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$CD4^+CD25^-LAG3^+$ regulatory T cells controlled by the transcription factor Egr-2

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Communicated by Tadatsugu Taniguchi, University of Tokyo, Tokyo, Japan, June 24, 2009 (received for review March 13, 2009)

Regulatory T cells (Tregs) are engaged in the maintenance of immunological self-tolerance and immune homeostasis. IL-10 has an important role in maintaining the normal immune state. Here, we show that IL-10-secreting Tregs can be delineated in normal mice as $CD4^+CD25^-Foxp3^-$ T cells that express lymphocyte activation gene 3 (LAG-3), an MHC-class-II-binding CD4 homolog. Although ≈2% of the $CD4^+CD25^-$ T cell population consisted of $CD4^+CD25^-LAG3^+$ T cells in the spleen, $CD4^+CD25^-LAG3^+$ T cells are enriched to ≈8% in the Peyer's patch. They are hypoproliferative upon in vitro antigenic stimulation and suppress in vivo development of colitis. Gene expression analysis reveals that $CD4^+CD25^-LAG3^+$ Tregs characteristically express early growth response gene 2 (Egr-2), a key molecule for anergy induction. Retroviral gene transfer of Egr-2 converts naïve $CD4^+$ T cells into the IL-10-secreting and LAG-3-expressing phenotype, and Egr-2-transduced $CD4^+$ T cells exhibit antigen-specific immunosuppressive capacity in vivo. Unlike $Foxp3^+$ natural Tregs, high-affinity interactions with selecting peptide/MHC ligands expressed in the thymus do not induce the development of $CD4^+CD25^-LAG3^+$ Tregs. In contrast, the number of $CD4^+CD25^-LAG3^+$ Tregs is influenced by the presence of environmental microbiota. Thus, IL-10-secreting $Egr\text{-}2^+LAG3^+CD4^+$ Tregs can be exploited for the control of peripheral immunity.

anergy | Blimp-1 | inflammatory bowel disease | IL-10 | type 1 regulatory T cells

Thymic T cell development efficiently regulates tolerance to self antigens (1, 2). However, in the last decade, rapid progress revealed the key role of peripheral tolerance in the maintenance of immunological homeostasis (3–5). In view of the recent reports, T cell subsets in the periphery are quite diverse. Naïve $CD4^+$ T helper cells may develop into different committed helper cell subsets characterized by distinct cytokine profiles, such as IFN-γ-secreting Th1, IL-4-secreting Th2, and IL-17-secreting Th17 cells (6–8). The versatile nature of T cells is found most strikingly in $Foxp3^+$ regulatory T cells (Tregs) (9). Therefore, identifying new subsets of effector and regulatory T cells is possible.

Naturally occurring $CD4^+CD25^+$ Tregs, which characteristically express the transcription factor Foxp3 (9), have been studied intensively, because their deficiency abrogates self-tolerance and causes autoimmune diseases (10). Mice with a null mutation of Foxp3, scurfy mice, have massive lymphoproliferation and severe inflammatory infiltration of the skin and liver (11). However, Aire is a gene responsible for autoimmune polyendocrinopathy–candidiasis–ectodermal dystrophy, which influences on the central induction of tolerance by regulating the clonal deletion of self-reactive thymocytes (12). Aire regulates the ectopic expression of a battery of peripheral-tissue antigens in the thymus [e.g., insulin, fatty-acid-binding protein, and salivary protein 1 (13)]. By an additional defect in central tolerance induction in scurfy mice, generated by crossing in a null mutation of the Aire gene, the range of affected sites was not noticeably extended, and many organs remained unaffected (3). This result suggests that additional important mechanisms other than central tolerance and the Foxp3 system are required to enforce immunological self-tolerance in the periphery.

Indeed, there are T cell populations with regulatory activity other than $CD4^+CD25^+Foxp3^+$ Tregs. The IL-10-secreting $Foxp3^-CD4^+$ T cells (4, 14) also have been a focus of active investigation, because, in contrast to $Foxp3^+$ natural Tregs, antigen-specific IL-10-secreting T cells can be adaptively induced in vitro and in vivo (15, 16). Because IL-10-secreting T cells also appear to be capable of controlling tissue inflammation under various disease conditions (14), IL-10-secreting regulatory T cells may be a tolerogenic machinery complementing $CD4^+CD25^+Foxp3^+$ Tregs. However, assessing the in vivo physiological function of IL-10-secreting regulatory T cells is difficult, because of the lack of specific markers that can reliably differentiate them from the other T cells (17).

Known regulatory T cells are closely related to anergy. Anergy is a tolerance mechanism in that T cells are functionally inactivated following an antigen encounter but remain alive for an extended period in the hyporesponsive state (18). A set of functional limitations characterizes the anergic state, including cell division, cell differentiation, and cytokine production. The E3 ligases c-Cbl, Cbl-b, GRAIL, Itch, and Nedd4 have been linked to the promotion of T cell anergy (19, 20). The RING-type E3 ubiquitin ligase Cbl-b promotes ubiquitination and degradation of signaling components, such as phospholipase C-γ and PKC-θ. Recently, early growth response gene 2 (Egr-2) and Egr-3 were reported to be transcription factors for the T cell receptor (TCR)-induced negative regulatory program controlling Cbl-b expression (21). Egr-2 is a C2H2-type zinc finger transcription factor that plays an essential role in hindbrain development and myelination of the peripheral nervous system (22), and Egr-2 null mutation resulted in perinatal or neonatal death. However, the role of Egr-2 in the regulatory function of T cells has not been described extensively.

We here report the identification of a Treg population that expresses Egr-2 and lymphocyte activation gene 3 (LAG-3). LAG-3, which negatively controls T cell proliferation (23, 24), was reported to be required for maximal regulatory functioning of murine $CD4^+CD25^+$ T cells. Ectopic expression of LAG-3 conferred regulatory activity to naïve T cells (25). Interestingly, LAG-3 protein was hardly detected on the cell surface of $CD4^+CD25^+$ T cells but was expressed by a sizable population of $CD4^+CD25^-$ T cells (26). We have found that IL-10-secreting $CD4^+CD25^-LAG3^+$ T cells show a significant regulatory activ-

Author contributions: T.O., K.F., S. Sakaguchi, and K.Y. designed research; T.O., K.F., M.S., S. Sumitomo, and H.S. performed research; T.O., K.F., S. Sakaguchi, and K.Y. analyzed data; and T.O., K.F., S. Sakaguchi, and K.Y. wrote the paper.

The authors declare no conflict of interest.

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This article contains supporting information online at www.pnas.org/cgi/content/full/0906872106/DCSupplemental.

www.pnas.org/cgi/doi/10.1073/pnas.0906872106

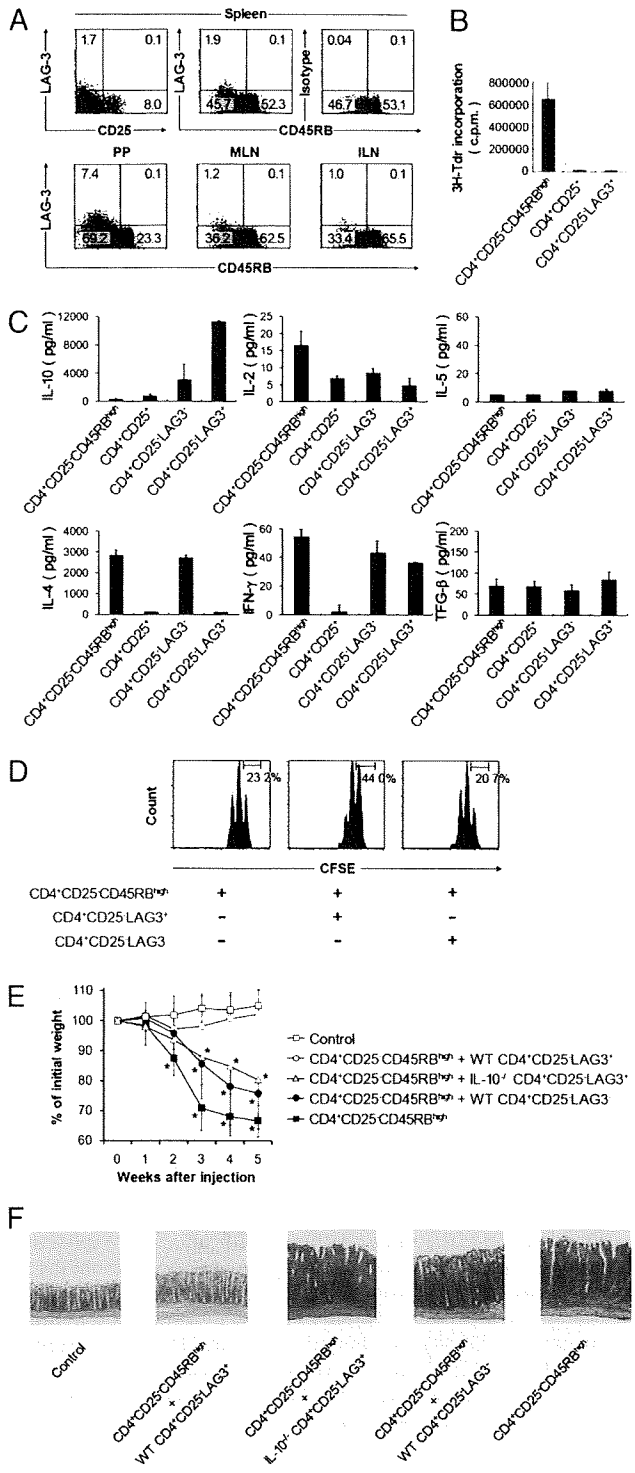

Fig. 1. Identification of $CD4^+CD25^-LAG3^+$ regulatory T cells. (*A*) LAG-3 expression in the spleen, Peyer's patch (PP), mesenteric lymph node (MLN), and inguinal lymph node (ILN). (*Top*) LAG-3 and CD25 or CD45RB expression in splenocytes from C57BL/6 is shown for the gated on $CD4^+$ (*Upper Left*) or $CD4^+CD25^-$ (*Upper Center* and *Upper Right*) T cells, respectively. (*Lower*) LAG-3 and CD45RB expression of PP, MLN, and ILN gated on $CD4^+CD25^-$ T cells. Representative FACS dot plots from at least three independent experiments are shown. (*B*) Proliferation of $CD4^+CD25^-CD45RB^{high}$, $CD4^+CD25^-$, and $CD4^+CD25^-LAG3^+$ splenocytes after 72 h stimulation with anti-CD3/anti-CD28. The results are the means of three independent experiments. (*C*) Cytokines in the culture supernatants of $CD4^+CD25^-CD45RB^{high}$, $CD4^+CD25^+$, and $CD4^+CD25^-LAG3^+$ T cells stimulated for 5 days with anti-CD3 mAb. Representative data from at least three independent experiments are shown. (*D*) Suppressive function of $CD4^+CD25^-LAG3^+$ T cells. Naïve $CD4^+CD25^-CD45RB^{high}$ $Thy1.1^+$ T cells were labeled with carboxyfluorescein diacetate succinimidyl ester (CFSE) and cocultured with the indicated $Thy1.2^+$ T cells and irradiated whole splenocytes plus anti-CD3 mAb. Representative data from three independent experiments are shown. (*E*) Suppression of $CD4^+CD25^-CD45RB^{high}$ T-cell-mediated colitis in RAG-$1^{-/-}$ mice by $CD4^+CD25^-LAG3^+$ T cells. Data represent body weight as a percentage of the initial weight of individual mice; $n = 6$ per group. (*F*) Representative photomicrographs of the colons stained with hematoxylin and eosin after transfer of the indicated cell populations. All error bars represent ±SD. (Scale bar, 100 μm.)

ity in vivo and characteristically express Egr-2. Conversion of Egr-2 transduced naïve $CD4^+$ T cells to IL-10-secreting and LAG-3-expressing Tregs suggested that Egr-2 is a key transcription factor for $CD4^+CD25^-LAG3^+$ T cells.

Results

IL-10-Secreting $CD4^+CD25^-CD45RB^{low}LAG3^+$ T Cells Exert Regulatory Activity. In agreement with previous results (26), flow cytometric analysis revealed that >90% of LAG-3-expressing cells belonged to the $CD4^+CD25^-CD45RB^{low}$ population (hereafter called $CD4^+CD25^-LAG3^+$ cells) (Fig. 1*A*). These $CD4^+CD25^-LAG3^+$ cells showed staining profiles of conventional $CD4^+TCR\alpha\beta^+$ T cells that did not express CD8, $TCR\gamma\delta$, and NK1.1 antigens (Fig. S1). The frequencies of $LAG3^+$ T cells in the $CD4^+CD25^-$ population were relatively low in the spleen (1.8 ± 0.18%), mesenteric lymph node (1.1 ± 0.09%), and inguinal lymph node (1.0 ± 0.07%) but characteristically high in Peyer's patch (PP) (7.7 ± 0.87%). These cells were hypoproliferative upon in vitro stimulation in a manner similar to $CD4^+CD25^+$ Tregs (Fig. 1*B*). They exclusively produced large amounts of IL-10 and low amounts of IL-2 and IL-4 (Fig. 1*C*). There were no significant differences in IL-5 and TGF-β production among the populations compared in the experiment. In anti-CD3-stimulated cocultures of $LAG3^+$ or $LAG3^-CD4^+CD25^-$ T cells with $CD4^+CD25^-CD45RB^{high}$ T cells, $CD4^+CD25^-LAG3^+$ T cells exhibited weak suppressive activity (Fig. 1*D*). In contrast, $CD4^+CD25^-LAG3^+$ T cells effectively inhibited colitis induced in RAG-1-deficient (RAG-$1^{-/-}$) recipients by the transfer of $CD4^+CD25^-CD45RB^{high}$ T cells (Fig. 1 *E* and *F* and Fig. S2). The in vivo suppressive activity was IL-10-dependent, because the transfer of $CD4^+CD25^-LAG3^+$ T cells from congenic IL-10-deficient (IL-$10^{-/-}$) mice failed to suppress colitis.

Cytofluorometric analysis revealed that $CD4^+CD25^-LAG3^+$ T cells did not express Foxp3 protein (Fig. S3 and Fig. S4). In addition, the number of $CD4^+CD25^-LAG3^+$ T cells was significantly increased in scurfy mice that lack functional Foxp3 protein (11). These cells expressed LAG-3 and IL-10 mRNA equivalently and exhibited distinct in vitro suppressive activity (Fig. S5). $CD4^+CD25^-LAG3^+$ T cells hardly expressed CD103 and latency-associated peptide (LAP) on the cell surface (Fig. S1 and Fig. S6), indicating that they were different from $CD103^+$ regulatory T cells and $CD4^+CD25^-LAP^+$ regulatory T cells, respectively (27, 28). These findings collectively indicate that $CD4^+CD25^-LAG3^+$ T cells exert regulatory activity in an IL-10-dependent and Foxp3-independent manner.

$CD4^+CD25^-CD45RB^{low}LAG3^+$ T Cells Exhibit a Distinct Transcriptional Profile. To further characterize $CD4^+CD25^-LAG3^+$ T cells, the mRNA expression profiles of four $CD4^+$ subsets ($CD4^+CD25^-LAG3^+$, $CD4^+CD25^-LAG3^-$, $CD4^+CD25^+$, and $CD4^+CD25^-CD45RB^{high}$) were examined. Gene expression profiling revealed six clusters of differentially expressed genes

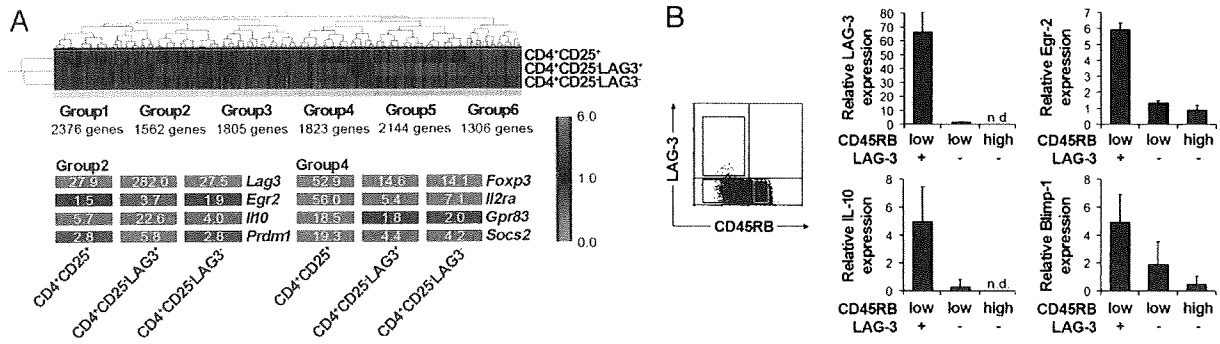

Fig. 2. Expression of Egr-2 in CD4$^+$CD25$^-$LAG3$^+$ T cells confers regulatory function. (*A*) Microarray comparisons of the gene expression profiles among CD4$^+$CD25$^+$, CD4$^+$CD25$^-$ LAG3$^+$, and CD4$^+$CD25$^-$LAG3$^-$ cells. Normalized expression values from naïve CD4$^+$CD25$^-$ CD45RB^{high} T cells are depicted according to the color scale shown. The expression profiles for each gene were classified into six groups. (*B*) LAG-3 and CD45RB expression of splenocytes from C57BL/6 mice gated-on CD4$^+$CD25$^-$ T cells (*Left*). Quantitative PCR for LAG-3, Egr-2, IL-10, and Blimp-1 in the indicated T cell subsets (*Right*). The results are the means of three independent experiments. All error bars represent ±SD.

(Fig. 2*A*). Signature genes for CD4$^+$CD25$^+$ Tregs, such as *Foxp3*, *Il2ra* (CD25), *Gpr83*, and *Socs2*, were preferentially expressed in one group (group 4). In contrast, the supposed signature genes for CD4$^+$CD25$^-$LAG3$^+$, such as *Lag3*, *Il10*, and *Prdm1* [B-lymphocyte-induced maturation protein 1 (Blimp-1)], were preferentially expressed in another group (group 2). Because CD4$^+$CD25$^-$LAG3$^+$ T cells were anergic in response to TCR stimulation (Fig. 1*B*), that the expression of the anergy-associated Egr2 gene was significantly increased in group 2 is particularly notable. Egr-2 was reported recently as a key negative regulator of T cell activation and was required for full induction of clonal anergy (21, 29). In accordance with the microarray analysis, quantitative real-time PCR confirmed the high expression levels of Egr2, LAG3, IL-10, and Blimp-1 genes in CD4$^+$CD25$^-$ LAG3$^+$ T cells (Fig. 2*B*).

Retroviral Transduction of Egr-2 Converts Naïve CD4$^+$ T Cells into IL-10-Secreting and LAG-3-Expressing Tregs. Next, we examined whether forced expression of Egr-2 in naïve CD4$^+$ T cells could convert them to the CD4$^+$CD25$^-$LAG3$^+$ phenotype using retrovirus vectors that coexpressed GFP and Egr-2 (pMIG-Egr2) (Fig. 3*A*). The TCR-stimulated pMIG-Egr2-transduced GFP$^+$ cells showed significant up-regulation of Egr2, LAG3, IL-10, and Blimp-1 genes (Fig. 3*B*). In addition, pMIG-Egr2-transduced GFP$^+$ cells produced significantly higher amounts of IL-10 and lower amounts of IL-2, IL-4, and IL-5 proteins (Fig. 3*C*).

Despite the expression of LAG-3 and IL-10 proteins, the present study was not able to confirm sufficient suppressive activity of pMIG-Egr2-transduced GFP$^+$ cells in in vitro coculture with freshly isolated CD4$^+$CD25$^-$CD45RB^{high} responder T cells stimulated with anti-CD3 mAb (Fig. 3*D*). To examine the in vivo suppressive activity of Egr-2, we next performed the delayed-type hypersensitivity (DTH) reaction of BALB/c mice against chicken ovalbumin (OVA) by using T cells transduced with the Egr2 gene. The in vivo functions of T cells transduced with regulatory genes have been verified (30, 31). In this experiment, CD4$^+$ T cells from BALB/c mice were transduced with pMIG or pMIG-Egr2. FACS-sorted retrovirus-infected CD4$^+$GFP$^+$ cells were injected intravenously 6 days after immunization with OVA, and OVA was rechallenged 2 days after the cell transfer. Notably, BALB/c CD4$^+$ T cells transduced with pMIG-Egr2 significantly suppressed DTH responses compared with BALB/c CD4$^+$ T cells transduced with pMIG (Fig. 3*E*). To explore the influence of antigen specificity, CD4$^+$ T cells from OVA-specific DO11.10 TCR transgenic mice also were transduced with pMIG or pMIG-Egr2, and mice transferred with these CD4$^+$GFP$^+$ cells were simultaneously analyzed for DTH. DO11.10 CD4$^+$ T cells transduced with pMIG-Egr2 significantly suppressed DTH responses compared with BALB/c CD4$^+$ T cells transduced with pMIG. Moreover, DO11.10 CD4$^+$ T cells transduced with pMIG-Egr2 suppressed DTH responses more efficiently than BALB/c CD4$^+$ T cells transduced with pMIG-Egr2, indicating a contribution of the antigen specificity to the enhancement of suppressive activity in Egr2-transduced cells. Thus, Egr-2 can confer in vivo suppressive activity on naïve T cells.

Development of CD4$^+$CD25$^-$LAG3$^+$ T Cells. We then explored whether CD4$^+$CD25$^-$LAG3$^+$ T cells could develop through the thymic selection process in a similar manner to Foxp3$^+$ Tregs, which require a high-affinity agonistic interaction with self-peptide/MHCs expressed by thymic stromal cells (32). RIP-mOVA/OT-II double-transgenic mice express a membrane-bound form of OVA in the pancreatic islets and the thymus together with a transgenic TCR (Vα2 and Vβ5.1) that recognizes the $OVA_{323-339}$ peptide in the context of I-A^b. The frequency of CD4$^+$CD25$^-$LAG3$^+$ T cells was not increased in the thymus and spleen of RIP-mOVA/OT-II mice, in contrast with an increase in the frequency of CD4$^+$CD25$^+$ Tregs in these organs as reported in ref. 32 (Fig. 4*A*). Thus, unlike Foxp3$^+$ natural Tregs, the development of CD4$^+$CD25$^-$LAG3$^+$ T cells does not appear to require high-affinity interactions with selecting peptide/MHC ligands expressed in the thymus.

Next, the influence of the environmental microbiota was studied for the development of CD4$^+$CD25$^-$LAG3$^+$ T cells with germfree (GF) mice. Although GF mice are exposed to self antigens, to food-derived antigens, and to microbial particles from dead microorganisms in the sterilized food or bedding, the absence of viable microbiota affects the immune homeostasis (33, 34). As shown in Fig. 4*B*, GF mice contained fewer CD4$^+$CD25$^-$LAG3$^+$ T cells than specific-pathogen-free mice in the spleen and PP. This result suggested that the exposure to viable microbiota affects the development of CD4$^+$CD25$^-$LAG3$^+$ T cells.

Discussion

We have shown the natural presence of Egr-2-dependent CD4$^+$CD25$^-$ Tregs in the normal immune system and characterized their function and development. CD4$^+$CD25$^-$LAG3$^+$ Tregs are clearly different from CD4$^+$CD25$^+$ Tregs in Foxp3 independency and development. T-cell-mediated colitis driven by enteric bacteria develops in lymphopenic mice after the transfer of CD4$^+$CD45RB^{high} T cells (35). The development of colitis can be prevented by cotransfer of the reciprocal

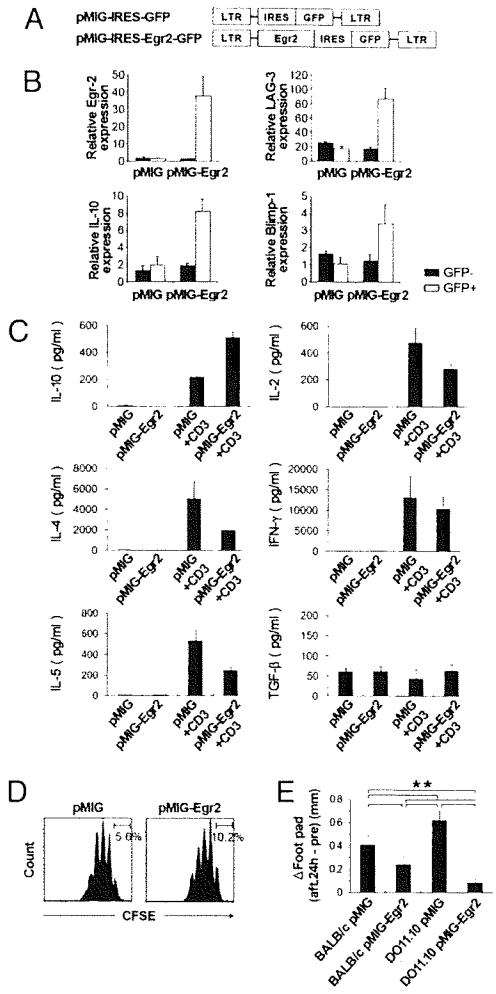

Fig. 3. Retroviral transduction of Egr-2 into naïve T cells. (*A*) Retroviral constructs for the transduction of Egr-2. (*B*) Ectopic Egr-2 expression induced the expression of LAG-3, IL-10, and Blimp-1. Quantitative PCR analyses of gene expression in sorted retrovirally transduced cell populations stimulated for 5 days with soluble anti-CD3 mAb (1 μg/mL). The results are the means of three independent experiments. (*C*) Cytokines in the culture supernatants of pMIG- and pMIG-Egr2-transduced $CD4^+GFP^+$ T cells stimulated for 48 h with or without plate-coated anti-CD3 mAb. The results are the means of three independent experiments. (*D*) Suppression of naïve carboxyfluorescein diacetate succinimidyl ester (CFSE)-labeled $CD4^+CD25^-CD45RB^{high}$ T cells by Egr-2-transduced T cells in vitro. Naïve $CD4^+CD25^-CD45RB^{high}$ $Thy1.1^+$ T cells were labeled with CFSE and cultured with the indicated retrovirally transduced $Thy1.2^+$ T cells and irradiated whole splenocytes plus anti-CD3 mAb. Representative data from three independent experiments are shown. (*E*) Antigen-specific suppression of the delayed-type hypersensitivity (DTH) response by Egr2-transduced $CD4^+$ T cells. Six days after primary immunization, FACS-sorted pMIG- or pMIG-Egr2-transduced $CD4^+$ T cells (1×10^6) from BALB/c or DO11.10 mice were transferred adoptively via i.v. injection into BALB/c mice. Two days after adoptive cell transfer, DTH response in the footpad was induced. Footpad thickness was determined 24 h later; $n = 6$ per group. All error bars represent ±SD. **, $P < 0.01$.

$CD4^+CD45RB^{low}$ subset in an IL-10-dependent manner (36). The suppressive activity was independent of $CD4^+CD25^+$ Tregs, because $CD4^+CD25^+$ T-cell-depleted $CD4^+CD25^-CD45RB^{low}$ T cells retained suppressive activity (37). The present findings that $CD4^+CD25^-CD45RB^{low}LAG3^+$ T cells exhibited stronger suppressive activity than $CD4^+CD25^-CD45RB^{low}LAG3^-$ T cells indicated that the suppressive activity of $CD4^+CD25^-CD45RB^{low}$ T cells was confined mainly to $CD4^+CD25^-CD45RB^{low}LAG3^+$ T cells expressing high levels of Egr-2. The association between LAG-3 and IL-10 production was consistent with previous observations (25). In addition to $CD4^+CD25^-CD45RB^{low}$ T cells, a decade of active research has focused on IL-10-producing type 1 regulatory T cells (Tr1) induced in vitro by antigenic stimulation (14). $CD4^+CD25^-LAG3^+$ Tregs were probably different from Tr1 in that $CD4^+CD25^-LAG3^+$ Tregs did not produce TGF-β and IL-5 (14). However, the precise relationships between $CD4^+CD25^-LAG3^+$ Tregs and Tr1 should be investigated further, because an optimal stimulation may induce TGF-β and IL-5 production in $CD4^+CD25^-LAG3^+$ Tregs.

In this study, the suppressive phenotype of $CD4^+CD25^-LAG3^+$ Tregs was determined by Egr-2. Egr-2 transduced T cells exhibited antigen-specific immunosuppressive capacity in vivo. Forced expression of Egr-2 in $CD4^+$ T cells induced the expression of LAG3, IL-10, and Blimp-1 genes. These results are consistent with the recent findings that T-cell-specific Blimp-1 conditional knockout mice showed impaired IL-10 production and increased IL-2 production in activated $CD4^+$ T cells and that they developed spontaneous colitis (38, 39).

The extrathymic development of IL-10-secreting T cells already has been reported (40). The severe decrease of $CD4^+CD25^-LAG3^+$ Tregs in GF mice shows the importance of environmental microbiota for the development of $CD4^+CD25^-LAG3^+$ Tregs. Germfree models represent an important tool for uncovering the function of gut microbiota, especially their effects on mucosal immunity (33, 34). Recently, gut-associated lymphoid tissue has been demonstrated to be a preferential site for the peripheral induction of $Foxp3^+$ regulatory T cells (41). In particular, dendritic cells (DCs) expressing $CD103^+$ from the lamina propria of the small intestine and from the mesenteric lymph node can induce $Foxp3^+$ T cells (42). Plasmacytoid DCs presenting dietary antigens are responsible for induction of oral tolerance and immune suppression affecting both $CD4^+$ and $CD8^+$ responses (43). The precise mechanisms of the development of $CD4^+CD25^-LAG3^+$ Tregs by environmental microbiota and antigen-presenting cells should be examined further.

Recent genome-wide association studies reported SNPs on chromosome 10q21 with a strong association to Crohn's disease (44, 45), a common form of chronic inflammatory bowel disease (IBD). The associated intergenic region is flanked by Egr-2, suggesting that this genetic variation could regulate Egr-2 expression. The characteristically high production level of IL-10 by Egr-2-dependent $CD4^+CD25^-$ T cells suggests that this Treg population may contribute to the control of organ inflammation. Moreover, T-cell-specific Egr-2-deficient mice showed autoimmune disease characterized by the enhanced expression of proinflammatory cytokines and massive infiltration of T cells into multiple organs (46). By exploiting the capacity of Egr-2-dependent $CD4^+CD25^-LAG3^+$ Tregs to produce a large amount of IL-10, they can be useful for antigen-specific treatment of inflammatory disease, in particular IBD.

Materials and Methods

Mice. BALB/c and C57BL/6 mice were purchased from Japan SLC. C57BL/6 recombinase-activating gene 1 (*rag-1*) deficient ($RAG1^{-/-}$) mice and TCR transgenic OT-II mice were purchased from Taconic. $RAG1^{-/-}$ mice were housed in microisolator cages with sterile filtered air. TCR transgenic DO11.10 mice, IL-10-deficient ($IL\text{-}10^{-/-}$) mice (47), B6.Thy1.1 mice, and Foxp3-eGFP mice (48) were purchased from Jackson Laboratory. RIP-mOVA (49) mice and B6.$Foxp3^{sfl/+}$ female mice were purchased from Jackson Laboratory and backcrossed with C57BL/6 males. B6.$Foxp3^{sfl/Y}$ male mice (11) were used at 21 days of age. All mice except B6.$Foxp3^{sfl/Y}$ and B6.$Foxp3^{sfl/+}$ were used at >7 weeks of age. All animal experiments were conducted in accordance with institutional and national guidelines.

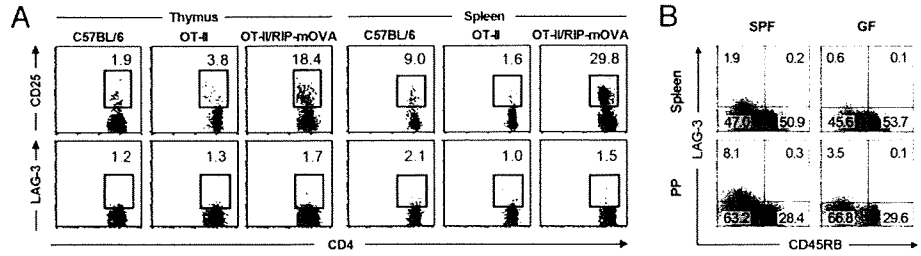

Fig. 4. Development of CD4$^+$CD25$^-$LAG3$^+$ T cells. (*A*) Flow cytometry of LAG-3 and CD25 expression in the thymus and spleen of OT-II TCR transgenic mice with or without the RIP-mOVA transgene. *Upper* and *Lower* plots are gated on CD4$^+$Vβ5.1/5.2$^+$ and CD4$^+$CD25$^-$Vβ5.1/5.2$^+$ T cells, respectively. Representative FACS dot plots from three independent experiments are shown. (*B*) Flow cytometry of LAG-3 and CD45RB expression in the spleen and Peyer's patch (PP) of specific-pathogen-free (SPF) (*Left*) and germfree (GF) (*Right*) mice gated on CD4$^+$CD25$^-$ T cells. Representative FACS dot plots from at least three independent experiments are shown.

Reagents. Purified and conjugated antibodies were purchased from BD Pharmingen, eBioscience, or Miltenyi Biotec, and recombinant cytokines were obtained from R&D Systems. See *SI Materials and Methods* for details.

RNA Isolation, cDNA Synthesis, and Quantitative Real-Time PCR. Total T cell RNA was prepared using an RNeasy Micro Kit (Qiagen). RNA was reverse-transcribed to cDNA, and quantitative real-time PCR analysis was performed as described in *SI Materials and Methods*. Relative RNA abundance was determined based on control β-actin abundance.

DNA Microarray Analysis. Total RNA of CD4$^+$CD25$^+$, CD4$^+$CD25$^-$CD45RB^{low}LAG3$^+$, CD4$^+$CD25$^-$CD45RB^{low}LAG3$^-$, and CD4$^+$CD25$^-$CD45RB^{high} FACS-purified T cells from C57BL/6 mice were harvested as described above and then prepared for Affymetrix microarray analysis as described in *SI Materials and Methods*. The data were analyzed using Bioconductor (version 1.9) (50) statistical software R and GeneSpring GX version 7.3.1 (Silicon Genetics). All microarray data have been deposited in the ArrayExpress database (http://www.ebi.ac.uk/arrayexpress) under accession number E-MEXP-1343.

Proliferation Assay. Each T cell population (1×10^5 cells per well) purified from C57BL/6 mice was cultured in U-bottomed 96-well plates coated anti-CD3 mAb for 72 h. ^{3}H-thymidine (1 μCi per well; NEN Life Science Products) was added during the last 15 h of culture. Cells were harvested and counted using a β^- counter. Results were expressed as the mean $\pm$ SD of triplicate cultures.

Suppression Assay. FACS-purified CD4$^+$CD25$^-$CD45RB^{high} T cells isolated from B6.Thy1.1 mice were stained with 5 μM carboxyfluorescein diacetate succinimidyl ester (CFSE) by incubating them for 10 min at 37 °C. The reaction was quenched by washing in ice-cold RPMI medium 1640 supplemented with 10% FCS. The CFSE-labeled CD4$^+$CD25$^-$CD45RB^{high} T cells (5×10^4) were cocultured with 1×10^5 irradiated whole splenocytes in the presence or absence of 5×10^4 retrovirally gene-transduced CD4$^+$GFP$^+$-sorted T cells or CD4$^+$CD25$^-$CD45RB^{low}LAG3$^{+\ or-}$ T cells from C57BL/6 mice in U-bottomed 96-well plates in the presence of 1.0 μg/mL anti-CD3 mAb. After 72 h, cells were analyzed by flow cytometry and gated on Thy1.1$^+$CD4$^+$ cells.

Colitis Model. Syngenic purified CD4$^+$CD25$^-$CD45RB^{high} T cells (1×10^5), described above, from C57BL/6 mice were injected i.p. into RAG1$^{-/-}$ mice alone or in combination with 1×10^5 wild-type CD4$^+$CD25$^-$CD45RB^{low}LAG3$^{+\ or-}$ or IL-10$^{-/-}$ CD4$^+$CD25$^-$CD45RB^{low}LAG3$^+$ T cells. Control mice received PBS. Mice were observed daily and weighed weekly. Seven weeks after cell transfer, the mice were killed, and sections of the colons were stained with hematoxylin and eosin. Mice were killed to assess the severity of colitis as described in *SI Materials and Methods*.

Cytokine Detection. Supernatants from cultures of CD4$^+$ T cells untreated or stimulated by plate-bound anti-CD3 (5 μg/mL) for 48 h or 5 days were harvested and pooled, and IL-2, IL-4, IL-5, IL-10, IFN-γ, and TGF-β concentrations were measured using a commercially available LINCOplex Mouse Cytokine kit (Linco Research) using fluorescently labeled microsphere beads and a Luminex reader according to the manufacturer's instructions at GeneticLabo. Raw data (mean fluorescence intensities) from the beads were analyzed using MasterPlex QT version 2.5 software (Hitachi) to obtain concentration values. All samples were run in duplicate, and results were obtained three times.

DTH Assay. BALB/c mice were immunized with OVA 6 days before the transfer of gene-transduced T cells. Retroviral gene transduction to CD4$^+$ T cells has been reported (51). The experimental groups consisted of CD4$^+$ T cells from BALB/c or DO11.10 mice transduced with pMIG or pMIG-Egr2. In accordance with our previous experiments (30, 31), the average transduction efficiency was $\approx$50%. The GFP-positive fraction of the transduced CD4$^+$ T cells were sorted with FACSAria and transferred to immunized mice. OVA was rechallenged to the footpad 2 days after the transfer, and footpad swelling was measured 24 h later. Detailed protocols are described in *SI Materials and Methods*.

Statistical Analysis. Statistical significance was analyzed using Statview software (SAS Institute). Body weight changes were analyzed by repeated measures two-way ANOVA followed by Bonferroni post test. Colitis scores, quantitative histology, and DTH responses were analyzed with the Mann–Whitney, Scheffé, and Bonferroni tests, respectively. Differences were considered statistically significant with *, $P < 0.05$ and **, $P < 0.01$.

ACKNOWLEDGMENTS. We thank K. Watada for excellent technical assistance. Flow cytometry analysis and cell sorting were done in the Department of Transfusion Medicine and Immunohematology, University of Tokyo, Japan. This work was supported by grants from the Japan Society for the Promotion of Science, Ministry of Health, Labor and Welfare, and the Ministry of Education, Culture, Sports, Science and Technology (MEXT) (in part by Global COE Program Chemical Biology of the Diseases, by the MEXT), Japan.

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The Journal of Toxicological Sciences (J. Toxicol. Sci.)
Vol.34, Special Issue II, SP349-SP361, 2009

Children's Immunology, what can we learn from animal studies (3): Impaired mucosal immunity in the gut by 2,3,7,8-tetraclorodibenzo-p-dioxin (TCDD): A possible role for allergic sensitization

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(Received February 17, 2009)

ABSTRACT — We have recently reported breakdown of mucosal immunity in the gut by tetraclorodibenzo-p-dioxin (TCDD). That is, single oral administration of low dose 2,3,7,8-TCDD resulted in a marked decrease in IgA secretion in AhR-dependent manner and impaired oral tolerance in the gut. In the present study, we found TCDD exposure by breast feeding also resulted in decreased level of IgA in the gut. Ig production by B cells by LPS stimulation was not affected by TCDD administration. Instead, particular chemokine receptor expression on B1 cells, a major cell source for intestinal IgA antibody, was decreased in mice treated with TCDD. In consistence with this observation, B1, but not B2 cells from TCDD treated mice showed impaired chemotaxis towards B lymphocyte chemokine (BLC)/CXCL13. In contrast, chemotaxis of intestinal dendritic cells (DCs) towards secondary lymphoid-tissue chemokine (SLC)/CXCL19 was not impaired in mice treated with TCDD. Furthermore, there was no change in the number and profile of intesitinal microflora in TCDD-treated mice. These results indicate that TCDD exposure by breast feeding results in breakdown of intestinal mucosal immunity of pups and that it may be attributed in part to impaired B1 cell migration from the peritoneal cavity to intestinal mucosa.

Key words: TCDD, Mucosal immunity, IgA, Oral tolerance, Allergy

INTRODUCTION

2,3,7,8-tetraclorodibenzo-p-dioxin (TCDD) has been reported to exert a variety of adverse effects on immune responses including antibody production and cytotoxic T lymphocyte (CTL) generation (Hollsopple *et al.*, 1991; Kerkvliet, 1995, 2002). Exposure to TCDD also results in decreased resistance to several infectious agents (Warren *et al.*, 2000). However, immunological effects of dioxins on mucosal immunity in the gut have not been intensively examined so far despite that most dioxins are exposed through the digestive tract. Intestinal mucosal immunity is characterized by massive IgA secretion into the gut lumen and induction of oral tolerance against huge amounts and kinds of dietary antigens. Both intestinal IgA and oral tolerance play pivotal roles for body defense to protect against pathogens and to avoid systemic allergic sensitization by oral antigens (Strobel and Mowat, 1998; Faria and Weiner, 1999). We previously demonstrated that mucosal immunity in the gut was impaired in BWF1 mouse strain, a murine model for systemic lupus erythematosus (SLE) (Akadegawa *et al.*, 2005). Aged BWF1 mice developing lupus nephritis showed a defective IgA secretion in the gut and increased susceptibility to bacterial infection. Oral tolerance was also impaired and orally administered-antigens induced systemic allergic sensitization in the respiratory tract in these mice. On the other hand, it is well recognized that allergic diseases have been increasing for the recent several decades in developed countries and that environmental factors are more involved in disease increase than genetic factors (Schultz-Larsen, 1993). These environmental factors include increased air pollution, dust mite, dietary antigens, environmental chemicals and so on (Hopkin, 1997). We hypothesized that environmental chemicals which disrupt mucosal immunity in the gut would result in allergic sensitization by oral antigens

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and could be a critical environmental factor for increased allergic diseases. In fact, we found that administration of low-dose TCDD resulted in defective IgA secretion in the gut in an AhR-dependent manner and in breakdown of oral tolerance leading to antigen-specific systemic sensitization (Kinoshita *et al.*, 2006).

In the present study, we suggest that TCDD exposure by breast feeding also results in decreased level of IgA in the gut of pups and that impaired chemotaxis of a particular B cell subset may be one of the possible mechanisms for TCDD-induced breakdown of mucosal immunity in the gut.

MATERIALS AND METHODS

Mice

Specific pathogen-free C57BL/6 mice, originally obtained from the Shizuoka Laboratory Animal Center (Shizuoka, Japan), were maintained under SPF condition in our animal facility at The University of Tokyo. 2,3,7,8-TCDD (Daiichikagaku Co., Tokyo, Japan) in corn oil was intragastrally administrated to mothers 3 days after delivery and fecal IgA level of pups was measured every 2 weeks. In some experiments, adult C57BL/6 mice aged 6-8 weeks were used. All animal experiments complied with the standards set out in the guidelines of the University of Tokyo.

Cell preparation

Peritoneal B1 cells were purified by MACS® magnetic beads (Miltenyi Biotech, Bergisch Gladbach, Germany) from whole peritoneal cells. Briefly, T-cells, macrophages and B2 cells were depleted by incubating with a biotinylated mAb cocktail (anti-Thy1.2, anti-F4/80 plus anti-CD23 mAbs) followed by incubation with streptavidin-conjugated magnetic beads. Splenic B2 cells and $CD4^+$ T cells were also isolated by MACS beads conjugated with anti-mouse B220 or anti-mouse CD4 mAb. Cell purity was more than 90% throughout the experiments.

ELISA for fecal IgA

One-hundred milligrams of fecal pellets were placed into 1.5 ml microcentrifuge tubes, added 1 ml (10 volumes, w/v) of phosphate buffered saline (PBS), and incubated at room temperature for 15 min. Samples were vortexed, left to settle for 15 min, revortexed until all material was suspended, then centrifuged at 12,000 rpm for 10 min. The supernatant was removed and stored at −80°C or immediately tested on ELISA kit for IgA (Bethyl Laboratories, Montgomery, TX, USA). Microtiter plates were coated with goat anti-mouse IgA affinity purified antibody and incubated for 60 min. Plates were washed with PBST (PBS containing 0.05% Tween 20) and each well was blocked with 200 μl of 50 mM Tris (pH 8.0) containing 0.15 M NaCl and 1% bovine serum albumin (BSA) for 30 min. After washing with PBST, 100 μl of test samples and standards was added per well and incubated for 60 min. Horse radish peroxidase (HRP) labeled goat anti mouse IgA-Fc specific Ab was added to each well and incubated for 60 min. Color was developed with HRP substrate (3,3',5,5'-tetramethyl benzidine) for 30 min and read at 450 nm with a Emax® precision microplate reader (Molecular Devices Corporation, Sunnyvale, CA, USA).

Flow cytometry

FITC-conjugated anti-CD4 (GK1.5), anti-CD5 (53-7.3RRH) and anti-CD11b (M1/70); PE-conjugated anti-CD8α (53-6.7), anti-CD11c (HL-3), anti-B220 (RA3-6B2); and APC-conjugated anti-B220 (RA3-6B2) mAbs were purchased from PharMingen (San Diego, CA, USA). Lymphoid cells were stained with 1) FITC-conjugated anti-CD4, PE-conjugated anti-CD8 and APC-conjugated anti-B220 mAbs, or 2) FITC-conjugated anti-CD5 and PE-conjugated anti-B220 mAbs, or 3) FITC-conjugated anti-CD11b and PE-conjugated anti-CD11c mAbs and analyzed on Epics Elite® cell sorter (Coulter Electronics, Hialeah, FL, USA).

Induction of oral tolerance

Induction of systemic unresponsiveness to OVA (Sigma Chemical Co., St. Louis, MO, USA) was performed as described previously [7]. Briefly, mice were given 25 mg of OVA in 250 μl PBS by gastric intubation at day 0. Control mice received PBS. At day 7 and 21, mice were immunized and challenged subcutaneously (s.c.) with 100 μg OVA in 100 μl CFA (Difco Laboratories, Detroit, MI, USA). OVA-specific Ab in the serum was measured 7 days after the second s.c. immunization.

OVA induced cell proliferation assay

Twenty-five mg of OVA in 250 μl PBS was administrated intragastrally three times in a week after TCDD treatment (day 0). Two weeks after the last administration, spleen and lymph nodes (axillar, pulmonary, mesenteric, renal, inguinal) were removed aseptically. Single-cell suspensions were obtained using fine-mesh screens (Cell Strainer, Becton Dickinson, Franklin Lakes, NJ, USA). 4×10^5 cells were cultured in the presence of OVA or KLH (200 μg/ml) for 5 days at 37°C in 5% CO_2 in atmosphere. Each well was pulsed with ^{3}H-thymidine (1 μCi/ml) for the last 18 hr of the culture. Cells were then harvested

onto a glass filter and radioactivity was counted with a liquid scintillation counter.

Chemotaxis assay

Chemotaxis assay using ChemoTx plate (Neuro Probe, Gaithersburg, MD, USA) was performed according to manufacturer's instructions. Briefly, spleen cells were suspended at 10^6 cells/ml in RPMI 1640 medium containing 0.5% BSA and 20 mM HEPES. Sixty μl of cell suspension was loaded on the membrane plate and placed onto a flat-bottomed microtiter plate with 96 wells containing 30 μl of serially-diluted B lymphocyte chemokine (BLC) solution in each well. The plate was then incubated at 37°C for 90 min and migrated cells were collected. Cells were then stained with FITC-labeled anti-CD5 and PE-labeled anti-B220 mAbs and counted on EPICS ELITE cell sorter. Chemotaxis assays for B1 and B2 cells were performed on the same plate and on the same day in each experiment because the absolute migrated cells varied in each chemotaxis assay. For chemotaxis assay for purified B1 and B2 cells, the mixture of 5 x 10^6 spleen and the peritoneal cells from young BWF1 mice was stained with FITC-labeled anti-CD5 and PE-labeled anti-B220 mAbs and subjected to cell sorting using EPICS ELITE cell sorter. The purity of B1 and B2 cells was more than 95% in all experiments.

DNA chip analysis

Total cellular RNA was prepared from B1 cell obtained TCDD-treated mice and DNA chip analysis performed using A24 GeneChips (Affmetrix, Santa Clara, CA, USA). Gene expression was confirmed by real-time PCR using ABI PRISM 7500 (Applied Biosystems, Foster City, CA, USA).

Statistical analysis

Statistical analysis was performed using Student's t-test. The 95% confidence limit was taken as significant.

RESULTS

Decreased IgA secretion in the gut by oral administration of TCDD

To investigate immunological effects of TCDD on intestinal mucosa, C57BL/6 mice were intragastrally administered various doses of TCDD and fecal IgA level determined by ELISA. The level of fecal IgA was dose-dependently decreased in mice treated with TCDD (Fig. 1, Modified from EHPM 11:256-263, 2006). It should be noted that relatively low doses of TCDD (0.1 μg/kg and

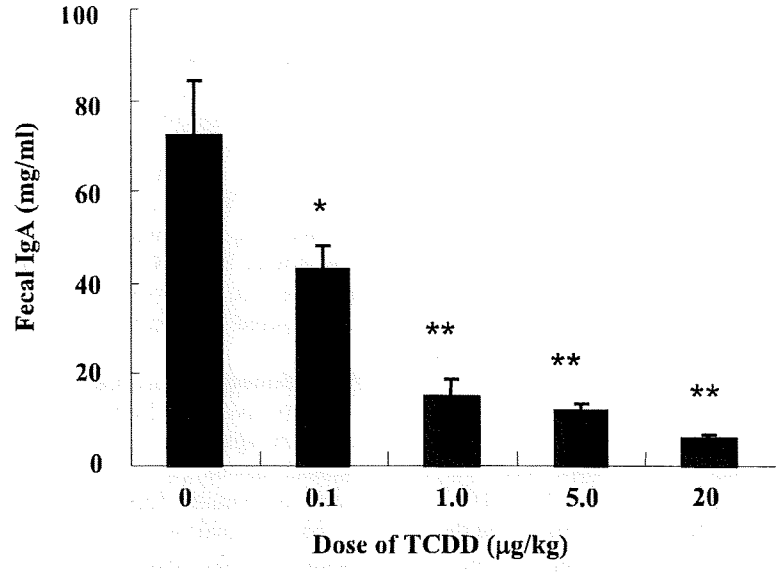

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Fig. 1. TCDD suppresses IgA secretion in the gut. Dose-ependent IgA suppression by TCDD. C57BL/6 mice (n = 5) were intragastrally administered with TCDD (0.1, 1.0, 5, 20 μg/kg) and fecal IgA level was determined by ELISA 1 week after TCDD treatment. Monoclonal IgA Ab was used as control. The mean concentration ± S.D. were presented in each graph. A representative result from four independent experiments is presented.

1.0 μg/kg) significantly inhibit IgA secretion into the gut lumen. IgA level returned to the normal level by 4 weeks after administration of 1 μg/kg TCDD (data not shown). To examine whether or not the inhibitory effect of TCDD on IgA secretion in the gut is mediated by AhR, a specific receptor for TCDD, fecal IgA level in AhR-deficient mice administered TCDD (1 μg/kg) was examined. The inhibitory effect of TCDD on IgA secretion in the gut was totally abrogated in AhR-deficient mice with C57BL/6 background while heterozygous littermates and C57BL/6 mice showed a marked decrease in IgA secretion in the gut (Fig. 2, Modified from EHPM 11:256-263, 2006). To examine the effect of TCDD exposure through breast feeding, mother mice were orally administered TCDD 3 days after delivery and fecal IgA level of pups measured by ELISA. As shown in Fig. 3 (Modified from EHPM 11:256-263, 2006), fecal IgA level was decreased in pups exposed to TCDD through breast feeding. It should be noted that the effect of TCDD on fecal IgA levels was more prominent in male than female mice.

Effect of TCDD on oral tolerance

Oral tolerance is historically and originally described as antigen-specific inhibition of antibody production by oral pre-administration of protein antigen. As shown in Fig. 4 (Modified from EHPM 11:256-263, 2006), OVA-specific IgG production was suppressed in mice which had been orally administered OVA before systemic immunization, demonstrating that oral tolerance was induced in these control mice. Oral administration of KLH did not inhibit OVA-specific IgG production (data not shown). In contrast, the suppression of IgG production was partially abrogated in TCDD treated-mice, suggesting a breakdown of oral tolerance. In consistence with the impaired oral tolerance in TCDD treated-mice, T-cells in PPs, axillar, inguinal, cervical LNs, and spleen of TCDD-treated mice were antigen-specifically sensitized and proliferated in the presence of OVA *in vitro* while KLH stimulation

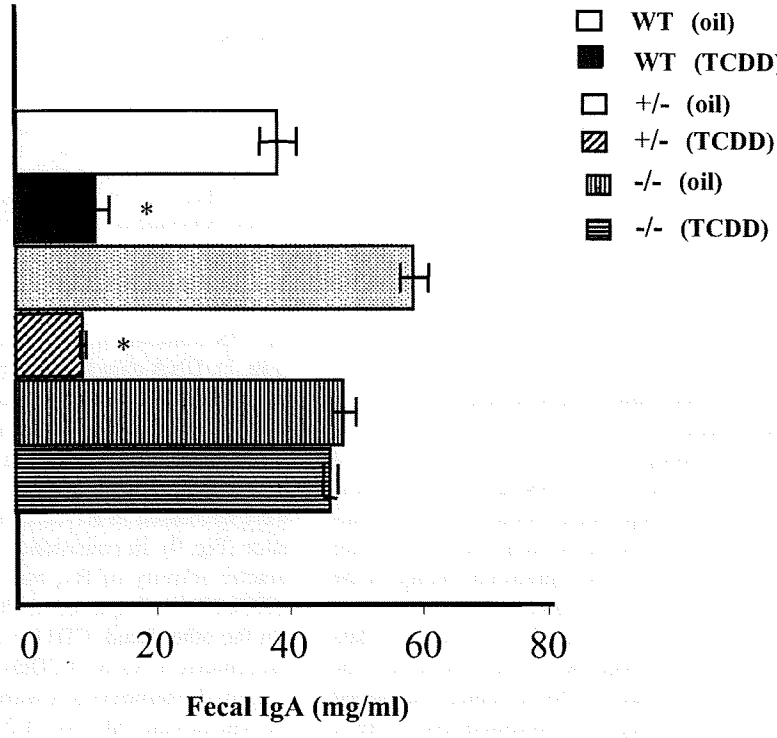

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Fig. 2. AhR dependent suppression of IgA secretion in TCDD-treated mice. TCDD (1 μg/kg) or corn oil was given to C57BL/6 (WT), AhR heterozygous (+/-), AhR deficient (-/-) mice and fecal IgA level was determined by ELSA 1 week after TCDD treatment (n = 5). A representative result from two independent experiments is presented. Statistical analysis was performed by Student's *t*-test. * $p < 0.001$.

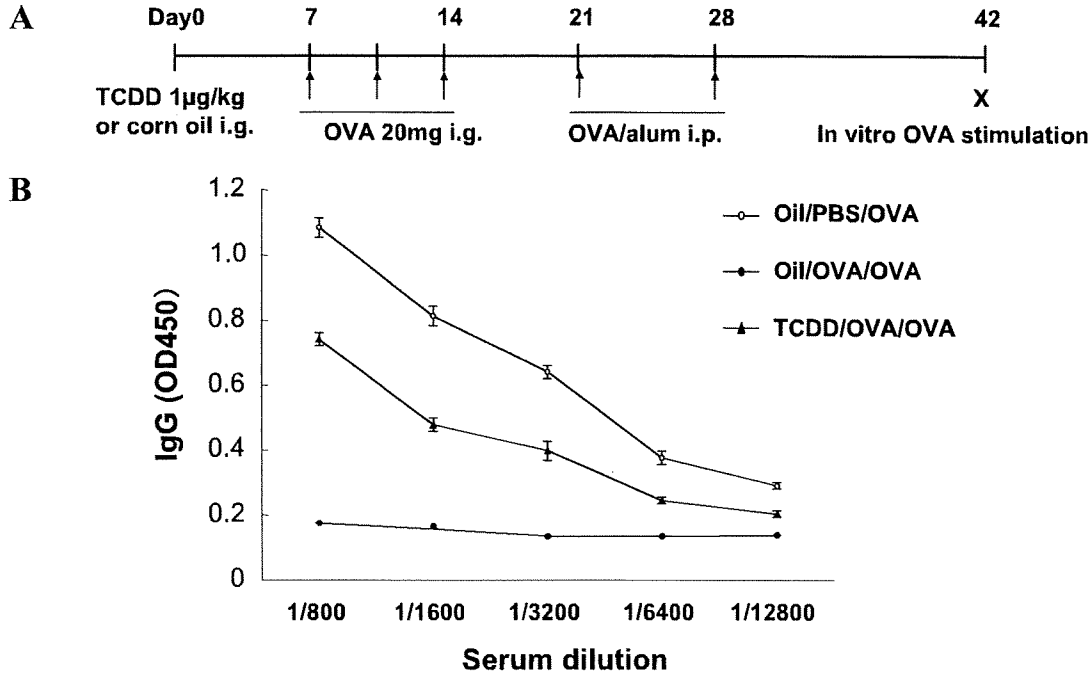

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Fig. 3. Breakdown of oral tolerance and systemic sensitization by oral antigens and intact antigen uptake in TCDD-reated mice. Mice were treated with TCDD (filled square, ■) or corn oil (open triangle, Δ) at day 0 and orally administered 25 mg of OVA at day 7 and 14. Then mice were immunized s.c. with 100 μg of OVA in CFA at day 21 and day 28 (n = 4). Mice immunized with OVA plus CFA were used as positive control (open diamond, ◊). The serum concentration of OVA specific IgG antibody at day 35 was determined by ELISA. The results are expressed as the mean ± S.D.. A representative data from three experiments is presented. * $p < 0.001$.

did not induce cell proliferation (Fig. 5).

Mechanisms for decreased IgA levels in TCDD-treated mice

There was no histological change in the intestine of TCDD-treated mice and Alexa-488 labeled OVA was incorporated into the subepithelial dome of PPs normally (data not shown). Fluorescent activated cell sorter (FACS) analysis also showed no significant change in the frequency of cellular subset of immunocompetent cells in lymphoid tissues including mesenteric LNs and PPs (data not shown). In particular, frequency of IgA^+ B-cells in the Peyer's patches and mesenteric LNs remained unchanged in TCDD-treated mice (Fig. 6A, Modified from EHPM 11:256-263, 2006). Furthermore, serum IgA level was not decreased in TCDD-treated mice (Fig. 6B, Modified from EHPM 11:256-263, 2006). Decreased level of IgA in the gut was not attributed to direct effect of TCDD on Ig production because *in vitro* IgM secretion by B-cells by LPS stimulation was not affected by TCDD treatment (Fig. 7). DNA chip analysis revealed that 231 genes were increased and 1,096 genes decreased in B1-cells obtained from TCDD-treated mice (Fig. 8). Real time PCR analysis confirmed that expression levels of particular chemokine receptors such as CCR2, CCR7, CXCR4 and CXCR5 were decreased in B1-cells obtained from TCDD-treated mice (Fig. 9). In consistence with this observation, chemotactic activity of B1, but not B2 cells towards BLC/CXCL13 was impaired in TCDD-treated mice (Fig. 10). On the other hand, $CD11c^+$ cells obtained from PPs and mesenteric LNs of TCDD-treated mice did not show impaired chemotaxis towards secondary lymphoid-tissue chemokine (SLC)/CCL21 (Fig. 11). Furthermore, the number and frequency of major commensal bacterial species which were believed to play a role in the maintenance of oral tolerance were not changed in TCDD-treated mice (Fig. 12).

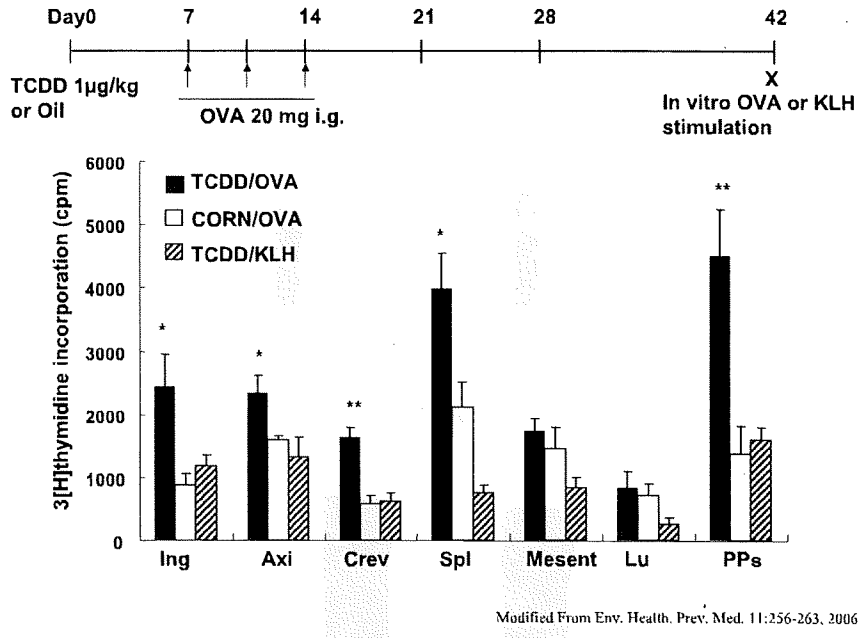

Fig. 4. Systemic sensitization with orally administered OVA by TCDD pretreatment. Mice were treated with TCDD on day 0 and then mice were intragastrally given 25 mg of OVA twice at day 7, 10 and 14. At day 28, single cell suspensions were obtained from spleen (Spl), inguinal (Ing), axillar (Axil), mesenteric (Mes), pulmonary (Pulm) lymph nodes, and Peyer's patches (PPs) and stimulated *in vitro* with OVA or KLH (200 μg/ml) at 37°C for 5 days. Cell proliferation was measured by ^{3}H-thymidine incorporation as described in Material and Methods. Results are presented as the means ± S.D. (n = 4). A representative data from three experiments is presented. *p < 0.05, **p < 0.01.

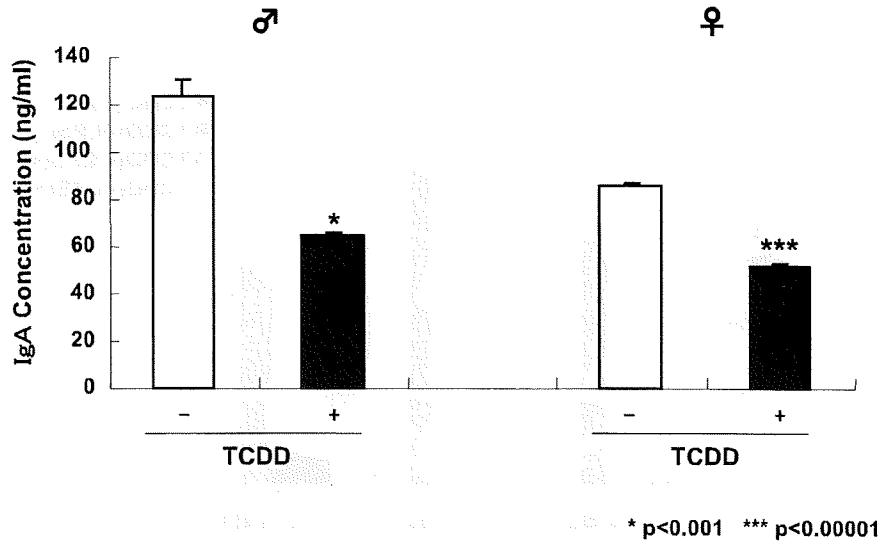

Fig. 5. Effect of TCDD exposure through mother milk on fecal IgA level of pups. TCDD was administered to mother 3 days after birth and fecal IgA levels of pups measured by ELISA 4 weeks after delivery (n = 5 or 6).

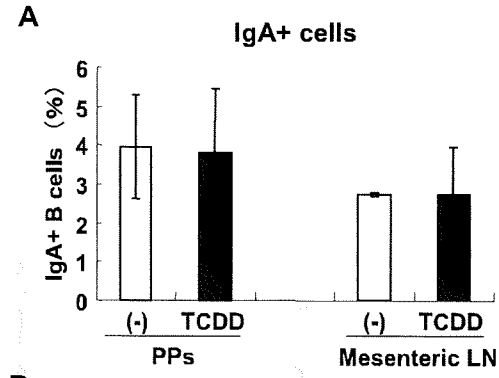

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Fig. 6. No change in the frequency of IgA$^+$ cells and serum level of IgA in TCDD-treated mice. **A.** Cells prepared from PPs or mesenteric LNs were stained with FITC-anti-IgA, PE-anti-B220, and APC-anti-CD19 Abs. The percentages of IgA$^+$B220$^+$ cells in CD19$^+$ cells were presented (n = 3). **B.** Serum concentration of IgA in TCDD-treated and control mice (n = 3) was measured by ELISA as described in Materials and Methods.

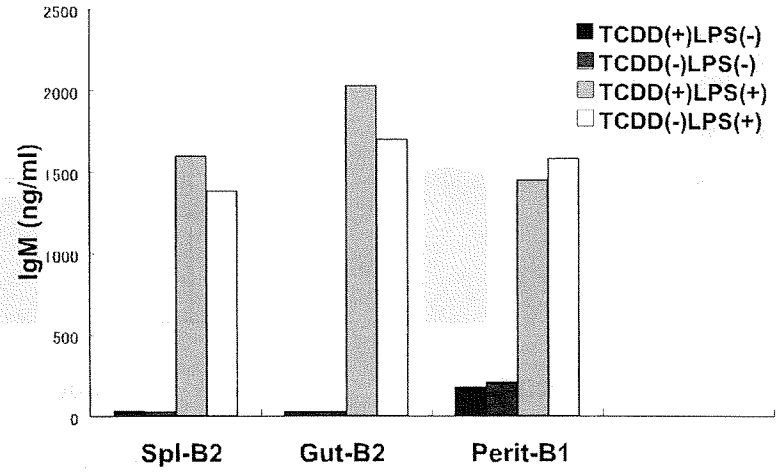

Fig. 7. Unimpaired IgM production by B1 and B2 cells on stimulation with LPS. B1 and B2 cells from TCDD-treated or control mice were stimulated *in vitro* in the presence of LPS (5 mg/ml) and IgM concentration in the culture supernatant was measured 5 days after stimulation.

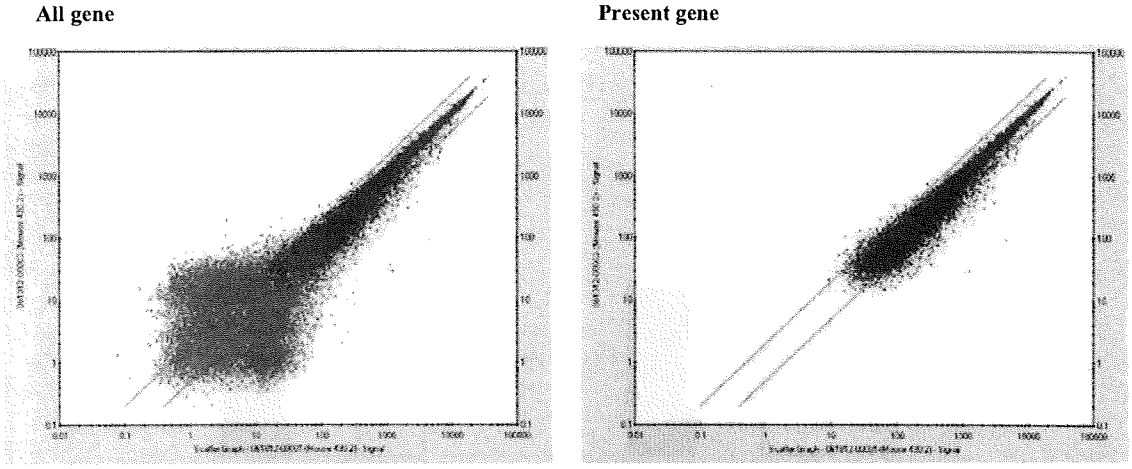

Fig. 8. DNA chip analysis on TCDD-treated B1 cells. Total cellular RNA was prepared from B1 cells obtained from TCDD-treated mice 1 week after injection and subjected to DNA chip analysis as described in Materials and Methods. Significant expression levelsof genes are dotted as present genes.

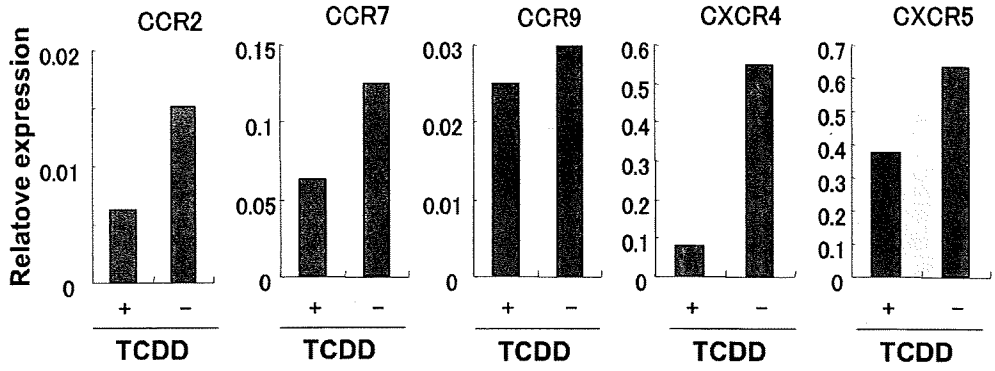

Fig. 9. Decreased expression of chemokine receptors in B1-cells in TCDD-treated mice. Total cellular RNA was prepared from sorted B1 cells from TCDD-treated or control mice and expression levels of chemokine receptors were measured by real-time PCR.

DISCUSSION

We previously reported breakdown of mucosal immunity in the gut by a single oral administration of 2,3,7,8-TCDD (Kinoshita *et al.*, 2006). That is, relatively low-dose TCDD administration resulted in a marked decrease in IgA level in the gut in an AhR-dependent manner and impaired oral tolerance in the gut. The mechanism for decreased IgA level in the gut, however, remained to be elucidated. There was no histological change in the intestine in TCDD-treated mice. Cellular subsets of immunocompetent cells in lymphoid tissues including PPs, spleen, thymus and peripheral LNs also remained unchanged. The frequency of IgA^+ B-cells was not decreased in the mesenteric LNs and PPs in TCDD-treated mice in FACS analysis whereas those in the intestinal lamina propria were decreased in immunofluorescent study in TCDD-treated mice. In the present study, we found that expression levels of par-

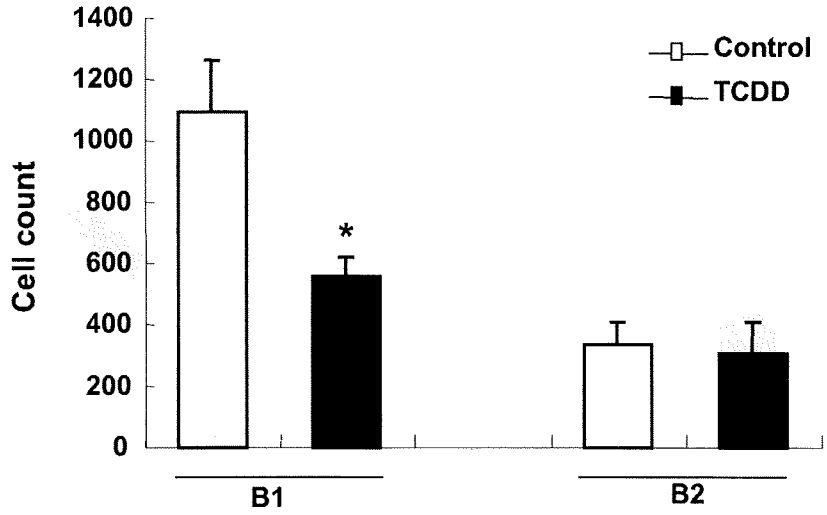

Fig. 10. Impaired chemotaxis of B1, but not B2 cells TCDD-treated mice. B1 and B2 cells enriched by MACS® beads were subjected to chemotaxis assay on BLC/cXCL13 as described in Materials and Methods. * $p < 0.001$.

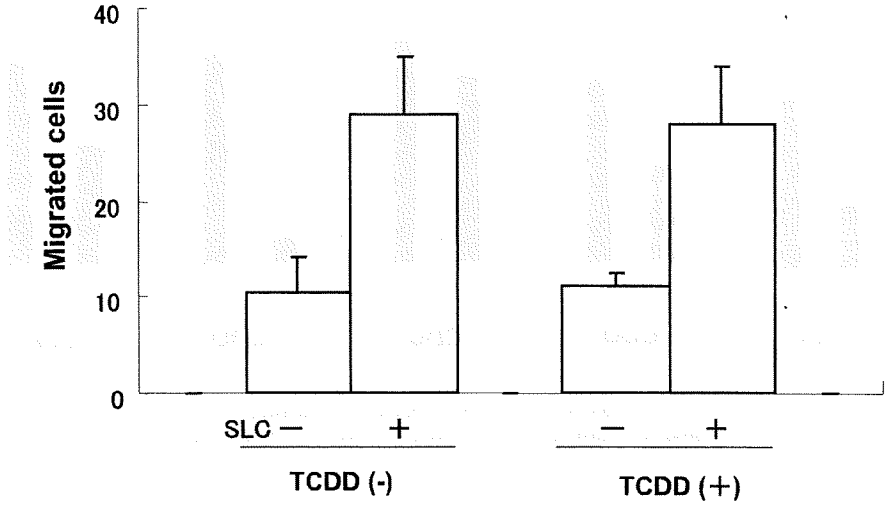

Fig. 11. Chemotaxis assay on dendritic cells (DCs). $CD11c^+$ cells obtained from mesenteric LNs and PPs of TCDD-treated or control mice by MACS® beads were subjected to chemotaxis assay on SLC/CCL21 as in Fig. 9.

ticular chemokine receptors were decreased in B1-cells, a unique B-cell subset which is distinguished from conventional B-cells (B2 cells) by their origin, cell surface phenotype and unique tissue distribution, capacity for self-renewal (Hardy and Hayakawa, 1986). B1-cells have been considered to be involved in autoantibody production in the development of particular autoimmune diseases. It is also reported that approximately half of IgA^+ cells in the intestinal lamina propria are derived from B1-cells and that they play a pivotal role for innate mucosal immunity in the gut although the site for IgA class-switching and differentiation to IgA-secreting plasma cells remains

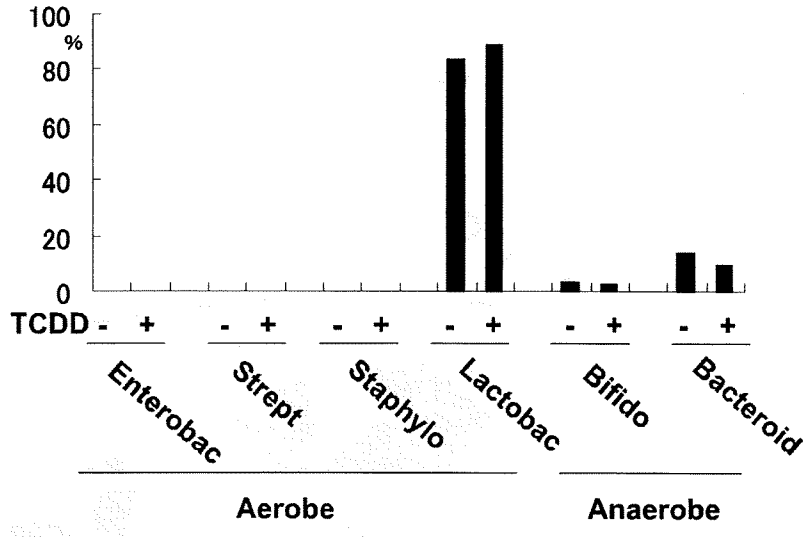

Fig. 12. Effect of TCDD on the number and frequency of commensal microflora in the intestine. Fecal samples were collected one week after TCDD administration and the number and frequency of aerobes (Lactobacillus, Enterococcus, Streptococcus, Staphylococcus) and anaerobes (Bacteroides and Bifidobacterium) were determined after appropriate culture at Intestinal flora laboratory of Calpis Co., Ltd..

to be elucidated (Kroese *et al.*, 1989; Beagley *et al.*, 1995; Murakami and Honjo, 1995; Macpherson *et al.*, 2000). It has been recently demonstrated that constitutively active aryl hydrocarbon receptor causes selective loss of peritoneal B1a ($CD5^{+}B220^{low}IgM^{high}$) cells (Anderson *et al.*, 2003), suggesting that the B1-cell is a sensitive cellular target for TCDD. On the other hand, ex vivo IgM secretion by B1-cells on LPS simulation was not affected by TCDD treatment as shown in the present study, suggesting that decreased level of IgA in the gut was not attributed to direct effect of TCDD on Ig production. Instead, we favor the idea that impaired B1-cell trafficking by TCDD from the peritoneal cavity to the intestinal mucosa could be one of the causes for decreased level of IgA in the gut (Fig. 13).

Another important finding in the present study is that TCDD exposure by breast feeding also results in decreased level of intestinal IgA in the pups. Maternal depots of TCDD, stored primarily in adipose tissue, are efficiently transferred to pups during nursing period. Maternal TCDD levels rapidly decreased during lactation period while tissue levels in the nursing pups increased. Tissue levels in the offspring even exceed those of their mothers during the 3-week period after birth. Thus, lactation serves as a significant route of exposure for the developing neonate (Nau *et al.*, 1986). It is previously reported that lactational exposure to TCDD induced hydronephrosis both in mice and rats (Couture-Haws *et al.*, 1991; Nishimura *et al.*, 2006). Since development of mucosal immune system does not cease at birth as well as renal development, it is not surprising that TCDD exposure by breast milk decreases IgA levels in the gut at relatively low dose. Furthermore, immature mucosal immune system of newborn infants may be much more sensitive to TCDD exposure. Therefore, our findings would have a significant impact on the risk assessment of TCDD for neonates and infants given that babies with breast-feeding take 15-20 times more TCDD than the dose of tolerable daily intake (TDI). Decreased level of IgA in the gut would result in increased frequency of infection and altered distribution of commensal bacterial microflora which plays a role for oral tolerance.

Breakdown of oral tolerance by TCDD is another interesting finding in the present study. Oral tolerance is historically and originally described as antigen-specific inhibition of systemic IgG antibody production by oral pre-administration of protein antigen (Strobel and Mowat, 1998; Faria and Weiner, 1999). Many studies have been performed using a similar experimental protocol to that used in the present study to demonstrate the presence or absence of oral tolerance. However, the precise mechanism for oral tolerance still remains controversial

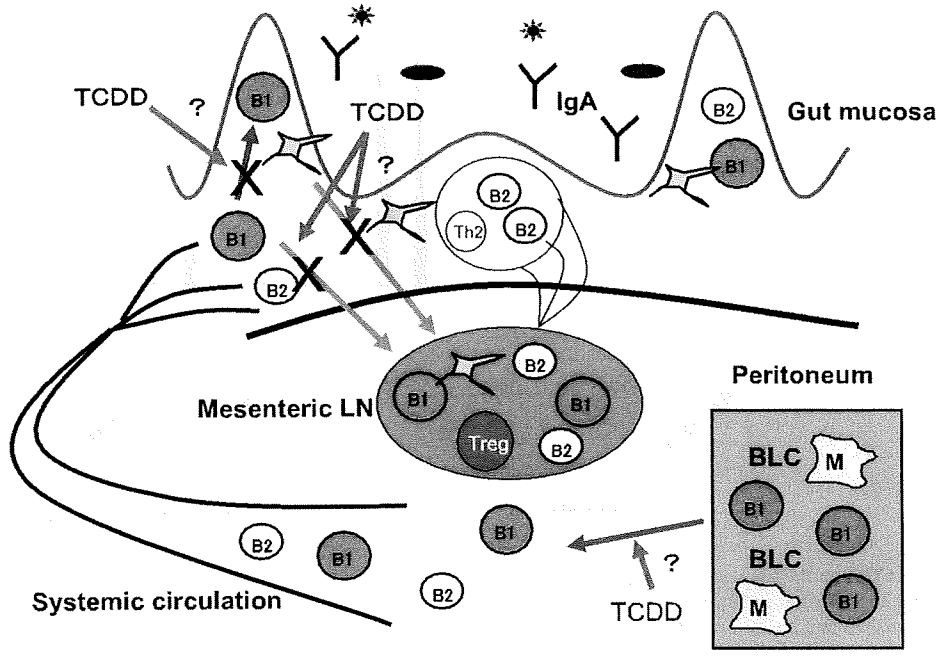

Fig. 13. Hypothetical model for TCDD-induced breakdown of mucosal immunity. TCDD treatment possibly impaires B1-cell trafficking from the peritoneal cavity to the lamina propria in gut. This results in decreased level of IgA in the gut lumen without directly affecting Ig secretion.

(Mowat, 2003). It was previously reported that regulatory T-cells producing TGF-β and/or IL-10 were induced in PPs upon oral administration of protein antigens (Santos *et al.*, 1994; Tsuji *et al.*, 2001). However, the classical idea for the pivotal role of PPs in oral tolerance has been challenged by several studies demonstrating that oral tolerance could be induced independently of PPs (Spahn *et al.*, 2001). It was also demonstrated that the spleen plays an important role for oral tolerance (Suh *et al.*, 1993). These results favor the idea that mesenteric LNs and/or spleen are critical lymphoid organs as the induction site for oral tolerance although they do not exclude a physiological role of PPs. Accumulating evidence also suggests that DCs in the gut play a pivotal role for oral tolerance (Viney *et al.*, 1998, Huang *et al.*, 2000; Chirdo *et al.*, 2000, Sun *et al.*, 2007). However, the frequency of $CD11c^+$ cells remained unchanged in PPs, mesenteric LNs and spleen before and after TCDD treatment. Functional analysis on DCs with different localization is under investigation to elucidate the mechanism involved in disrupted oral tolerance by TCDD. It has been recently demonstrated that TCDD generates $CD25^+CD4$ T cells with regulatory function in a GVH model (Funatake *et al.*, 2005). However, FACS analysis showed only a marginal change in the frequency of $CD25^+CD4$ T cells in the PPs, mesenteric LNs, and spleen (6.3 ± 0.28, 12.3 ± 0.28, 8.95 ± 0.21 in TCDD-treated mice and 4.25 ± 0.35, 11.4 ± 0.21, 7.6 ± 0.28 in control mice, respectively). Effect of TCDD on Treg trafficking remains to be examined. Although commensal bacterial microflora plays a role in the development of oral tolerance (Sudo *et al.*, 1997), there was no change in the number and frequency of major bacterial species.

As a result of breakdown of oral tolerance, T-cells in PPs, axillar inguinal and cervical LNs were sensitized by orally administered OVA. It is known that patients with atopic dermatitis show high frequency of food allergy and that dietary allergens such as egg albumin often turn out to be the allergen in the skin in these patients, indicating the existence of immunological cross talk between the intestinal mucosa and the skin. It is considered that microbial infection, excessive antibiotic administration, early onset of a weaning diet and so on are the causes for systemic allergic sensitization to oral antigens in infants.

Our findings suggest that TCDD can be a possible candidate for such disruptors for mucosal immunity leading to allergic sensitization.

Collectively, we have demonstrated that relatively low dose of TCDD results in breakdown of intestinal mucosal immunity and systemic sensitization by oral antigen in mice. Disrupted chemotaxis of B1 cells may be one of the mechanisms for defective IgA in the gut in TCDD-treated mice. Thus, immunological effects of environmental chemicals such as dioxins should be assessed on the basis of mucosal immunity in the gut. This may also provide a new insight for understanding environmental factors responsible for increased allergic diseases in recent decades.

ACKNOWLEDGMENTS

We thank Dr. C. Tohyama (Univ. of Tokyo) and Dr. R.E. Peterson (Univ. of Wisconsin) for kind gift of AhR deficient mice and Ms. Y. Kurotaki and Y. Mochimaru for excellent technical assistance. This work was supported by grants from SORST (Solution Oriented Research for Science and Technology, Japan Science and Technology Corporation), LRI (The Long-ranged Research Initiative) by Japan Chemical Industry Association, and The Japan Health Sciences Foundation.

This peer-reviewed article is based upon a lecture presented at the 35th Annual Meeting of Japanese Society of Toxicology, June 2008 in Tokyo under the theme of "Children's Toxicology", June 2008 in Tokyo.

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