fig. 7). In normal PP, T cells are located in both the PFZ and IFZ, with the PFZ more densely populated. In mutant mice, however, T cells were found in the central regions of the PP. An analysis of the cells dissociated from the PP showed a significant reduction in the ratio of CD3+ cells in CXCR4 flox/+ mice (23.9 ± 2.3% and 7.7 ± 0.18%, respectively; Fig. 6), indicating a reduction in overall T cell accumulation (Fig. 7). However, no difference in the ratio of CD3+/CD45+ cells in the LNs was noted between CXCR4 flox/+ and CXCR4 flox/− mice (51.4 ± 4.4% and 51.2 ± 7.2%, respectively), which indicated that the deletion of CXCR4 by RORγt-Cre did not affect the total number of peripheral CD3+ cells. In addition, PPi cells relocated normally in nu/nu mice lacking T cells (Supplemental Fig. 4B), suggesting that T cells may not play an important role in T cell zone formation. Thus, PPi cell relocation is likely required to direct T cell distribution to the IFZ.
In contrast, the processes occurring in the FZ, such as B cell accumulation and FDC formation, were less affected in these mouse strains. In addition, no difference in CXCL13 localization was observed between normal and CXCR4 knockout mice (Supplemental Fig. 3C). Although the PFZ in mutant mice did not contain Ppi cells, the distribution of CD11c+ cells (data not shown) and the formation of MadCAM+ vessels in this region occurred normally. Together, these results indicate that Ppi cell relocation is specifically required for T cell distribution to T cell zones.

**Discussion**

The aim of this study was to elucidate the mechanism underlying initial cellular compartmentalization in PLTs, which includes the formation of segregated B and T cell zones. Although chemokines and their receptors have been implicated in the distribution of cells to specific zones, previous analyses have mostly investigated these processes in adult PLTs, in which the basic structure has already been established (3, 65, 66). As shown in this study as well as our previous studies, initial compartmentalization in the PPs is completed within the first neonatal week (6). Thus, studies of perinatal processes are instrumental to understanding the mechanisms underlying the formation of compartmentalized regions in PLTs. In the spleen, LTi cells play an essential role in the segregation of B and T cells and are involved in the functional activity of the T cell zone (7, 8). However, the regulation of normal PLT development and the role that LTi cells play during this process remain unresolved. To our knowledge, our study is the first to describe the neonatal process of PLT development.

**FIGURE 4.** Chemokine receptor switch of Ppi during neonatal PF development. Expression of three chemokine receptors—CXCR4, CXCR5, and CCR7—of Ppi was examined at E17.5 and P4. During this period, Ppi undergoes a switch of chemokine receptors from CXCR4+CXCR5CCR7+ to CXCR4+CXCR5CCR7+. Each panel is a representative result confirmed by at least three independent experiments performed with four to eight neonatal mice.

**FIGURE 5.** Induction of CXCR4 in Ppi by TGF-β1. (A) Ppi isolated from embryonic intestine was cultured on OP9 feeder layer in the presence of stem cell factor. The cells were stimulated by either TGF-β1 or activin A. TGF-β1, but not activin A, can induce CXCR4 in Ppi. Each panel is a representative result confirmed by at least three independent experiments performed with 8 to 20 neonatal mice. (B) However, neonatal injection of anti–TGF-β1/β2 mAb (1D11) failed to inhibit CXCR4 induction in mice. Each panel is a representative result confirmed by at least two independent experiments performed with four neonatal mice.
By carefully analyzing the initial process of cell compartmentalization in PPs, we observed that IL-7Rα+ PPi cells play a leading role in the formation of both B and T cell zones. In the embryo, PPi cells are distributed homogeneously throughout the entire PP anlage (6, 25, 28, 39, 43). At the time of birth, this homogeneous PPi cell cluster breaks up into smaller clusters (Fig. 1B). B cells are attracted to these clusters, and the mature FZ containing FDCs is formed around P4. Immediately after clustering in the FZ, PPi cells translocate from the FZ to the outer zones, which is where T cells are attracted. The establishment of PPi cells in the T cell zones is consistent with previous studies showing that LTi cells are present in the T cell zones of the spleen (7). Our study shows that this final localization of LTi cells is the result of the intricate control of LTi cell localization. Furthermore, the observed migration pattern led us to hypothesize that PPi cells are involved in the formation of not only the PP anlage but also the B and T cell zones.

The mechanism for how PPi cells are initially distributed homogeneously throughout the entire PP anlage (6, 25, 28, 39, 43). At the time of birth, this homogeneous PPi cell cluster breaks up into smaller clusters (Fig. 1B). B cells are attracted to these clusters, and the mature FZ containing FDCs is formed around P4. Immediately after clustering in the FZ, PPi cells translocate from the FZ to the outer zones, which is where T cells are attracted. The establishment of PPi cells in the T cell zones is consistent with previous studies showing that LTi cells are present in the T cell zones of the spleen (7). Our study shows that this final localization of LTi cells is the result of the intricate control of LTi cell localization. Furthermore, the observed migration pattern led us to hypothesize that PPi cells are involved in the formation of not only the PP anlage but also the B and T cell zones.

The mechanism for how PPi cells are initially distributed homogeneously throughout the PP anlage and then suddenly break up to form segregated clusters remains unknown (6, 25, 28, 39, 43). However, it is known that these clusters develop into FZs by attracting B cells. When we blocked the interaction between PPi and PPo cells by administering a single injection of LTβR-Fc at P1, which is when cluster formation starts, B cell accumulation in the FZs was inhibited for many months (Fig. 3A). Thus, the interaction between PPi and PPo cells in these clusters promotes the
formation of B cell zones by attracting B cells into the FZ. Of note, the transient inhibition of LTβ signaling at P1 resulted in a long-lasting effect, which strongly suggests that the PPi cell clusters in the FZs are required not only to attract B cells but also to trigger subsequent processes that establish tissue organization and enable the constant recruitment of B cells to the FZ in later life. Because PPi cells migrate from the FZ after B cell accumulation, PPi cells are not involved in the maintenance of the final tissue organization that is required for constant recruitment of B cells. Previous studies demonstrated that FDCs and B cells are the major factors that maintain the function of the FZ in mature PLTs (44, 67). Thus, it is likely that FZ development occurs in two steps. In the first step, the interactions between PPi and Pp0 cells induce the initial accumulation of B cells into PPi cell clusters. This accumulation then leads to the interaction between FDCs and B cells, which regulates sustained B cell recruitment. Although CXCL13 is the major chemokine involved in this process throughout life, the cells involved in CXCL13 induction and expression shift from PPi/PPo cells to B cells/FDCs.

Previous studies have demonstrated that LTI cells exist in the T cell zones and affect both the segregation of T and B cells and the adaptive T cell response (7, 49, 50). However, the process leading to LTI cell localization in the T cell zone remains unclear. In this study, we demonstrate that during the neonatal process, CXCR5 on PPi cells and CXCL13 on PPo cells have a central role in directing PPi cell localization (43). In contrast, at P3–4, the time at which B cells enter the FZ and FDCs emerge, PPi cells leave the FZ to migrate to the outer zones, even though the pattern of chemokine expression remains consistent (CXCL13 in the FZ and CXCL12 in the PFZ to IFZ). Therefore, the chemokine expression pattern cannot account for PPi cell behaviors; rather, this behavior occurs through the switching of chemokine receptors on PPi cells from CXCL5 to CXCR4. Moreover, we provide evidence that PPi cell relocation is dependent on CXCR4, as the conditional knockout of CXCR4 in RORγ T PPi cells resulted in the complete failure of PPi relocation. Strikingly, most PPi cells were retained in the FZ even after the accumulation of B cells and the development of FDCs (Fig. 7). Moreover, we found that T cell distribution through the IFZ was disturbed in this mouse strain, and this result is consistent with a previous study using LTIβ knockout mice, which suggested that LTI cells are involved in T cell zone formation (31, 33, 35–38, 68). In this study, we provide clear evidence that PPi cells migrate to the T cell zone to induce activity that attracts T cells. Taken together, these results indicate that PPi cells play a role in all of the key processes during PP organogenesis, namely, the formation of the anlage, B cell zone, and T cell zone.

Many questions concerning the initial process of compartmentalization remain unanswered. One important question is the following: How is chemokine receptor switching induced in PPi cells? The results presented in Fig. 3 demonstrate that this switch was inhibited by the blockade of LTIβ signaling. However, this result does not necessarily indicate that the LTIβ signal is sufficient for the switch. The LTIβ signal is present during embryonic PP organogenesis (25), but the receptor switch does not occur prior to P1. Because the LTIβ signal is the fundamental basis for PPi cell interactions with stromal cells (11, 13–16, 28), it is likely that additional signals are specifically induced in the FZ to activate the switch. As this switch is concomitant with the accumulation of B cells into the FZ, we also investigated the possibility that B cells were involved in the chemokine receptor switch. As shown in Supplemental Fig. 4A, however, chemokine receptor switching on PPi cells was shown to occur in scid/scid as well as JH−/− mice (61, 69). In addition, we examined PPi cell relocation in nu/nu mice that lack T cells and found that PPi cells relocated normally in this strain (Supplemental Fig. 4B). Thus, lymphocyte accumulation in the FZ is not required for receptor switching. Similarly, FDCs do not induce receptor switching because FDC development was suppressed in these strains. At present, the cell population responsible for receptor switching remains unknown, but our results suggest that these cells are induced in the FZ during the first 3 d of the neonatal period.

The addition of TGF-β to PPi cells in vitro induced the same chemokine receptor switching as that observed in vivo (Fig. 5A) (64). In contrast, the addition of activin A had no effect on chemokine receptor expression on PPi cells (Fig. 5A). However, daily injections of an anti–TGF-β mAb (100 µg per neonate) (60) from P0 to P2 failed to inhibit receptor switching (Fig. 5B). Thus, the cells and signals involved in this switch should be investigated in future studies.

Under culture conditions with IL-7, CXCR5 expression remains even though CXCR4 is induced by TGF-β stimulation, which indicates that CXCR4 and CXCR5 expression is differentially regulated. However, the specific cells and signals involved in this switch should be investigated in future studies.

Of note, chemokine receptor switching appears to be specific to the PPi. In LNs, CXCR4 is already expressed during the embryonic stage, and CXCR4 expression does not coincide with the down-regulation of CXCR5 (Supplemental Fig. 1A). Thus, the mechanisms underlying chemokine receptor expression may vary significantly between different PLTs. Moreover, the role of CXCR4 in the migration of LTI cells to the T cell zone in other PLTs remains unknown, although knocking out CXCR4 in RORγ T cells had almost no effect on the organogenesis of the LNs or spleen (Supplemental Fig. 3D). Thus, further analysis is necessary to define the behaviors of LTI cells during the compartmentalization of cells in PLTs. Moreover, the histological architecture differs between PPi and LNs; PPi lack afferent lymphatics, whereas LNs are sandwiched between afferent and efferent lymphatics (70, 71). The current results represent another example of the diverse mechanisms underlying the organogenesis of lymphoid tissues. Taken together, these data indicate the existence of multiple pathways to attain the tissue architecture of PLT. Because the cellular basis for the formation of B and T cell zones in other PLTs is unknown, it is difficult to extrapolate our results to the organogenesis of other PLTs. Nonetheless, additional studies on LT development should take this functional role of LTI cells into account. In particular, it would be interesting to investigate the role of inducer cells in various stages of chronic inflammation (72–74) because the course of chronic inflammation varies according to the incidental conditions and may induce phenotype switching of LTI cells, as shown in this study.

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Disclosures

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References


