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The effects of vitamin A supplementation with measles vaccine on leucocyte counts and in vitro cytokine production

Kristoffer Jarlov Jensen1,2,3*, Ane Bærent Fisker1,2, Andreas Andersen2, Erliyani Sartono4, Maria Yazdanbakhsh1, Peter Aaby1,2, Christian Erikstrup5 and Christine Stabell Benn1,2,6

1 Bandim Health Project, INDEPTH Network, Apartado 861, Bissau Codex 1004, Bissau, Guinea-Bissau
2 Research Center for Vitamins and Vaccines, Bandim Health Project, Statens Serum Institut, Artillerivej 5, DK-2300 Copenhagen S, Denmark
3 Section for Immunology and Vaccinology, National Veterinary Institute, Technical University of Denmark, Bülowsvej 27, DK-1870 Frederiksberg C, Denmark
4 Leiden University Medical Center, Gebouw 1, Kamer P4-25a, Postbus 9600, 2300 RC Leiden, The Netherlands
5 Department of Clinical Immunology, Aarhus University Hospital, Palle Juul-Jensens Boulevard 99, DK-8200 Aarhus, Denmark
6 Odense Patient data Explorative Network (OPEN), Department of Clinical Research, Odense University Hospital, J.B. Winsløws Vej 9A, 3, DK-5000 Odense C, Denmark

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Abstract
As WHO recommends vitamin A supplementation (VAS) at vaccination contacts after age 6 months, many children receive VAS together with measles vaccine (MV). We aimed to investigate the immunological effect of VAS given with MV. Within a randomised placebo-controlled trial investigating the effect on overall mortality of providing VAS with vaccines in Guinea-Bissau, we conducted an immunological sub-study of VAS placebo with MV, analysing leucocyte counts, whole blood in vitro cytokine production, vitamin A status and concentration of C-reactive protein (CRP). VAS compared with placebo was associated with an increased frequency of CRP ≥ 5 mg/l (28 vs. 12%; P = 0.005).

Six weeks after supplementation, VAS had significant sex-differential effects on leucocyte, lymphocyte, monocyte and basophil cell counts, decreasing them in males but increasing them in females. Mainly in females, the effect of VAS on cytokine responses differed by previous VAS: in previous VAS recipients, VAS increased the pro-inflammatory and T helper cell type 1 (Th1) cytokine responses, whereas VAS decreased these responses in previously unsupplemented children. In previous VAS recipients, VAS was associated with increased IFN-γ responses to phytohaemagglutinin in females (geometric mean ratio (GMR): 3.97; 95% CI 1.44, 10.90) but not in males (GMR 0.44; 95% CI 0.14, 1.42); the opposite was observed in previously unsupplemented children. Our results corroborate that VAS provided with MV has immunological effects, which may depend on sex and previous VAS. VAS may increase the number of leucocytes, but also repress both the innate and lymphocyte-derived cytokine responses in females, whereas this repression may be opposite if the females have previously received VAS.

Key words: Vitamin A supplementation: Paediatric nutrition: Cytokines: Differential count: Heterologous immunity: Inflammation

Vitamin A is important for fundamental immunological functions, including modulation of differentiation, maturation, migration or activation of dendritic cells, T cells and NK cells(1). The WHO estimates that 190 million children under the age of 5 years worldwide are at risk of vitamin A deficiency (VAD), especially in Africa and South East Asia(2). To alleviate and prevent VAD, the WHO recommends high-dose vitamin A supplementation (VAS) at routine vaccination contacts after 6 months of age(3). According to the current vaccination schedule, the first vaccine to be given after the age of 6 months is the measles vaccine (MV) scheduled at age 9 months(4).

Vaccines may have effects on overall mortality and morbidity beyond the specific protection against the targeted disease – the so-called non-specific effects(5). Many studies have shown that live attenuated MV has beneficial effects on mortality far exceeding what can be ascribed to the prevention of measles cases, presumably due to immune-modulating effects, leading to increased resistance towards unrelated infections(5–7).

Abbreviations: CRP, C-reactive protein; GMR, geometric mean ratio; MV, measles vaccine; PHA, phytohaemagglutinin; PR, proportion ratio; RBP, retinol-binding protein; VAD, vitamin A deficiency; VAS, vitamin A supplementation.
* Corresponding author: K. J. Jensen, email kjj@ssi.dk
† Data and study protocol are available upon request to the corresponding author.
Several studies have suggested that high-dose VAS and vaccines interact with effects on overall mortality and morbidity. Our group has previously found that VAS together with MV increases the MV-specific antibody response\(^9\).\(^{10}\) We have hypothesised that VAS may enhance both the measles-specific and the non-specific effects of MV via beneficial general immune-stimulating effects\(^9\).\(^{10}\)

In Guinea-Bissau, from 2007 to 2011, before the implementation of the WHO policy of giving VAS at vaccination contacts, we conducted a randomised placebo-controlled trial to evaluate the effect of this recommendation. At vaccination contacts after 6 months of age, children were randomised to VAS or placebo, the main outcomes being all-cause child mortality and morbidity.

Nested within the trial, we performed a sub-study to investigate the effects of VAS together with MV on non-measles-specific immunological outcomes. At baseline and 6 weeks after randomisation, we measured vitamin A levels, C-reactive protein (CRP) levels, differential counts and \textit{in vitro} cytokine production to allow simultaneous evaluation of the effect of VAS on different parts of the immune system.

Prompted by previous studies showing that the effect of VAS on morbidity or mortality depends on sex\(^{11}\).\(^{12}\), season of supplementation\(^1\) or previous high-dose VAS\(^1\), we pre-specified to investigate the possible interactions between VAS, sex, season of supplementation and previous VAS. Indeed, the main trial corroborated that there are important interactions: there was no overall mortality effect of VAS, but the effect was sex-differential, with VAS being beneficial for females but detrimental for males. These sex-differential effects were most evident in the dry season and in children who had previously received VAS\(^1\).

\section*{Methods}

The present immunological sub-study was nested within a randomised trial of administering VAS \textit{v.} placebo together with routine vaccinations in Guinea-Bissau, described in detail elsewhere\(^1\).

\section*{Main trial}

Between August 2007 and November 2010, children aged between 6 and 23 months were invited to participate in the main trial when they came to the healthcare centres for routine vaccination. A study nurse inspected the vaccination cards and identified eligible children. VAS within the preceding month was an exclusion criterion. If parents provided oral and written consent, the children were randomised to vitamin A or placebo groups. Randomisation was stratified by child sex. Mothers drew a lot from an envelope containing twenty lots; ten for each treatment arm. The number on the lot indicated from which of the two numbered bottles the children would receive an oral supplement. Children under the age of 1 year received 0.5 ml; children who had reached 1 year of age received 1 ml. For the children in the VAS group, this meant that they received 100 000/200 000 IU vitamin A (retinyl palmitate) dissolved in vegetable oil with vitamin E added as an antioxidant (40 IU/ml).

Children in the placebo group received the same amount of oil with vitamin E. MV was supplied by UNICEF\(^1\). National VAS campaigns were conducted by the Ministry of Health approximately every 6 months. One month before the announced date of a campaign, inclusion into the main trial was paused in order to prevent children from receiving two doses of VAS within a month\(^1\). In the month following a campaign, we included only children who had not received VAS in the campaign.

\section*{The immunological sub-study}

Between September 2007 and June 2009, children who were due to receive MV were additionally invited to participate in the immunological sub-study. The mothers were explained that participation was voluntary and that participation in the main study was not contingent upon enrolment in the sub-study. Oral and written consent was obtained separately for the sub-study.

With consent, a blood sample was obtained before randomisation in the main trial to vitamin A or placebo. All children from whom we had obtained a blood sample at inclusion were visited by a field assistant 6 weeks after inclusion and were asked to visit the healthcare centres for the follow-up blood sample collection. If the child could not be found at home, the assistant kept revisiting the home until 100 d had passed since inclusion; the child was then registered as lost to follow-up.

\section*{Blood sampling procedures and analyses}

Before blood sampling, axillary temperature, weight and mid-upper arm circumference (MUAC) were measured, and the mother was interviewed about the health of the child, including symptoms of disease on the day of blood draw and use of medicines during the 3 d before blood draw. Venous blood was drawn into a heparinised tube and an EDTA tube. The EDTA tubes were kept in a cool box until arrival at the laboratory where they were left at ambient temperature to acclimatise before measurement. The heparinised blood was maintained at ambient temperature. A thick and thin blood slide was prepared for examination of malaria. The slides were Giemsa-stained and microscopically examined for malaria parasites by an experienced laboratory technician. All mothers were informed of the results of the malaria slide by a visiting field assistant on the following day. None of the children had positive malaria slides.

\section*{Leucocyte counts}

Automated differential counts were performed on blood collected in EDTA tubes using an ABX pentra 60 (HORIBA ABX). The accuracy and precision of measurements were validated at regular intervals using a commercial standard preparation (ABX Diffrot; HORIBA ABX). After the analyses, the EDTA tubes were centrifuged to separate plasma.

\section*{Retinol-binding protein and C-reactive protein}

Plasma was analysed for retinol-binding protein (RBP) and CRP. RBP and CRP were analysed using sandwich ELISA as described elsewhere\(^{17}\), except that the poly-clonal chicken anti-human RBP secondary antibody was from Immunology Consultants Laboratory (cat. no: CRBP-80P-Z). Before measurements, we
validated the performance of the antibody against the originally used antibody in collaboration with the developer of the assay (Jürgen Erhardt). Samples were measured in duplicate and re-measured if the CV between duplicates was above 20% for RBP and above 20% for samples with a mean value between 3 and 7 mg/l for CRP.

**Whole blood stimulation assay**

The heparinised blood was maintained at ambient temperature but shielded from direct sunlight until processing. The blood was diluted 1:10 with RPMI-1640 medium without glutamine with added streptomycin (100 µg/ml), penicillin A (100 IU/ml), glutamate (2 mM) and pyruvate (1 mM) (all from Invitrogen). Stimulations were performed in sterile multiwell plates (Nunc U-shape; NUNC) in a final volume of 200 µl using phytohaemagglutin (PHA, 2 µg/ml; Wellcome Diagnostics), Lipopolysaccharide (LPS, 1 ng/ml; Sigma-Aldrich Chemie), Polyinosine-polycytidylic acid (Poly I:C, 10 µg/ml; InvivoGen), palmitoyl(3)-cysteine-serine-lysine(4) (Pam3cys, 100 ng/ml; InvivoGen), purified protein derivative of Mycobacterium tuberculosis (PPD, 10 µg/ml; Statens Serum Institut), tetanus toxoid (TT, 1.5 IU/ml; Statens Serum Institut), Bacille Calmette-Guérin vaccine (BCG, 1:1000 of vaccine preparation; Statens Serum Institut), oral polio vaccine (OPV, 1:100 dilution of vaccine preparation; GlaxoSmithKline Biologicals) and diphtheria toxoid (DT, 1 IU/ml; Statens Serum Institut). Medium alone samples (medium) were included as well. Culture plates were incubated at 37°C/5% CO₂/100% humidity. Supernatants (the lower limit of detection LLD of the assay, defined by the manufacturer) were measured in duplicate and re-measured if the CV between duplicates was above 20% for RBP and above 20% for samples with a mean value between 3 and 7 mg/l for CRP.

**Sample size considerations**

In previous studies utilising a similar setup, we had observed significant differences in cytokine production using samples sizes of approximately 200 children in each group in a cross-sectional design. In the present study, we included baseline samples to reduce the intra-individual noise and the necessary sample size accordingly. With an expected 20% loss to follow-up, we aimed to include 125 children per group— that is, 100 children per group for the final analyses.

**Statistical analysis**

Analyses were performed using Stata 12 (StataCorp LP). Cytokine data were log transformed. For several of the cytokine outcomes, a proportion of the measurements was below the LLD of the assay, defined by the manufacturer (see above), and denoted here as non-detectable (ND) measurements. ND measurements were handled by multiple imputations based on Tobit regression \(^{(18,19)}\). The parameters of the underlying normal distribution are estimated by Tobit regression and values below the detection limit are drawn multiple times from a truncated normal distribution. The imputations incorporate the correlation between baseline and follow-up samples. Geometric mean ratios (GMR) were obtained as anti-logged coefficients. For distributions with >50% ND measurements, the proportion of detectable samples was analysed by Poisson regression giving proportion ratios (PR).

Where all the measurements in a subgroup analysis were below LLD in either of the randomisation groups, Poisson regression was not possible, and CI were obtained using profile-log-likelihood estimation \(^{(20)}\).

For distributions with <50% ND measurements, the ratios of IFN-γ, IL-5 and TNF-α, IL-10 responses were analysed as crude markers of the balance of Th1 v. Th2 cytokine responses and the pro- v. anti-inflammatory cytokine responses, respectively; we report GMR ratios.

To test the effect of VAS on overall cytokine responsiveness, irrespective of stimulation, a collective test for each cytokine was performed, including all conditions and adjusting for the main effect of stimulation. This, however, was only done if the test of homogeneity for the BCG effect across the different stimulations was non-significant (test of homogeneity: \(P > 0.05\)) in the particular analysis, indicating that the stimulations could be merged.

Blood cell counts were analysed by linear regression on the log-transformed values, anti-log-likelihood estimates to present GMR, with CI obtained by bootstrap. Plasma levels of CRP were analysed as the frequency of individuals having a measurement above 20% for samples with a mean value between 3 and 7 mg/l using Poisson regression with robust standard errors providing PR. RBP was analysed with linear regression giving a numerical difference of the mean between VAS and placebo, prevalence of VAD (RBP < 0.83 mg/dl) \(^{(21)}\) was analysed with Poisson regression giving PR.

Estimates were reported with 95% CI. A GMR or PR > 1 can be interpreted as an increasing effect of VAS, whereas a GMR or PR < 1 represents a decreasing effect of VAS.

All analyses were adjusted for baseline levels and sex, as the initial randomisation was performed by sex. Children who had previously received VAS were slightly older than children not previously supplemented (data not shown). Adjusting for age in the analysis of the VAS effect stratified by previous VAS did not affect the VAS estimates (data not shown).

The estimates of the effect of VAS were stratified by sex, season of supplementation (rainy v. dry season) and previous VAS (yes or no); the stratification by previous VAS was further stratified by sex, as the effect modification had previously been found to be sex specific \(^{(14)}\).

We have corrected all estimates for multiple comparisons, separately for cytokines, leucocyte counts and CRP/RBP, using Simes false discovery rate procedure \(^{(22,23)}\). The statistical tests in the text are presented, both adjusted and unadjusted, whereas estimates in tables are highlighted only if significance was maintained after adjustment; \(P\) values in the figures are unadjusted.
Ethical considerations

The trial including the immunological sub-study was conducted according to the guidelines laid down in the Declaration of Helsinki, and all procedures were approved by the Ministry of Health’s Committee on Research Coordination in Guinea-Bissau and by the Danish Central Ethical Committee. The trial was registered at clinicaltrials.gov (no. NCT00514891).

Results

We included 280 children, of which 258 had a blood sample taken at inclusion. At follow-up, 146 blood samples were successfully obtained and analysed (Fig. 1), giving a loss to follow-up of 43%, evenly distributed between VAS and placebo arms. Of the 146 children, seventy-three had differential counts performed, 134 had RBP and CRP measured and 120 had cytokines measured. Overall, children with a successful laboratory analysis were not notably different from the children lost to follow-up with respect to background parameters, except for a larger frequency of lost males (61% lost v. 45% followed-up) (online Supplementary Table S1). Among the analysed infants, the VAS and placebo arms were comparable followed-up (Fig. 1), giving a loss to

Effect of vitamin A supplementation on vitamin A status and inflammation at follow-up

At baseline and follow-up, 70 and 72%, respectively, were VAD (RBP ≤0.83 μmol/l; 19% had CRP ≥5 mg/l and 14% had CRP ≥10 mg/l). VAS had no effect on levels of plasma RBP or on the frequency of VAD, overall or by sex (Table 2), and this was unaffected by vitamin A status at baseline, or by elevated CRP (≥5 mg/l) at follow-up (data not shown). Compared with placebo, VAS significantly increased the risk of elevated CRP (≥5 mg/l) (VAS: 28% v. placebo: 12%; PR: 3.15 (95% CI 1.49, 6.63), adjusted for multiple comparisons \( P = 0.005 \) (Table 2). The same conclusion was reached using a cut-off of 10 mg/l (data not shown). Sex (Table 2), season of supplementation and previous VAS (data not shown) did not significantly modify this effect.

Effect of vitamin A supplementation on leucocyte count values

Overall, there was no effect of VAS on leucocyte counts (Table 2). There was a significant interaction between VAS and sex for several subsets. In males, VAS was associated with significantly lower counts of total leucocytes, lymphocytes and monocytes, whereas the effect tended to be opposite in females (interaction between sex and VAS adjusted for multiple comparisons \( P = 0.01, P = 0.04, P = 0.03 \), respectively). The same

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![Flow chart](image-url)  
**Fig. 1.** Flow chart. Percentages are the fraction of total enrolled infants (n 146). VAS, vitamin A supplementation; RBP, retinol-binding protein; CRP, C-reactive protein.
pattern was observed for basophils (adjusted \( P = 0.01 \)) (Fig. 2(a) and Table 2). Season did not modify the effect of VAS (data not shown). The sex-differential effects for total leucocytes, lymphocytes, monocytes and basophils were stronger in children not previously supplemented compared with those previously supplemented due to a stronger increasing effect of VAS among previously unsupplemented females than among previously supplemented females (online Supplementary Table S2).

### Effect of vitamin A supplementation on in vitro cytokine production, overall and by sex

Overall, no cytokine outcomes were associated with VAS after adjustment for multiple comparisons (online Supplementary Table S3). The effect of VAS did not depend on vitamin A status at baseline (data not shown).

There was no interaction between VAS and sex for any of the cytokine responses (Fig. 2(b)–(f)), or between VAS and season, when adjusted for multiple comparisons (data not shown).

**Effect of vitamin A supplementation on in vitro cytokine production, by previous vitamin A supplementation, overall and by sex**

VAS was differentially associated with several cytokine responses in children with previous VAS compared with no previous VAS (Fig. 3). For children without previous VAS, VAS was associated with a tendency towards reduced TNF-α.
Table 2. The effect of vitamin A supplementation (VAS) on leucocyte counts and plasma biomarkers, overall and stratified by sex* (Geometric means (GM) and interquartile ranges (IQR); GM ratios (GMR) and 95 % confidence intervals; difference in means (diff.) and 95 % confidence intervals; proportion ratios (PR) and 95 % confidence intervals)

<table>
<thead>
<tr>
<th>Sex†</th>
<th>Male</th>
<th>Female</th>
</tr>
</thead>
<tbody>
<tr>
<td>GM (n 39)</td>
<td>95 % CI</td>
<td>GM (n 34)</td>
</tr>
<tr>
<td>VAS‡</td>
<td>Placebo‡</td>
<td></td>
</tr>
<tr>
<td>Total leucocytes</td>
<td>10.3 (n 35)</td>
<td>8.4–12.7</td>
</tr>
<tr>
<td>Lymphocytes</td>
<td>5.5 (n 35)</td>
<td>4.3–7.0</td>
</tr>
<tr>
<td>Monocytes</td>
<td>1.8 (n 35)</td>
<td>1.3–2.3</td>
</tr>
<tr>
<td>Neutrophils</td>
<td>2.1 (n 35)</td>
<td>1.3–2.7</td>
</tr>
<tr>
<td>Eosinophils</td>
<td>0.3 (n 35)</td>
<td>0.2–0.6</td>
</tr>
<tr>
<td>Basophils</td>
<td>0.2 (n 35)</td>
<td>0–1.0</td>
</tr>
<tr>
<td>Mean IQR</td>
<td>GM</td>
<td>Mean IQR</td>
</tr>
<tr>
<td>RBP (μmol/l)</td>
<td>Proportion</td>
<td>Proportion</td>
</tr>
<tr>
<td>RBP &lt;0.83 μmol/l</td>
<td>0.70 (n 65)</td>
<td>0.57–0.87</td>
</tr>
<tr>
<td>CRP ≥5 mg/l</td>
<td>0.28 (n 34)</td>
<td>0.12</td>
</tr>
</tbody>
</table>

RBP, retinol-binding protein; CRP, C-reactive protein.
* Infants with a plasma RBP <0.83 μmol/l were defined as vitamin A deficient.
† GM or diff or PR with 95 % CI comparing infants receiving VAS with infants receiving placebo. A GMR >1 can be interpreted as an increasing effect of VAS on the cell count.
‡ GM with IQR of leucocyte counts, or means and IQR for RBP levels, or proportion of individuals with RBP <0.83 μmol/l, or proportion of individuals with CRP ≥5 mg/l at follow-up for the placebo group and the VAS group, respectively. GM presented as 10^6 cells/ml for all cell values.
§ Statistical test for interaction between VAS and sex.
|| Estimates and interaction P values that are still significant after adjustment for multiple comparisons.

responses to all stimuli compared with placebo, whereas the opposite tendency was observed in children who had received VAS previously. The same pattern was also observed for IL-10 and IFN-γ responses. Consequently, the TNF-α:IL-10 ratio tended to be down-regulated by VAS compared with placebo in children not previously supplemented, with the opposite tendency in children with previous VAS. A similar effect was observed for the IFN-γ:IL-5 ratio (Fig. 3(g) and (h)).

VAS had opposite sex-differential effect directions for responses to PHA in children with v. without previous VAS. Among previously supplemented children, VAS tended to be associated with increased IFN-γ responses to PHA in females but decreased responses in males (interaction between VAS and sex, adjusted P=0.23). Among children without previous VAS, VAS was associated with decreased IFN-γ responses in females but increased responses in males (interaction between VAS and sex, adjusted P=0.13). This resulted in a significant three-way interaction between VAS, previous VAS and sex (adjusted P=0.0007) (Fig. 2(g) and online Supplementary Table S4).

Discussion

VAS v. placebo given with MV from 9 months of age was associated with a number of immunological effects. First, VAS was associated with a higher proportion of children with elevated plasma CRP levels at follow-up. Second, VAS was associated with a decrease in concentrations of several blood cell subsets in males but an increase in females. Third, there was an interaction between VAS and previous VAS on several cytokine responses: VAS decreased particularly pro-inflammatory and Th1 responses in children who had not previously received VAS with an opposite effect in previously supplemented children, particularly so in females. Fourth, VAS increased PHA responses in females who had previously received VAS with an opposite effect in previously unsupplemented females; for males, this modulation of previous VAS on the effect of VAS was in the opposite direction, especially for the responses of typical lymphocyte-derived cytokines (IL-2, IL-5, IFN-γ).

Strengths and weaknesses

To our knowledge, the present study is the first randomised study to investigate the general (non-specific) immunological effects of VAS given with MV in a real-life setting, therefore directly testing the immunological implication of this WHO policy.

However, some limitations are noted. First, our loss to follow-up was higher than anticipated; many mothers refused the second blood sample. The loss to follow-up was equally distributed across the randomisation groups. Although more boys than girls were lost to follow-up, the distribution of treatment allocation among the lost was similar for boys and girls. Second, the subgroup analyses were based on small numbers, as the study was not originally designed to power the three-way interactions by sex and previous VAS. These analyses, however, were posteriorly indicated by the epidemiological study showing three-way interactions with respect to the main mortality outcome. Third, multiple testing increased the risk of chance
The main trial found that the sex-differential effect of VAS was strongest in the dry season\textsuperscript{159}. In the present sub-study, we found no evidence for a season-differential effect of VAS overall or by sex.
Fig. 3. The effect of vitamin A supplementation (VAS) on in vitro cytokine responses, stratified by previous VAS. Geometric mean ratios (GMR) of cytokine responses to innate agonists and vaccine antigens (a–e) for VAS compared with placebo. If ≥50% of the measurements of a given cytokine outcome included in the analysis was non-detectable (ND), the estimate was obtained with Poisson regression, giving prevalence ratios (PR). (f) The cytokine concentrations were analysed collectively for all stimulations in a combined analysis for each cytokine, including all stimulations and adjusting for the main effect of stimulation. Panels (g, h) present GMR ratios (GMRR) for the effect of VAS on ratios of responses of TNF-α:IL-10 and IFN-γ:IL-5, respectively. The analyses was only performed on distributions with <50% ND measurements. ‘Group’ designates ratios of cytokine responses analysed collectively for all stimulations with <50% ND observations. All estimates were adjusted for baseline level and sex. A GMR or GMRR (or PR) > 1 can be interpreted as an increasing effect of VAS on the outcome. The estimates beyond the range of 0.25–4 were truncated: TNF-α to medium3, TNF-α to polyinosine-polycytidylic acid (Poly I:C), TNF-α to Poly I:C and TNF-α:IL-10 to Poly I:C in the no previous VAS stratum. § The cumulative estimate for the VAS effect on TNF-α responses in previous VAS recipients could not be generated, because the estimates for the respective stimulations were too heterogeneous to be analysed collectively (test of homogeneity: P < 0.05). † No estimate for the effect of VAS could be obtained for TNF-α to diphtheria toxoid (DT), IL-2 to Poly I:C and IFN-γ to medium3, due to all observations being ND at follow-up among VAS recipients (TNF-α to DT and IFN-γ to medium3) or placebo recipients (IL-2 to Poly I:C), respectively, not having previously received VAS. Estimates that are significant after adjustment for multiple comparisons: * P < 0.05; for interaction between VAS and previous VAS: † P < 0.05; †† P < 0.01. Medium1, culture medium only in 1-d incubation; LPS, lipopolysaccharide; pam: palmitoyl(3)-cysteine-serine-lysine(4); medium3, culture medium only in 3-d incubation; PHA, phytohaemagglutinin; poly I:C, polyinosine-polycytidylic acid; BCG, Bacille Calmette–Güerin; PPD, purified protein derivative from Mycobacterium tuberculosis; OPV, oral polio vaccine; TT, tetanus toxoid. ▦, No previous VAS; ☐, previous VAS.
Previous vitamin A supplementation modulating the effect of vitamin A supplementation

The main trial found a strong interaction between VAS and previous VAS. In previous VAS recipients, the MRR of VAS was 5.98 (1.34–26.7) in males and 0.18 (0.05–0.62) in females. Among children not previously supplemented, the effects were 1.19 (0.53–2.65) in males and 0.82 (0.35–1.89) in females (P = 0.007 for three-way interaction between VAS, previous VAS and sex). This corroborated observations from previous studies of a particularly beneficial effect of receiving repeated doses of VAS in females.

In line with the mortality findings, in the present sub-study, the immunological effect of VAS was modulated by previous VAS, for some outcomes in a sex-differential manner. VAS tended to increase the TNF-α:IL-10 ratios and IFN-γ:IL-5 ratios in previous VAS recipients, with opposite effects in previously unsupplemented children. To our knowledge, no other study has investigated the immunological effect of repeated dosing of VAS.

In an immunological study of the effect of MV at 4–5 months of age, a large subgroup of children had previously received VAS at birth. Exclusively among neonatal VAS recipients, MV had sex-differential effects on plasma IL-1 receptor agonist and IL-8. Furthermore, MV tended to increase the TNF-α:IL-10 response ratios among neonatal VAS recipients, with the opposite effect of MV in previously unsupplemented infants.

These findings are in parallel with the present study, supporting differential effects of immune-modulators (be it MV or VAS) depending on previous VAS, with a dampening effect in children who receive VAS for the first time, but a larger inflammatory response in children who have previously received VAS.

The effect modulation of previous VAS on cytokine responses was furthermore sex dependent for the PHA stimulations, most significantly for IFN-γ. Of note, high IFN-γ responses to PHA is a marker of improved survival in children. Intriguingly, the immunological interactions for IFN-γ to PHA were in line with the mortality findings for previously supplemented children.

Biological mechanisms

Using serum RBP as indicator of vitamin A stores, many children in the present study had biochemical VAD, but VAS did not seem to affect the prevalence of VAD. A previous study from Guinea-Bissau examined the effect of VAS at birth on vitamin A status at age 6 weeks and at age 4 months and also found no measurable effect on vitamin A status (13), but in line with the present trial there were, nonetheless, measurable effects on mortality and immunological outcomes (24). Of note, a biological model of vitamin A uptake and catabolism in children has predicted a return of serum retinol levels to baseline only 2 months after high-dose VAS (26). These findings may suggest that changes in vitamin A status measured as blood biochemical markers do not serve as a good predictor of VAS effects on mortality or on immune function. In other words, the effect of VAS seems not to be mediated via an effect on vitamin A status, but rather through immunomodulation. Other analyses such as tissue examination may be more sensitive indicators of vitamin A status than blood biomarkers. This, however, is not feasible in population studies such as the present; in order to categorise children as deficient or not, serum biomarkers can indeed be used (31).

Most immunological in vitro studies assign anti-inflammatory capacities to retinoid acids, metabolites of vitamin A (22–26). Most recently, it has been shown that pre-incubation of human monocytes with all-trans retinoic acid (ATRA) reduces the secondary inflammatory responses to innate agonist stimulation in an ATRA dose-dependent manner. Moreover, ATRA suppressed the increasing effect on BCG priming of monocytes in the secondary responses. The suppressive effect of ATRA was observed at the epigenetic level by an increase in suppressive methylation markers at the IL-6 and TNF-α promoters, which lasted at least 10 d in the in vitro model (27). The dampening effect in vitro of vitamin A on cytokine responses is in concordance with the present in vitro findings in children not previously supplemented.

In conclusion, the present study supports that VAS has immune-modulating effects and that the effects may depend on the sex of the recipient. The immunological effects of VAS may be modified by previous VAS, corroborating epidemiological studies indicating a long-lasting imprinting effect of VAS on the immune system.

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C. S. B., P. A., A. B. F. conceived the idea for the study; C. S. B., C. E., E. S., M. Y. designed the experiments; A. B. F. supervised the collection of samples and field data; E. S. performed the laboratory analyses; K. J. J. analysed the data; A. A. supervised the statistical analyses; K. J. J. wrote the first draft of the manuscript; all the authors read and approved the final version of the manuscript.

The authors declare that there are no conflicts of interest.
Supplementary material

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