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DOI:

[10.1016/j.jsbmb.2017.06.012](https://doi.org/10.1016/j.jsbmb.2017.06.012)

[10.1016/j.jsbmb.2017.06.012](https://doi.org/10.1016/j.jsbmb.2017.06.012)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Liu, N, Larner, D, Yao, Q, Chun, R, Ouyang, YB, Zhou, R, Tamblyn, J, Wagner, CL & Hewison, M 2017, 'Vitamin D-deficiency and sex-specific dysregulation of placental inflammation', *The Journal of Steroid Biochemistry and Molecular Biology*. <https://doi.org/10.1016/j.jsbmb.2017.06.012>, <https://doi.org/10.1016/j.jsbmb.2017.06.012>

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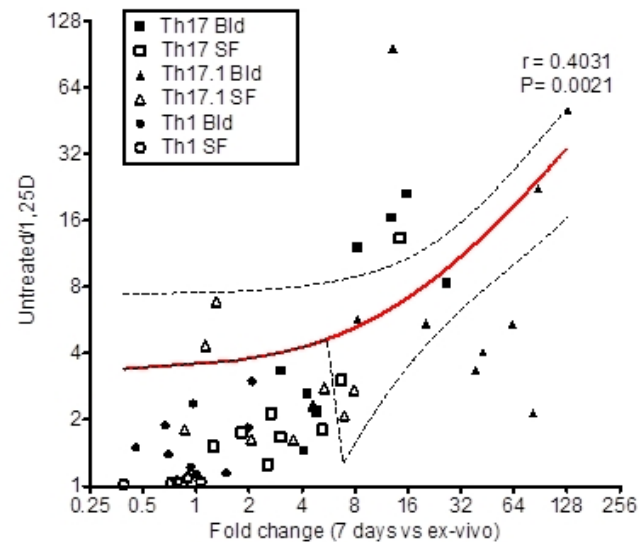
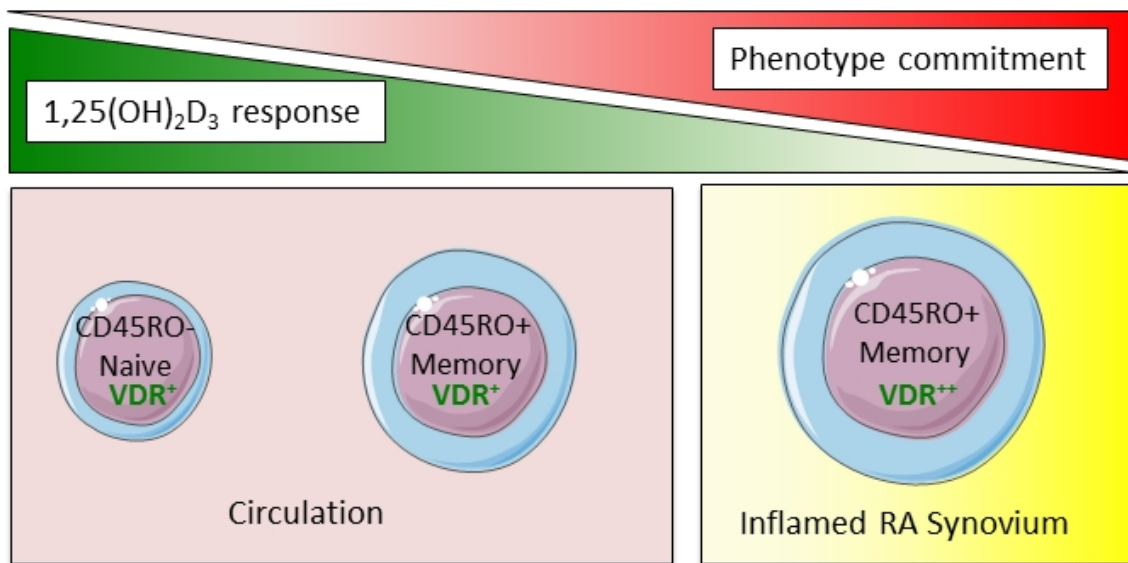
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T cell responses to $1,25(\text{OH})_2\text{D}_3$ correlate directly with capacity for phenotype change which is reduced in memory T cells from the inflamed joints of RA patients despite high vitamin D receptor (VDR) expression.



Decreased sensitivity to 1,25-dihydroxyvitamin D3 in T cells from the rheumatoid joint

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Key words:

Vitamin D, rheumatoid arthritis, synovial fluid, peripheral blood, T cell, vitamin D receptor

Abstract

1,25-dihydroxyvitaminD₃ (1,25(OH)₂D₃), has potent anti-inflammatory effects, including suppression of IL-17+ and IFN γ + T cells implicated in rheumatoid arthritis (RA), but efficacy at the site of active disease is unclear. To investigate this, CD4+T cells from synovial fluid (SF) and paired blood of patients with active RA were studied. 1,25(OH)₂D₃ had significantly less suppressive effect on Th17 cells (IL-17+IFN γ -) and Th17.1 cells (IL-17+IFN γ +) from SF compared to those from blood, and had no effect on SF CD4+IFN γ + T cell frequencies. Memory T cells (CD45RO+) predominate in SF, and 1,25(OH)₂D₃ had less effect on memory T cells relative to naïve (CD45RA+) T cells. RT-PCR and flow cytometry showed that this was not due to decreased expression of the vitamin D receptor or its transcription partners in memory T cells. Further studies using stimulated CD4+ T cells sorted according to IL-17 and IFN γ expression confirmed the ability of 1,25(OH)₂D₃ to suppress pre-existing cytokines. However, 1,25(OH)₂D₃ was most effective at suppressing *de novo* IL-17 and IFN γ induction. Correspondingly, T cell responses to 1,25(OH)₂D₃ correlated directly with capacity for phenotype change, which was lower in cells from SF compared to blood. These findings indicate that anti-inflammatory effects of 1,25(OH)₂D₃ in active RA are impaired because of reduced effects on phenotype-committed, inflammatory memory T cells that are enriched in SF. Restoration of 1,25(OH)₂D₃ responses in memory T cells may provide a new strategy for treatment of inflammatory diseases such as RA.

235 Words

1. Introduction

The active form of vitamin D, 1,25-dihydroxyvitamin D₃ (1,25(OH)₂D₃) promotes anti-inflammatory responses in a diverse array of cell types, supporting the potential use of vitamin D in the prevention and/or treatment of inflammatory disorders [1, 2]. In previous studies we have shown that anti-inflammatory actions of vitamin D may occur indirectly through localized synthesis of 1,25(OH)₂D₃, and reduced expression of major histocompatibility and co-stimulatory molecules by antigen-presenting dendritic cells (DCs), monocytes and macrophages [3-6]. However, 1,25(OH)₂D₃ can also act directly on T-lymphocytes (T cells), inhibiting their proliferation [7], especially under conditions of weak co-stimulation [8], and suppressing their production of pro-inflammatory cytokines such as IFN γ , IL-17 and IL-21 [9-13], whilst promoting their expression of regulatory markers including CTLA-4, FoxP3, and IL-10 [13] even in the presence of pro-inflammatory cytokines [14]. Crucially almost all of these observations have stemmed from experiments using T cells from the blood of healthy donors and much less is known about the effects of 1,25(OH)₂D₃ in established inflammatory disease, especially its effects upon T cells from inflamed compartments such as the joint of a patient with rheumatoid arthritis (RA).

Epidemiology suggests that many autoimmune diseases and common chronic inflammatory diseases such as RA are associated with vitamin D-deficiency [15-17]. Vitamin D metabolites such as 1,25(OH)₂D₃ may therefore provide an alternative strategy for the prevention and/or treatment of RA [18], possibly as an adjunct to existing RA therapies [8]. Previous studies have highlighted aberrant metabolism of vitamin D in disease-affected synovial fluid (SF) from RA patients [19], but the impact of 1,25(OH)₂D₃ on T cells from the site of inflammation, the inflamed joint, has yet to be studied.

How $1,25(\text{OH})_2\text{D}_3$ affects T cell function is important in RA as T cells accumulate in the RA synovium and genetic risk factors for RA are largely related to T cell activation [20-25]. $\text{IFN}\gamma^+$ Th1 cells and IL-17^+ Th17 cells are regarded as important mediators of chronic synovial inflammation. Increased levels of their hallmark and differentiating cytokines are found in the serum and synovial fluid of patients relative to controls [26], and elevated frequencies of both have been detected in the blood and joints of RA patients [27]. $\text{IFN}\gamma$ produced by Th1 cells promotes APC maturation whilst IL-17 has pleiotropic effects, driving fibroblast-like synoviocytes (FLS) to release pro-inflammatory cytokines and chemokines [28], that further amplify the inflammation by facilitating the recruitment and retention of immune cells, including $\text{CCR5}^+\text{CXCR3}^+$ Th1 cells [29, 30] and CCR6^+ Th17 [31, 32] cells into the joint. IL-17 from Th17 cells also promotes cartilage and bone resorption by stimulating MMP release from FLS [28] and the induction of RANKL on FLS and osteoblasts leading to activation of RANK^+ osteoclasts [33].

The aim of the current study was to investigate further the potential use of vitamin D as a therapy for RA, by determining whether anti-inflammatory effects of $1,25(\text{OH})_2\text{D}_3$ are achievable on T cells from the site of inflammation. By comparing cells isolated from RA patient SF and peripheral blood we were able to demonstrate relative T cell insensitivity to $1,25(\text{OH})_2\text{D}_3$ in inflamed joints. This dysregulation of the anti-inflammatory effects of $1,25(\text{OH})_2\text{D}_3$ was associated with memory (CD45RO^+) T cell phenotype commitment. Since activated memory T cells characterize the inflamed tissues in multiple inflammatory diseases [34], T cell insensitivity to $1,25(\text{OH})_2\text{D}_3$ may be a feature of other inflammatory conditions and may reduce its potential therapeutic benefit, especially in established disease.

2. Materials and Methods

Patients were recruited for the study if they fulfilled 1987 ACR criteria for RA [35]. All patients and age and gender-matched healthy controls gave full written consent. Ethical approval for the work was granted by Solihull Research Ethics Committee (REC reference number 07/Q2706/2) and the University of Birmingham Ethics Committee (ERN_14-0446). For naïve and memory T cell comparison studies, as well for as cytokine-expression cell capture experiments, cells were isolated from fully anonymised leukocyte cones obtained from the National Blood Service, Birmingham, UK.

2.1. Cell isolation and culture

Synovial Fluid (SF) was extracted by ultrasound guidance as described previously [36] or by palpation guidance. Prior to SF Mononuclear Cell (SFMC) isolation, SF was treated with hyaluronidase (10U/ml) for 30 minutes at 37°C. PBMCs and SFMCs were isolated by the Ficoll-Paque PLUS method of density gradient centrifugation (GE Healthcare). SF was layered on Ficoll-Paque PLUS undiluted, fresh blood was diluted 1:1 with PBS and leukocyte cones were diluted 1:4 with PBS before layering. Isolated SFMCs and PBMCs were cultured at 37°C, 5% CO₂ in RPMI 1640 medium and supplemented with 1% penicillin and streptomycin, 2mM L-glutamine, and 5% self-serum or SF that was pre-filtered through a 22 µm filter. For *ex vivo* cytokine expression analysis, cells were allowed to rest overnight at 1x10⁶ cells/ml without stimulation before being stimulated for 6-7 hours with phorbol myristate acetate (PMA) (50ng/ml) and ionomycin (1µM). Brefeldin A (10 µg/ml) was added during the last 4 – 5 hours. For seven-day cultures, mononuclear cells were stimulated with anti-CD3 (0.5µg/ml, clone OKT3) at 2.5 x 10⁵ cells/ml. 1,25(OH)₂D₃ was added to cultures at 100 nM and ethanol used as a vehicle control at 0.1%. At seven days, cells were restimulated with PMA/ionomycin in the presence of brefeldin A for cytokine expression analysis by flow cytometry.

For experiments using isolated CD45RA+CD4+ naïve T cells, CD45RO+CD4+ memory T cells and CD14+ monocytes, cells were enriched by negative selection using cell separation reagents (StemCell Technologies and Biolegend). For 24 hr post-stimulation analysis of gene expression, T cells were stimulated with anti-CD3/CD28 dynabeads (Life Technologies) at a ratio of 1 bead: 2 T cells in medium supplemented with 5% human AB serum (TCS Biosciences, Buckingham UK). For longer-term stimulations a ratio of 1 bead: 4 T cells was used. Where T cells were stimulated with monocytes, a ratio of 1 monocyte: 4 T cells and OKT3 0.5µg/ml was used.

2.2. Isolation and culture of Th17, Th17.1 and Th1 cells

Expanded populations of Th17, Th17.1 and Th1 cells were generated by stimulating magnetically purified monocytes and CD4+ T cells at 1:5 ratio with 0.5ug/ml antiCD3 for seven days. IL-17-PE and IFN γ -APC cytokine secretion detection kits (Miltenyi Biotech) were used to label live Th17, Th17.1 and Th1 cells. In brief, cultures were re-stimulated with Phorbol 12,13-dibutyrate (PDBu) (10ng/ml) and ionomycin (1nM) for 2hours before labeling with IL-17 and IFN γ catch reagents on ice at 10×10^6 cells/80µl MACS buffer for 5mins. Cells were transferred to pre-warmed RPMI and incubated for 40mins at 37°C at 4×10^5 cells/ml under continual rotation. Cells were then diluted 1:1 with ice-cold MACS buffer and chilled on ice for 10 minutes before centrifuging and labelling with IL-17-PE and CD3-PerCP for 15 minutes on ice with addition of IFN γ -APC during the final 10 minutes. After washing, Th17, Th17.1, Th1 and cytokine double-negative (DN) populations were collected into RPMI by FACS. Sorted T cells were then stimulated with negatively enriched (StemCell Technologies) and CD14+ FACS-purified allogenic monocytes at 1:4 ratio and 0.5µg/ml anti-CD3 (OKT3) for 2 days in the presence of 40units/ml IL-2 (Immunotools) \pm 100nM 1,25(OH) $_2$ D $_3$. Cell purities were >99% for Th17, Th1, DN and

monocytes and >90% for Th17.1 cells.

2.3. Flow cytometry

CD45-RO⁺ frequencies were assessed directly *ex vivo* by surface staining at 4°C in PBS with antiCD45RO-FITC, CD3-PE and CD4-APC (all from BD Biosciences). For post-stimulation cultures, dead cells were labelled with near-IR LIVE/DEAD fixable dead cell stain (Molecular Probes, Life Technologies) before fixation. For analysis of regulatory markers: CTLA-4, Foxp3 and CD25, cells were fixed, permeabilised and stained with ebioscience/Thermofisher Foxp3 staining buffers according to the manufacturer's instructions. For analysis of cytokine expression, PMA/ionomycin-restimulated cells were fixed with 3% paraformaldehyde in PBS for 12 minutes followed by a 5-minute wash with PBS under centrifugation. Fixed cells were permeabilised with 0.1% saponin (Acros Organics) prepared in PBS and stained with IL-17-PE, IFN γ -e450, IL-21-APC, CD3-PERCP, CD4-FITC. For all studies cells were acquired on a Dako Cyan flow cytometer (Dako Cytomation) and data analysed using FlowJo software (Tree Star version 8.8.6). All antibodies were purchased from ebioscience/Thermofisher or BD Biosciences and expression quantified relative to the appropriate isotype control.

2.4. Quantitative Real-time PCR

Total RNA was extracted by phenol/chloroform method after cell lysis in TRIzol (Life Technologies/Invitrogen). 0.3-0.5 μ g RNA was reverse transcribed with random hexamers using TaqMan reverse transcription reagents (Thermofisher/Applied Biosystems). Quantitative real-time PCR for 18S rRNA, VDR, RXR, DRIP-205, NCoA1, NCOR1 and NCOR2, IL-17 or IFN γ was then performed on an Applied Biosystems 7900 machine using assays on demand from Applied Biosystems: 18S rRNA, (4319413E); VDR (Hs00172113_m1); RXR (Hs01067640_m1), NCoR1 (Hs01094540_m1), NCoR2 (Hs00196955_m1), DRIP205 (Hs01062349_m1), NCoA1

(Hs00186661_m1); IL-17 (Hs99999082_m1) and IFN γ (HS00989291_m1). Amplification of cDNAs involved incubation at 50°C for 2 minutes and 95°C for 10 minutes followed by 40 cycles of 95°C for 15 seconds and 60°C for 1 minute. VDR mRNA expression was then calculated relative to 18S rRNA using the delta Ct method as described previously [37].

2.5. Statistical analysis

GraphPad Prism 5.0a software (GraphPad) was used for graphical summary and statistical analysis. For analysis of normality and Q-Q plot inspection SPSS statistics version 22 was used. Non-parametric Wilcoxon tests were used to test significance between two conditions. To test interactions between 1,25(OH) $_2$ D $_3$ and cell source location repeated measures two factor within subject analysis with Huynf-Feldt correction was performed. The Shapiro-Wilk normality test and inspection of normal Q-Q plots were used to confirm that the data could be tested with these parametric models. For data sets that did not pass the normality test (VDR mRNA) the data were log $_{10}$ transformed, since by this transformation the residuals from the mean became normally distributed.

3. Results

3.1. Anti-inflammatory effects of 1,25(OH) $_2$ D $_3$ are reduced in synovial fluid T cells

To determine whether T cells from patients with active RA are sensitive to the anti-inflammatory effects of 1,25(OH) $_2$ D $_3$, peripheral blood mononuclear cells (PBMCs) from the blood of healthy controls and established RA patients, as well as synovial fluid (SF) mononuclear cells (SFMCs) from RA patients, were stimulated with anti-CD3 in the presence or absence of 1,25(OH) $_2$ D $_3$ for seven days and the frequency of CD4+ T cells expressing IL-17 or IFN γ measured by flow cytometry (**Figure 1A and 1B**). 1,25(OH) $_2$ D $_3$ decreased IL-17+ and IFN γ + T cell frequencies in HC and RA

PBMCs. It also reduced frequencies of IL-17+ T cells in SFMC cultures. However 1,25(OH)₂D₃ had no effect on the frequency of IFN γ + T cells in SFMCs (**Figure 1B**). Further classifying T cells according to their combined expression of IL-17 and IFN γ revealed significantly greater suppressive effects of 1,25(OH)₂D₃ on Th17 (IL-17+IFN γ -) and Th17.1 (IL-17+IFN γ +) T cells in RA blood relative to SF, whilst Th1 (IL-17-IFN γ +) frequencies were not affected by 1,25(OH)₂D₃ in blood or SF (**Figure 1C**). Thus Th17 and Th17.1 populations from the inflamed joints of RA patients are less sensitive to the anti-inflammatory effects of 1,25(OH)₂D₃ than equivalent circulating T cells.

3.2. Effects of 1,25(OH)₂D₃ are greater on blood naïve versus memory T cells

Consistent with previous studies [38], only 47% (\pm 12%) T cells isolated from blood were memory (CD45RO+). By contrast, 98% (\pm 2%) SF T cells were CD45RO+ (**Supplemental Figure 1**). We therefore determined whether the decreased effect of 1,25(OH)₂D₃ upon SF T cells could be attributed to differences between memory and naïve T cells. As shown in **Figure 2A**, IL-17+ and IFN γ + T cells were more abundant in memory T cell populations. Treatment with 1,25(OH)₂D₃ suppressed IFN γ + and IL-17+ frequencies in both naïve and memory subsets. For IL-17, 1,25(OH)₂D₃ had equal effect on naïve and memory T cells whereas the effect of 1,25(OH)₂D₃ on IFN γ expression was greatest for naïve T cells (**Figure 2B**). 1,25(OH)₂D₃ also had greatest effect upon IL-21 and CTLA-4 expression in naïve T cells compared to memory T cells, with 1,25(OH)₂D₃ inducing CTLA4 in naïve T cells but having no effect on memory T cells (**Figure 2A and 2B**).

As it is unclear how many rounds of stimulation circulating memory T cells have experienced *in vivo*, we also compared the effect of 1,25(OH)₂D₃ on naïve and memory T cells during sequential rounds of stimulation (**Supplemental Figure 2**). Analysis of three cytokines (IL-17, IFN γ , and IL-21) showed that 1,25(OH)₂D₃ was

more effective in naïve versus memory T cells at the first round of stimulation, but this difference in sensitivity was lost following the second round of T cell stimulation. These data support the concept that induction of a memory T cell phenotype reduces the anti-inflammatory effects of $1,25(\text{OH})_2\text{D}_3$ on T cells, which may in part explain the differences in $1,25(\text{OH})_2\text{D}_3$ responses between blood and SF T cells.

3.3. $1,25(\text{OH})_2\text{D}_3$ signaling components in naïve versus memory T cells

To investigate the underlying basis for reduced $1,25(\text{OH})_2\text{D}_3$ responsiveness in memory versus naïve T cells, expression of the nuclear vitamin D receptor (VDR), its retinoid X receptor (RXR) heterodimer partner, as well as associated activator/repressor proteins was assessed. RT-PCR analyses and flow cytometry showed similar low levels of VDR in unstimulated naïve and memory T cells, with VDR expression increasing in both T cell populations following stimulation ($p < 0.05$ for mRNA and protein in stimulated naïve and memory T cells versus unstimulated naïve and memory T cells) (**Figure 3A**). Similar to VDR, unstimulated naïve and memory T cells showed comparable low expression of RXR, but only memory T cells showed induction of this receptor upon stimulation (**Figure 3B**). In addition to VDR and RXR, several co-regulators participate in $1,25(\text{OH})_2\text{D}_3$ -mediated transcriptional responses, and these factors may contribute to variable responses to $1,25(\text{OH})_2\text{D}_3$ [39]. However, analysis of mRNAs for the co-enhancers DRIP205 and NcoA1, and co-repressors NcoR1 and NcoR2, showed no difference in expression between naïve and memory T cells (**Figure 3C**). The decreased $1,25(\text{OH})_2\text{D}_3$ responsiveness of memory versus naïve T cells could therefore not be attributed to impaired expression of VDR or its signaling partners.

3.4. Effects of $1,25(\text{OH})_2\text{D}_3$ in SF versus blood memory T cells

To determine whether decreased responses to $1,25(\text{OH})_2\text{D}_3$ in SF compared to blood T cells involve differences between memory T cells from the two compartments,

matched CD45RO+ CD4+ memory T cells from paired blood and SF of RA patients were stimulated in the presence or absence of 1,25(OH)₂D₃. Flow cytometry for IFN γ and IL-21 showed decreased anti-inflammatory effects of 1,25(OH)₂D₃ in SF versus blood memory T cells, whilst a non-significant trend was observed for IL-17 (**Figure 4A**). Flow cytometry and RT-PCR revealed enhanced VDR expression in unstimulated memory T cells isolated from SF relative to those obtained from blood (**Figure 4B and 4C**), consistent with their more activated (CD69+) phenotype (**Figure 4C**). VDR expression increased following memory T cell stimulation ($p < 0.001$ for stimulated versus unstimulated cells), but there was no significant difference in VDR expression between stimulated blood and stimulated SF cells (**Figure 4B**). By contrast, mRNA for RXR did not differ in blood versus SF memory T cells in the stimulated or unstimulated state (**Figure 4B**). The co-regulators DRIP205, NcoA1, NcoR1 and NcoR2 also showed elevated expression in unstimulated memory SF T cells (**Supplemental Figure 3**), similar to that observed for VDR. Collectively these data indicate that SF memory T cells are less affected by 1,25(OH)₂D₃ than memory T cells from blood, but this is not due to impaired expression of VDR or its signaling partners.

3.5. Effects of 1,25(OH)₂D₃ on Th17, Th17.1 and Th1 cells

To date, reported anti-inflammatory effects of 1,25(OH)₂D₃ have been based on data from mixed cultures of cytokine-expressing and non-expressing T cells. Further studies were therefore carried out to determine the effects of 1,25(OH)₂D₃ on T cells expressing specific cytokines. By combining anti-IL-17-PE and anti-IFN γ -APC cytokine detection reagents, live T cells were labeled according to their expression of IL-17 and/or IFN γ , and Th17, Th17.1, Th1 cells were obtained by FACS as well as T cells double negative for IL-17 and IFN γ (DN). RT-PCR analysis of IL-17 and IFN γ mRNA in the sorted populations confirmed cytokine purity of the sorted cells (**Supplemental Figure 4**). The Th17, Th17.1 and Th1 T cells generated in this

manner were then re-stimulated in the presence or absence of $1,25(\text{OH})_2\text{D}_3$ for two days. In vehicle-treated re-stimulated populations, we observed plasticity of phenotype between Th17, Th17.1 and Th1, including the generation of T cells double negative for IL-17 and IFN γ (**Figure 5A**). Th17 cells could give rise to IFN γ -expressing T cells, and Th1 cells could induce IL-17 expression. DN cells could also give rise to IL-17 and IFN γ (**Figure 5A**).

Treatment with $1,25(\text{OH})_2\text{D}_3$ reduced expression of IL-17 or IFN γ in T cells pre-committed to Th17 and Th1 phenotypes respectively, but $1,25(\text{OH})_2\text{D}_3$ had a much greater inhibitory effect on *de novo* expression of IL-17 or IFN γ (**Figure 5A & Figure 5B**). In Th17 cells, $1,25(\text{OH})_2\text{D}_3$ -sensitivity was greater for IFN γ than IL-17, whilst the opposite response was observed in Th1 cells. Moreover, $1,25(\text{OH})_2\text{D}_3$ actively suppressed the development of Th17, Th17.1 and Th1 populations from DN T cells, but had little effect on IL-17 or IFN γ expression in Th17.1 T cells that had pre-existing expression of both IL-17 and IFN γ (**Figure 5B**).

3.6. Capacity for phenotype change is low in SF T cells

Further studies were carried out to determine if the impaired response to $1,25(\text{OH})_2\text{D}_3$ observed for SF versus blood T cells was due to differences in T cell phenotype commitment and plasticity. This was carried out by comparing the cytokine profiles of blood and SF T cells *ex vivo* and after stimulation. There were few IL-17 $^+$ T cells in blood *ex vivo* and these were almost exclusively Th17 (**Figure 6A, 6B and 6D**). IL-17 expression was also low in SF, but this was evenly distributed across Th17 and Th17.1 populations (**Figure 6D**). Compared to IL-17, considerably more T cells expressed IFN γ *ex vivo* in blood and SF, however, the frequency of IFN γ $^+$ cells was much higher in SF compared to paired blood. Culture of T cells from blood for 7 days resulted in significant expansion of IL-17 $^+$ T cells (12-fold) (**Figure 6C**), with the Th17.1 population showing greatest fold change (50-fold) (**Figure 6D**).

IFN γ + Th1 cells from blood showed no change in frequency from *ex vivo* to 7 days of culture (**Figure 6A and 6D**). In contrast to blood, culture of T cells from SF resulted in only a 2-fold induction of Th17 T cells and a 4-fold induction of Th17.1 T cells, with Th1 cells (the largest fraction of IFN γ + T cells in SF), again showing no change in frequency from *ex vivo* to 7 days of culture (**Figure 6D**).

The capacity for expansion of IL-17+ T cells during culture correlated directly with the ability of these cells to respond to 1,25(OH) $_2$ D $_3$, with Th17 and Th17.1 cells from blood being more effectively suppressed by 1,25(OH) $_2$ D $_3$ than their SF counterparts (**Figure 7**). By contrast, the lack of phenotype plasticity shown for Th1 cells and cells from SF (**Figure 6A-D**), was associated with lower sensitivity to 1,25(OH) $_2$ D $_3$ (**Figure 7**). The lack of an anti-inflammatory response to 1,25(OH) $_2$ D $_3$ in SF T cells therefore appears to be due to the limited phenotype plasticity exhibited by these cells.

4. Discussion

Vitamin D metabolites such as pro-hormone 25-hydroxyvitamin D (25OHD) and active 1,25(OH) $_2$ D $_3$ are detectable in SF from RA patients [19, 40], and monocytes isolated from SF have been shown to actively synthesize 1,25(OH) $_2$ D $_3$ from 25OHD [19, 41]. Thus, there is significant potential for elevated concentrations of 1,25(OH) $_2$ D $_3$ within inflamed joints. In addition, VDR is broadly expressed and present within cells from synovial tissue and fluid [42] indicating that different components of the inflamed joint have the capacity to respond to 1,25(OH) $_2$ D $_3$, in an intracrine or paracrine fashion [18]. As recently summarized [18], multiple *in vitro* studies also demonstrate anti-inflammatory effects of 1,25(OH) $_2$ D $_3$ upon the immune cells that contribute to RA pathology. However, these studies have focused on cells from the blood of healthy controls or RA patients. The extent to which anti-inflammatory responses to 1,25(OH) $_2$ D $_3$ also occur in immune cells from inflamed tissue is still poorly understood, but is nevertheless crucially important when

considering the potential use of $1,25(\text{OH})_2\text{D}_3$ as a therapy for inflammatory diseases. Th1 and Th17 cells are believed to contribute to inflammatory conditions such as RA [43], and are both recognized inhibitory targets for $1,25(\text{OH})_2\text{D}_3$. Vitamin D supplementation may prevent, slow or reverse inflammatory disease by inhibiting these T cell subsets. The current study addressed the question of $1,25(\text{OH})_2\text{D}_3$ responsiveness in cells from inflamed tissues by comparing effects of $1,25(\text{OH})_2\text{D}_3$ on IL-17 and IFN γ expression by CD4 $^+$ T cells derived from matched blood and SF samples from RA patients. Whilst $1,25(\text{OH})_2\text{D}_3$ strongly inhibited both IL-17 $^+$ and IFN γ $^+$ frequencies in cells from blood, there was no significant effect on IFN γ frequencies in cells from SF, suggesting a loss of $1,25(\text{OH})_2\text{D}_3$ sensitivity in T cells from the inflamed site.

Both naïve (CD45RA $^+$) and memory (CD45RO $^+$) T cells were able to respond to $1,25(\text{OH})_2\text{D}_3$, but inhibition of inflammatory cytokines was more pronounced for naïve T cells, and became less effective upon transition from naïve to memory. These findings suggest that variations in the proportion of naïve to memory T cells play a key role in defining the anti-inflammatory impact of $1,25(\text{OH})_2\text{D}_3$ *in vivo*, especially at the inflammatory site where memory T cells are the dominant T cell type [38]. Furthermore, whilst naïve to memory transition accounted for most of the loss in $1,25(\text{OH})_2\text{D}_3$ effect upon SF T cells, comparing memory T cells from blood with those from SF revealed a further decline in $1,25(\text{OH})_2\text{D}_3$ sensitivity in SF cells. Collectively, these data indicate that analysis of $1,25(\text{OH})_2\text{D}_3$ -responses using T cells from blood, even blood from RA patients, may over-estimate the ability of vitamin D to regulate inflammatory T cells in disease-affected synovial fluid.

Th17 and Th1 T cell subsets not only play a critical role in the pathophysiology of inflammatory diseases such as RA, they are also pivotal to host responses to infectious pathogens such as *Mycobacterium tuberculosis* [44]. In this setting,

1,25(OH)₂D₃ is proposed to be less effective in the early stages of infection, where T cells are not chronically activated and therefore have lower levels of VDR expression. The resulting insensitivity to 1,25(OH)₂D₃ during early infection is advantageous in enabling maintenance of inflammatory T cell populations for maximal clearing of pathogenic antigen [45]. By contrast, at later stages of immune response to infection, more activated T cells express higher levels of VDR and are therefore more sensitive to 1,25(OH)₂D₃, with the principal response being minimization of T cell activity and chronic inflammation [45]. Data from the current study suggest that in chronically activated T cells from inflammatory sites such as the rheumatoid joint, there is re-instigation of 1,25(OH)₂D₃-insensitivity. However, in contrast to early stage T cell responses, decreased responsiveness to 1,25(OH)₂D₃ in activated SF T cells does not appear to be due to lower VDR-binding capacity for 1,25(OH)₂D₃: VDR expression was increased in SF T cells *ex vivo* consistent with the activated CD69+ phenotype of these cells, and levels of VDR and co-regulator proteins were similar for blood and SF T cells following *in vitro* stimulation. Likewise differential expression of VDR and its co-regulators did not account for the lesser effect of 1,25(OH)₂D₃ on anti-inflammatory responses by memory vs naïve T cells.

An additional feature of memory T cells versus naïve is their commitment to phenotype as defined by cytokine expression. T cells that express multiple inflammatory cytokines including those doubly expressing IL-17 and IFN γ (Th17.1 cells) are regarded the most pathogenic in inflammatory disease [46]. Correspondingly, Th17.1 cells were present at increased frequency in SF T cells *ex vivo* compared to blood. Previous studies into 1,25(OH)₂D₃ effects upon T cell cytokine expression have used mixed cultures of cytokine-expressing and non-expressing cells, making it impossible to determine effects of 1,25(OH)₂D₃ upon phenotype-committed T cells which, as our data on phenotype maintenance following stimulation suggest, are more enriched in SF compared to blood. By using novel

cytokine cell capture methods to sort live Th17, Th17.1, Th1 and double negative cells into separate populations, the current study showed that responses to $1,25(\text{OH})_2\text{D}_3$ are in fact highly dependent on the commitment of T cells to a particular phenotype: $1,25(\text{OH})_2\text{D}_3$ treatment strongly suppressed conversion of cytokine naïve T cells into inflammatory effector cells as well as the transition of one effector phenotype to another through induction of a new cytokine. By contrast, $1,25(\text{OH})_2\text{D}_3$ was much less efficient at suppressing an existing T cell phenotype. T cells from SF displayed a more committed phenotype relative to blood as indicated by only small increases in Th17 and Th17.1 and no change in Th1 frequency following stimulation. Thus, whilst $1,25(\text{OH})_2\text{D}_3$ reduced expression of IL-17 and IFN γ in less phenotype-committed blood T cells by preventing new cytokine gene expression, it was much less effective as an inhibitor of established cytokine gene expression in SF T cells.

An important conclusion from these studies is that terminal commitment of memory T cells to a specific phenotype, as prevalent in disease-affected tissues such as RA synovium, plays a central role in attenuating anti-inflammatory effects of $1,25(\text{OH})_2\text{D}_3$. In concert with $1,25(\text{OH})_2\text{D}_3$, VDR functions as a transcription factor to regulate expression of genes such as IL-17 and IFN γ that have functional vitamin D response elements (VDRE) [47, 48]. This process is subject to genomic variation, but is also strongly influenced by epigenetic mechanisms that may lead to intra-individual [49], or disease-specific [39] changes in $1,25(\text{OH})_2\text{D}_3$ -VDR signaling. Recent studies have shown that memory T cell development is associated with specific epigenetic signatures that strongly influence transcriptional regulators [50]. Thus, it seems likely that variations in response to $1,25(\text{OH})_2\text{D}_3$ according to naïve and memory state and extent of phenotype commitment will be due to epigenetic modifications that could strongly influence chromatin remodeling, and VDRE accessibility. In future studies it will be interesting to investigate the potential use of epigenetic modulators in

correcting the 1,25(OH)₂D₃-insensitivity characteristic of T cells from RA disease-associated tissue.

5. Conclusion

Data in the current study endorse the potential use of vitamin D and/or 1,25(OH)₂D₃ in controlling the *de novo* generation of Th17 and Th17.1 cells that are associated with inflammatory disease. However, the limited effect of 1,25(OH)₂D₃ on phenotype-committed T cells from the site of inflammation suggests that vitamin D supplementation is unlikely to be successful as treatment for established active RA patients. Consistent with this hypothesis, not all early vitamin D supplementation trials in RA have reported positive effects of the treatment [51-53]. The fact that peripheral blood T cells from patients were responsive to the anti-inflammatory effects of 1,25(OH)₂D₃, and equally as responsive as those from healthy donors, nevertheless supports a use for vitamin D in the management of RA, either as a prophylactic or to reduce the risk of future disease flares in patients in remission. Owing to its powerful anti-inflammatory effects *in vitro*, vitamin D supplementation has been proposed as a cost-efficient, 'natural' and low-risk treatment strategy in multiple inflammatory diseases. However, since memory T cells with committed inflammatory phenotypes dominate the inflamed tissues in multiple inflammatory conditions, this study raises questions about widespread application of vitamin D therapy in the management of inflammatory diseases, especially cases of established, active disease. Further studies are required to identify the cause of the insensitivity to 1,25(OH)₂D₃ at the molecular level. Strategies to overcome this and restore 1,25(OH)₂D₃ sensitivity in inflammatory phenotype-committed memory T cells at the inflamed site may provide a novel approach to the treatment of RA and other inflammatory diseases.

6. Acknowledgements

The authors would like to thank Kath Howlett and Holly Adams for help in processing patient samples. LJ, DS, KR, MH designed the research. AF, and KR, consulted and consented patients and obtained clinical samples. LJ, PH, NM performed experiments. LJ analysed data and performed statistical analyses. LJ, KR and MH wrote the manuscript. Research was funded by the European Union (FP7-HEALTH-F2-2012-305549 to KR), National Institutes of Health (R01 AR063910 to MH), and Arthritis Research UK (The Arthritis Research UK Rheumatoid Arthritis Pathogenesis Centre of Excellence is funded by Arthritis Research UK grant number 20298). PH and NM were funded by Wellcome Trust and Dr Hadwen Trust summer studentships respectively. This report is independent research supported by the National Institute for Health Research/Wellcome Trust Clinical Research Facility at University Hospitals Birmingham NHS Foundation Trust. The views expressed in this publication are those of the author(s) and not necessarily those of the NHS, the National Institute for Health Research or the Department of Health.

Figure Legends

Figure 1. Anti-inflammatory effects of 1,25(OH)₂D₃ are reduced in T cells from synovial fluid compared to peripheral blood. Mononuclear cells from the peripheral blood of healthy controls (HC) and the blood and synovial fluid (SF) of RA patients were stimulated with anti-CD3 for seven days in the presence or absence of 1,25(OH)₂D₃ (+1,25D) and frequencies of IL-17+ and IFN γ + CD4+ T cells quantified by flow cytometry **(A)**. Representative bivariate plots of IL-17 versus IFN γ expression by CD4+ T cells showing IL-17+/IFN γ - (Th17), IL-17+/IFN γ + (Th17.1) and IL-17-/IFN γ + (Th1) subsets for cells from RA blood vs RA SF. **(B)**. Significant effects of 1,25(OH)₂D₃ were tested for HC (n=9), RA blood (n=12), RA SF (n= 11) by Wilcoxon matched pairs or Mann Whitney nonparametric tests as appropriate **(C)**. Effect of 1,25(OH)₂D₃ on Th17, Th17.1 and Th1 populations quantified by frequency in respective gate under untreated/1,25D conditions. Significance was tested by repeated measures two-way ANOVA. ns= non-significant, * = P<0.05, **=P<0.01, ***=P<0.001.

Figure 2: Effects of 1,25(OH)₂D₃ are greater on naïve than memory T cells. Naïve and memory CD4+ T cells were purified from the peripheral blood of healthy controls and stimulated with autologous monocytes and anti-CD3 in the presence or absence of 1,25(OH)₂D₃ (+1,25D). Frequency of cells expressing IL-17, IFN γ and IL-21 was quantified at seven days and expression of CTLA-4 and FoxP3 measured at four days by flow cytometry. **(A)** Representative FACS plots for one donor are shown (left), and frequencies of cytokine positive cells and CTLA-4 median fluorescence intensity (MFI) summarised as dot plots for n=6 donors for vehicle (closed symbols) and 1,25(OH)₂D₃ (+1,25D)-treated cells (open symbols) (right). **(B)** The effect of 1,25(OH)₂D₃ on IL-17, IFN γ and IL-21 was compared for naïve and memory T cells by frequency of positive cells under untreated/1,25D conditions. A lower frequency

limit of 0.001% was used for these calculations. 1,25(OH)₂D₃ effect on CTLA-4 was estimated by MFI under 1,25D/untreated conditions. Significant differences were tested using Wilcoxon matched pairs tests. ns= non-significant, * = P<0.05, **=P<0.01, ***=P<0.001.

Figure 3: Memory and naïve T cells express similar levels of vitamin D response machinery. RNA was purified from naïve and memory CD4⁺ T cells from the peripheral blood of healthy controls before and after stimulation with antiCD3/CD28 beads. Regulators of response to 1,25(OH)₂D₃ including **(A)** Vitamin D receptor (VDR), **(B)** Retinoid X Receptor (RXR), **(C)** VDR co-regulators: DRIP205, NcoA1, NcoR1 and NcoR2 were measured by qPCR. mRNA expression for each gene is shown relative to matched memory T cells. VDR protein in T cells was also measured by flow cytometry before and after stimulation with PMA and ionomycin. Stimulated T cells were defined as CD69⁺. Statistical significance was tested by repeated measures two-way ANOVA. * = P<0.05, **=P<0.01.

Figure 4. Memory T cells from synovial fluid are relatively insensitive to 1,25(OH)₂D₃ compared to memory T cells from peripheral blood. CD45-RO⁺ memory T cells were isolated from synovial fluid (SF) and peripheral blood of established RA patients and stimulated with anti-CD3/CD28 beads in the presence or absence of 1,25(OH)₂D₃ (+1,25D) overnight or for 5 days. Response to 1,25(OH)₂D₃ was assessed by measurement of IL-17, IFN γ and IL-21 by flow cytometry at 5 days and relative expression of cytokines in the presence vs the absence of 1,25(OH)₂D₃ calculated for n>9 donors **(A)**. Significant differences were tested using Wilcoxon matched pairs tests. ns= non-significant, * = P<0.05. **(B)** Effects of cell location and 20hr stimulation on VDR and RXR mRNA transcripts were examined by qPCR **(B)**. Expression is given relative to the level in unstimulated memory cells. Statistical

significance was tested by repeated measures two-way ANOVA. * = $P < 0.05$, ***= $P < 0.001$, ns = not significant. VDR expression in CD4+ T cells from blood and synovial fluid was also assessed by flow cytometry for n=3 donors. Representative data for CD69 versus VDR are shown in (C).

Figure 5. 1,25(OH)₂D₃ suppresses cytokine expression by pre-committed Th17, Th17.1 and Th1 cells but most potently affects novel phenotype induction

CD4+ T cells from healthy control blood were stimulated with monocytes and anti-CD3 for seven days and sorted into IL-17+IFN γ - (Th17), IL-17+IFN γ + (Th17.1), IL-17-IFN γ + (Th1) or double negative (DN) subsets using cytokine secretion assays and flow cytometry. After two day culture with monocytes and anti-CD3 in the presence or absence of 1,25(OH)₂D₃ (+1,25D) T cells were re-analysed for IL-17 and IFN γ expression by flow cytometry. (A) Data from one donor, representative of three studied. (B) Effect of 1,25(OH)₂D₃ upon total IL-17 and total IFN γ expression by sorted subsets, calculated as the ratio of cells expressing the cytokine under untreated vs treated conditions.

Figure 6. Capacity for phenotype change upon stimulation is reduced in SF T cells. IL-17 and IFN γ expression by CD4+ T cells from the peripheral blood and synovial fluid of RA patients was measured by flow cytometry *ex vivo* and after anti-CD3 stimulation for seven days. (A) Representative bidirectional FACS plots of IL-17 versus IFN γ in T cells from blood and synovial fluid (SF) from a single RA donor *ex vivo* and after 7 days of culture. (B) Summary of T cell frequencies in blood and synovial fluid (SF) for multiple donors *ex vivo* and after 7 days of culture. Significant differences were tested using Wilcoxon matched pairs tests. * = $P < 0.05$, **= $P < 0.01$, ***= $P < 0.001$. (C) XY plots for frequencies of IL-17+ and IFN γ + CD4+ T cells *ex vivo* and after seven days. Diagonal lines indicate equal frequencies at each time point. (D) Pie charts summarizing the frequencies of Th17 (pale grey), Th17.1 (dark grey),

Th1 (black) and double negative (DN) (white) CD4+ T cells from blood and SF ex vivo and after 7 days of culture (n=12 donors).

Figure 7. T cell responses to 1,25(OH)₂D₃ correlate directly with capacity for phenotype change. Bidirectional plot of fold change in frequency of the population (Th17 blood (Bld), Th17 synovial fluid (SF), Th17.1 Bld, Th17.1 SF, Th1 Bld, Th1 SF) after seven day culture under control conditions versus the ratio of the population frequency in the presence versus the absence of 1,25(OH)₂D₃. Correlation significance was tested by Pearson's analysis and the linear regression line with 95% confidence interval (hashed line) is shown.

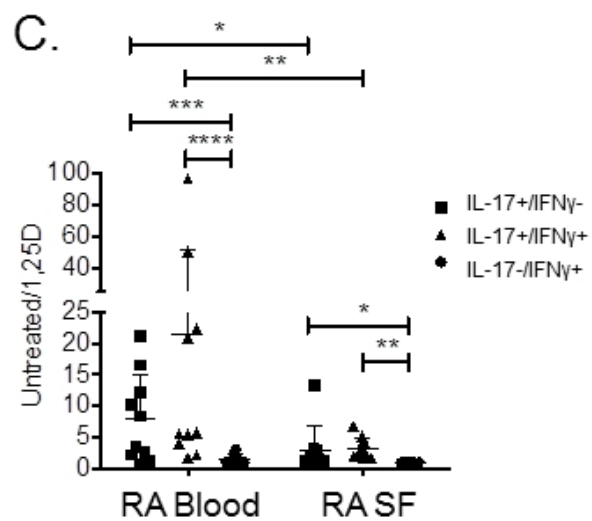
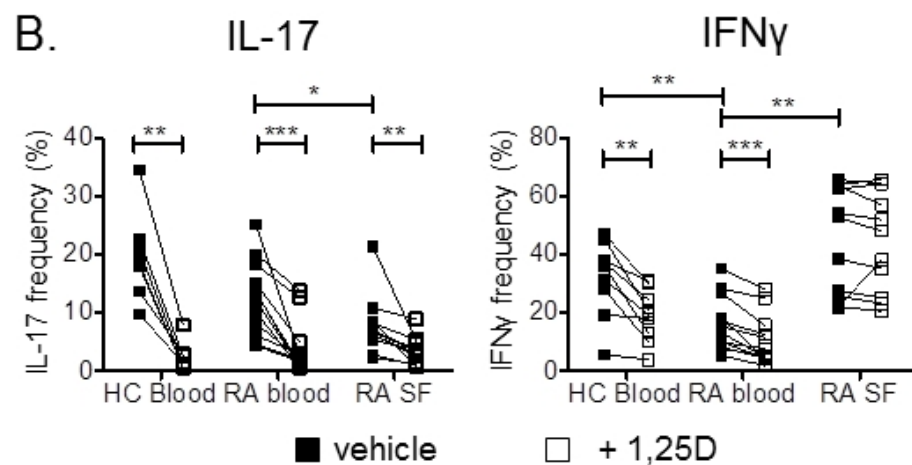
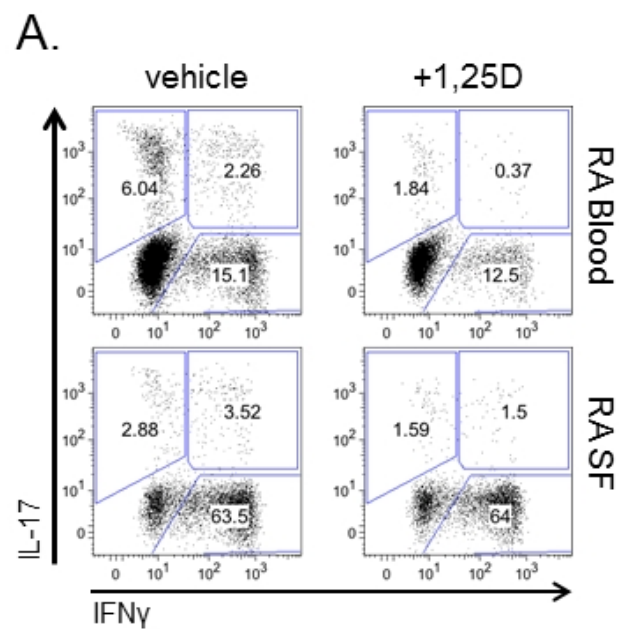
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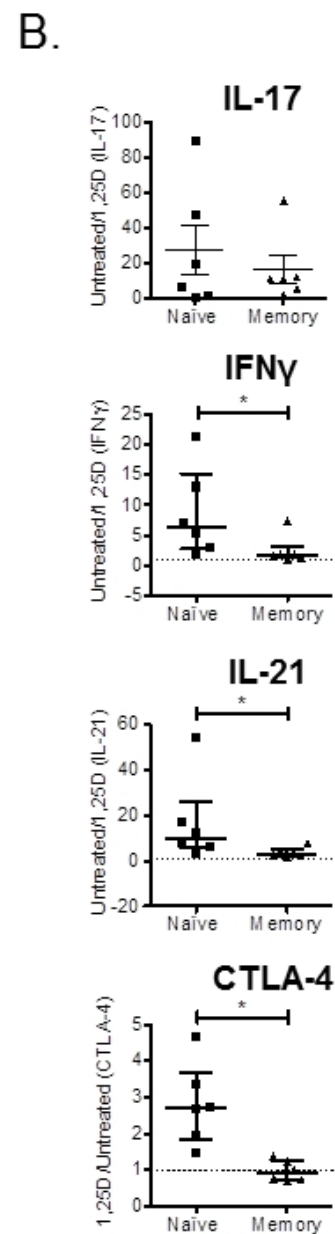
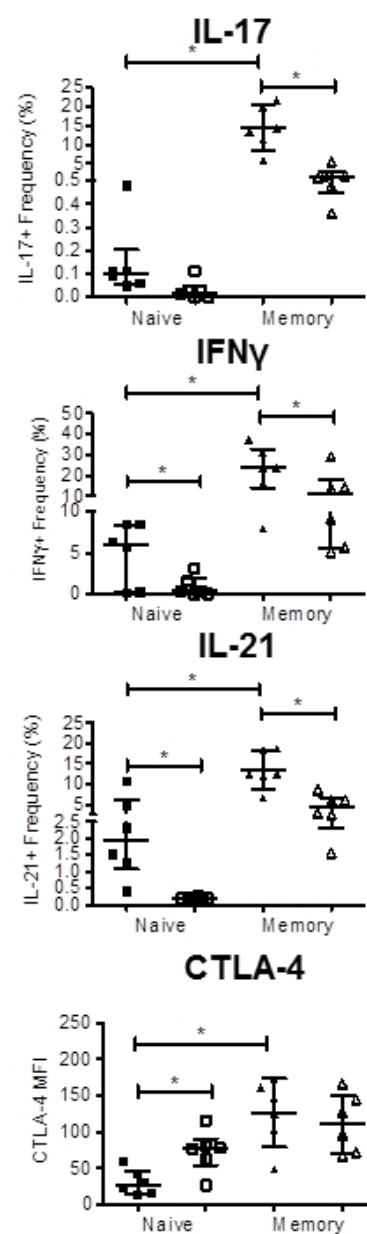
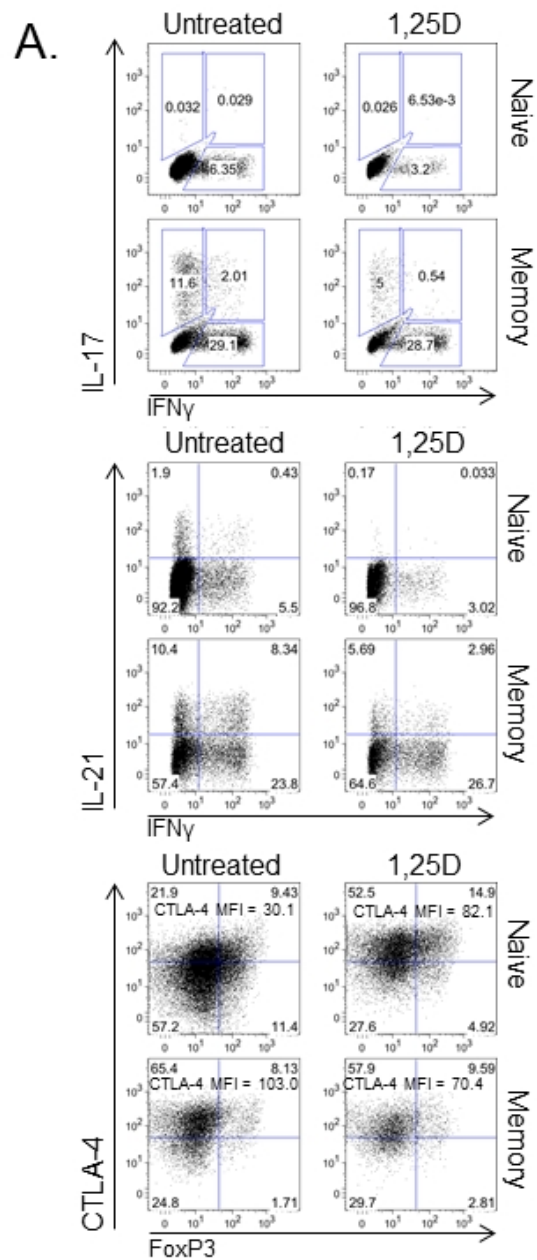
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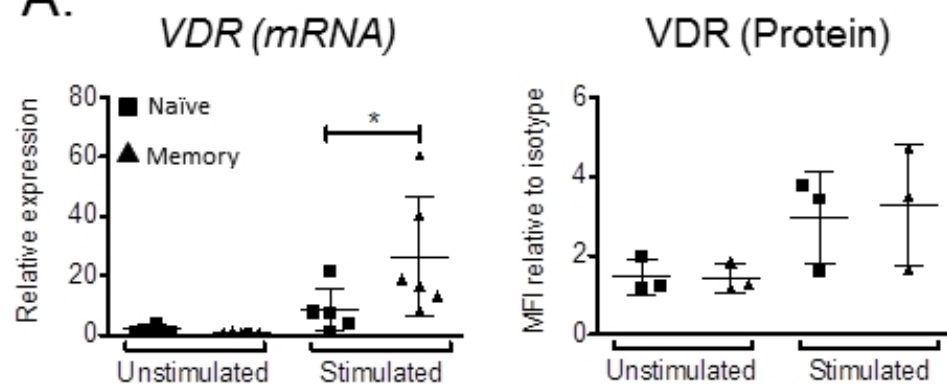
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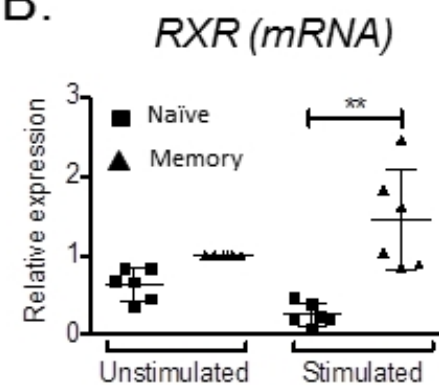




A.

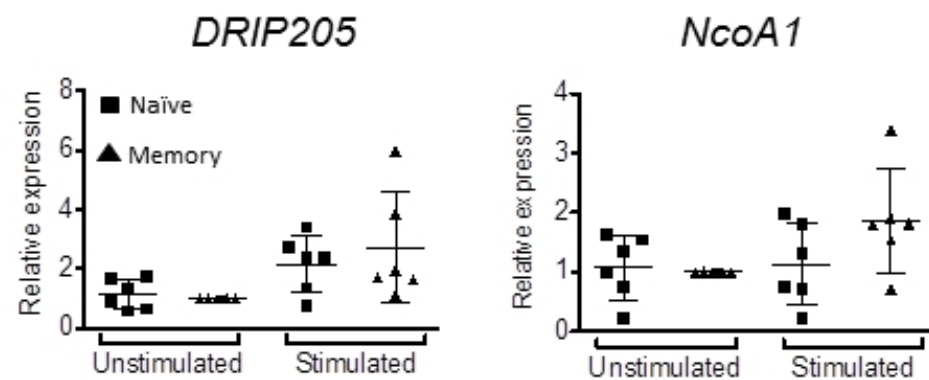


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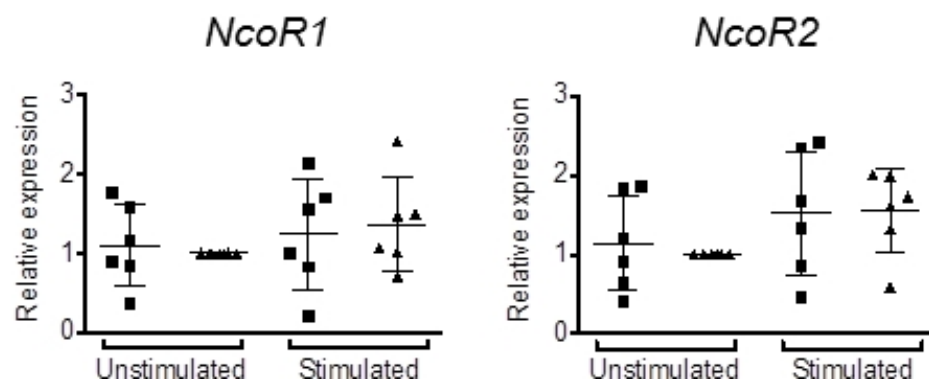


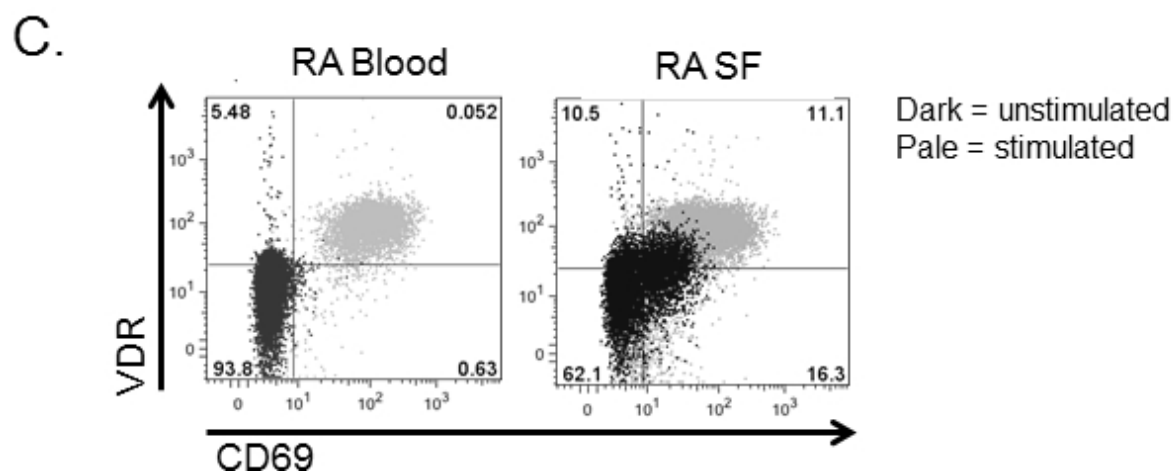
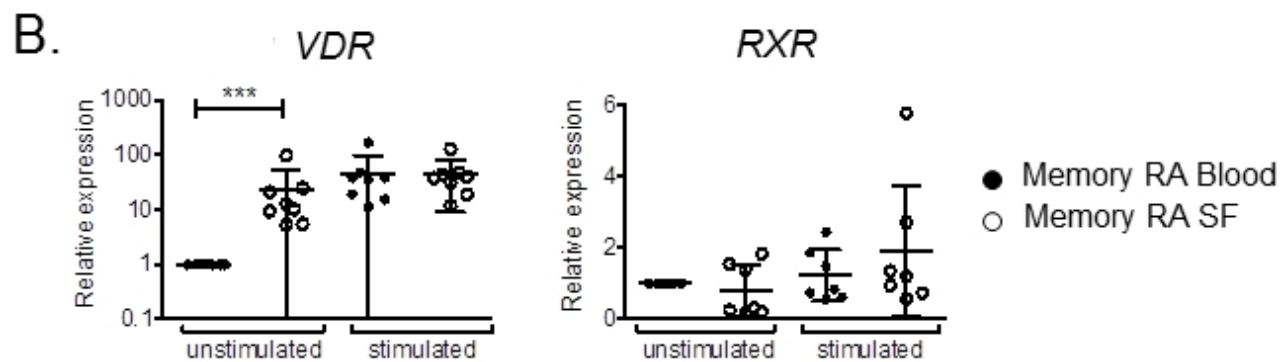
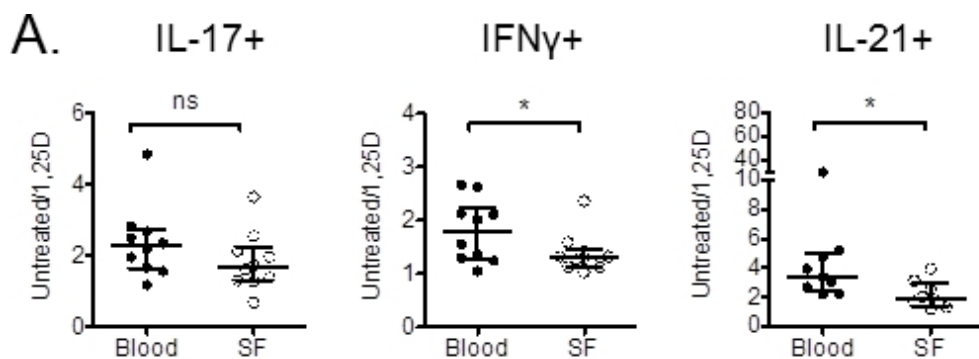
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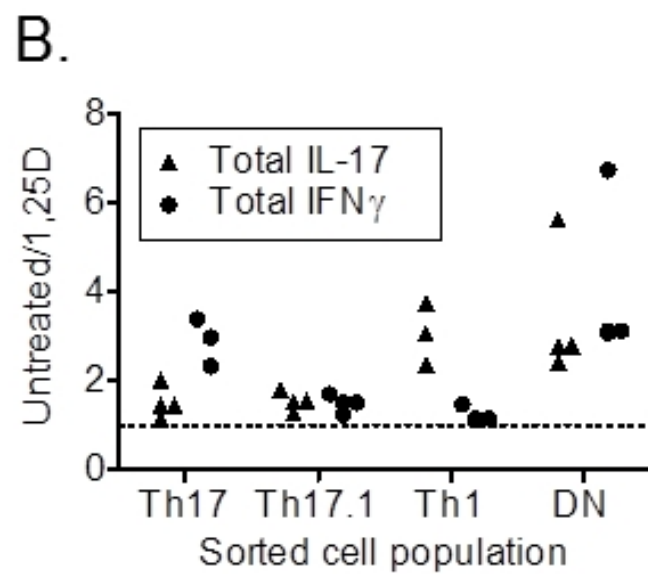
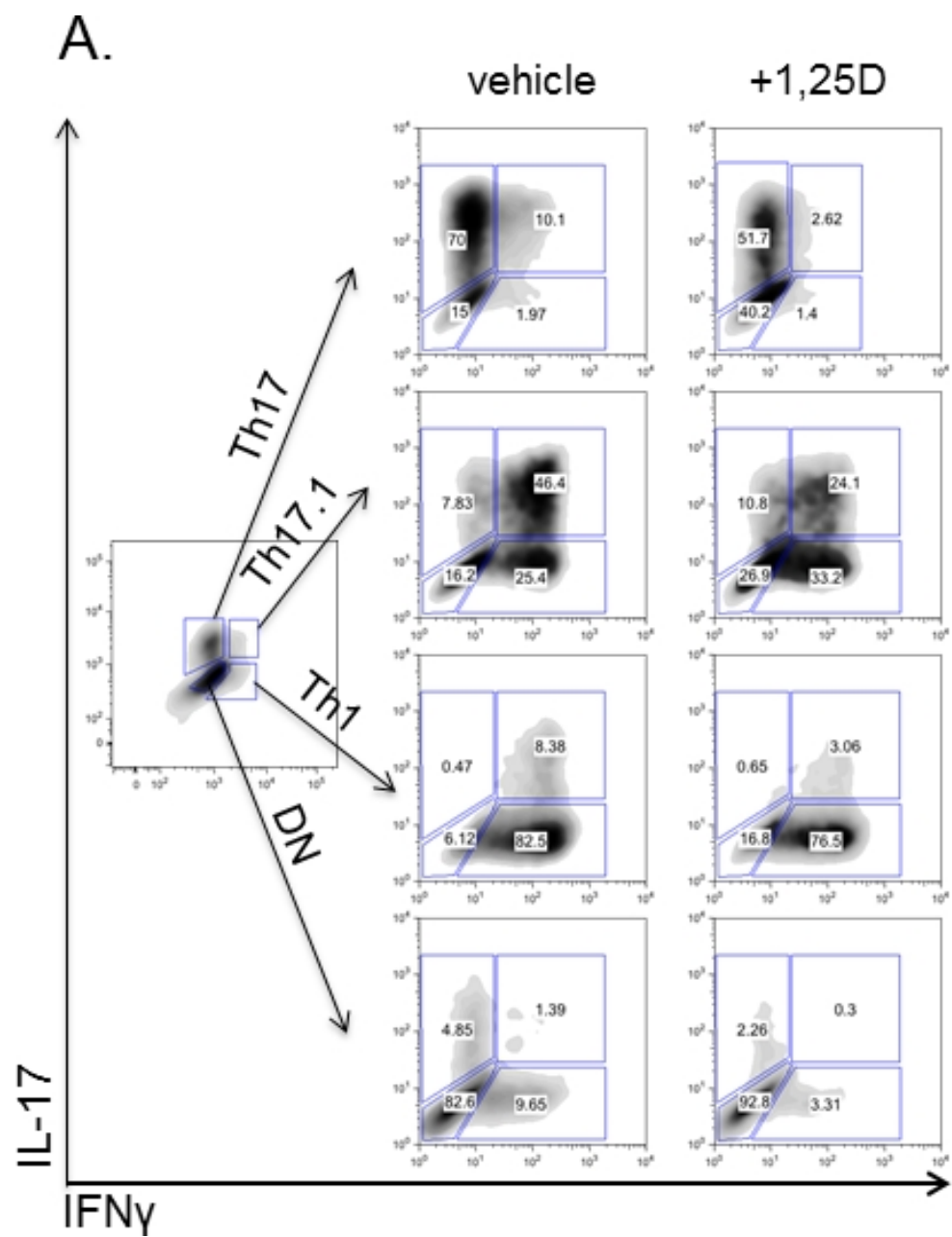
Co-enhancers

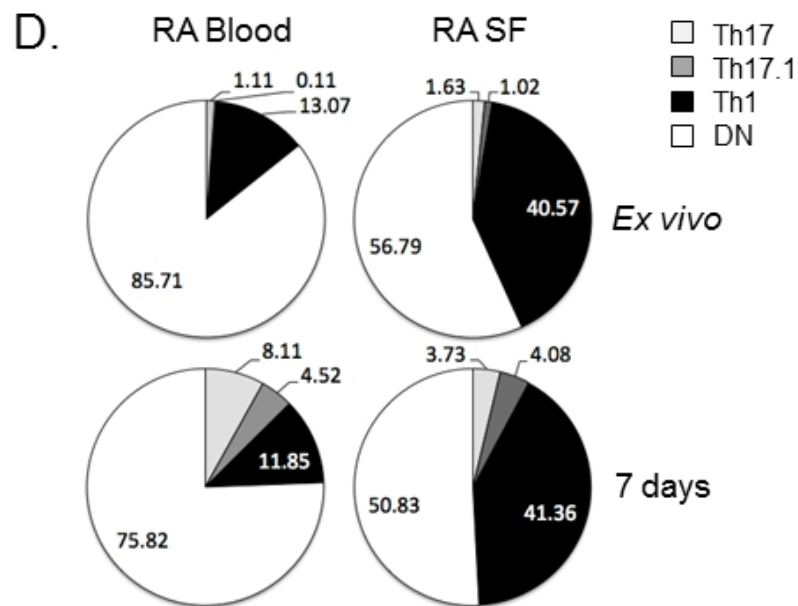
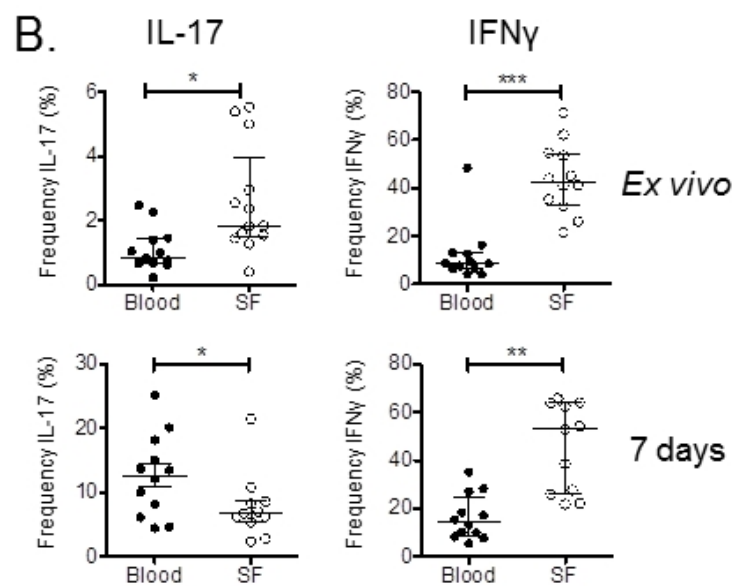
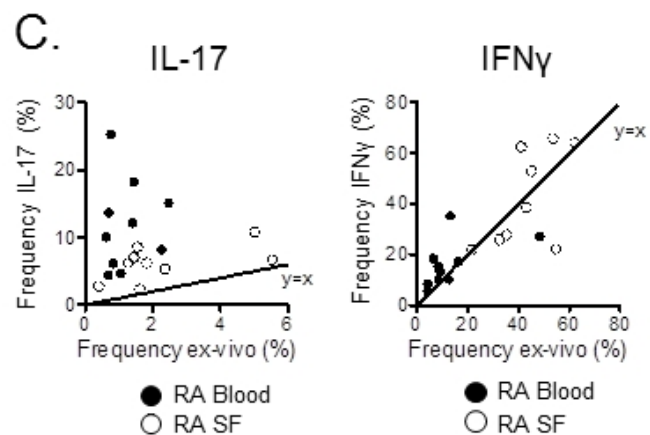
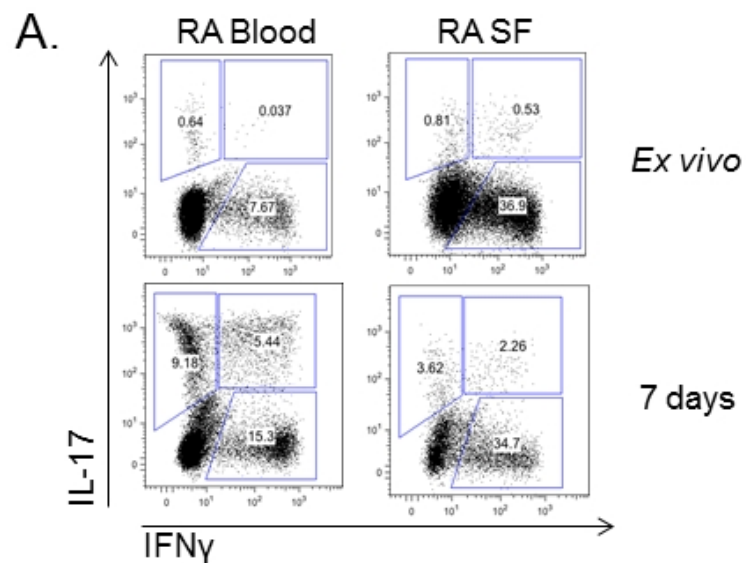


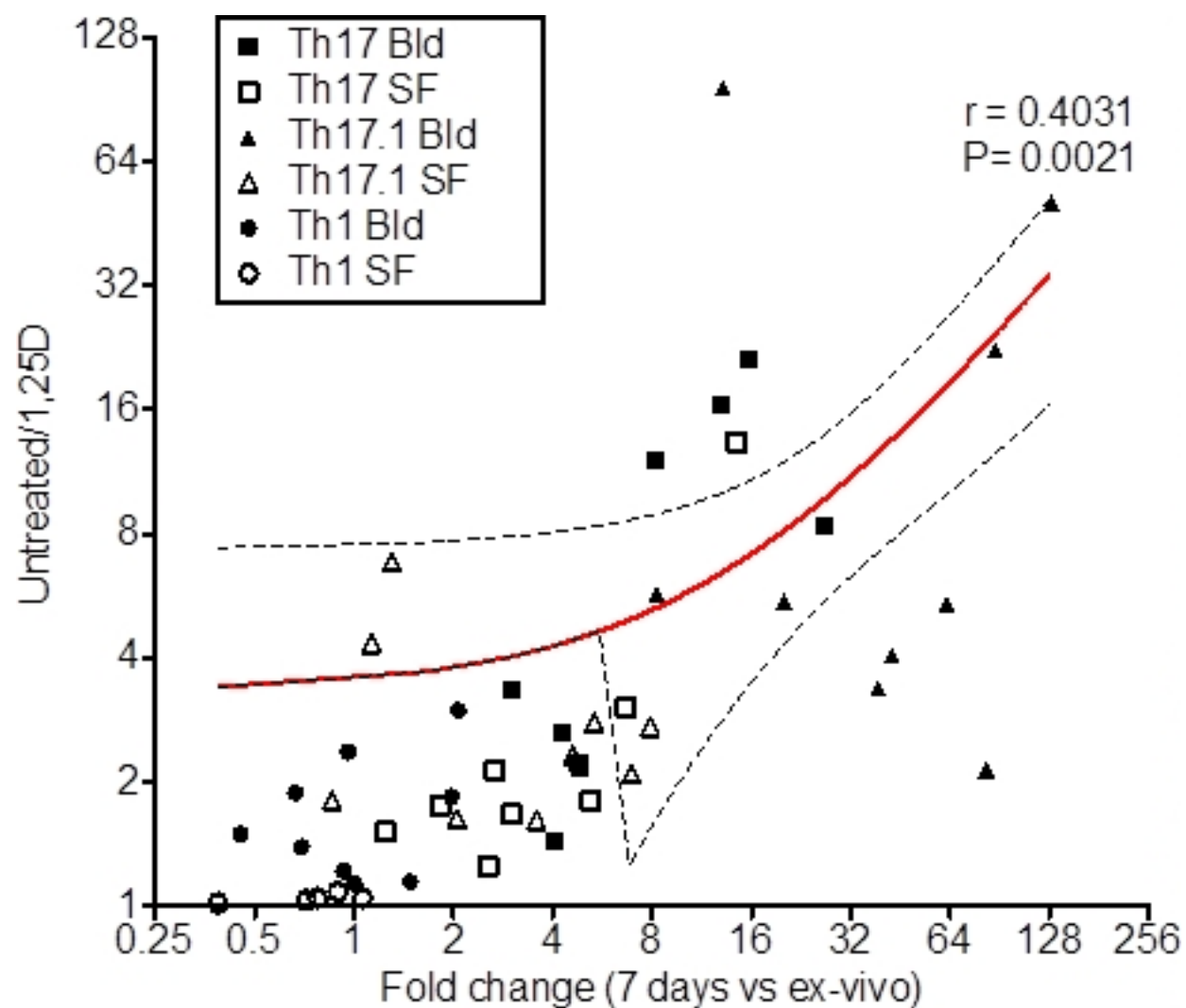
Co-repressors

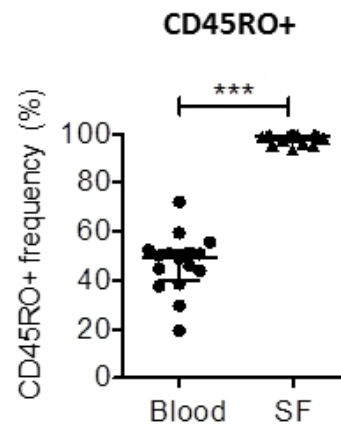




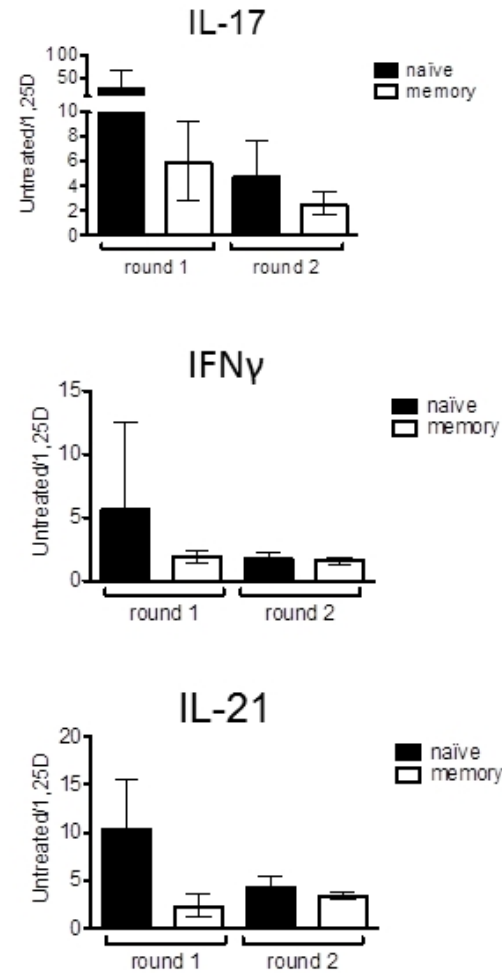








S1. Memory T cells are abundant in synovial fluid. Frequency of CD45RO+ CD4+ T cells in the blood and synovial fluid of RA patients was assessed by flow cytometry. Significance was tested by Wilcoxon matched pairs analysis *** = $P < 0.001$.

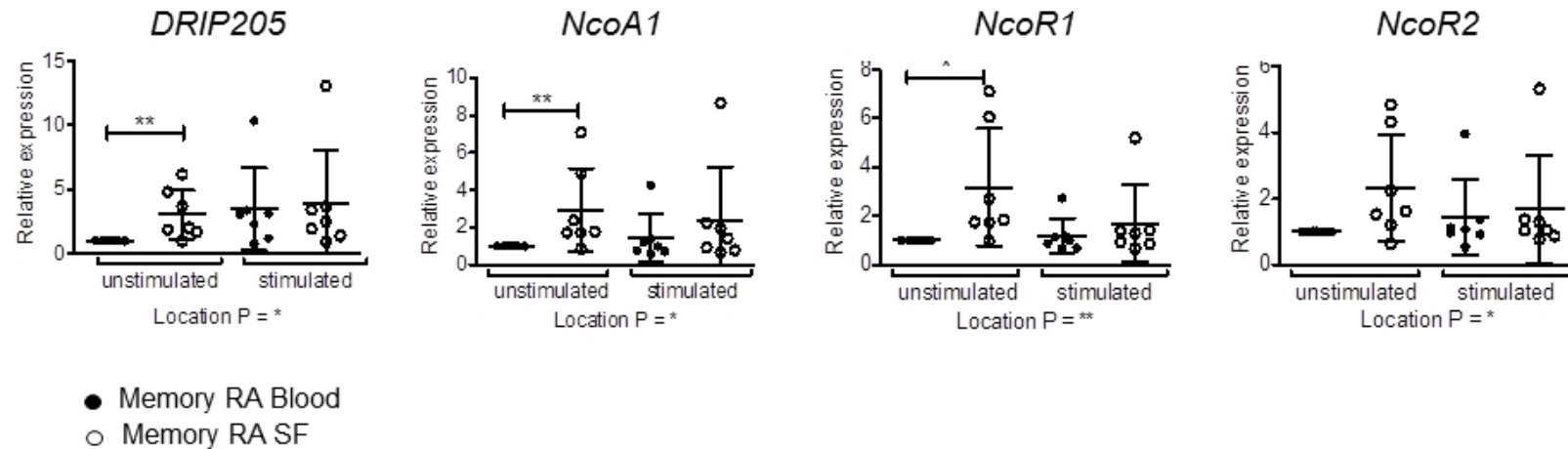


S2. Naïve T cell sensitivity to 1,25(OH)₂D₃ decreases following stimulation

Naïve and memory CD4⁺ T cells were stimulated with monocytes and anti-CD3 for two sequential rounds of stimulation. The effect of 1,25(OH)₂D₃ upon IL-17⁺, IFN γ ⁺ and IL-21⁺ frequencies is given as the relative frequency of positive cells under untreated/1,25(OH)₂D₃ conditions. Graphs show the mean and range of effect for n=3 donors.

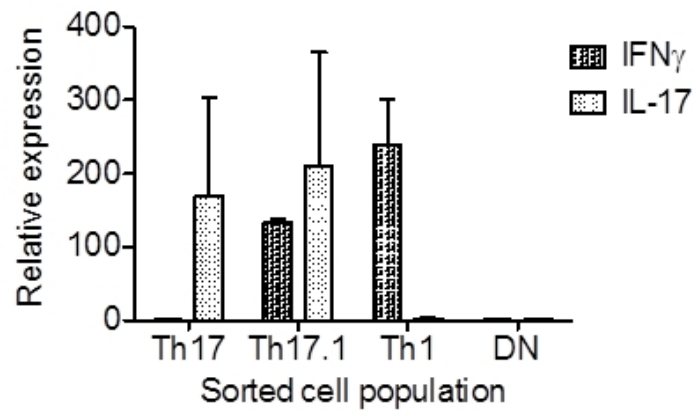
Co-enhancers

Co-repressors



S3. Expression of mRNA for VDR co-regulators in blood versus SF memory T cells

In CD45RO+ memory T cells from RA patient blood and SF, qPCR was used to measure mRNA for the VDR co-activators DRIP205, NcoA1 and the VDR co-repressors NcoR1 and NcoR2. Data are shown for n=7 donors. Statistical significance was tested by repeated measures two-way ANOVA. * = P<0.05, **=P<0.01.



S4. IL-17 and IFN γ expression in purified Th17, Th17.1, Th1 and DN CD4+ T cells. qPCR was used to measure IL-17 and IFN γ mRNA expression in CD4+ T cells sorted into Th17, Th17.1, Th1 and DN subsets using cytokine secretion assays and flow sorting. Expression is given relative to the level in DN T cells.