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*J Immunol* published online 15 July 2011
http://www.jimmunol.org/content/early/2011/07/13/jimmunol.1101248

Supplementary Material
http://www.jimmunol.org/content/suppl/2011/07/13/jimmunol.1101248.DC1

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Vitamin A Deficiency Impairs Vaccine-Elicited Gastrointestinal Immunity

David R. Kaufman,* Jaime De Calisto,† Nathaniel L. Simmons,* Ashley N. Cruz,* Eduardo J. Villablanca,† J. Rodrigo Mora,† and Dan H. Barouch*,‡

Vitamin A deficiency is highly prevalent in much of the developing world, where vaccination programs are of paramount importance to public health. However, the impact of vitamin A deficiency on the immunogenicity and protective efficacy of vaccines has not been defined previously. In this article, we show that the vitamin A metabolite retinoic acid is critical for trafficking of vaccine-elicited T lymphocytes to the gastrointestinal mucosa and for vaccine protective efficacy in mice. Moderate vitamin A deficiency abrogated Ag-specific T lymphocyte trafficking to the gastrointestinal tract, gastrointestinal cellular immune responses, and protection against a mucosal challenge following immunization with a recombinant adenovirus vaccine vector. Oral vitamin A supplementation as well as retinoic acid administration fully restored the mucosal immune responses and vaccine protective efficacy. These data suggest that oral vitamin A supplementation may be important for optimizing the success of vaccines against HIV-1 and other mucosal pathogens in the developing world, highlighting a critical relationship between host nutritional status and vaccine efficacy. The Journal of Immunology, 2011, 187: 000–000.

The World Health Organization estimates that vitamin A deficiency affects >20% of preschool-age children and >10% of pregnant women in >50 countries, including much of Africa and southern and central Asia (1). These are regions where the burden of infectious diseases is high and where vaccination programs may bring enormous public-health benefits. However, the impact of vitamin A deficiency on vaccine-elicited cellular immunity has not been defined previously. Although some clinical and animal studies have shown reduced vaccine-elicited peripheral Ab production and seroconversion in the setting of vitamin A deficiency (2–5), the majority of studies have failed to demonstrate an impact of either vitamin A deficiency or supplementation on vaccine-elicited Ab responses (6). Comparable studies of vaccine-elicited cellular immunity and immunity at mucosal surfaces have not been performed previously.

We explored whether vitamin A may be specifically required for the induction of vaccine-elicited cellular immunity in the gastrointestinal tract, as the vitamin A metabolite all-trans retinoic acid (RA) has been shown to be critical for programming B and T lymphocytes to upregulate mucosal homing molecules and traffic to the gastrointestinal mucosa (7, 8). Although vitamin A deficiency has been shown to adversely impact the steady-state accumulation of T and B lymphocytes in the gastrointestinal mucosa (7), the impact of vitamin A deficiency on Ag-specific mucosal T cell responses has not been defined previously.

Gastrointestinal cellular immunity may be critical for vaccine-elicited protection against HIV-1 and other pathogens. HIV-1 preferentially targets CD4+ T lymphocytes within the gastrointestinal mucosa (9–12), resulting in chronic intestinal inflammation, breakdown of mucosal epithelial integrity, and translocation of gut microflora into the intestinal lamina propria (13). These processes drive systemic inflammation that contributes significantly to HIV-1 pathogenesis (13). Recombinant adenovirus (rAd)-based vectors are currently being investigated as HIV-1 vaccine candidates and have been shown to induce potent gastrointestinal cellular immunity in mice and rhesus monkeys (14) and to abrogate the mucosal destruction of CD4+ T lymphocytes following SIV infection (15). In this study, we demonstrate that vitamin A deficiency selectively impairs vaccine-elicited gastrointestinal immunity by interfering with RA-dependent upregulation of mucosal homing integrins, blocking the trafficking of Ag-specific T lymphocytes to the gastrointestinal tract, and abrogating protection from gastrointestinal infectious challenge.

Materials and Methods

Animals, vectors, treatments, and immunizations
rAd5, rAd26, and rAd5HVR48 vectors and pCMV plasmids expressing SIVmac239 Gag and Ova have been described previously (16–19). All immunizations were performed i.m. in 100 μl PBS divided equally between both quadriceps. rAd vectors were administered at a dose of 109 viral particles (VP). C57BL/6 (B6), B6.SJL, B6.PL, β integrin−/−, and Ova TCR-I and II (OT-I and OT-II) mice were obtained from The Jackson Laboratory. Vitamin A-deficient mice were generated at The Jackson Laboratory. Pregnant B6 and B6.SJL mice were maintained on a vitamin A-sufficient (4000 IU/kg; Harlan TD96007) or vitamin A-deficient (20,000 IU/kg; Harlan TD88407) diet through weaning. Pups were maintained on vitamin A-replete (20,000 IU/kg; Harlan TD88406), vitamin A-deficient (TD88407), or low vitamin A (400 IU/kg; Harlan TD99775) diets. Serum retinol levels were determined in serum by HPLC at 8 wk of age. FTY720 (Cayman Chemical) was administered daily at 1 mg/kg in DMSO by i.p. injection beginning at 48 h prior to immunization. All-trans RA (Sigma-Aldrich) was administered at 250 μg/mouse.

Abbreviations used in this article: DC, dendritic cell; LN, lymph node; OT-I, Ova TCR-I; OT-II, Ova TCR-II; RA, retinoid acid; rAd, recombinant adenovirus; rAd5-Ova, recombinant adenovirus serotype 5 vector expressing Ova; RALDH, retinaldehyde dehydrogenase; RP, retinyl palmitate; VP, viral particle; WT, wild-type.

Received for publication April 28, 2011. Accepted for publication June 9, 2011.

This work was supported by National Institutes of Health Grant K08 AI083079 (to D.R.K.) and by National Institutes of Health Grants U19 AI066305, U19 AI078526, and R01 AI069924 and Bill and Melinda Gates Foundation Grant 38614 (to D.H.B.).

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The online version of this article contains supplemental material.

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were isolated from inguinal and mesenteric LN, and aldehyde dehydrogenase activity in DC subsets was determined by Aldefluor assay. Error bars are SE. * p < 0.05.

Lymphocyte adoptive transfer studies

Lymphocytes were isolated from the spleens and cervical, axillary, and inguinal lymph nodes (LN) of naive OT-I or OT-II mice. CD4+ or CD8+ T lymphocytes were purified from pooled lymphocyte populations by negative selection using immunomagnetic beads (CD4+ and CD8+ T cell isolation kits; Miltenyi Biotec). OT-I CD8+ T lymphocytes were >95% pure by OT-I tetramer-binding assays. CD4+ T lymphocytes were >90% pure by immunophenotyping. Purified OT-I and OT-II lymphocytes were labeled with CFSE (Invitrogen), and 2.5 × 10^6 cells were transferred to recipient CD45-congenic (B6.SIL) mice by tail vein injection. Mice were immunized i.m. at 48 h following adoptive transfer with 10^9 VP rAd5-Ova. For competitive adoptive transfer studies, B6.PL (Thy1.1, CD45.1) and B6.129 (Thy1.2, CD45.2) mice were pooled at a 1:1 ratio, and 2.5 × 10^6 total Gag-specific CD8+ T lymphocytes were adoptively transferred to naive, CD45-congenic recipients (B6.SIL, CD45.1+). Mice were immunized i.m. at week 0 and week 6 with 10^9 VP rAd55-Gag.

Vaccine-elicited CD8+ T lymphocyte priming and mucosal homing marker upregulation. A total of 2.5 × 10^6 CFSE-labeled OT-I CD8+ T lymphocytes were adoptively transferred to naive, CD45-congenic recipients (B6.SIL; n = 8/group) that were untreated or treated i.p. from 48 h prior to immunization with FTY720. Mice were immunized i.m. in the quadriceps with 10^9 VP of each rAd vector. All animals used in this study were maintained in accordance with institutional guidelines, and all studies were approved by the institutional animal care and use committee of Beth Israel Deaconess Medical Center.

Mucosal lymphocyte isolation

Mucosal lymphocyte populations were isolated as described previously (14). Bowel specimens were digested with Liberase TL (0.15 mg/ml; Roche) and DNase 1 (325 U/ml; Sigma-Aldrich) in HBSS for 45 min at 37˚C. Remaining tissue was disrupted with Liberase TL (0.15 mg/ml; Roche) and DNase 1 (325 U/ml; Sigma-Aldrich). Total RNA from inguinal LN lysates was extracted using the RNeasy kit (Qiagen). Total RNA (2 μg) was used to synthesize cDNA using iSCRIPT cDNA Synthesis kit (Bio-Rad). Gene expression was quantified using TaqMan PCR master mix (Applied Biosystems) with primer probes for Cd45, Ccr9, and Aldh1a1 (Mm00657317_m1 and Mm00501306_m1; Applied Biosystems). Relative expression was calculated using the ACT method, and samples were normalized to β-actin. For Aldefluor assays, LN were digested with Liferase TL (0.15 mg/ml; Roche) and DNase 1 (325 U/ml; Sigma-Aldrich) in HBSS for 45 min at 37˚C. Remaining tissue was disrupted mechanically. Cells were incubated with anti-CD11c microbeads (Miltenyi Biotec) for 20 min and purified by positive magnetic selection. A purity of 90%–95% was achieved.

FIGURE 1. Vaccine-elicited CD8+ T lymphocyte priming and mucosal homing marker upregulation. A. Localization of vaccine-elicited CD8+ T lymphocyte priming. A total of 2.5 × 10^6 CFSE-labeled OT-I CD8+ T lymphocytes were adoptively transferred to naive, CD45-congenic recipients (B6.SIL; n = 8/group) that were untreated or treated i.p. from 48 h prior to immunization with FTY720. Mice were immunized i.m. in the quadriceps with 10^9 VP rAd5-Ova, and proliferation was assessed by CFSE dilution on day 3 following immunization. Numbers in black and red represent percentages of total and proliferating OT-I cells, respectively.

B. Dendritic cell isolation, Aldefluor assays, and real-time PCR

Biosciences (CD8α-PerCP-Cy5.5, [53-6.7], CD3-allophycocyanin [145-2C11], CD3-PE [145-2C11], [D1.1c-PerCP-Cy5.5 [HL3], CD19-PE [1D3], NK1.1-PE [PK136], and CD11b-PE [M1/70]) and eBioscience (CD45.1-PE-Cy7 [A20], CD45.2 allophycocyanin [104], Thy1.2-allophycocyanin [53-2.1] αβ, integrin-PE [DATK32], CCR9-PE [CW1.2], and CD103-allophycocyanin [2e7]). LIVE/DEAD Fixable Violet (Invitrogen) and Aldefluor (StemCell Technologies) were used according to the manufacturer’s instructions. Samples were analyzed using an LSRII flow cytometer (BD Biosciences) and Flio software (Tree Star).

Mucosal lymphocyte isolation

Mucosal lymphocyte populations were isolated as described previously (14). Bowel specimens were then digested with two serial 30-min incubations at 37˚C in RPMI 1640 medium containing 5% FBS supplemented with type II collagenase (Sigma-Aldrich) at 300 U/ml with vigorous shaking to release the lamina propria lymphocytes, which were purified on a Percoll gradient as described above.

Dendritic cell isolation, Aldefluor assays, and real-time PCR

Total RNA was extracted from inguinal LN lysates using the RNeasy kit (Qiagen). Total RNA (2 μg) was used to synthesize cDNA using iSCRIPT cDNA Synthesis kit (Bio-Rad). Gene expression was quantified using TaqMan PCR master mix (Applied Biosystems) with primer probes for Aldh1a1 and Aldh1a2 (Mm00657317_m1 and Mm00501306_m1; Applied Biosystems). Relative expression was calculated using the ACT method, and samples were normalized to β-actin. For Aldefluor assays, LN were digested with Liferase TL (0.15 mg/ml; Roche) and DNase 1 (325 U/ml; Sigma-Aldrich) in HBSS for 45 min at 37˚C. Remaining tissue was disrupted mechanically. Cells were incubated with anti-CD11c microbeads (Miltenyi Biotec) for 20 min and purified by positive magnetic selection. A purity of 90%–95% was achieved.

FIGURE 1. Vaccine-elicited CD8+ T lymphocyte priming and mucosal homing marker upregulation. A. Localization of vaccine-elicited CD8+ T lymphocyte priming. A total of 2.5 × 10^6 CFSE-labeled OT-I CD8+ T lymphocytes were adoptively transferred to naive, CD45-congenic recipients (B6.SIL; n = 8/group) that were untreated or treated i.p. from 48 h prior to immunization with FTY720. Mice were immunized i.m. in the quadriceps with 10^9 VP rAd5-Ova, and proliferation was assessed by CFSE dilution on day 3 following immunization. Numbers in black and red represent percentages of total and proliferating OT-I cells, respectively. C. Kinetics of induction of Aldh1a1 and Aldh1a2 RNA, encoding RALDH1 and RALDH2, following rAd immunization. C57BL/6 mice (n = 4/group) were immunized IM with 10^9 VP rAd55-Gag. RALDH expression was determined in inguinal LN by real-time PCR. D. DC aldehyde dehydrogenase activity following rAd immunization. B6 mice (n = 4/group) were immunized as in D. DC were isolated from inguinal and mesenteric LN, and aldehyde dehydrogenase activity in DC subsets was determined by Aldefluor assay. Error bars are ± SE, *p < 0.05.
98% CD11c+ cells was routinely attained. Cell suspensions (1 × 10^6 cells/ml) were incubated for 45 min at 37°C in Aldefluor assay buffer containing activated Alfdefluor (StemCell Technologies). Cells were stained with specific mAbs and analyzed on an LSR-II flow cytometer (BD Biosciences). Background Aldefluor staining was <0.5% in the presence of the retinaldehyde dehydrogenase (RALDH) inhibitor diethylaminoenzaldehyde.

**Oral Listeria challenge**

*Listeria monocytogenes*-expressing Ova was a gift from F. Frankel (University of Pennsylvania). Mice were fasted overnight and challenged orally with 10^10 CFU Lm-Ova in PBS by gavage. At day 3 following oral challenge, livers were harvested and homogenized in 1.5 ml PBS/1% saponin. Serial dilutions were plated on brain heart infusion agar plates, and quantitative colony counts were performed following a 36-h incubation at 30°C. The identity of bacterial colonies was confirmed by PCR for the Ova insert.

**Statistical analyses**

Statistical analyses were performed with GraphPad Prism version 4.01 (GraphPad Software). Immune responses among groups of mice are presented as means with SEs. Comparisons of mean immune responses were performed using two-sided t tests or Fisher’s exact test. In all cases, p < 0.05 was considered significant.

**Results**

We next assessed the induction of αβ7 integrin in CCR9, cell surface molecules critical for lymphocyte homing to the small intestine (23–25), on vaccine-elicited CD8+ T lymphocytes. At 60 h following immunization, αβ7 integrin was upregulated on 30–65% of responding cells in the spleen, mesenteric LN, and Peyer’s patches (Fig. 1B). CCR9 was initially downregulated during the first three to four rounds of cell division but was subsequently upregulated on 20–30% of responding cells that had trafficked to mesenteric LN and Peyer’s patches (Fig. 1B). Peripheral αβ7 integrin and CCR9 upregulation peaked on day 3 following immunization and then rapidly declined (Fig. 1C), consistent with previous observations (26). Thus, peripheral vaccine-elicited CD8+ T lymphocytes exhibited a marked induction of gastrointestinal homing markers within the first few days following immunization.

RA regulates the expression of αβ7 integrin and CCR9 on T and B lymphocytes (7, 8). Although a subset of mucosal dendritic cells (DC) constitutively produces RA (7, 27, 28), peripheral DC can produce RA inductively when activated through TLR (29). Therefore, we evaluated RA production at the anatomic sites of vaccine-elicited CD8+ T lymphocyte priming and early trafficking. In the inguinal LN draining the inoculation site, i.m. immunization with 10^9 VP rAd5 induced a transient 3-fold induction of the retinaldehyde dehydrogenase isoform RALDH1 and a marginal induction of RALDH2, as measured by real-time PCR at 8 h following immunization (Fig. 1D). p < 0.05 using a two-tailed t test for RALDH1, consistent with previous in vitro observations (26). This was accompanied by a comparable and transient 1.5-fold increase in aldehyde dehydrogenase activity in inguinal LN CD11c+CD103+ DC at 24 h following immunization (Fig. 1E). In contrast, mesenteric LN DC exhibited a high basal level of aldehyde dehydrogenase activity that was restricted primarily to the CD11c+CD103+ subset and was not affected by rAd immunization, as expected (Fig. 1E). These data suggest that vaccine-elicited CD8+ T lymphocytes encountered RA first during local priming in inguinal LN and subsequently following trafficking to mucosal lymphoid inductive sites.

We determined the functional significance of vaccine-induced αβ7 integrin upregulation by comparing the anatomic trafficking patterns of vaccine-elicited CD8+ T lymphocytes from WT and β7 integrin-deficient mice. Mice were immunized with a heterologous rAd26/rAd5HV48 prime-boost regimen using vectors expressing SIV Gag (14) to generate high frequencies of circulating Gag-specific CD8+ T lymphocytes (15–20% of total CD8+ T lymphocytes; data not shown). Peripheral WT and β7 integrin-deficient Gag-specific CD8+ T lymphocytes were then purified and transferred i.v. in a 1:1 ratio to naive recipients in competitive
adoptive transfer studies. WT and β7 integrin-deficient CD8+ T lymphocytes expressed distinct congenic markers, allowing their trafficking efficiency to be compared at multiple anatomic sites (Fig. 2A). Gag-specific CD8+ T lymphocytes from WT and β7 integrin-deficient mice trafficked with comparable efficiency to the spleen and inguinal LN, as expected. However, β7 integrin-deficient lymphocytes were selectively impaired in their capacity to traffic to mesenteric LN, Peyer’s patches, and mucosa of the small and large intestine (Fig. 2B; p < 0.005 for each comparison using two-tailed t tests), showing the importance of β7 integrin-dependent mechanisms for vaccine-elicited CD8+ T lymphocyte trafficking to the gastrointestinal tract.

We next assessed the impact of vitamin A deficiency on mucosal homing marker upregulation on vaccine-elicited CD8+ T lymphocytes. Naive CFSE-labeled OT-I lymphocytes from healthy mice were adoptively transferred to recipient mice that were bred from gestation on either a normal diet or a vitamin A-deficient diet. Following i.m. immunization with 10⁹ VP rAd5-Ova, total CD8+ T lymphocyte proliferation was comparable in both groups of mice at 60 h following immunization (Fig. 3A). However, α4β7 integrin upregulation on proliferating CD8+ T lymphocytes was markedly abrogated in animals that received the vitamin A-deficient diet (Fig. 3A). α4β7 integrin upregulation on proliferating CD4+ T lymphocytes was also abrogated in mice fed the vitamin A-deficient diet (Supplemental Fig. 1). Intraperitoneal administration of RA to animals fed the vitamin A-deficient diet completely restored α4β7 integrin upregulation (Fig. 3A), indicating that RA can fully compensate for the defective induction of mucosal homing markers induced by vitamin A deficiency.

Mice bred on a vitamin A-deficient diet had a mean serum retinol level of 0.42 μmol/l, whereas mice bred on a diet containing 400 IU/kg vitamin A had a mean serum retinol level of 0.77 μmol/l (Fig. 3B). On the basis of World Health Organization-defined levels for severe (<0.35 μmol/l) or moderate (<0.7 μmol/l) vitamin A deficiency in humans (1), these data suggest that mice that received the vitamin A-deficient diet and the low vitamin A diet exhibited physiologically relevant moderate and mild levels of vitamin A deficiency, respectively. In contrast, mice bred on the control diet had a mean serum retinol level of 1.33 μmol/l, within the normal range for humans (30). α4β7 integrin upregulation on vaccine-elicited CD8+ T lymphocytes was dramatically abrogated in moderately vitamin A-deficient mice but was also partially decreased in mice with only mild levels of vitamin A deficiency (Fig. 3C; p < 0.05 for each comparison with control animals). Vaccine-elicited α4β7 integrin induction was completely restored in moderately vitamin A-deficient mice that received either a normal vitamin A-containing diet for 1 wk prior to immunization or two oral doses of RP, a vitamin A formulation commonly used for dietary supplementation in humans (Fig. 3C). These data demonstrate that clinically relevant levels of vitamin A deficiency and typical dietary supplementation regimens markedly impacted vaccine-elicited mucosal homing marker upregulation.

**FIGURE 3.** Vaccine-induced mucosal homing marker upregulation is abrogated by vitamin A deficiency but restored by RA or oral vitamin A. A, Mucosal homing marker upregulation in vitamin A-deficient hosts. A total of 2.5 × 10⁶ CFSE-labeled OT-I CD8+ T lymphocytes were adoptively transferred to vitamin A-sufficient or vitamin A-deficient, CD45-congenic recipients (B6.SJL; n = 4/group). RA supplementation was given as indicated on days −1 and +1 relative to immunization. Recipient mice were immunized i.m. with 10⁹ VP rAd5-Ova. total CD8+ T lymphocyte proliferation was compared in both groups of mice at 60 h following immunization (Fig. 3A). However, α4β7 integrin upregulation on proliferating CD8+ T lymphocytes was markedly abrogated in animals that received the vitamin A-deficient diet (Fig. 3A). α4β7 integrin upregulation on proliferating CD4+ T lymphocytes was also abrogated in mice fed the vitamin A-deficient diet (Supplemental Fig. 1). Intraperitoneal administration of RA to animals fed the vitamin A-deficient diet completely restored α4β7 integrin upregulation (Fig. 3A), indicating that RA can fully compensate for the defective induction of mucosal homing markers induced by vitamin A deficiency.

B, Serum retinol levels were determined by HPLC in mice (n = 8/group) bred on vitamin A-sufficient, vitamin A-deficient, or 400 IU/kg vitamin A diets. *p = 0.05, **p < 0.001. C, Adoptive transfer and immunization were performed as in A using mice (n = 4/group) bred on the indicated diets. Oral vitamin A supplementation was provided either by gavage with 600 IU RP on days −1 and −3 relative to immunization or with a vitamin A-sufficient diet for 1 wk prior to immunization. Error bars are ± SE. *p < 0.005.
We next evaluated the impact of vitamin A deficiency on vaccine-elicited, Ag-specific cellular immune responses. Control mice and mice with moderate vitamin A deficiency were immunized i.m. with 10^9 VP of a rAd vector expressing SIV Gag, and Gag-specific CD8+ T lymphocyte responses were observed in the peripheral blood of vitamin A-replete and moderately vitamin A-deficient animals (Fig. 4A, Supplemental Fig. 2). In contrast, Gag-specific CD8+ T lymphocyte responses were dramatically abrogated in the small intestine and were moderately reduced in the large intestine of the mice with moderate vitamin A deficiency (Fig. 4A, Supplemental Fig. 2; p = 0.005 in by two-tailed t tests). The less dramatic effect of vitamin A deficiency in the large intestine likely reflects compensatory α4β7 integrin- and CCR9-independent mechanisms of T lymphocyte trafficking (31, 32). Importantly, administration of either i.p. RA or oral RP prior to immunization fully restored Gag-specific CD8+ T lymphocyte responses in the gastrointestinal mucosa (Fig. 4A).

To investigate the impact of vitamin A deficiency on vaccine protective efficacy against a mucosal challenge, we infected control and moderately vitamin A-deficient mice orally with the gastrointestinal pathogen L. monocytogenes expressing Ova (rLm-Ova) (33). Protective efficacy was assessed by determining bacterial loads in the liver on day 3 following challenge to quantitate bacterial translocation from the intestine (34). To evaluate vaccine-induced cellular immune protection, mice were immunized i.m. with 10^9 VP of a rAd vector that expressed the immunodominant CD8+ T cell epitope from Ova (rAd5-SIINFEKL). Immunization with rAd5-SIINFEKL afforded significant protective efficacy against oral Lm-Ova challenge, as evidenced by a substantial reduction of bacterial loads following challenge of vaccinated mice as compared with unvaccinated mice (Fig. 4B; p < 0.05 by Fisher’s exact test). Importantly, this vaccine-elicited protection was dramatically abrogated in vaccinated mice with moderate vitamin A deficiency (Fig. 4B; p < 0.05) but could be fully restored by oral RP administration immediately prior to vaccination (Fig. 4B; p < 0.05).

**Discussion**
Vitamin A deficiency remains an important public-health problem in the developing world. Recent meta-analyses suggest that vitamin A supplementation can significantly reduce all-cause and diarrheal

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**FIGURE 4.** Vitamin A deficiency abrogates vaccine-elicited protection from gastrointestinal mucosal challenge. A. Control and vitamin A-deficient B6 mice (n = 8/group) were immunized i.m. with 10^9 VP rAd5HVR48-Gag. At week 2 following immunization, Gag-specific CD8+ T lymphocyte responses were assessed in the blood and small bowel mucosa by D^7/AL11 tetramer-binding assays. Mice were supplemented as indicated with RA at days −1 and +1 relative to immunization or orally with RP at days −3 and −1 relative to immunization. Error bars are ±SE. B. Vitamin A-replete or -deficient CB6 mice were immunized i.m. with 10^9 VP rAd5-luc-SIINFEKL. Oral vitamin A supplementation was provided by gavage with 600 IU RP on days −1 and −3 relative to immunization. At day 21 following immunization, mice were challenged orally with Lm-Ova by gavage. At day 3 following challenge, liver homogenates were prepared, and quantitative colony counts were performed by plating serial dilutions of the homogenates. *p < 0.05, **p < 0.005. IEL, intraepithelial lymphocyte; LPL, lamina propria lymphocyte.
disease-specific mortality in infants and children in this setting (35, 36), whereas a benefit of vitamin A supplementation in preventing mortality from other causes such as measles, respiratory diseases, or HIV is not evident (35–37). Moreover, vitamin A supplementation has specifically been shown to reduce the prevalence and clinical severity of gastrointestinal norovirus infections while prolonging viral shedding (38). It is unknown whether specific immunologic mechanisms underlie these effects. In particular, no studies have yet explored whether specific defects in RA-mediated T and B lymphocyte trafficking to mucosal surfaces underlie the clinical outcomes observed in these studies.

Clinical studies that have evaluated the impact of vitamin A deficiency or supplementation on vaccine-elicited immunity have primarily focused on seroconversion or peripheral immune responses as immunologic end points and have not evaluated responses at mucosal surfaces (6). These studies have typically been performed using vaccines that have a high rate of peripheral seroconversion such as tetanus, measles, and polio (4, 26, 34, 39–44). A preponderance of these studies has failed to demonstrate a significant effect of vitamin A deficiency or supplementation on peripheral vaccine-elicited immunity. Studies in animal models have shown that severe vitamin A deficiency can impact peripheral B cell development, germinal center formation, and Ag-specific Ab responses (33). However, the impact of vitamin A deficiency on vaccine-induced gastrointestinal immunity has not been previously described in either clinical studies or animal models, despite the critical importance of gastrointestinal immunity for protection against HIV-1 and other mucosal pathogens. Our data define key molecular mechanisms that account for gastrointestinal cellular immunity elicited by rAd vaccine vectors and, to our knowledge, demonstrate for the first time the impact of vitamin A deficiency on vaccine-induced gastrointestinal cellular immune protection. Vitamin A and its metabolite RA potentiate vaccine-elicited gastrointestinal cellular immune responses by upregulating mucosal homing receptors on Ag-specific CD8+ T lymphocytes, likely first in draining LN and subsequently in mucosal inductive sites. These responses are selectively abrogated in mice with moderate vitamin A deficiency but can be fully restored by the administration of oral RP at the time of vaccination. Similar results were seen following i.m. immunization of plasmodium DNA vaccines (Supplemental Fig. 3), suggesting the generalizability of our findings for other vaccine platforms.

Previous studies have shown that T lymphocytes transiently upregulate gastrointestinal homing markers following activation by a wide variety of antigenic stimuli, including systemic infection or infection localized outside of the gastrointestinal tract (23, 26, 35). We demonstrate that transient gastrointestinal homing marker induction also occurs when T cell priming is restricted to a peripheral lymphoid inductive site following i.m. immunization. Moreover, our data demonstrate that this phenomenon is not part of the intrinsic T lymphocyte activation program but rather is dependent on exogenous vitamin A and RA and therefore adversely impacted in the setting of vitamin A deficiency. Although the RA dependence of T lymphocyte mucosal homing marker upregulation has been well documented in vitro (7, 45, 46), our data demonstrate that vitamin A-derived RA is also strictly required for mucosal homing marker induction in vivo.

Our data demonstrate that oral vitamin A supplementation at the time of vaccination is critical for mucosal immune responses and protective efficacy in mice. Although our current studies are restricted to a murine model, the dramatic abrogation of gastrointestinal cellular immunity at clinically relevant levels of vitamin A deficiency and the complete restoration of these responses by oral vitamin A supplementation suggests potential clinical implications of these results. Given the high prevalence of vitamin A deficiency, our data suggest that oral vitamin A supplementation may be critical for optimizing the success of vaccines against mucosal pathogens in the developing world. Moreover, our findings highlight a critical mechanism that links nutritional status with vaccine protective efficacy.

Acknowledgments
We thank F. Frankel, D. Lynch, E. Rhee, H. DaCosta, M. Lifton, V. Toxavidis, J. Tiggles, L. Stone, and F. Stephens for generous advice and assistance.

Disclosures
The authors have no financial conflicts of interest.

References


SUPPLEMENTAL FIGURE 1. Vaccine-induced mucosal homing marker upregulation on CD4+ T-lymphocytes is abrogated by vitamin A deficiency. CFSE-labeled OT-II CD4+ T-lymphocytes, which express a transgenic T-cell receptor specific for a MHC class II-restricted peptide from Ova, were adoptively transferred to vitamin A-sufficient or vitamin A-deficient recipients (C57.SJL; n=4/group). Recipient mice were immunized IM with 10⁹ VP rAd5-Ova. Proliferation and α4β7 integrin upregulation were determined at day 3 following immunization by multiparameter flow cytometry. A representative experiment is shown.

SUPPLEMENTAL FIGURE 2. Vitamin A deficiency abrogates gastrointestinal but not mucosal vaccine-elicited CD8+ T-lymphocyte responses. Control and vitamin A deficient C57BL/6 mice (n=8/group) were immunized IM with 10⁹ VP rAd5HVR48-Gag. At week 2 following immunization, Gag-specific CD8+ T-lymphocyte responses were assessed in the blood and small bowel mucosa by D<sup>b</sup>/AL11 tetramer-binding assays. Mice were supplemented as indicated with RA at days -1 and +1 relative to immunization or orally with RP at days -3 and -1 relative to immunization. LPL: lamina propria lymphocytes. IEL: intraepithelial lymphocytes. A representative experiment is shown here; collated data for n=8/group are shown in Fig. 4a.

SUPPLEMENTAL FIGURE 3. Mucosal homing marker upregulation is abrogated by vitamin A deficiency following plasmid DNA vaccination. A, Anatomic distribution of vaccine-elicited CD8+ T-lymphocyte responses following plasmid DNA immunization. C57BL/6 mice were immunized IM with 50 µg pCMV-Gag. Gag-specific CD8+ T-lymphocyte responses were evaluated in each anatomic compartment at day 14 following immunization by D<sup>b</sup>/AL11
tetramer-binding assays. B, DNA-induced α4β7 integrin upregulation is abrogated in the setting of vitamin A deficiency. CFSE-labeled OT-1 lymphocytes from vitamin A sufficient animals were adoptively transferred to control or vitamin A-deficient CD45-congenic recipients (C57.SJL, n=4/group). Recipient animals were immunized IM with 50 µg pCMV-Ova and α4β7 integrin upregulation was assessed on proliferating CD8+ T-lymphocytes by multiparameter flow cytometry. Error bars are +/- S.E.