

Role of TNF ligand and receptor family in the lymphoid organogenesis defined by gene targeting

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Abstract : The molecular basis of lymphoid organogenesis has recently been elucidated using gene-targeted mice. Mice deficient in lymphotoxin- α (LT α) lack lymph nodes and Peyer's patches. The action of LT α in lymphoid organogenesis is mediated mostly by the membrane form of LT by a mechanism independent of TNF receptor I (TNFR-I) or II (TNFR-II). Additionally, follicular dendritic cell (FDC) clusters or germinal centers fail to develop in the spleen of LT α -deficient mice. Mice deficient in either TNFR-I or LT β R also fail to develop splenic FDC clusters and germinal centers, indicating that signaling through both TNFR-I and LT β R is required for the development of these structures. The mechanisms underlying the defective lymphoid organogenesis in LT α -deficient mice, together with a natural mutant strain, alymphoplasia (aly) mice, which manifest a quite similar phenotype to LT α -deficient mice, were investigated by generating aggregation chimeras. These studies demonstrate that LT α and the aly gene product together control lymphoid organogenesis with a close mechanistic relationship in their biochemical pathways through governing distinct cellular compartments; the former acting as a circulating ligand and the latter as a LT β R-signaling molecule expressed by the stroma of the lymphoid organs. *J. Med. Invest.* 46 : 141-150, 1999

Key words : *lymphotoxin, TNF, lymph node, spleen, knockout mice*

INTRODUCTION

Secondary lymphoid organs such as spleen, lymph node (LN) and Peyer's patches (PPs) are the sites where immune cells interact with each other, and a strong immune response against foreign antigens is initiated. Lymphocytes continuously migrate from the blood to secondary lymphoid organs. The mechanisms for lymphocyte migration have been well documented; homing to LN and PP occurs through the interaction between adhesion molecules expressed on high endothelial venules (HEVs) of the lymphoid tissues and their counter-receptors on lymphocytes (1, 2). Lymphocytes begin to populate LN from the second day after birth, and lympho-

cyte diapedesis through the HEV becomes readily apparent from day 4 (3). While much is known of the molecular basis for the lymphocyte migration to the developed lymphoid organs, the mechanisms behind the incipient lymphoid organogenesis have been enigmatic. In other words, the molecular basis for the ontogenic development of lymphoid organs is not well understood.

Recent studies with gene-targeted mice manifesting abnormal development of the lymphoid organs have provided new insight into these undefined processes (summarized in Table 1). Mice deficient in lymphotoxin- α (LT α) (previously known as TNF β) were born with a systemic absence of LN and PP (4, 5) with disturbed spleen architecture (6-9), which

Abbreviations : LT, lymphotoxin ; LN, lymph node ; PP, Peyer's patch ; EF, embryonic fibroblast ; FDC, follicular dendritic cell ; GC, germinal center ; HEV, high endothelial venule ; TNFR-I, type I TNF receptor ; LT β R, lymphotoxin- β receptor ; LT β R-Ig, LT β R-IgG1 fusion protein ; TNFR-I-Ig, TNFR-I-IgG1 fusion protein ; BM, bone marrow ; GFP, green fluorescence protein ; Tg, transgenic mice ; PNA, peanut agglutinin.

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Table 1. Gene-targeted mice with defective lymphoid organogenesis.

Disrupted gene	Lymph node	PP	Spleen
LT α			
LT β *1			
LT β R			
CXCR 5 (BLR 1)*2			+
Ikaros			
Id2			
OPGL		+	+
IL-2 R γ (γ C)			
IL-7 R α	+		+
Jak 3*3			
Hox11	+	+	

*1 : Mesenteric and cervical lymph nodes are present in LT β -deficient mice (see Table 2).

*2 : Among all lymph nodes in BLR1-deficient mice, only inguinal nodes are missing and other lymph nodes are normally developed. About half of the BLR 1-deficient mice do not have PPs at all, and the rest possess a few.

*3 : Some of the mice lack peripheral lymph nodes.

will be discussed in detail in this article. Cytokine related genes other than LT have been also recognized to be involved in the lymphoid organogenesis ; mice deficient in either IL-2R γ chain (10), IL-7R α or Jak3 (11) have defective PP development. Chemokine receptor CXCR5 (also known as BLR1) has been also demonstrated to be essential for the development of inguinal LN and PP as well as for the formation of B cell follicles in the spleen (12). Recently, it was also demonstrated that mice deficient in osteoprotegerin ligand (OPGL) have defective LN genesis (13). In addition, targeted deletion of transcription factors has caused abnormal development of lymphoid organs and/or lymphoid cells ; Hox11-deficient mice lack spleen (14), Id2-deficient mice lack LN and PP (15), and Ikaros-deficient mice lack cells of all lymphoid lineages, LN and PP (16). Mice deficient in both NF- κ B1 (p50) and NF- κ B2 (p52) also lack LN with a disorganized spleen architecture (17). Thus, a broader spectrum of factors than had been anticipated influence the lymphoid organogenesis. Because secondary lymphoid organs are essential for the development of immune response, elucidating the genes which control lymphoid organogenesis is critical for a better understanding of the mechanisms for host defence. In this article, I will discuss how the lymphoid organogenesis is controlled at the molecular level focusing on the biology of the LT and tumor necrosis factor (TNF).

I. Ligand and receptor interactions of LT and TNF ; a historical perspective

Because both the LT α and the TNF homotrimers were recognized to bind with similar affinity and to activate in similar fashion both of the defined TNF receptors (p55 or TNFR-I, and p75 or TNFR-II) (18), LT α and TNF were for many years thought to be redundant *in vivo*, differing only in their cellular sources and perhaps the signals that induced their expression. Studies by Browning and Ware have, however, demonstrated that LT can exist in two forms, the initially characterized secreted homotrimeric form and a membrane heterotrimer form which in its most prevalent form consists of one LT α subunit associated with two copies of the type II transmembrane protein LT β (19). The LT β gene is located adjacent to the TNF locus within the HLA complex (19, 20). The membrane LT protein (LT α 1 LT β 2) is not a ligand for TNFR-I or TNFR-II, but interacts with another member of the TNF receptor family designated the LT β receptor (LT β R) (21). The cytoplasmic domain of the LT β R shares little homology with the cytoplasmic domains of TNFR-I or TNFR-II, suggesting that activation of the LT β R should induce cellular responses distinct from those mediated by the defined TNF receptors. These observations suggest that LT α acts to signal two distinct sets of cellular responses, one set determined by its homotrimeric form binding to TNFR-I and/or TNFR-II and one set determined by its membrane form binding to the LT β R or related receptors (20). In this model, we expect that many of the functions of LT *in vivo* do not overlap with those of TNF.

In addition, a new TNF ligand and receptor family members closely related to LT and TNF have been recently identified. Herpes simplex virus (HSV) 1 and 2 infect activated T lymphocytes by attachment of the HSV envelope glycoprotein D to the cellular herpesvirus entry mediator (HVEM) (22). It was shown that HVEM binds two cellular ligands, LT α homotrimer (LT α 3) and LIGHT (homologous to *L*ymphotoxins, exhibits *i*nducible expression, and competes with HSV *g*lycoprotein D for *H*VEM, a receptor expressed by *T* lymphocytes) ; LIGHT is a 29-kD type II transmembrane protein produced by activated T cells. LIGHT also binds to LT β R as the membrane form of LT does (23). These ligand and receptor interactions are illustrated in Fig. 1.

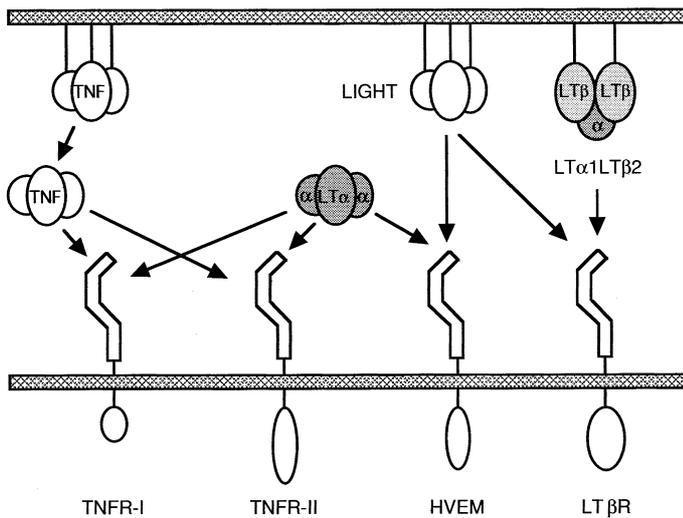


Fig.1. Ligand and receptor interactions of LT and TNF. Three distinct ligand/receptor pathways exist as follows ; 1) TNF/LTα3-TNFR, 2) LTα1LTβ2/LIGHT-LTβR, 3) LTα3/LIGHT-HVEM.

II. LT as an essential factor for the lymphoid organogenesis

LTα, originally discovered as a pro-inflammatory molecule (24), has turned out to be an essential factor that controls the genesis of the secondary lymphoid organs as well as for the organized spleen architecture (25-27). A spectacular phenotype of mice deficient for LTα was systemic absence of LN and PP (4, 5). Subsequent analyses of mice deficient

for other LTα-related molecules have provided more detailed information on the action of LT in the lymphoid organogenesis (summarized in Table 2). Although mice deficient for LTβ also lacked PP and most LN, they did possess mesenteric LN (28, 29). These results suggested that LTα 1 LTβ 2 plays major roles of LT in the development of LN and PP, and that there also exists an LTα/β heteromer independent pathway required for the development of mesenteric LN. This hypothesis was later proven by the *in vivo* administration of LTβR-Ig and TNFR-I-Ig fusion protein which block the signals through LTβR and TNFR-I, respectively. Normal mice treated in utero with LTβR-Ig alone lacked systemic LN except for mesenteric LN, whereas concomitant administration of LTβR-Ig and TNFR-I-Ig or anti-TNF blocked the development of all LN including mesenteric LN, indicating that the TNF-TNFR-I axis also contributes to LN genesis (30, 31). Consistent with this model, mice deficient for both LTβ and TNFR-I lacked all LN including mesenteric LN (32). Conflicting data, however, also exist. It was demonstrated that mice deficient for LTβR lack all LN including mesenteric LN, suggesting that LTβR is a primary receptor responsible for the development of all LN (33). Phenotypic difference between

Table 2. Role of TNF ligand and receptor family members in lymphoid organogenesis and lymphoid structure.

Disrupted gene	LTα	LTβ	LTβR	TNF	TNFR-I	TNFR-II	LTβ/TNFR-I
Lymph node							
Mesenteric	-*1	+	-	+	+	+	-
Other peripheral	-	-*2	-	+	+	+	-
PP	-	-	-	+/-*3	+/-*3	+	-
Spleen structure							
T/B segregation	-	-*4	-	+#5	+#5	+	ND
Marginal zone*6	-	+/-	-	ND	+	+	ND
Germinal center	-	-*7	-	-	-	+	ND
FDC network*8	-	-	-	-	-	ND	-

*1 : About 2% of mice have mesenteric lymph nodes.

*2 : Most of the mice possess cervical lymph nodes.

*3 : Although PPs exist, the development of B cell follicles and germinal center formation is defective.

*4 : Less marked compared with LTα-deficient mice.

*5 : Development of B cell follicles is poor.

*6 : Revealed by immunohistochemistry using MOMA-1 monoclonal antibody.

*7 : Small numbers of PNA (peanut agglutinin) positive cells exist in both T-cell and B-cell areas.

*8 : Assessed by immunohistochemistry with monoclonal antibody against complement receptors and/or FDC-M1, monoclonal antibody specific for FDC.

LT β -deficient mice and LT β R-deficient mice also suggested that LT β R binds not only to LT α / β heteromer but to other ligand(s), such as LIGHT (23), which may mediate signals required for the development of mesenteric LN. Thus, the integration of the detailed phenotypic analyses of these gene-targeted mice with current perspectives of LT/TNF biology may illuminate many aspects of the lymphoid organogenesis.

III. LT and TNF as essential factors for the lymphoid organ structure

Studies with knockout mice of LT/TNF-related molecules have also unravelled essential actions of LT and TNF for the organization of lymphoid structure. In mice deficient for either LT α (6, 7), LT β (28, 29) or TNF (34, 35), organized clusters of follicular dendritic cells (FDCs) and germinal centers (GCs) are absent from the spleen.

GCs are histologically well defined structures that develop in secondary lymphoid organs shortly after challenge with T cell-dependent antigens. B cells within the GC can be clearly identified by their ability to bind to peanut agglutinin (PNA). It has been suggested that it is within GCs that somatic hypermutation and affinity maturation of the antibody response occur (36). Both primary and secondary lymphoid follicles characteristically contain clusters of FDC. FDC trap and can retain antigen-antibody complexes for long periods, apparently by means of receptors for the third complement component (CR) as well as Fc γ receptors (36). We and others have shown that an organized FDC structure, a major morphological characteristic of GCs, is absent in LT α -, LT β -, TNF-, TNFR-I-, and LT β R-deficient mice (26, 33).

1. Role of LT and TNFR-I in the development of GC and organized FDC clusters

Interestingly, in LT α -deficient mice, formation of FDC clusters and GCs was restored by transplantation of normal bone marrow (BM), indicating that the LT α -expressing cells required to establish these lymphoid structures are derived from BM (6). Subsequent analyses have identified B cells as an essential source of LT required for this action (37, 38). In contrast to LT α -deficient mice, when TNFR-I-deficient mice were reconstituted with wild-type BM cells, they showed no detectable FDC clusters or GC formation, suggesting that TNFR-I-expression on

non-BM-derived cells is necessary for the establishment of these structures (39, 40). An analysis using LT β R-deficient mice has demonstrated similar results; LT β R-deficient mice reconstituted with wild-type BM cells showed no detectable FDC clusters or GC formation (41). Thus, both BM-derived (expressing LT α , LT β and TNF) and non-BM-derived (expressing TNFR-I and LT β R) cells contribute to the organization of the lymphoid structure.

To further demonstrate the role of LT α as a signal required to establish an organized FDC structure and to investigate the cell lineage of FDC, we used BM cells from CR 1/2-deficient mice to reconstitute irradiated LT α -deficient mice. In this context, donor CR 1/2-deficient BM-derived cells are LT α wild-type, but can be distinguished from the LT α -deficient recipient cells by their failure to stain with anti-CR1/2 monoclonal antibody. After reconstitution, spleen sections were stained with anti-CR1/2 monoclonal antibody and PNA to assay for the presence of FDC clusters and GC, respectively. Similar to the results obtained after transfer of wild-type BM cells, clustered FDCs were identified with anti-CR1/2 monoclonal antibody (39). These results clearly indicate that the clustered FDCs induced in these BM-chimeric mice are derived from the LT α -deficient recipient, and that LT α provides a signal that supports the development of FDC clusters. Thus, LT α is not absolutely required for the production of the FDC lineage, but rather it is necessary for its maturation or for organization of the mature cells.

2. Dysfunctional antibody responses in the absence of GC

When LT α -deficient mice were immunized with low doses of T cell-dependent antigens such as (4-hydroxy-3-nitrophenyl) acetyl-ovalbumin (NP-OVA) in alum, although a strong IgM anti-NP response developed, no IgG anti-NP was observed (7). The development of an IgM anti-NP response indicated that the failure to produce serum IgG anti-NP antibodies did not represent failure to deliver antigen to the responding B cells in the absence of LN in LT α -deficient mice. Rather, it appeared to indicate an inability to activate productive isotype switching in the setting of a disturbed primary follicle structure.

LT α -deficient mice also showed an impaired IgG response when immunized with sheep red blood cells (SRBCs) without adjuvant (9). When irradiated wild-type mice received splenocytes from LT α -deficient mice, however, a strong IgG anti-SRBC response was

observed, again supporting the idea that $LT\alpha$ -deficient B cells and T cells have no intrinsic defect in ability to generate an IgG response. Rather, the altered microenvironment characteristic of $LT\alpha$ -deficient mice appears to result in an impaired ability to switch to a productive IgG response.

3. Affinity maturation without GC in $LT\alpha$ -deficient mice

Although immunization of $LT\alpha$ -deficient mice with low doses of T cell-dependent antigens elicited an exclusively IgM B cell response as described above, immunization with high doses (100 or 200 μ g of heavily haptenated NP-OVA) adsorbed to alum resulted in production of serum IgG anti-NP at levels similar to those detected in wild-type mice (7). This ability to form an IgG response permitted us to use these mice to test the role of the splenic GC in the maturation of the immune response. In previous elegant microdissection studies, the GC compartment has been shown to contain B lymphocytes with somatic mutations of their rearranged heavy and light chain variable regions, suggesting that it is in the GC that the signals for activation of the somatic mutation process are given (36, 42). We have analyzed the quality of the antibody response in $LT\alpha$ -deficient mice after immunization with high doses of NP-OVA adsorbed to alum. Surprisingly, $LT\alpha$ -deficient mice immunized with high doses of NP-OVA in alum, still without GCs, generate high affinity IgG anti-NP antibodies at levels similar to wild-type mice (7). Furthermore, analysis of the expressed V gene repertoire in splenocytes isolated from the $LT\alpha$ -deficient mice showed activation of a somatic mutation with all of the characteristics of that process in wild-type mice. This included mutation of codon 33 in the heavy chain variable region VH186.2 from Trp to Leu in 50% of the amplified VH186.2 sequences. This Trp to Leu mutation has been shown to correlate closely with acquisition of higher affinity for NP and is a reliable marker for the activation of affinity maturation by somatic mutation (42). These results demonstrate that somatic mutation and affinity maturation can occur independent of morphologically defined GCs. They have additional implications regarding the nature of the cells that give signals that regulate the somatic hypermutation response. They suggest that specific cellular elements that are characteristic of GCs are not essential for activation of somatic mutation. For example, clusters of FDCs are absent from the follicles of $LT\alpha$ -deficient mice. It remains possible that

the splenic white pulp of these animals contains dispersed FDCs or immature FDC precursors without detectable surface CR1 or immune complex binding activity. Nevertheless, it is clear that the somatic mutation process can occur without the presence of clusters of mature FDCs. The fact that the defect in isotype switching and somatic mutation observed in $LT\alpha$ -deficient mice can be overcome by providing the antigen at high doses together with an adjuvant such as alum (7) or Freund's adjuvant (9) suggests that the physical form and perhaps the density of the antigenic epitopes determines the ability to respond in the absence of a proper follicle structure. This is consistent with the role of the natural follicle organization to facilitate focusing of antigen in the environment of the responding B and T lymphocytes.

VI. Analysis of a natural mutant strain resembling $LT\alpha$ -deficient mice

In addition to the gene-targeted mice described above, alymphoplasia (aly) mice, an autosomal recessive natural mutant strain, have provided a novel and unique model for the abnormal development of lymphoid organs (43). Like $LT\alpha$ -deficient mice, aly mice lack LN and PPs, and the spleen architecture such as the development of GCs and FDC clusters as well as marginal zone formation is disturbed (44, 45). aly mice manifest additional immunodeficiencies including a disorganized thymic architecture, low serum immunoglobulin (Ig) level and impaired allogeneic skin rejection, which are not observed in $LT\alpha$ -deficient mice (4, 5, 43). A gene responsible for this mutant strain has just been identified as NF- κ B inducing kinase (NIK) (46) by positional cloning (47, 48), but little is known about how the NIK contributes to the lymphoid organogenesis.

Our studies were undertaken to clarify the mechanisms underlying the defective lymphoid organogenesis in both aly mice and $LT\alpha$ -deficient mice. Two issues were specifically addressed. First, although dominant roles of $LT\beta$ R as well as supportive roles of TNFR-I in the development of secondary lymphoid organs have been demonstrated as already described, exactly how LT control the development of lymphoid organs through these receptors was largely unknown. Second, we had no clue as to the role of the aly gene product (i.e. NIK) in the lymphoid organ development. Consequently, we have generated aggregation chimeras; *ex vivo* fused

morulae were implanted into pseudo-pregnant host females and allowed to develop to term (49). Chimeric analyses demonstrated that $LT\alpha$ and NIK control lymphoid organogenesis by governing distinct cellular compartments; $LT\alpha$, expressed by the BM-derived cells, is essential not only for the organization of spleen architecture but also for lymphoid organogenesis. By contrast, the aly gene product NIK from BM-derived cells, if expressed, has no major role in the development of secondary lymphoid organs. Rather, the lack of LN and PPs in aly mice may be caused by a defect of non-BM-derived cells, possibly through a defective development of the incipient stromal cells of the LN and PP (50). Strategies undertaken to clarify these findings are as follows.

1. Complementation of abnormal LN genesis in aly mice with LT -deficient mice

Although there is some phenotypic difference between $LT\alpha$ -deficient mice and aly mice, these two strains possess an extremely similar phenotype; lack of LN and PPs, and a disorganized spleen architecture. It was still possible that the altered function of NIK perturbs the expression of the membrane form of LT to cause the $LT\alpha$ -deficient phenotype in aly mice. We therefore first examined the expression of the membrane form using $LT\beta R$ -Ig which binds to membrane-associated $LT\alpha 1LT\beta 2$. $LT\beta R$ -Ig bound to activated aly spleen cells, demonstrating that expression of the membrane form of LT is retained in aly mice with this *in vitro* system.

If the membrane form of LT is present and functional per se in aly mice, as suggested by the *in vitro* studies, cells from aly mice should reverse the phenotype of $LT\alpha$ -deficient mice, and this was the case; a chimeric mouse from $LT\alpha$ -deficient mice and aly mice was generated, in which cells from both strains co-exist and interact with each other throughout development. Upon detailed inspection, mesenteric LN and one lumbar LN were observed in this chimera. Thus, lack of LN genesis in aly mice could not be attributed to the lack of functional membrane-associated LT.

2. A novel approach to define the mechanisms underlying the defective lymphoid organogenesis in LT -deficient mice and aly mice

1) Defective lymphoid organ development in $LT\alpha$ -deficient mice is almost completely restored by the generation of chimeras with normal animals

Lack of FDC clusters as well as the defective GC

formation in the spleen from $LT\alpha$ -deficient mice were restored by the transfer of wild-type BM cells, indicating that the $LT\alpha$ -expressing cells required to establish these lymphoid structures are derived from BM (6, 39). In contrast to in the spleen architecture, the development of LN and PP was not restored in the same animals (51). Given that the lack of LN and PP in $LT\alpha$ -deficient mice is developmentally fixed, we speculated that $LT\alpha$ -expressing cells required to generate LN and PP are also BM-derived. This hypothesis, however, has not been formally tested, since BM cells were transferred only into the adult mice in these experiments. We have approached this issue by generating aggregation chimeras from $LT\alpha$ -deficient mouse morulae and $LT\alpha$ -sufficient mouse morulae; both $LT\alpha$ -deficient BM-derived cells and $LT\alpha$ -sufficient BM-derived cells are expected to circulate in the body and to interact with the incipient stromal cells of the lymphoid organs throughout the development. We used GFP-Tg as wild-type mice in order to monitor the chimeric contribution from each strain by the detection of GFP (52). In particular, detection of GFP from the thymocytes and/or splenocytes by flow cytometry enabled us to focus on the chimerism of BM-derived cells which are the major source of membrane-associated LT.

Upon detailed inspection, all 10 chimeric mice generated showed lymphoid organ development indistinguishable from that seen in wild-type mice. Percentages of the $LT\alpha$ -expressing cells evaluated by the detection of GFP from thymocytes and splenocytes varied among the chimeras (ranging from 8 to 66%), and this variation did not apparently affect the extent of restoration of lymphoid organogenesis in this range. Development of LN and PP occurred irrespective of the status of GFP expression from the body as long as $LT\alpha$ -expressing cells exist in the spleen and thymus. As expected, spleen architecture was also restored in these mice; organized FDC clusters as well as GCs were present in the spleens from all chimeric mice. Thus, $LT\alpha$ -expressing BM-derived cells, if present throughout the development, could restore the lymphoid organogenesis in $LT\alpha$ -deficient mice, supporting the idea that $LT\alpha$ -dependent interactions must occur during development in order for LN and PP to develop.

2) Defective lymphoid organ development in aly mice is only partially restored by the generation of chimeras with normal animals

To investigate how NIK contributes to the lymphoid organogenesis, chimeric mice from aly mice and GFP-Tg were also generated and evaluated for the restoration of lymphoid organ development.

Out of 11 chimeras generated, two showed no inguinal LN and one had only right inguinal LN. Although 4 mice had more than four PPs, 7 mice had either less than three or none at all. Furthermore, one mouse which lacked inguinal LN and PPs had only one small mesenteric LN. It is particularly important to note that there were many spleen cells derived from GFP-Tg even in the chimeric animals defective in the development of LN and/or PPs. Because BM-derived cells from GFP-Tg should have the normal NIK, if expressed, a lack of LN and/or PP in these chimeras would be independent of the presence of NIK on the BM-derived cells. This limited restoration of lymphoid organ development sharply contrasted to that seen in the chimeras of LT α -deficient mice and GFP-Tg in which relatively small numbers of LT α -expressing cells were sufficient to restore the lymphoid organogenesis, as illustrated in Fig. 2.

Despite the partial restoration of LN and PP development in these chimeras, histological evaluation showed spleen architecture indistinguishable from that seen in wild-type mice ; GC and FDC formation

were apparently normal in all 11 chimeras some of which showed abnormal LN and/or PP development. These results demonstrated that an organized spleen architecture can be formed independent of the defective development of LN and/or PP.

3. Possible involvement of LT R signaling in the abnormal lymphoid organ development in aly mice

The similar phenotypes of the LT α -deficient and aly mouse strains suggested that there might be a close mechanistic relationship in their affected biochemical pathways. The results described above, however, showed no detectable alteration in the expression of the membrane-associated LT ligand in aly mice. We therefore examined downstream elements of the pathway at the level of LT β R signaling using embryonic fibroblast (EF) isolated either from aly mice or from C57BL/6 wild-type mice. We found that the up-regulation of VCAM-1 after stimulation either with agonistic anti-LT β R monoclonal antibody or with recombinant LT α 1LT β 2 was defective in aly EF suggesting that signaling through LT β R is impaired in aly mice. Taken together, we concluded that LT α and NIK together control lymphoid organogenesis, governing distinct cellular compartments but with a close mechanistic relationship in their biochemical pathways, ligand-binding and receptor-signaling.

Because LT β R is exclusively expressed by non-lymphoid cells (20, 21), a defect in LT β R signaling in aly mice is consistent with the idea that the lack of lymphoid organogenesis in this strain is caused by the defect of non-BM-derived cells as demonstrated by the chimeric analysis.

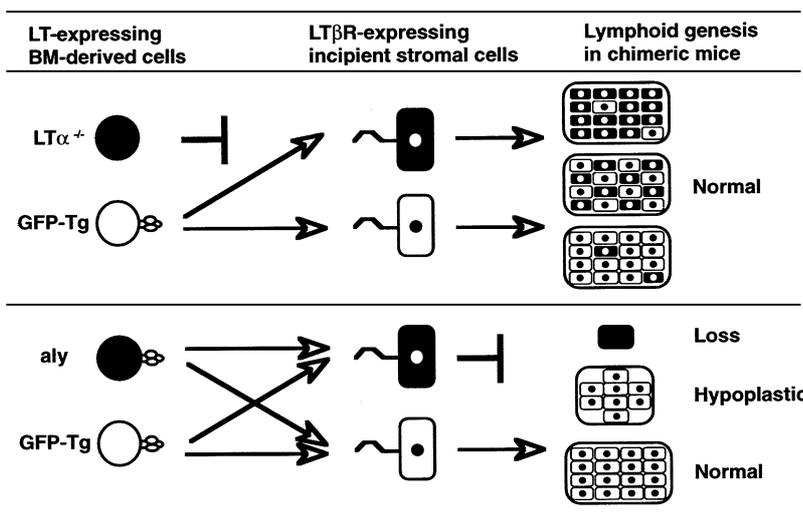


Fig. 2. Presumed mechanisms underlying the defective lymphoid organogenesis in LT α -deficient mice and aly mice revealed by the chimeric analysis. Chimeric mice of LT α -deficient mice and GFP-transgenic mice (GFP-Tg) had restored LN and PPs, because incipient stromal cells derived from both LT α -deficient mice and GFP-Tg can respond to LT provided by the cells from GFP-Tg. By contrast, the development of LN and PP in chimeric mice of aly mice and GFP-Tg showed a different outcome depending on the chimerism of the LT β R-expressing incipient stromal cells ; cells from aly mice cannot contribute to the lymphoid organogenesis because of the defect of LT-LT β R signaling. LT-expressing BM-derived cells and LT β R-expressing incipient stromal cells from GFP-Tg are shown in white, whereas cells from LT α -deficient mice or aly mice are shown in black.

CONCLUDING REMARKS

The various studies described in this review have established that both LT and TNF provide essential signals for the development of a proper peripheral lymphoid organ structure. Together with experiments demonstrating essential roles for CD40 and its ligand (53, 54) and for OX40 and its ligand (55) in the development of a mature antibody response, these studies demonstrate critical roles for multi-

ple members of the TNF ligand and receptor family in controlling organized T cell-dependent B cell responses. LT appears to be important both during ontogeny to establish the architecture within which immunocytes interact and later to maintain the full cellular constituency of the lymphoid follicles. TNF and TNFR-I appear to act in the establishment of clusters of FDCs within the follicles of the splenic white pulp (6, 34, 39, 40). Signals through CD40 and OX40 participate in the direct interactions between T and B cells during the antigen-driven portion of the immune response. Thus, this family of cytokines acts at multiple levels of lymphoid organ morphogenesis and responsiveness. Other components of the signaling pathway undoubtedly remain to be defined.

Identification of essential signaling molecules that act to establish a proper peripheral lymphoid tissue structure provides important information that will ultimately lead to the identification of the specific cell types that must interact for the initial establishment of this structure. It is now important to define the developmental expression patterns of the different members of the TNF ligand and receptor family during ontogeny of the immune system. Once the essential regulatory cells have been identified, then it may become feasible to develop new strategies to interfere with immune responses by changing the lymphoid organ tissue structure.

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