On the Key Role of Secondary Lymphoid Organs in Antiviral Immune Responses Studied in Alymphoplastic (aly/aly) and Spleenless (Hox11−/−) Mutant Mice

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Summary

The role of the spleen and of other organized secondary lymphoid organs for the induction of protective antiviral immune responses was evaluated in orphan homeobox gene 11 knockout mice (Hox11−/−) lacking the spleen, and in homozygous alymphoplastic mutant mice (aly/aly) possessing a structurally altered spleen but lacking lymph nodes and Peyer’s patches. Absence of the spleen had no major effects on the immune response, other than delaying the antibody response by 1–2 d. In aly/aly mice, the thymus-independent IgM response against vesicular stomatitis virus (VSV) was delayed and reduced, whereas the T-dependent switch to the protective IgG was absent. Therefore, aly/aly mice were highly susceptible to VSV infection. Since aly/aly spleen cells yielded neutralizing IgM and IgG after adoptive transfer into recipients with normally structured secondary lymphoid organs, these data suggest that the structural defect was mainly responsible for inefficient T–B cooperation. Although aly/aly mice generated detectable, but reduced, CTL responses after infection with vaccinia virus (VV) and lymphocytic choriomeningitis virus (LCMV), the elimination of these viruses was either delayed (VV) or virtually impossible (LCMV); irrespective of the dose or the route of infection, aly/aly mice developed life-long LCMV persistence. These results document the critical role of organized secondary lymphoid organs in the induction of naive T and B cells. These structures also provide the basis for cooperative interactions between antigen-presenting cells, T cells, and B cells, which are a prerequisite for recovery from primary virus infections via skin or via blood.

The immune system is functionally compartmentalized into primary lymphoid organs responsible for the generation and differentiation of mature naive T and B cells and into secondary lymphoid organs where immune responses are initiated. Only after activation do T and B cells emigrate from secondary lymphoid organs to seek antigen in the periphery (1–3). Secondary lymphoid organs include the spleen, LN, and organized lymphoid tissues associated with mucosal membranes such as the tonsils, the appendix, and the Peyer’s patches (PP). These highly organized secondary lymphoid organs provide the structures where antigen is efficiently retained and presented and where ordered cellular interactions between APCs, T cells, and B cells take place to initiate and promote efficient immune responses (1). Although it has been postulated that T or B cells get anergized during possible initial peripheral encounter with antigen (4, 5), there is good experimental evidence indicating that antigen encounter by naive T cells does not occur, in general, outside of organized lymphoid tissues and does not lead to activation (1–3, 6–9).

Classical experiments using isolated skin flaps connected to the host via blood vessels with or without afferent lyn-
phatic vessels showed that antigen to the skin flap induced a specific immune response only when both the afferent lymphatic vessel and the draining LN were intact (7, 10). These studies document, in our modern understanding, that emigrating APCs, in particular, dendritic cells (DC) reaching local LN, are essential for the induction of a specific immune response (11).

The role of the spleen in immune responses has been studied in splenectomized patients and mice. The function of the spleen is mainly to filter particulate and soluble antigens from the blood (1, 12). Absence of the spleen caused an increased susceptibility to generalized infections with encapsulated bacteria (13–15) because the thymus independent type 2 (TI-2) Ab response to polysaccharide components of bacterial cell walls was markedly reduced (16–18).

Recently, two mouse strains with interesting changes of secondary lymphoid organs have been developed or discovered. First, a mutant mouse lacking a functional form of the orphan homeobox gene 11 (Hox11) has been generated by gene targeting. Hox11−/− knockout mice (Hox11−/−) lack the spleen, but otherwise appear normal. In particular, no defects in other secondary lymphoid organs, in the thymus, or the bone marrow have been detected (19). Second, a mouse strain with a spontaneous autosomal recessive single gene mutation, termed lymphoplasia (aly) has been described. The homozygous aly/aly mutant mice lack all secondary lymphoid organs (especially LN and PP) except the thymus, which, however, exhibited a disturbed structure. The bone marrow appeared to be normal, whereas the morphological distinction between thymic cortex and medulla was unclear (20, 21). These mutant mice that lack either the spleen but not other secondary lymphoid organs, or lack LN, PP etc. but not the spleen, now offer a new and unique possibility to assess the role of these secondary lymphoid organs in the induction and maintenance of immune responses, particularly against viral infections.

Our study revealed that absence of the spleen had only minimal effects on antiviral immune responses, whereas absence of LN and other organized secondary lymphoid tissues caused a drastic change in the kinetics of virus replication and dissemination relative to the kinetics of the protective immune response, particularly against the noncytopathic lymphocytic choriomeningitis virus (LCMV). Lack of LN led to overwhelming viral spread in vivo and, as a consequence, to specific T cell exhaustion and virus persistence.

Materials and Methods

Mice and Animal Experiments. aly/aly mutant mice lacking LN and PP were purchased from CLEA Inc. (Tokyo, Japan) and bred locally under specific pathogen-free conditions by mating heterozygous (aly+/+) females and homozygous (aly/aly) males. aly/aly mutant mice were distinguished from aly+/+ littermates by a virtual absence of IgA in their sera measured with an anti-IgA ELISA as described (20). Heterozygous littermates, which are known to be fully immunocompetent (20), or C57BL/6 (B6) mice and/or 129Sv(ev) were used as controls. In all experiments presented in this study, no significant differences between these different mouse strains used as normal controls were detected; therefore, data from one control strain (usually B6) are presented. Hox11−/− mice were generated by gene targeting on a 129Sv background and bred locally under specific pathogen-free conditions. Both mutant mice have been described in detail (19, 20). B6 and 129Sv were purchased from the breeding colony of the Institut für Laborrziertechnik (University of Zürich, Zürich, Switzerland). All animal experiments were performed with age- and sex-matched mice of 8–12 wk of age with permission of the veterinary office according to cantonal and federal law requiring the use of minimal numbers of animals.

Viruses. The LCMV isolate WE (LCMV-WE) was originally provided by Dr. F. Lehmann-Grube (Heinrich Herre Institute, Hamburg, Germany) and the LCMV isolate Armstrong (LCMV-Arm) by Dr. M.B.A. Oldstone (Scripps Clinic, La Jolla, CA). LCMV-WE was grown on L929 cells and LCMV-Arm on BHK-21 cells with a low multiplicity of infection (MOI). Vesicular stomatitis virus, serotype Indiana (VSV IND; Mudd-Summers isolate), originally obtained from Dr. D. Kolakofsky (University of Geneva, Geneva, Switzerland) was grown on BHK-21 cells infected at low multiplicity and plaqueed on Vero cells (22). Vaccinia virus (VV, strain Lancy) was obtained from the Schweizerisches Serum und Impfinstitut (Bern, Switzerland). VV (strain WR) and recombinant VV expressing the glycoprotein of VSV IND (VaccIND) were generous gifts of Dr. B. Moss (Laboratory of Viral Diseases, National Institute of Health, Bethesda, MD). (23). These viruses were both grown at a low MOI and plaqueed on BSC 40 cells. The recombinant baculovirus expressing the glycoprotein of VSV IND (IND-G) was a gift of Dr. D.H.L. Bishop (Institute of Virology, Oxford, U.K.). The recombinant baculovirus was derived from nuclear polyhedrosis virus and was grown at 28°C in Spodoptera frugiperda cells in spinner cultures using TC-100 medium. Recombinant protein was produced as described (23).

Virus Titration. LCMV titers of blood, centrifuged tissue homogenates, and virus stock solutions were determined with an immunological focus assay as described (24). VV was quantified by growing dilutions of tissue homogenates for 24–36 h on confluent monolayers of BSC 40 cells. Plaques were visualized by staining with crystal violet. All virus titers were expressed as log10 (PFU of virus per organ or per gram organ) or as log10 (PFU of virus per milliliter blood). The detection limits of the assays are indicated in the figures.

Statistical comparisons were made using the two-tailed unpaired Student’s t test. A P value of <0.01 was regarded as significant.

Immunohistochemistry. Freshly removed organs were immersed in Hank’s balanced salt solution and snap frozen in liquid nitrogen. Tissue sections of 5-μm thickness were cut in a cryostat, placed on siliconized glass slides, air dried, fixed with acetone for 10 min, and stored at −70°C. Secondary affinity-purified polyclonal anti-Ig antisera were diluted in Tris-buffered saline (TBS; pH 7.4) containing 5% normal mouse serum. All other dilutions were made in TBS alone. Incubations were done at room temperature for 30 min; TBS was used for all washing steps. Alkaline phosphatase was visualized using naphthol AS–BI phosphate and new fuchs in as substrate. Endogenous alkaline phosphatase was blocked by levamisole. All color reactions were performed at room temperature for 15 min with reagents from Sigma Chemical Co. (St. Louis, MO). Sections were counterstained with hemalum. Coverslips were mounted with glycerol and gelatin.

For staining for LCMV and cell differentiation markers, rehydrated tissue sections were incubated with the following rat pri-
ary mAbs: anti–MHC class I (anti–H-2K<sup>bd</sup>; M1/42; TIB-126; American Type Culture Collection, Rockville, MD), anti–MHC class II (anti-I<sup>A</sup>b4; M5/114; TIB-120; American Type Culture Collection), anti-CD4 (YTS 191; reference 25), anti-CD8 (YTS 169; reference 25), anti-CD45R/B220 (RA3-6B2; Pharmingen, San Diego, CA), anti–LCMV (VL-4; reference 26), anti–red pulp macrophages (RPM; F4/80; HB-198; American Type Culture Collection), anti–marginal metallophil cells (MM; MOMA-1; Biomedicals, Augst, Switzerland), anti–marginal zone macrophages (MZM; ERTR-9; reference 27), anti–follicular dendritic cells (FDC; 4C11; reference 28), anti–mucosal addressin cell adhesion molecule 1 (MAdCAM-1; MECA-367; Pharmingen), anti–interdigitating dendritic cells (IDC; NLDC-145; Biomedicals). Primary rat mAb were revealed by a twofold sequential incubation with rabbit anti–rat Ig and rat alkaline phosphatase anti–alkaline phosphatase complex (DAKO, Glostrup, Denmark). CD11c on dendritic cells was stained with the hamster mAb N418 (HB-224; American Type Culture Collection). Primary hamster Ig were detected by alkaline phosphatase–labeled rabbit anti–hamster Ig followed by alkaline phosphatase labeled goat anti–rabbit Ig. Germinal centers (GC) were stained with peanut agglutinin (12). To stain for Ig, sections were incubated with biotinylated monoclonal rat anti–mouse IgM (R6-60.2) or rat anti–mouse IgD (217-170) (Pharmingen), followed by alkaline phosphatase–labeled avidin–biotin complexes (DAKO).

**Detection of Virus-specific Cytotoxic T Cells In Vitro.** CTL activity of spleen or LN cells was determined by a 51Cr-release assay as described previously (29). In brief, mice were infected with VV, VSV, or LCMV at the indicated doses. 6 d (VV, VSV) or 8 d (LCMV) later, spleen or LN cells were suspended at 9 × 10<sup>6</sup> cells in 2 ml of IMDM supplemented with 2% FCS. MC57G (H-2<sup>b</sup>) or rat anti–mouse IgD (R6-60.2) or rat anti–mouse IgD (217-170) (Pharmingen), followed by alkaline phosphatase–labeled avidin–biotin complexes (DAKO).

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**Flow Cytometry.** 50 μl of blood was prepared in PBS containing 2% FCS, 0.2% NaN<sub>3</sub>, and 10 mmol EDTA. Cell surface markers were quantified by staining with mAb conjugated with fluorochromes. The following Abs were used: anti–CD4 PE (clone H129,19), anti–CD8 FITC (clone 53-6.7) from Gibco BRL (Uxbridge, U.K.), anti–CD45R/B220 PE (clone RA3-6B2) from Sigma Chemical Co. Multiparameter analysis was performed with a FACSscan® using logarithmic scales. Viable cells were gated by forward and side scatter of light.

**Results**

**Immunohistochemistry of aly/aly and aly/+ Spleen**

The histological structures of the spleen of unimmunized aly/aly mice and of heterozygous littermates were evaluated with different mAb by immunohistochemistry (Fig. 1). The absence of the distinct follicular structure of the white pulp with an ill-defined boundary between white and red pulp was obvious at low magnifications. This is clearly demonstrated by the stainings for B cells (B220, IgM, IgD) and for certain macrophage populations such as RPM, MM, or MZM.

The T cell areas stained with anti–CD4 or anti–CD8 mAbs seemed to be largely intact in the spleen of aly/aly mice and of heterozygous littermates. In contrast, numbers of B cells were about threefold reduced in spleen and peripheral blood (FACS® analyses not shown). In addition, the expression of class I and II MHC molecules did not markedly differ. IDC and DC seemed to be present in aly/aly mice in numbers and distribution that were comparable to that of their heterozygous littermates. In contrast, numbers of B cells were about threefold reduced in spleen and peripheral blood (FACS® analyses not shown) of aly/aly mice, and no primary or secondary follicles or GC were detectable in the
Lymphoid Organ Defects Lead to Impaired Antiviral Immune Responses
1°CTL ex vivo

aly/aly
Hox11+/−

aly/aly
Hox11+/−

aly/aly
Hox11+/−

B6

B6

Spleen

LN

A

1° CTL ex vivo

aly/aly
Hox11+/−

aly/aly
Hox11+/−

aly/aly
Hox11+/−

B6

B6

Spleen

LN

B

2° CTL after in vitro restimulation

aly/aly
Hox11+/−

aly/aly
Hox11+/−

aly/aly
Hox11+/−

B6

B6

Spleen

LN

C

Footpad swelling in aly/aly and Hox11+/− mice

aly/aly
Hox11+/−

aly/aly
Hox11+/−

aly/aly
Hox11+/−

B6

B6

Spleen

LN

D

LCMV-specific CTL Activity and Footpad Swelling Reaction in aly/aly and Hox11+/− Mice

Figure 2. CTL response, footpad swelling reaction, and blood virus titer after LCMV infection of aly/aly and Hox11+/− mice. Mice were immunized with 200 PFU LCMV-WE intravenously (A, left, B and D), LCMV-Arm intravenously (A, right), or 100 PFU LCMV-WE into both hind footpads (i.pl., A, middle, and C). After 8 d, spleens were removed and single cell suspensions were tested directly ex vivo in a conventional 51Cr-release assay (primary [1°] CTL ex vivo) with LCMV-infected (open symbols) or untreated (closed symbols) MC57G as target cells. △, aly/aly spleen cells; ○, Hox11+/− LN cells; □, spleen cells of control B6 mice; ●, LN cells of control B6. Each line represents an individual mouse with the exception of the B6 mice in A, middle and right (squares and circles) representing the mean of three mice. (B) Spleens were removed at the indicated time points after infection with 200 PFU LCMV-WE intravenously and restimulated in vitro for 5 d (secondary [2°] CTL after in vitro restimulation) with irradiated LCMV-infected spleen cells. Cultures were then tested on LCMV-infected (open symbols) or untreated (closed symbols) MC57G cells radioactively labeled with 51Cr. △, aly/aly mice; ○, Hox11+/− mice; □, aly/+ control mice. Each line represents one individual mouse. (C) Mice were infected with 100 PFU LCMV-WE into both hind footpads. The footpad thickness was measured daily with a spring-loaded caliper. △, aly/aly mice; ○, Hox11+/− mice; □, B6 controls. Each line represents the mean of both hind footpads of three mice. Error bars indicate the SD within the experimental group. Results of one (out of three) similar experiments are shown. (D) Mice were infected with 200 PFU LCMV-WE intravenously. Blood was taken at the indicated time points and virus titers were determined as described (24). LCMV titers are given as log10 (virus titer/ml blood). △, aly/aly mice; ○, Hox11+/− mice; □, control B6 mice. Each line represents one mouse. Data of 4 mice/group are shown. The detection limit of the assay is indicated (det. lim.). One out of two similar experiments is shown.

Figure 1. Immunohistochemical analysis of aly/aly and aly/+ spleens. Spleen sections of unimmunized (exception: LCMV staining) aly/aly and aly/+ mice were stained with Abs of the indicated specificity. MM, MOMA-1; MZM, ERTR-9; MAdCAM-1 on endothelial cells of the marginal sinus, MECAM-367; RPM, F4/80; FDC, 4C11; GC, PNA; IgM, surface IgM+ B cells, R6-60.2; IgD, surface IgD+ B cells, 217-170; B220, CD45R+ B cells, RA3-6B2; CD4, CD4+ T cells, YTS-191; CD8, CD8+ T cells, YTS-169; MHC I, H-2Kd, M1/42; MHC II, B2m on macrophages, DC, and B cells, M5/114; IDC, NLDC-145; DC, CD11c on dendritic cells N418; LCMV*, LCMV-infected cells 8 d after infection with 200 PFU LCMV-WE intravenously, VL-4. Original magnification: 100-fold for all panels.

Karrer et al.
Table 1. LCMV Titers of aly/aly and aly/+ Mice Early after Infection with 10⁴ PFU LCMV-WE Intravenously

| Time after infection | Spleen      | Liver        | Lung         |
|----------------------|-------------|--------------|--------------|
|                      | aly/aly     | aly/+        | aly/aly      | aly/+        |
| 12                   | <DL‡        | 3.7 ± 0.6*   | 3.2 ± 0.2    | 3.3 ± 0.5    |
| 24                   | 3.7 ± 0.7*  | 6.6 ± 0.1*   | 3.5 ± 0.4    | 3.9 ± 0.4    |
| 48                   | 6.0 ± 0.3*  | 7.8 ± 0.2*   | 4.3 ± 0.3    | 3.4 ± 0.7    |
| 96                   | 6.6 ± 0.1   | 6.4 ± 0.1    | 5.4 ± 0.3*   | 4.6 ± 0.3*   |

Mice were infected with 10⁴ PFU LCMV-WE intravenously. At the indicated time points after infection mice were killed and virus titers were determined in different organs. Values are given as log₁₀(PFU LCMV/g organ) ± SD of 3–4 mice/experimental group.

* P < 0.01, significant difference of LCMV titers between aly/aly and aly/+ mice (Student’s t test).
‡ DL, detection limit of the assay (spleen, 2.0; liver, 3.0; lung, 2.5).

Representative data of one out of three comparable experiments are shown.

To assess the in vivo consequences of the in vitro–measured CTL activities, the CD8⁺ T cell–dependent immunopathological footpad swelling reaction was measured daily after local infection with 100 PFU LCMV-WE into both hind footpads (Fig. 2 C). Control and Hox11⁻/⁻ mice exhibited a similar CD8⁺ T cell–mediated swelling reaction from day 6 until day 10. The swelling reaction was prolonged in Hox11⁻/⁻ mice, possibly reflecting a more pronounced CD4⁺ T cell response (31). In contrast, aly/aly mice showed no footpad swelling reaction. After intracerebral (i.c.) infection with 3, 30, or 300 PFU of the neurotropic LCMV-Arm, aly/aly mice did not succumb to the usually observed lethal immunopathological choriomeningitis mediated by CD8⁺ CTLs; nine of nine aly/aly mice (three mice per virus dose) survived for >30 d without clearance of the virus, whereas nine of nine control B6 and six of six Hox11⁻/⁻ mice died between 7–9 d after infection.

To evaluate the kinetics of virus clearance in vivo, the elimination of LCMV after peripheral infection was monitored. As shown in Fig. 2 D, aly/aly mutant mice were not able to clear the virus from their blood or any other organ tested (spleen, see Fig. 1, LCMV staining). Virus persisted for life after infection with any of the tested doses (3–10,000 PFU) or routes of infection (intravenous, intraperitoneal, intracerebral, or subcutaneous) of both LCMV strains (WE or Arm) used in this study. It has been shown that >10⁶ PFU of intravenous LCMV-WE are needed to provoke CTL exhaustion and virus persistence in adult immunocompetent B6 mice (36). Thus, aly/aly mice were at least 10⁸-fold more susceptible to become LCMV carriers than normal B6 mice. In contrast to aly/aly mutant mice, blood virus titers of control and Hox11⁻/⁻ mice reached barely detectable levels (Fig. 2 D); the latter mice cleared LCMV from the tested organs at the latest by day 15 (not shown).

Careful analysis of LCMV titers in different organs of aly/aly and aly/+ mice during the first 4 d after intravenous infection revealed that virus titers of the spleen were ~100 times lower in aly/aly mice, 12, 24, and 48 h after infection, whereas in peripheral solid organs (liver and lung) the titers were generally higher (Table 1). This suggests that LCMV particles were less efficiently removed from the blood by the spleen of aly/aly mice. Therefore, probably more infectious viral particles reached peripheral solid organs.

To test whether only the induction of LCMV-specific CTL responses was less efficient or whether effector functions of primed CD8⁺ T cells were affected by the structural defect of aly/aly mice also, the following adoptive transfer experiments were performed. Naive aly/aly or aly/+ recipient mice were infected with 2 × 10⁵ LCMV-WE intravenous into the footpads. 3 h later, 5 × 10⁷ spleen cells of either naive or day-8 LCMV–primed B6 mice (200 PFU LCMV-WE intravenous) were adoptively transferred. Thereafter, the immunopathological footpad swelling reaction was monitored. aly/aly and aly/+ recipients of LCMV–primed spleen cells showed a similar early swelling peak already 18–24 h after transfer, reflecting the local LCMV-specific effector phase of the transferred LCMV–primed cells. In contrast, recipients of naive spleen cells showed no early swelling reaction. The usual primary footpad swelling reaction peaking around day 8 after LCMV infection was only detectable in aly/+ recipients of naive spleen cells (Fig. 3 A). aly/aly recipients of naive B6 spleen cells did not mount a detectable swelling reaction. On day 9 after infection, LCMV titers in different organs and the CTL response of 5 d in vitro restimulated splenocytes was measured. aly/+ recipients of naive and primed spleen cells showed a potent CTL response and complete clearance of the virus from the tested organs. In contrast, aly/aly recipients exhibited clear differences in virus titers and CTL activity dependent upon whether the transferred cells were primed or naive. Viral titers were about 100 times lower and the CTL activity 10–30-fold higher in the aly/aly recipients of primed spleen cells, demonstrating that the effector function of the transferred primed T cells was unimpaired in aly/aly mice. (Fig. 3, B and C).
VV-specific CTL Responses and Virus Elimination Kinetics of aly/aly and Hox11−/− Mice

To test the CTL response of these mutant mice against a cytopathic virus, mice were immunized with 2 × 10⁶ PFU vaccinia virus (VV) strain WR or Lancy. 6 d later, spleens and/or LN were removed and tested directly in a VV-specific ⁵¹Cr-release assay with VV-infected MC57G fibroblasts as target cells. LN cells of Hox11−/− mice exhibited comparable CTL activity to LN cells of B6 and 129Sv controls (Fig. 4 A).

The VV-WR–specific CTL response of aly/aly mice was only ∼5–10-fold reduced compared to control B6 mice (Fig. 4 B). If mice were infected with VV–Lancy, an attenuated VV strain that does not measurably replicate in immunocompetent mice (37), the CTL response was reduced by at least a factor of 30 (Fig. 4 C). The elimination of VV-WR from the tested organs was clearly delayed in aly/aly mice compared to Hox11−/− or control B6 mice (Fig. 4, D and E).

Immune Responses against VSV

VV-specific CTL Response. The dispensable but usually induced VSV-specific primary CTL response on day 6 after immunization with 2 × 10⁶ live VSV IND of Hox11−/− and control B6 mice was comparable (Fig. 5 A). No primary ex vivo CTL activity could be detected in aly/aly mice (Fig. 5 B). Upon in vitro restimulation for 5 d with VSV-infected, irradiated spleen cells, VSV-specific CTLs were also detectable in aly/aly mice, but still 10–30-fold reduced compared to B6 mice (Fig. 5 C).

V SV-specific Neutralizing Ab Response. The VSV-neutralizing Ab response of aly/aly, Hox11−/−, and control mice was assessed using different antigenic preparations derived from VSV IND, e.g., live and UV-inactivated VSV IND particles, a recombinant VV expressing the glycopro-
Effect of Reciprocal Adoptive Transfer of Naive Spleen Cells Between aly/aly and Control Mice on the Neutralizing IgM Response after Immunization with VSV IND or VaccINDG

The role of secondary lymphoid organs in TI-1 B cell responses was further assessed in mice lacking all secondary lymphoid organs, i.e., splenectomized aly/aly mice. aly/aly and control aly/+ mice were splenectomized or sham operated and 3 wk later they were immunized with 2 × 10⁶ PFU live VSV IND intravenously. The IgM response was completely absent in three out of four splenectomized aly/aly mice. Only one mouse still produced a low neutralizing IgM titer on day 8, whereas the IgM response of sham operated aly/aly mice was similar to untreated ones. All aly/aly mice, splenectomized or not, died from VSV-induced encephalitis within 9 d. The IgM response of splenectomized aly/+ (or 129Sv, not shown) controls was very similar to the response of Hox11⁺⁻/⁻ mice showing a delay after intravenous immunization compared to sham-operated control mice (Fig. 7 A).

To further analyze whether the IgM response to the TI B cell Ag VaccINDG or VSV IND was still independent of T help in these mutant mice, aly/aly, Hox11⁻⁻/⁻, and B6 control mice were depleted of CD4⁺ T cells before immunization. The neutralizing IgM response after immunization with the TI-2 Ag VaccINDG was T help dependent in aly/aly mice, but it was largely T help independent in Hox11⁻⁻/⁻ and in B6 controls (Fig. 7 B). This indicates that a low level of cooperation between T and B cells still occurs in aly/aly mice, which is sufficient to support the IgM response to VaccINDG, but not sufficient to induce the switch to IgG. As expected, aly/aly, Hox11⁻⁻/⁻, and B6 control mice treated identically with anti-CD4 and immunized with the TI-1 Ag live VSV IND generated a T help independent IgM response (data not shown).

Effect of Reciprocal Adoptive Transfer of Naive Spleen Cells Between aly/aly and Control Mice on the VSV-specific Ab Response

To evaluate in vivo whether the defect of cognate interaction between B and T cells in aly/aly mice seen in the previous experiments is mainly due to a cellular defect of the B or T cell compartment, or of both together, or is due to the structural defect of secondary lymphoid organs in aly/aly mice, reciprocal adoptive transfer experiments between aly/aly and control mice were performed (Fig. 8).
On day −2 recipients were irradiated with 5.0 gray, on
day −1 indicated numbers of spleen cells were transferred,
and on day 0 mice were immunized with $2 \times 10^6$ PFU live
VSV IND or VaccIND$_G$. $10^8$ aly/aly spleen cells or a ti-
trated number of aly/+ spleen cells ($10^9, 3 \times 10^7$, or $10^7$)
were transferred into irradiated B6 recipients (Fig. 8 A). Ir-
radiated B6 recipients without adoptive cell transfer did not
respond to both immunization protocols, demonstrating
the effectiveness of the irradiation. After transfer of graded
numbers of aly/+ spleen cells, the recipients responded with
correspondingly graded neutralizing Ab responses; the mice
receiving the highest cell number responded the best. Re-
cipients of $10^8$ aly/aly spleen cells exhibited a neutralizing
IgM and IgG response against VSV IND and VaccIND$_G$
that was comparable to that of recipients transfused with
$10^7 - 3 \times 10^7$ aly/+ spleen cells. This result indicates that
aly/aly spleen cells exhibit the capacity to respond to thy-
mus-dependent and -independent Ag after transfer into a
recipient with an intact structure of secondary lymphoid
organs. After compensation for the threefold reduced num-er of B cells (FACS® analysis not shown), the response
was almost comparable to recipients of aly/+ spleen cells.

A second adoptive transfer experiment evaluated whether
naive spleen cells of B6 mice adoptively transferred into ir-
radiated aly/aly or aly/+ recipients were able to respond to
immunization with VaccIND$_G$ (Fig. 8 B). The transfer of

Figure 6. VSV-neutralizing IgM and IgG responses. Mice were immunized with $2 \times 10^6$ PFU live VSV IND intravenously (A), $2 \times 10^6$ PFU Vacc-
IND$_G$ intravenously (B), or with $10 \mu g$ IND-G in balanced salt solution intravenously (C), or emulsified in IFA and injected subcutaneously at the base
of tail (D). Blood was taken at the indicated time points and the neutralizing IgM (upper panel) or IgG titers (lower panel) were determined in the sera. Ti-
ters represent log$_2$ dilutions of 40-fold prediluted sera. △, aly/aly mice; ◇, Hox11$^{-/-}$ mice; ■, B6 control mice. Each line represents one individual
mouse. One out of three similar experiments is shown.
10^8 B6 spleen cells into aly/aly recipient mice failed to increase the neutralizing IgM or IgG response compared to untreated aly/aly mice. Irradiation prevented aly/aly and aly/+ mice from responding to VaccIND_G. In control experiments, 10^8 B6 spleen cells were transferred into aly/+ recipients and neutralizing IgM and IgG were readily induced.

These adoptive transfer experiments indicate that the T and B cells of aly/aly mice can respond to viral antigens if transferred into normal mice possessing organized secondary lymphoid organs. In contrast, spleen cells of normal B6 mice transferred into aly/aly mice did not function properly.

Discussion

In this study we investigated the effects of an altered morphology of secondary lymphoid organs on antiviral immune responses using Hox11^-/- and aly/aly mutant mice. Absence of the spleen in Hox11^-/- mice resulted in a certain delay of the systemic Ab response without measurable consequences for T cell–dependent immune functions. Absence of LN and PP, together with structural alterations of the splenic white pulp, resulted in a complete shift of the balance between virus replication and the host’s antiviral immune defense, with, as a consequence, establishment of persistent infection with a noncytopathic virus (LCMV) and increased susceptibility to cytopathic viruses such as VSV and VV.

The immunohistological analysis of aly/aly spleens shown in this study confirms and extends previous reports on the absence of MM and MZM and of FDC in aly/aly mice (32, 34). The genetic defect leading to the aly/aly phenotype is not yet defined (43). Since mice deficient for lymphotoxin α or for both lymphotoxin α and TNF-α also lack LN and PP and show similar structural changes in the splenic white pulp, there might be a common mechanism during organogenesis, even though the genomic localizations of the affected genes are different (43–47).

Although LCMV infection led to the induction of virus-specific CTLs in the spleen of aly/aly mice, virus replicated throughout the whole body and life-long virus persistence was established. The absence of organized secondary lymphoid organs led to rapid exhaustion of CTLs after infection with very low doses of a rather slow replicating strain of LCMV, even if administered locally into the footpads.
Previous experiments had shown that exhaustion by activation and deletion of LCMV-specific CTLs in adult immunocompetent mice was only possible with high doses (>10^6 PFU) of fast replicating LCMV strains after systemic intravenous infection (36). Exhaustion was not established after subcutaneous infection apparently because staggered induction of LCMV-specific CTL precursors, first in the draining LN, and subsequently in other secondary lymphoid organs, reduced their concerted end differentiation (48). Absence of LN in aly/aly mice correlated with the dramatically increased susceptibility to exhaustion after subcutaneous infection; due to this absence, the distribution of virus and the kinetics of CTL activation and exhaustion were apparently similar after local subcutaneous and systemic intravenous infection in aly/aly mice. Our results offer at least two possible explanations for the tremendously increased susceptibility to exhaustion of LCMV-specific CTLs in aly/aly mice. Due to the poor organization of the white pulp with the lack of the MZ Ag trapping and probably Ag presentation was less efficient in spleens of aly/aly mice due to the lack of the MZ and due to the poor organization of the splenic white pulp. This could first lead to a delay in CTL induction. Second, the initial virus distribution was different in aly/aly mice; less viral particles were retained in the spleen and therefore more virus reached peripheral solid organs where replication is probably less restricted (Table 1) and where induced CTL in addition may die because of interleukin deprivation.

Although we were not able to demonstrate a less efficient CTL induction early after LCMV infection (Fig. 2 B), the 3–30-fold reduced VV- and VSV-specific CTL responses suggested that CTL induction was affected in these mice. This impairment was modulated by the amount of inflammation and bystander activation correlating with the virulence of the infecting virus (49, 50).

aly/aly mice produce delayed and reduced T help–independent neutralizing IgM against live VSV. Since early IgM responses are usually associated with antigen in MM and MZM (12, 26, 51, 52), this result probably also reflects the insufficiency of aly/aly spleens to filter out antigen due to the absence of an organized MZ. The defect of aly/aly mice also prevented cooperative interactions of B and T cells to induce isotype switch. Adoptive transfer experiments indicated that the B and T cells of aly/aly mice were able to cooperate and to mount an immune response upon transfer into a recipient with a normal structure of secondary lymphoid organs. In contrast, transfer of spleen cells of B6 origin into aly/aly recipients did not reconstitute the immune response. These data are compatible with in vitro findings showing normal activities of aly/aly spleen cells when used in mitogen–induced in vitro proliferation of B and T cells, and also in mixed lymphocyte reactions as responders and stimulators (20). We therefore conclude that the defect of aly/aly mice relevant for the observed immunodeficiency is mainly related to the impaired structure of secondary lymphoid organs, i.e., the lack of LN and PP and the described alterations of the spleen, and not due to a cellular defect of the T and/or B cell compartment. However, the minor effect shown in Fig. 8, where we had to transfer ~10 times more aly/aly than aly/+ spleen cells to elicit the same neutralizing IgM response, could correlate with a possible impairment of B cells, as it has been suggested in a recent report showing a defect of aly/aly B cells in class switching and somatic hypermutation (32).

It is well established in humans and mice that the spleen plays a major role in the protection against blood borne infectious agents, particularly encapsulated bacteria (13–15). Especially the TI-2 Ab response to polysaccharide components of bacterial cell walls is known to be dependent on an intact spleen. Splenectomized patients and mice have been shown to respond very poorly to primary immunizations with TI-2 antigens (16, 17). In earlier studies, mainly MZM of the spleen were regarded as critical components in the induction of TI-2 responses (53, 54). More recent data suggested that FDC, rather than MZM, are the critical cells in the initiation of TI-2 responses (55, 56). Since aly/aly mice lack both MZM and FDC, it was not surprising that their Ab response to the TI-2 antigens VaccInD$_G$ and IND-G was severely reduced. CD4 depletion revealed that the IgM response of aly/aly mice against VaccInD$_G$ was T help dependent (Fig. 7 B). This finding, therefore, suggests that T–B collaboration in the spleen of aly/aly mice is not sufficient to induce class switch to IgG, but is sufficient to promote the TI-2 IgM response to VaccInD$_G$.

It was surprising that Hox11$^{-/-}$ mice responded nearly normally to the glycoprotein of VSV IND offered as a TI-2 antigen. The IgM response to intravenous immunization with VaccInD$_G$ and IND-G was delayed by 1–2 d, but was otherwise unaltered, even after CD4 depletion (Fig. 7 B). Apparently, the spleen is not critical for these responses and/or Hox11$^{-/-}$ mice have developed compensational mechanisms for their absent spleen during ontogeny and the neonatal period. This is also suggested by a finding in rats that only adult, but not neonatal, splenectomy resulted in a depression of the Ab response to TI-2 antigens (57).

Thus, the importance of antigen migration to LN in the induction of immune responses to model antigens or to skin allografts is confirmed in this study for antiviral immunity (7, 9, 10). The experiments here also show that effector cells, once they were induced, functioned in aly/aly mice and that LN were not limiting for emigration and function of activated effector T cells (Fig. 3). This result is compatible with the classical experiments of Frey and Wenk and those of Barker and Billingham, who showed that primed, immune T cells were capable of inflaming or rejecting skin in the absence of afferent lymph vessel or LN connection (7, 10).

Splenectomized aly/aly mice devoid of all organized secondary lymphoid organs did not respond to immunizations with potent TI-1 B cell antigens. This finding complements those for T cells as just discussed and indicates that induction of B cells must occur in organized secondary lymphoid organs. Once B cells are induced, they can emigrate to the bone marrow and home as Ab-forming cells (12, 58).

In conclusion, this study shows that the induction of an
efficient and balanced antiviral immune response is not only dependent on mature B and T cells and APCs; without critical interactions in the highly organized structure of secondary lymphoid organs, T and B cells are not properly induced. These results suggest that naive T cells do not usually encounter antigen and cannot be induced in the periphery (a) because they cannot emigrate into solid tissue, (b) because antigen transport via afferent lymph to organized secondary lymphoid organs is critical for the prompt induction of an immune response, and (c) because only upon specific activation can T cells emigrate to seek antigen in the periphery. Therefore, the balance between kinetics and distribution of antigen in the periphery versus antigen in organized lymphoid organs seems to determine whether antigen is ignored or induces or exhausts T cells.

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