MyD88 and Retinoic Acid Signaling Pathways Interact to Modulate Gastrointestinal Activities of Dendritic Cells

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Abstract

BACKGROUND & AIMS—Gut-associated dendritic cells (DC) metabolize vitamin A into all-trans retinoic acid (RA), which is required to induce lymphocytes to localize to the gastrointestinal (GI) tract and promotes the differentiation of Foxp3+ regulatory T cells (T_{REG}) and immunoglobulin (Ig)A antibody-secreting cells (IgA-ASC). We investigated whether RA functions in a positive-feedback loop, via DC, to induce its own synthesis.

METHODS—We measured levels of retinoids in intestine tissues from mice and assessed the role of RA in activities of gut-associated DC in cell cultures and mice. We used pharmacologic antagonists to determine the signaling pathways involved in regulation of DC and used MyD88−/− mice to determine the contribution of Toll-like receptor (TLR) signaling in RA-mediated activities of DC.

RESULTS—The concentration of retinoids decreased in a proximal-to-distal gradient along the intestine, which correlated with the activity of gut-specific DC. Importantly, RA regulated the...
ability of gut-associated DC to produce RA, induce T cells to localize to the GI tract, and generate $T_{\text{REG}}$ and IgA secreting cells. RA was sufficient to induce its own production by extra-intestinal DC, in vitro and in vivo. RA-mediated regulation of DC required signaling through the mitogen-activated protein kinase signaling pathway and unexpectedly required MyD88, which has been associated with TLR, interleukin (IL)-1, and IL-18 signaling.

**CONCLUSIONS**—RA is necessary and sufficient to induce DC to regulate T-cell localization to the GI tract and IgA secretion. These findings indicate crosstalk between the RA receptor and MyD88-dependent TLR signaling pathways.

**Keywords**
Inflammation; IBD; immune response; mouse model

Lymphocyte migration is a key event during intestinal inflammation. Therefore, it is critical to understand how T and B cells migrate to the intestine and how their migration patterns could be manipulated for therapeutic purposes. The gut-homing receptors integrin $\alpha_4\beta_7$ and chemokine receptor CCR9 are required for T and B lymphocyte migration to the gut mucosa in the steady state and also during intestinal inflammation in mice and humans, thus acting as molecular “zip codes” by controlling lymphocyte migration in a tissue-specific fashion.

DC from mesenteric lymph nodes (MLN-DC), Peyer’s patches (PP-DC) and small intestine lamina propria (gut-associated DC), but not DC from extra-intestinal sites, induce a high expression of gut-homing receptors on lymphocytes, which is explained by their ability to metabolize vitamin A (retinol) into all-trans retinoic acid (RA). RA is necessary to imprint gut-homing lymphocytes, to promote differentiation of IgA-ASC and to control the balance between $T_{\text{REG}}$ and $T_{\text{H17}}$ cells in the gut mucosa. Therefore, given the essential role of RA in intestinal immune homeostasis, it is important to understand how the synthesis of RA is modulated in the gut mucosa.

Here we show that RA controls RA-synthesizing capacity in DC in vitro and in vivo, hence inducing a positive feedback loop on its own synthesis and conferring DC with gut-specific imprinting properties. In addition, we found that RA-mediated DC education requires the expression of the intracellular adaptor MyD88, which is conventionally associated with TLR and IL-1/IL-18 signaling, suggesting a novel crosstalk between RA- and MyD88-dependent pathways.

**Results**

**DC ability to imprint gut homing correlates with retinoid levels in the gut**

RA and its precursors retinol and retinyl esters were readily detected in the intestinal mucosa and their concentrations followed a gradient from proximal to distal, with the highest concentrations being found in the duodenum and jejunum (Fig. 1A). Interestingly, retinoid levels correlated with DC imprinting ability. PP-DC or lamina propria DC (LP-DC) from duodenum and jejunum induced higher levels of gut-homing receptors ($\alpha_4\beta_7$ and CCR9) and Foxp3+ T cells as compared to their counterparts in ileum, colon or spleen (Fig. 1B, C and Fig. S1A). Reciprocally, the skin-homing receptors E- and P-selectin ligands were more efficiently induced by ileum PP-DC/LP-DC, colon LP-DC and Spleen-DC than by duodenum or jejunum PP-DC/LP-DC (Fig. S1B), consistent with the notion that the induction of these receptors occurs as a default pathway in T cells activated without RA. Consistent with their higher gut-homing imprinting capacity, PP-DC and LP-DC from duodenum and jejunum exhibited higher Raldh activity (Aldefluor staining) than ileum or
colon DC (Fig. 1D), which was not explained by different proportions of CD103+ DC (Fig. S1C). Of note, the expression of Aldh1a2 mRNA (encoding Raldh2) was not significantly different among DC from different intestinal segments and their relative mRNA levels were lower than those found in MLN-DC (Fig. S1D), suggesting that Aldh1a2 mRNA levels in DC do not always fully correlate with their Raldh activity or gut-homing imprinting capacity. Whether this dissociation between Aldh1a2 mRNA and Raldh activity reflects local differences in Raldh protein expression or stability remains to be determined. In addition, using DR5-luciferase reporter mice, in which luciferase is controlled by a promoter with RA response elements (RARE) 

RA is necessary in vivo for gut-associated DC education

We depleted mice of the RA precursor retinol by feeding them a vitamin A-deficient (VAD) diet, as described. Since vitamin A is abundantly stored in the liver it is difficult to attain complete vitamin A depletion, even when using a VAD diet for several months. To address this shortcoming we used mice deficient in lecithin:retinol acyltransferase (LRAT), which cannot store retinol in the liver, to develop normally when maintained on a vitamin A-sufficient diet, but they become vitamin A depleted after only 2–4 weeks on a VAD diet, with the additional advantage of avoiding potential unwanted effects of chronic vitamin A depletion. In agreement with a critical role of RA in gut-associated DC education, PP-DC and MLN-DC from VAD mice induced lower levels of gut-homing receptors on T cells as compared to their counterparts from mice on a vitamin A-sufficient diet (Fig. 2A). In addition, MLN-DC and PP-DC from VAD mice were impaired in inducing Foxp3+ T cells (Fig. 2B) and IgA-ASC (Fig. 2C), respectively. Moreover, MLN-DC from VAD mice showed a marked reduction in Aldh1a2 mRNA expression (Fig. 2D) and an impaired Raldh activity in total and CD103+ MLN-DC (Fig. 2E), which was rescued by oral RA supplementation (Fig. 2F). Thus, RA is necessary in vivo to educate gut-associated DC with critical gut-specific imprinting properties.

RA is sufficient to confer DC with RA synthesizing capacity in vitro and in vivo

Murine Spleen DC pre-treated with RA (RA-DC) upregulated Aldh1a2 mRNA (Fig. 3A and Fig. S2A, B). This effect was not limited to RA, as other natural and synthetic RA receptor (RAR-RXR) agonists (Am80, 9-cis RA, 13-cis RA) also induced Aldh1a2 in Spleen-DC. In contrast, agonists for RXR-RXR (HX630, PA024), PPARγ-RXR (Rosiglitazone), PPARβ/δ-RXR (GW0742), LXR-RXR (TO901317) or AHR (ITE) nuclear receptors did not induce Aldh1a2 mRNA. RA also induced Aldh1a2 in murine peripheral lymph node (PLN)-DC and bone marrow (BM)-derived DC (Fig S2C) as well as ALDH1A2 mRNA in human monocyte-derived DC (Mo-DC) (Fig. S2D), suggesting that our findings could be extrapolated, at least in part, to human DC.

Consistent with their higher expression of Aldh1a2 mRNA, RA-DC displayed higher Raldh activity as compared to untreated Spleen-DC (UT-DC) (Fig. 3B), which was also observed when treating PLN-DC and BM-DC with RA (Fig. S2E), indicating that RA-DC acquired RA-synthesizing capacity. Importantly, RA-DC induced significantly higher levels of gut-homing receptors α4β7 and CCR9 on activated T cells as compared to UT-DC, which was abrogated when T cells were activated in retinol-free media (Fig. 3C) or in the presence of the Raldh inhibitor diethylaminobenzaldehyde (DEAB) (Fig. 3D), implying that the induction of gut-homing receptors by RA-DC required active RA synthesis and was not due to RA carry-over, which happens when DC are incubated with high concentrations of RA. Similarly, human monocyte-derived DC (Mo-DC) pre-treated with RA induced higher levels...
of gut-homing receptors on polyclonally activated human T cells than untreated Mo-DC (Fig. S2F). Adding the RAR-inhibitor LE540 during the co-culture abrogated gut-homing imprinting by RA-DC (Fig. S2G), indicating that gut-homing imprinting by RA-DC requires RA activity via RAR nuclear receptors. Consistent with their higher expression of gut-homing receptors, T cells activated with RA-DC migrated significantly more to the small intestine as compared to those activated with UT-DC (Fig. 3E). In addition, analogous to gut-associated DC, RA-DC also promoted the induction of Foxp3+ TREG (Fig. 3F).

To obtain mechanistic clues on Aldh1a2 induction by RA in DC, we incubated Spleen-DC from DR5-luciferase mice with RA in the presence or absence of the transcription inhibitor actinomycin-D or the translation inhibitor cycloheximide as described. RA-treated Spleen-DC exhibited increased Raldh and luciferase activities (induction of Aldh1a2 mRNA and a RAR-dependent reporter by RA, respectively), which were abrogated by actinomycin-D or cycloheximide treatment (Fig. S3A, B), suggesting that RA-mediated DC education to express Raldh and synthesize RA requires de novo transcription and protein synthesis. Moreover, actinomycin-D inhibited RA-mediated induction of Aldh1a2 mRNA and Rarb mRNA (encoding RARβ, a known RA-induced gene) (Fig. S3C), indicating that their increase is mostly due to de novo transcription rather than enhanced mRNA stability. Interestingly, cycloheximide blocked Aldh1a2 but not Rarb mRNA induction, suggesting that the increased Aldh1a2 mRNA transcription in RA-treated Spleen-DC requires newly synthesized proteins, whereas Rarb appears to be directly induced by RA without requiring de novo protein synthesis. This finding is consistent with their distinct transcription kinetics, as Rarb mRNA was clearly induced as quickly as 1 hour post RA treatment, whereas Aldh1a2 mRNA exhibited a more delayed kinetics (Fig. S3D). In sum, RA-induction of Aldh1a2 mRNA in Spleen-DC appears to occur indirectly in a process that requires prior de novo protein synthesis.

Of note, although Spleen-DC acquired Raldh activity when pre-treated with RA for 24 hours, this was not observed when DC were exposed to RA for 30 min (i.e., only during the Aldefluor assay) (Fig S3E). Moreover, MLN-DC maintained the same high Raldh activity regardless of whether the mice were supplemented or not with oral RA (Fig S3F). Thus, RA does not appear to directly induce, enhance or otherwise affect Raldh enzymatic activity, suggesting that its main effect on DC education involves de novo Aldh1a2 mRNA and Raldh protein induction.

To assess whether RA can also educate extra-intestinal DC in vivo, we treated mice with RA via oral gavage and then analyzed PLN-DC for their expression of Aldh1a2 mRNA, Raldh activity and gut-homing imprinting capacity (Fig. 4A). As expected, PLN-DC from control mice expressed much lower levels of Aldh1a2 mRNA and Raldh activity as compared to MLN-DC (Fig. 4B, C and Fig. S4A). By contrast, PLN-DC from mice treated with oral RA exhibited significantly higher levels of Aldh1a2 mRNA and Raldh activity than PLN-DC from control mice. Moreover, PLN-DC from RA-treated mice were able to induce gut-homing receptors on activated T cells, an effect that was dependent on the presence of retinol and Raldh activity (Fig. 4D), demonstrating that it required active RA biosynthesis.

We did not detect RA in PLN from untreated animals, even using the most sensitive methods, whereas RA was readily detected in PLN from RA-treated animals with levels approaching those found in MLN from untreated animals (Fig. S4B). Moreover, luciferase activity in PLN cells from RA-treated DR5-luciferase mice was similar to that in MLN or PP cells from control animals (Fig. S4C).

Of note, RA supplementation was associated with increased proportions of activated CCR9+ CD8 T cells in PLN and spleen upon s.c. immunization, reaching levels comparable to
control MLN (Fig. S4D). Thus, oral RA treatment increases RA concentration and RA-dependent activity in PLN to levels comparable to those in the normal MLN environment, suggesting that RA or other RAR agonists, such as 13-cis RA (isotretinoin) (Fig. 3A), could be used as “mucosal adjuvants” to increase gut-associated immune responses in peripheral compartments.

In summary, our data show that RA is sufficient to induce a positive feedback loop in extra-intestinal DC, conferring them with the capacity to synthesize RA and to generate gut-homing T cells in vitro and in vivo.

RA-mediated DC education requires ERK/MAPK signaling

To obtain further mechanistic insights on how RA educates DC we tested the role of canonical signaling pathways in RA-mediated DC education by adding pharmacological inhibitors concomitant with RA treatment. Blockade of p38/MAPK (SB203580), JNK/MAPK (SP600125) or NF-κB (SN50) pathways did not affect RA-mediated DC education (Fig. 5A). However, inhibition of ERK/MAPK (U0126) during RA treatment of DC significantly decreased their capacity to induce gut-homing receptors on T cells. Moreover, blocking ERK completely abolished Aldh1a2 mRNA induction in RA-DC (Fig. 5B), indicating that ERK signaling is required for RA-mediated DC education. Interestingly, ERK inhibition in Spleen-DC isolated from DR5-luciferase mice abrogated RA-mediated luciferase induction (Fig. 5C), suggesting that ERK signaling might be required for general RAR-dependent effects on DC.

To assess whether ERK signaling plays a physiological role in gut-associated DC education, we treated mice with PD0325901, an orally bioavailable ERK inhibitor that has been recently used in vivo. Consistent with a physiological role of ERK signaling in gut-associated DC education, treatment with PD0325901 significantly decreased Raldh activity in endogenous CD103+ MLN-DC (Fig. 5D), without decreasing the frequency of CD103+ DC in MLN (data not shown).

Thus, ERK signaling is needed for RA-mediated DC education and is also required in vivo for endowing gut-associated DC with RA-synthesizing capacity.

MyD88 is required for RA-mediated DC education

Given that some TLR-agonists can induce Raldh enzymes in DC in an ERK-dependent manner and that RA-mediated DC education also requires ERK signaling, we explored whether TLR signals might modulate RA effects on DC. Consistent with this possibility, Spleen-DC from mice lacking MyD88 (essential for most TLR signaling) were impaired in their RA-mediated DC education. MyD88−/− RA-DC induced lower levels of gut-homing receptors on T cells as compared to wild type RA-DC (Fig. 6A) and the induction of Aldh1a2 mRNA was completely abrogated in MyD88−/− RA-DC (Fig. 6B). Similarly, Tgm2 mRNA (encoding tissue transglutaminase, a well-known RA target gene) was not induced in MyD88−/− RA-DC, whereas it was readily induced in wild type RA-DC (Fig. 6B), suggesting that MyD88 fulfills a more general role in RA-mediated effects on DC. Of note, DC subset composition and maturation status were comparable in MyD88−/− and wild type Spleen-DC (data not shown).

Next, we asked whether MyD88 was required in vivo for RA-mediated DC education. MyD88−/− or wild type mice were orally supplemented with RA. Spleen-DC from RA-treated mice were used to activate naïve CD8 T cells. PLN-DC isolated from RA-treated MyD88−/− mice exhibited lower Raldh activity than PLN-DC from RA-treated wild type mice (Fig. 6C and Fig. S5A). Moreover, Spleen-DC from RA-treated MyD88−/− mice induced lower levels of α4β7 and CCR9 on T cells as compared to Spleen-DC from RA-
treated wild type mice (Fig. S5B). In addition, the expression of the RA-induced gene Tgm2 was lower in MyD88−/− PP-DC as compared to wild type PP-DC, whereas Fabp4 mRNA, a PPARγ-RXR target gene, was expressed at similar levels in MyD88−/− and wild type PP-DC (Fig. S5C). These data suggest that MyD88 expression is necessary for RAR-RXR mediated effects on DC, but is not generally required for the activity of other nuclear receptors sharing the RXR nuclear receptor partner.

Wild type and MyD88−/− Spleen-DC did not differ in the expression of CrabpII and Fabp5 mRNA, which encode proteins that modulate RA signaling by channeling RA to either RAR-RXR or PPARβ/δ-RXR, respectively (Fig. S5D).

Interestingly, RA induced Tlr1 and Tlr2 mRNA (Fig. S5E). Thus, RA might contribute to sensitizing DC to TLR1/2 ligands, suggesting a potential intersection point between TLR- and RA-mediated effects on DC. In addition, RA induces Rarb mRNA in DC (Fig. S3C, D and Fig. S5E), hence exerting a positive feedback loop in its signaling.

We found that RA-mediated education was ERK dependent (Fig. 5) and it has been shown that TLR engagement results in ERK activation in DC. Moreover, RA has been shown to rapidly induce ERK phosphorylation, suggesting that ERK signaling might represent another potential intersection point between TLR- and RA-mediated signaling in DC. Therefore, we assessed whether RA can induce ERK phosphorylation in Spleen-DC from wild-type and MyD88−/− mice. Interestingly, although RA induced ERK1/2 phosphorylation in Spleen-DC, this effect was decreased on MyD88−/− DC (Fig. S5F, G). Of note, ERK phosphorylation was not affected in TLR4−/− Spleen-DC, hence excluding an effect due to LPS contamination. These results suggest that RA induces ERK1/2 phosphorylation, an effect that requires MyD88 expression in Spleen-DC.

The mechanism by which lack of MyD88 impairs RA-mediated ERK1/2 phosphorylation remains undefined, although we hypothesize that it might be related, at least in part, to decreased RA-mediated signaling. In fact, whereas wild type and MyD88−/− Spleen-DC did not differ in the expression of most RAR and RXR isoforms, Rarb mRNA (encoding RARβ) was not detected in MyD88−/− Spleen-DC (Fig. 6D), suggesting that lack of RARβ might explain, at least in part, the decreased RA-mediated education on MyD88−/− DC. In agreement with this possibility, LE540, a predominantly RARβ inhibitor, completely abrogated RA-mediated Aldh1a2 induction (Fig. 6E) and RA-induced luciferase activity in Spleen-DC from DR5-luciferase mice (Fig. 6F). Thus, the mechanism by which MyD88 controls RA-mediated effects on DC might involve RARβ modulation.

**TLR signals contribute to RA-mediated DC education**

Since our data suggest that MyD88 is critical for RA-mediated DC education, we hypothesized that TLR-agonists contribute to DC education. Consistent with this possibility, human Mo-DC treated with RA and/or a TLR1/2-agonist (Pam3CSK4) exhibited higher Raldh activity as compared to untreated Mo-DC (Fig. 7A). The increased Raldh activity in Mo-DC correlated with their ability to induce Foxp3 in human CD4 T cells (Fig. 7B). Moreover, mouse Spleen-DC or human Mo-DC treated with αβ7+ and CCR9+ T cells as compared to DC RA plus Pam3CSK4 induced higher proportions of treated with either RA or Pam3CSK4 alone (Fig. 7C, D). Moreover, TLR1/2 stimulation and RA synergized to confer Spleen-DC with the capacity to induce IgA-ASC upon B cell activation (Fig. 7E), an effect that correlated with the upregulation of April, Baff, and Nos2 in DC (encoding APRIL, BAFF and iNOS, respectively) (Fig. S6), all of which are important factors for inducing IgA-ASC. Of note, RA-treated human Mo-DC did not enhance IgA production by polyclonally activated human B cells (data not shown), suggesting that Mo-DC (differentiated with IL-4 and GM-CSF) are not permissive for IgA class-switching or that
there are some species-specific differences in this regard. Therefore, in addition to modulating RA synthesis and gut-homing imprinting, RA- and MyD88-dependent pathways synergize to confer DC with the capacity to induce Foxp3 T cells and IgA-ASC, which are hallmarks of mucosal-specific imprinting.

Discussion

RA is synthesized from all-trans retinol, which is obtained from the food as all-trans retinol, retinyl esters or β-carotenes (provitamin A) 26. Interestingly, we found that retinoids follow a proximal-to-distal gradient in the intestine, with the highest levels being found in the duodenum and jejunum. This retinoid gradient might be explained, at least in part, by differences in the absorption and/or synthesis of retinoids along the intestinal tract, which is supported by the higher levels of carotenoid receptor SI-B1 (scavenger receptor type B, class I) and carotenoid metabolizing enzyme BCMO1 (β,β-carotene-15,15′-monoxygenase 1) found in the proximal intestine as compared to ileum 27. A similar proximal-to-distal expression gradient has been described for cellular retinol binding protein (CRBP)-II and LRAT 28, which might contribute to further enhance the pool of retinol and retinyl esters found in the proximal intestine (see also Supp. Text-2).

A model in which RA is physiologically required to induce its own synthesis implies the existence of another (primary) source of RA to educate DC. In this regard, it has been shown that intestinal epithelial cells (IEC) express high levels of Raldh1 30,31 and can produce RA 7,32. In fact, in contrast to Raldh2 which is decreased in MLN-DC from VAD mice (our data and ref. 17), Raldh1 expression in IEC does not require RA 32,33, suggesting that IEC might be either “hard-wired” to synthesize RA or that their RA-synthesizing capacity depends on other environmental factors (e.g., TLR signals, microbiota). Thus, IEC might provide, at least in part, a primary supply of RA in the gut mucosa, which in turn induces Raldh2 in gut-associated DC, conferring them with RA-synthesizing capacity (see also Supp. Text-2).

A recent report suggested that GM-CSF is physiologically required for gut-associated DC education and that RA might be important for DC education by inducing GM-CSF-expressing macrophages in MLN 17. However, we did not observe impairment in Aldh1a2 mRNA expression, Raldh activity or gut-homing imprinting capacity in gut-associated DC from GM-CSF−/− mice (data not shown), suggesting that GM-CSF may not be essential for gut-associated DC education in vivo. These discrepancies could be partially explained by the fact that we used DC from mice deficient only in GM-CSF, whereas Yokota et al. isolated DC from mice deficient in the common β-c subunit, which is shared by GM-CSF, IL-3 and IL-5 receptors 17.

Similar to TLR2 stimulation 20, RA-mediated DC education also required signaling via ERK/MAPK. This finding is in line with previous studies showing that some RA-mediated effects depend on ERK/MAPK, but not on p38/MAPK or JNK/MAPK signaling 35. However, despite the fact that RA share some signaling mechanisms with TLR2 stimulation, including ERK/MAPK and MyD88, these pathways are not redundant, because we observed additive and even synergistic effects on DC education when pre-treating DC with RA and a TLR1/2-agonist (see also Supp. Text-3).

We show that RA is a critical factor in gut-associated DC education, which is necessary and sufficient to confer DC with key gut-specific imprinting properties, including the capacity to synthesize RA, imprint gut-tropic lymphocytes and TREG, as well as promote IgA-ASC differentiation (Fig. S7). Nevertheless, some of our results in murine DC were not
completely reproduced using human Mo-DC and further investigation will be needed to
determine whether there are some species-specific differences in this regard.

In conclusion, our data highlight an unexpected link between RAR nuclear receptor and
MyD88/TLR-dependent pathways, indicating that gut-associated DC specialization
integrates signals derived from both dietary components acting on nuclear receptors, and
from the intestinal microbiota acting via pathogen-recognition receptors. These signals could
be eventually manipulated to improve vaccination strategies aimed at enhancing intestinal
immunity.

**Supplementary Material**

Refer to Web version on PubMed Central for supplementary material.

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Figure 1. DC ability to imprint gut homing correlates with retinoid levels in the gut

(A) Quantification of retinyl esters, retinol and RA in duodenum (duo), jejunum (jej), ileum (ile) and colon (n=6). (B) LP-DC or PP-DC from duo, jej, ile, colon were used to activate naïve CD8 T cells. After 4–5 days T cells were analyzed for α4β7 and CCR9 expression (n=5). (C) DC were used to activate naïve CD4 T cells. After 4 days T cells were analyzed for Foxp3 expression. FACS plots are representative of two independent experiments. (D) Raldh activity in DC (n=4). (E) Luciferase activity in DC from DR5-luciferase mice (n=4).

Mean ± SEM, *p<0.05, **p<0.01, ***p<0.001
Figure 2. RA is necessary in vivo for gut-associated DC education

(A–G) DC were isolated from mice on a vitamin A deficient (VAD) or control diet. (A) DC were used to activate naïve CD8 T cells. After 4–5 days T cells were analyzed for α4β7 and CCR9 expression (n=4). (B) DC were used to activate naïve CD4 T cells. After 4–5 days T cells were analyzed for Foxp3 expression. FACS plots are representative of two independent experiments. (C) DC were co-cultured with naïve B cells activated with anti-IgM plus IL-5. After 4 days the co-cultures were analyzed for intracellular IgA in B220Int cells and IgA in the supernatant (n=4). (D) Aldh1a2 mRNA and (E) Raldh activity in CD11c+ and CD11c+CD103+ DC (n=5). (F) Raldh activity in CD11c+ DC from control or VAD mice ± oral RA supplementation. FACS plots are representative of two independent experiments. Mean ± SEM, *p<0.05, **p<0.01
Figure 3. RA is sufficient to confer DC with RA synthesizing capacity in vitro

(A) Aldh1a2 mRNA in Spleen-DC incubated for 24 h with 100 nM all-trans RA (RA) or 100 nM of the indicated nuclear receptor agonists. HX630 and PA024 were used at 1 or 10 μM, with similar results (n=5–10). (B–F) Spleen-DC were incubated for 24 h with or without 100 nM RA (RA-DC and UT-DC, respectively) and analyzed for (B) Raldh activity (n=5) or (C) washed, pulsed with antigen and used to activate naïve CD8 T cells from TCR transgenic OT-1xRAG2−/− mice in FBS-free media ± 50 nM retinol. After 4–5 days T cells were analyzed for α4β7 and CCR9 expression (n=7). (D) Co-cultures were performed as described in (C) either in the presence or absence of the Raldh inhibitor DEAB (n=7). (E) Competitive homing experiment between CD8 T cells activated with RA-DC or UT-DC (n=5). (F) Naïve CD4 T cells from OT-1xRAG2−/− mice were activated with UT-DC or RA-DC. Five days later CD4 T cells were analyzed for Foxp3 expression (n=3).
Figure 4. RA is sufficient to confer DC with RA synthesizing capacity in vivo

(A) Wild type mice were supplemented orally with RA (400 μg/dose) every other day for 6 days. After that, MLN-DC and PLN-DC were isolated and analyzed for the expression of (B) Aldh1a2 mRNA and (C) Raldh activity (n=5). (D) PLN-DC from control or RA-treated mice were used to activate naïve CD8 T cells in FBS-free media ± retinol and either in the presence or absence of DEAB. FACS plots are representative of two independent experiments. Mean ± SEM, *p<0.05, **p<0.01, ***p<0.001
Figure 5. DC education requires ERK/MAPK signaling

(A–C) Spleen-DC were incubated for 24 h with or without 100 nM RA and in the presence or the absence of inhibitors for p38 (SB203580, 10 μM), ERK (U0126, 10 μM), NF-κB (SN50, 50 μM) or JNK (SP600125, 50 μM). (A) DC were used to activate naïve CD8 T cells. After 4–5 days T cells were analyzed for α4β7 and CCR9 expression (n=9). (B) Aldh1a2 mRNA expression in DC (n=3). (C) Spleen-DC from DR5-luciferase mice were incubated for 24 h with or without RA and in the presence or absence of the ERK inhibitor (U0126, 10 μM) and analyzed for their luciferase activity (n=3). (D) Wild type mice were orally treated with the ERK inhibitor PD0325901 (25 μg/g/dose) every other day for 6 days. After that, CD11c+ MLN-DC were analyzed for CD103 expression and Raldh activity (n=5). Mean ± SEM, *p<0.05, **p<0.01
Figure 6. MyD88 is required for RA-mediated DC education

(A–B) Wild type or MyD88−/− spleen-DC were incubated with 100 nM RA for 24 h. (A) DC were used to activate naïve CD8 T cells. After 4–5 days T cells were analyzed for α4β7 and CCR9 expression (n=5). (B) Aldh1a2 (n=4) or Tgm2 (n=5) mRNA expression in DC.

(C) Wild type or MyD88−/− mice were supplemented orally with RA (400 μg/dose) every other day for 6 days and PLN-DC were analyzed for Raldh activity (n=7). (D) Spleen-DC from wild type or MyD88−/− mice were analyzed for their expression of Rara, Rarb, Rarg mRNA (n=4–6). ND: not detected. (E) Spleen-DC were incubated for 24 h with or without 100 nM RA and either in the presence or absence of the RAR® inhibitor LE540 (1 μM) and then analyzed for Aldh1a2 mRNA expression (n=3). (F) Spleen-DC from DR5-luciferase mice were incubated for 24 h with or without 100 nM RA and either in the presence or absence of LE540 and then analyzed for their luciferase activity (n=3). Mean ± SEM, *p<0.05, **p<0.001.
Figure 7. TLR signals contribute to RA-mediated human and murine DC education

(A) Monocyte-derived DC (Mo-DC) from healthy donors were treated with either RA (100 nM), Pam3CSK4 (0.5 μg/ml) or both from day 3 of differentiation. Raldh activity was analyzed at day 6 in CD11c+ cells (n=4). FACS plots show representative results in Mo-DC from two donors. (B) Mo-DC pretreated with either RA, Pam3CSK4 or both were washed and cultured with allogenic CD4 T cells activated with anti-CD3 plus anti-CD28 and hTGF-β1 (2 ng/ml). After 4 days, CD4 T cells were analyzed for Foxp3 expression. FACS plots show one representative experiment out of two. (C) Spleen-DC were incubated for 24 h in the presence of 100 nM of RA, Pam3CSK4 (0.5 μg/ml) or both, washed and used to activate naïve CD8 T cells. After 4 days, T cells were analyzed for their expression of α4β7 and CCR9. FACS plots are representative of three experiments. (D) Human Mo-DC were treated at day 6 with or without 100 nM of RA, Pam3CSK4 (0.5 μg/ml) or both for 24 h, washed and co-cultured with total human T cells activated with plate-bound anti-CD3 plus anti-CD28 antibodies. After 6 days, CD4 and CD8 T cells were analyzed for their expression of α4β7 (n=3). (E) Spleen-DC were incubated for 24 h in the presence of 100 nM of RA, Pam3CSK4 (0.5 μg/ml) or both, washed and co-cultured with naïve B cells activated with anti-IgM plus IL-5. After 4 days IgA levels were measured in the culture supernatants (n=7). Mean ± SEM, *p<0.05, ***p<0.001