Journal of
Clinical & Cellular Immunology

Davtyan et al., J Clin Cell Immunol 2014, 5:2
DOI: 10.4172/2155-9899.1000196

Research Article Open Access

Diminished IL-10 production is Associated with Impaired Versatility of Monocytes in Familial Mediterranean Fever

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Received date: Jan 15, 2014, **Accepted date:** Mar 10, 2014, **Published date:** Mar 17, 2014

Abstract

Purpose: The nature of the heightened endotoxin sensitivity state observed in Familial Mediterranean Fever (FMF) at present remains unknown. To assess the possibility that IL-10 plays a role in setting the inflammatory threshold, we studied IL-10 production by monocytes and dendritic cells as well as endotoxin tolerance induction in FMF patients.

Methods: 46 attack-free FMF patients were included in this study. The production of IL-10 by NLR- or TLR-agonist-stimulated monocytes and dendritic cells were assayed either by conventional ELISA or flow cytometry. The versatility of monocytes was studied by measuring the production of IL-10 and IL-1β after stimulation by pro- and anti-inflammatory agents, and after stimulation arrest or a further counter stimulation. Monocyte endotoxin tolerance and cross-tolerance induction were assayed by measuring the production of IL-1β, IL-10, TNF-α and IFN-γ after pre-stimulation by NLR- or TLR-ligands and after re-stimulation with LPS.

Results: In FMF patients, we observed down-regulation of circulating $CD36^+$ peripheral blood lymphoid cells but not monocytes, constitutively producing IL-10. The production of IL-10 by TLR- and NLR-agonist-stimulated monocytes and dendritic cells declines in FMF patients. Monocytes isolated from FMF patients failed to switch from a pro-inflammatory activated state to anti-inflammatory phenotype and still produce IL-1β but not IL-10, which cause impaired endotoxin tolerance and cross-tolerance induction. The IL-10 production and endotoxin tolerance induction by monocytes and dendritic cells were restored by NOD2- ligand MDP and colchicine treatment.

Conclusion: The reduced IL-10 production was associated with the impaired setting of feedback inhibition of inflammatory response and caused impaired resolution of inflammation and endotoxin tolerance induction.

Keywords: Familial Mediterranean fever; IL-10; Endotoxin tolerance; Monocyte; Dendritic cells; IL-1β

Introduction

Familial Mediterranean fever (FMF) is a systemic relapsing auto-inflammatory disorder, heritable as an autosomal recessive trait, which is caused by various mutations in the gene *MEFV*. This gene encodes a protein called pyrin, expressed primarily on the innate immune system cells, including neutrophils, and cytokine-activated monocytes [1-3]. Through homotypic domain interactions, pyrin binds the common adaptor - apoptosis-associated speck-like protein (ASC) and participates in at least three important cellular processes: apoptosis, recruitment and the activation of pro-caspase-1 (with associated processing and secretion of IL-1β) and activation of the NF-κβ transcription factor [4]. Macrophages from mice expressing truncated pyrin similar to FMF patients – exhibit heightened sensitivity to bacterial lipopolysaccharide (LPS), produce more active caspase-1 and IL-1β and show resistance to cytokine- and LPS-induced apoptosis [5,6].

Although the nature of heightened endotoxin sensitivity state observed in FMF at present remains unknown, it was suggested that it may be due to impaired endotoxin tolerance induction. Prior exposure to LPS leads to a transient state of LPS hyporesponsiveness *in vivo* and *in vitro*, termed 'endotoxin tolerance' [7]. Endotoxin tolerance is thought to limit the inflammatory response induced during infection, and protects the host from developing shock caused by the excessive production of inflammatory cytokines by monocytes and macrophages [8]. Recently, we have shown that induction of monocyte homologous endotoxin tolerance occurs during an FMF attack, whereas monocytes from patients in the attack-free period fail to induce LPS tolerance and exhibit heightened sensitivity to bacterial endotoxin [9,10]. Impaired LPS tolerance induction in attack-free FMF patients correlates with both the increased LPS-induced pro-inflammatory cytokine synthesis polarization and the different time course pattern of LPS-induced changes on monocytic surface expression of CD14, CD11a/CD18 and CD11b co-receptors. In addition, enhancement of LPS-induced apoptosis of neutrophils is observed in FMF patients, which is further confirmed by the fact that neutrophils from FMF patients previously unexposed to *Salmonella enteritidis* exhibited heightened

susceptibility to the LPS of this pathogen similar with that of *Salmonella enteritidis* infected patients [11].

Although dominance of anti-inflammatory cytokines such as IL-10 is associated with reduced immune responsiveness and susceptibility to persistent infection, conditions such as chronic inflammation are linked to lower IL-10 levels [12]. An appropriate threshold for immune activation is critical for optimal protection from infection and conversely, from short- and long-term side-effects of immune effector mechanisms. In the absence of appropriate feedback control, inflammatory responses can lead to vast immunopathology and death. Due to its primary ability to restrain inflammation, IL-10 has been a topic of long-standing interest [13]. Numerous clinical observations have validated mouse studies by linking IL-10 levels with disease outcomes [14,15]. Likewise, disease association studies identifying correlations between IL-10 levels and disease susceptibility have bolstered the belief that appropriate regulation of IL-10 expression is fundamental to governing host inflammatory responses [16,17]. To assess the possibility that IL-10 plays a role in setting inflammatory threshold and immune silence in auto-inflammatory disorders, we characterized the IL-10 production by monocytes and dendritic cells and endotoxin tolerance induction in patients with FMF.

Material and Methods

Patient population

Peripheral blood samples were obtained from 46 attack-free FMF patients with family history (26 male, 20 female, aged between 18-41 years), diagnosed according to the Tel-Hasomer criteria [18]. *MEFV* mutations in exon 10 were identified in all patients (patients were compound heterozygous for the M694V and one of the V724A, M680I, E148Q, R761H and F749L mutations). The following selection criteria were applied to the patients enrolled in the study: 1) age>16 years, 2) absence of chronic diseases such as chronic renal failure, renal amyloidosis, diabetes mellitus, ischemic heart disease, malignancy, trauma, infections and rheumatic disease, 3) treatment-naïve and no drug administration within 4 weeks before blood drawing. All patients had given their informed consent to the inclusion in this study. Heparinized peripheral blood was obtained from 43 sex- and age-matched normal donors (ND) (23 male and 20 female). No significant differences existed between FMF and ND with respect to mean levels of ESR, albumin and WBC counts (markers of disease activity and other laboratory parameters of the patients and normal donors are provided in the Electronic Supplementary Material —Supplementary methods Table S1).

Serum cytokine profiling

Serum samples were collected from 43 ND and 46 FMF patients and samples were stored at -80°C until solid phase enzyme-immune assay. IL-10 and IL-1β concentration in serum samples was determined by conventional ELISA using human IL-10 and IL-1β Ready-SET-Go test kit (eBioscience), with a detection limit of 2 pg/ml, according to the manufacturer's recommendations.

Monocytes isolation and activation

Heparinized peripheral blood samples were obtained from 15 (9 male, 6 female) out of a randomly selected 46 FMF patients, and from 7 out of 43 sex- and age-matched (3 male and 4 female) ND. Peripheral blood mononuclear cells (PBMC) were separated from heparinized whole blood by Ficoll-Hypaque (histopaque) (Sigma Chemical Co., St. Louis, MO) density gradient centrifugation. Peripheral blood monocytes were isolated by cell adherence of PBMC to 25 cm^2 plastic flasks during 45 min incubation at 37°C in an atmosphere containing 6% CO_2 [19]. Monocytes (95% CD14 positive cells) were then washed three times with endotoxin-free PBS and cultured at 5 $\times 10^5$ cells/ml density in RPMI-1640 containing 10% FCS, 2 mM L-glutamine, 1 mM sodium pyruvate, 100 U/ml penicillin and 100 μg/ml streptomycin. Either of 2.5 μg/ml peptidoglycan (PGN) from *E. coli 0111:B4* (an NOD1 and NOD2 ligand) and synthetic Pam_3CSK4 bacterial liporotein (an TLR2-TLR1 ligand) or 5 μg/ml muramyl dipeptide (MDP, an NOD2 ligand) were included in the culture media from day 0 to day 3. All reagents were purchased from InvivoGen (San Diego, USA). To assess the versatility of monocyte activation, 5×10^5 cells in 1 ml of complete RPMI-1640 medium were incubated with recombinant IL-4 (10 ng/ml, eBioscience) or 100 ng/ml LPS from *E. coli 026:B6* (Sigma Chemical Co., St. Louis, MO) from day 0 to day 3. One day 3, the cells washed and fresh medium added or stimulated with opposite pro-inflammatory (LPS) or anti-inflammatory (IL-4) molecules for an additional 3 days [19]. Cell-free supernatants were decanted at days 3 and 6, then stored at -80°C and IL-10 and IL-1β concentration in samples determined by ELISA.

Generation of monocyte-derived dendritic cells (DCs)

For the generation of immature DCs (iDCs), plastic adherence monocytes were cultured for 6 days with GM-CSF (10 ng/ml) and IL-4 (10 ng/ml) as originally described by Morse et al. [20]. Mature DCs (mDCs) were generated *in vitro* by monocytes by incubation with GM-CSF (10 ng/ml), IL-4 (10 ng/ml) and pro-inflammatory TNF-α (10 ng/ml) and cultured for 6 days [20]. On day 6, the cells were washed and fresh medium was added or stimulated with 100 ng/ml LPS or 2 μg/ml colchicine for an additional 24 h. Cell free supernatants were decanted and stored at -80°C and IL-10 concentration in samples determined by ELISA.

Flow cytometry

PBMC were surface-stained by 0.3 μg fluorescein isothiocyanate (FITC)-conjugated anti-CD36 (Serotec) or IgM-FITC isotype control and fixed in 1% paraformaldehyde (Becton Dickinson). Stained cells were incubated with 1% FACS permeabilizing solution (Becton Dickinson) and incubated with phycoerythrin (PE)-conjugated anti-human IL-10 (eBioscience) or matched isotype control. DC surface staining was done as described in Electronic Supplementary Material —Supplementary methods. Cells were fixed in 1% paraformaldehyde and subjected to FACS analysis on a Becton Dickinson FACSCalibur flow cytometer with CellQuest® software (Becton Dickinson, San Jose, CA, USA).

Endotoxin tolerance

Endotoxin tolerance was monitored by measuring the production of IL-1β, IL-10, IFN-γ and TNF-α by monocytes in response to LPS after preincubation in the presence or absence of two doses of LPS [9]. Monocytes at 5 $\times 10^5$ cells/ml density were cultured for 18 h in the presence or absence of 100 ng/ml LPS or either with 2 μg/ml colchicine or 2.5 μg/ml PGN or 5 μg/ml MDP or 10 ng/ml recombinant IL-4. After the first 18 h of culture, samples were washed three times with endotoxin-free PBS, and cultured for an additional 4 h in the presence of 1 μg/ml LPS. At the end of the culture period, cell-free supernatants were harvested, and endotoxin tolerance assayed by

conventional ELISA determination of human IL-1β, IL-10, IFN-γ and TNF-α using Ready-SET-Go test kit (eBioscience) according to the manufacturer's recommendations.

Statistics

The method of dispersion analysis with parametric and non-parametric procedures was used in this study. Results of independent experiments were used to calculate mean values ± SD, and differences were defined as statistically significant by Student's t-test (P_t), paired t-test (P_p), Wilcoxon-Mann-Whitney, and Welch's test (P_W) at $P \leq 0.05$.

Results

IL-10 production in FMF patients

IL-10 and IL-1β concentration in serum samples was measured in 43 ND and 46 FMF patients. The serum IL-10 was detectable only in 7 (16.3%) ND and in only 2 (4.2%, $P_w<0.04$ compared with the ND) FMF patients (described in Electronic Supplementary Material—Supplementary results, Figure S1). We found that the serum IL-1β is not detectable either in ND or in FMF.

Next, we studied how cellular production of IL-10 is different between ND and FMF patients. Previously it had been shown that circulating $CD36^+$ peripheral blood cells constitutively produce IL-10 in healthy individuals and play a potential role in homeostatic innate immune suppression [21]. In PBMC isolated from ND and FMF patients, the number of $CD36^+$ cells intracellulary synthesizing IL-10 was determined by flow cytometry (described in Electronic Supplementary Material—Supplementary results, Figure S2). The percentage of $CD36^+$ monocytes (Figure 1A) was found to be significantly higher than $CD36^+$ lymphocytes both in FMF and ND ($P_t<0.0001$ and $P_t<0.0008$ respectively). Interestingly, the percentage of $CD36^+$ monocytes was found to be significantly higher ($P_W<0.05$) in FMF patients compared with ND (Figure 1A). In contrast to this, the number of $CD36^+$ lymphocytes is higher in ND (9.7 ± 3.7%) compared with FMF patients (6.9 ± 0.8%), however, this difference did not reach a statistically significant level (the variances were found to be higher in ND, $P<0.0003$). The number of IL-10 synthesizing $CD36^+$ monocytes was found to be significantly higher than IL-10 synthesizing $CD36^+$ lymphocytes (Figure 1 B) in FMF patients (6.0 ± 0.8 vs 2.5 ± 0.4 % respectively, $P_t<0.04$), but not in ND (5.0 ± 1.0 versus 4.5 ± 0.6 % respectively). The number of IL-10 synthesizing $CD36^+$ monocytes was found to be higher in FMF patients compared with ND, however this difference did not reach a statistically significant level. In contrast to this, the percentage of IL-10 synthesizing $CD36^+$ lymphocytes was found to be higher in ND compared with FMF patients ($P_t<0.04$).

Production of IL-10 by monocytes and monocyte-derived dendritic cells in FMF patients

Furthermore, we studied whether the production of IL-10 by isolated monocytes and monocyte-derived dendritic cells is different between ND and FMF patients when the cells are stimulated with pro-inflammatory and anti-inflammatory molecules. LPS, colchicine and IL-4 were included in the culture medium of isolated monocytes for 3 days and IL-10 production by monocytes was assayed by ELISA (Figure 2A). We found that IL-10 production by untreated as well as IL-4-treated monocytes in ND does not significantly differ from the IL-10 production by the monocytes isolated from FMF patients. Surprisingly, we found that LPS-stimulation significantly enhanced IL-10 production ($Pt<0.04$) by monocytes isolated from ND in comparison with the LPS-stimulated monocytes isolated from FMF patients. As shown in Figure 2A, colchicine induced a weak increase of IL-10 production by monocytes in FMF, while in ND it induced a statistically significant increase in the production of IL-10 ($P_p<0.02$).

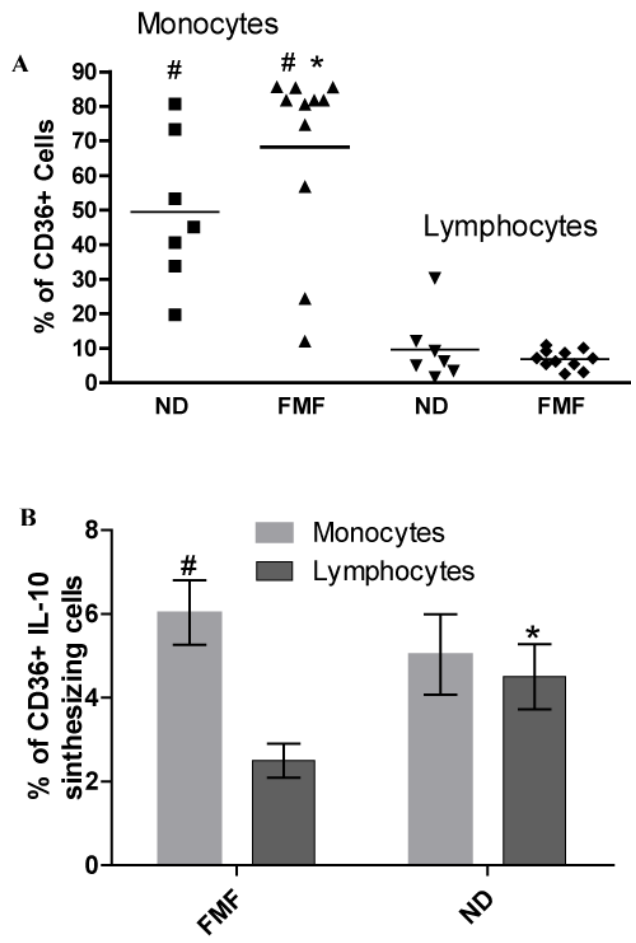

Figure 1: Flow cytomety analysis of CD36+ monocytes and lymphocytes (A) and CD36+ cells, intracellularly synthesizing IL-10 (B) in ND and FMF patients. PBMC were surface stained by anti-CD36, CD3 or CD14 and fixed and permeabilized cells incubated with anti-human IL-10 or matched isotype control and subjected to FACS analysis. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (* $Pw<0.05$) or comparing monocytes with lymphocytes (# $P_t<0.001$).

Next, we evaluated the production of IL-10 by unstimulated or LPS- and colchicine-treated iDCs and mDCs. We observed that the production of IL-10 by both types of unstimulated DCs, generated from ND is significantly higher ($P_t<0.05$) compared to that in FMF patients (Figures 2B and 2C). However, the pattern of IL-10 production by LPS- and colchicine-treated DCs was found to be quite different in ND and FMF patients. LPS stimulation or treatment with colchicine caused a dramatically reduction of IL-10 production by iDCs, generated from ND. In contrast, iDCs from FMF patients produced an elevated level of IL-10 after treatment with colchicine ($P_p<0.05$). LPS stimulation or treatment with colchicine did not cause

up-regulation of IL-10 production by mDCs generated from ND monocytes (Figure 2C). In contrast, mDCs from FMF patients produced an elevated level of IL-10 after treatment with both LPS and colchicine (P_p<0.05). Thus, we saw that, during FMF, both iDCs and mDCs produced a decreased level of anti-inflammatory cytokine IL-10. However, IL-10 production by DCs was restored after LPS stimulation or colchicine treatment which indicates that they induced tolerogenic DCs in FMF patients but not in ND.

To confirm this, we evaluated the expression of CD86, CD206, CD14 and Annexin V in unstimulated, LPS- and colchicine-treated DCs, generated from FMF patients and ND. The results suggested that the surface expression of CD86, which is the marker for pro-inflammatory activated DCs, is up-regulated in FMF patients and LPS stimulation, in contrast to colchicine, caused further enhancement of this activation pattern (described in Electronic Supplementary Material - Figure S3). In addition, neither any analyzed surface marker nor apoptosis induction were found in parallel with the pattern of IL-10 production by differentially activated DCs in FMF patients (discussed in Electronic Supplementary Material—Supplementary results). Therefore, we postulated that the cellular pro- and anti-inflammatory activation plasticity is altered in FMF, and furthermore we studied the versatility of monocytes activation type switching.

Versatility of monocyte pro-inflammatory activation switching in FMF patients

Next, we studied how reduced LPS-induced IL-10 production by monocytes, isolated from FMF patients, is associated with the impaired versatility of monocyte activation switching. Monocytes were incubated with or without recombinant IL-4 or LPS for 3 days and on day 3, cells were washed and a fresh medium was added or stimulated with opposite pro- or anti-inflammatory molecules for an additional 3 days. Monocyte CD206 mannose receptor surface expression was analyzed by flow cytometry and IL-10 production by monocytes assayed by ELISA.

We found that CD206 surface expression, as a marker of alternatively activated monocytes [19], in differentially activated monocytes during stimulation arrest or counter stimulation, did not significantly differ between ND and FMF patients (described in Electronic Supplementary Material - Figure S4), which may suggest that the activation of monocytes during FMF is not associated with the impaired versatility of cell activation switching.

To confirm these results, we next studied the pattern of IL-10 production by differentially activated monocytes. We found that the pattern of IL-10 production by activated and, through future stimulation, arrested or counter-stimulated monocytes is quite different in ND and FMF patients. IL-10 production by untreated and future IL-4- and LPS-stimulated monocytes was significantly enhanced (P_t<0.04 and P_t<0.02, accordingly) in ND, compared with monocytes isolated from FMF patients (Figure 3A). IL-10 production by IL-4-pretreated and future counter-stimulated by LPS monocytes was significantly enhanced (P_t<0.03) in ND, compared with FMF patients (Figure 3B). IL-10 production by LPS-pretreated (but those not future stimulation-arrested or counter-stimulated by IL-4) monocytes were found to be enhanced in ND (P_t < 0.04) compared to FMF (Figure 3C). Thus, in contrast to ND, monocytes from FMF patients failed to switch from a pro-inflammatory activated state to anti-inflammatory phenotype, which may cause the impaired resolution of inflammation.

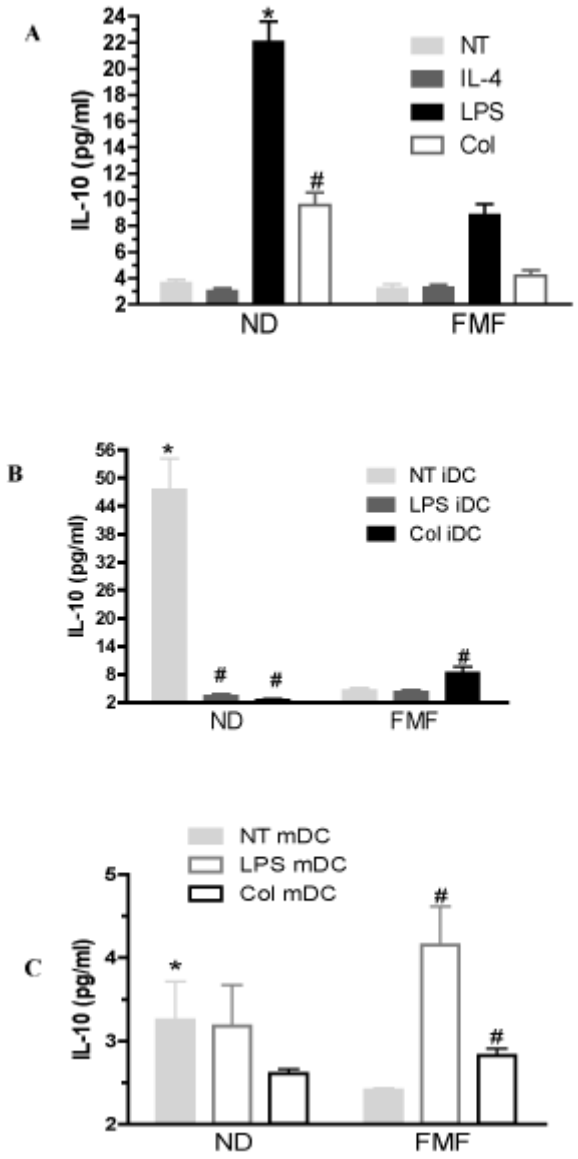

Figure 2: Production of IL-10 by monocytes (A) and monocyte-derived immature (B) and mature (C) dendritic cells in FMF patients. Peripheral blood monocytes were incubated with medium alone (NT) or 10 ng/ml IL-4 or 100 ng/ml LPS or 2 μg/ml colchicine for 3 days. Monocyte-derived iDCs and mDCs, described in section Material and methods, stimulated with 100 ng/ml LPS or 2 μg/ml colchicine for 24 h and IL-10 concentration in cell free supernatants determined by ELISA. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (* P_t<0.05) or comparing with NT (# P_p<0.05).

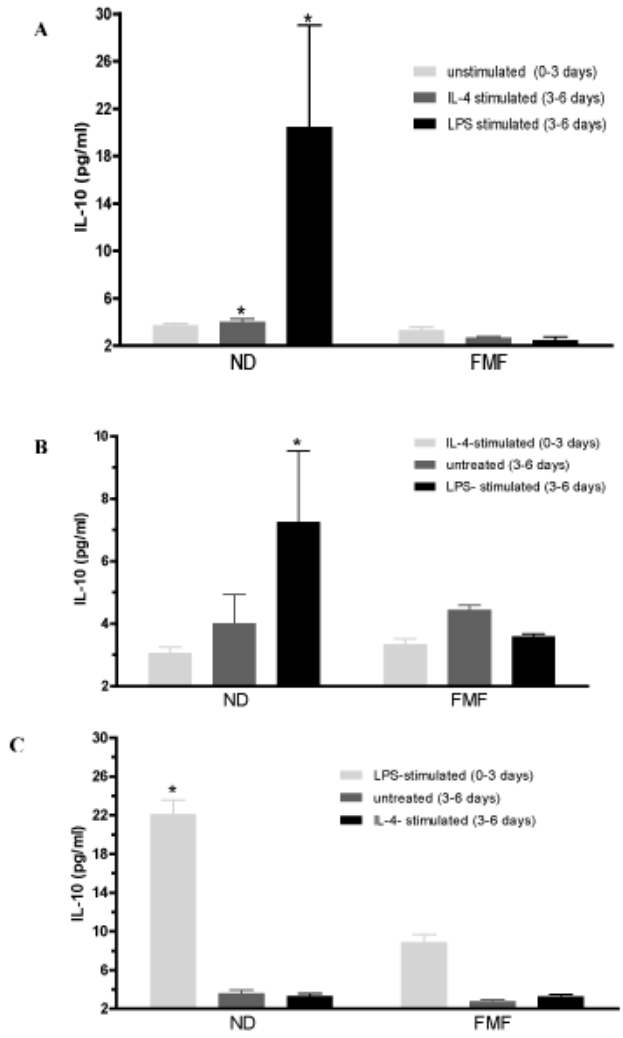

Figure 3: Versatility of monocytes pro-inflammatory activation switching in FMF patients. IL-10 production by monocytes isolated from ND and FMF patients after stimulation by pro- and anti-inflammatory agents and after stimulation arrest or a further counter stimulation (A, B and C). Monocytes were unstimulated or stimulated by recombinant IL-4 or LPS for 3 days and on day 3, cells washed and fresh medium added or stimulated with opposite pro- or anti-inflammatory molecules for additional 3 days. The IL-10 production by monocytes was assayed by ELISA. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (* P_t<0.05).

Influence of TLR-, NOD-agonists and colchicine on monocyte IL-10 and IL-1β production in FMF patients

We studied whether the production of IL-10 and IL-1β by isolated monocytes is different between ND and FMF patients, when the cells are stimulated with NOD1 and NOD2 ligand PGN or TLR2-TLR1 ligand Pam_3CSK4 or NOD2 ligand MDP for 3 days. We found that PGN, MDP and Pam_3CSK4 significantly enhanced IL-10 production (P_t<0.04, Pt<0.05 and P_p<0.02, respectively) by monocytes isolated from ND in comparison with stimulated monocytes isolated from FMF patients (Figure 4A).

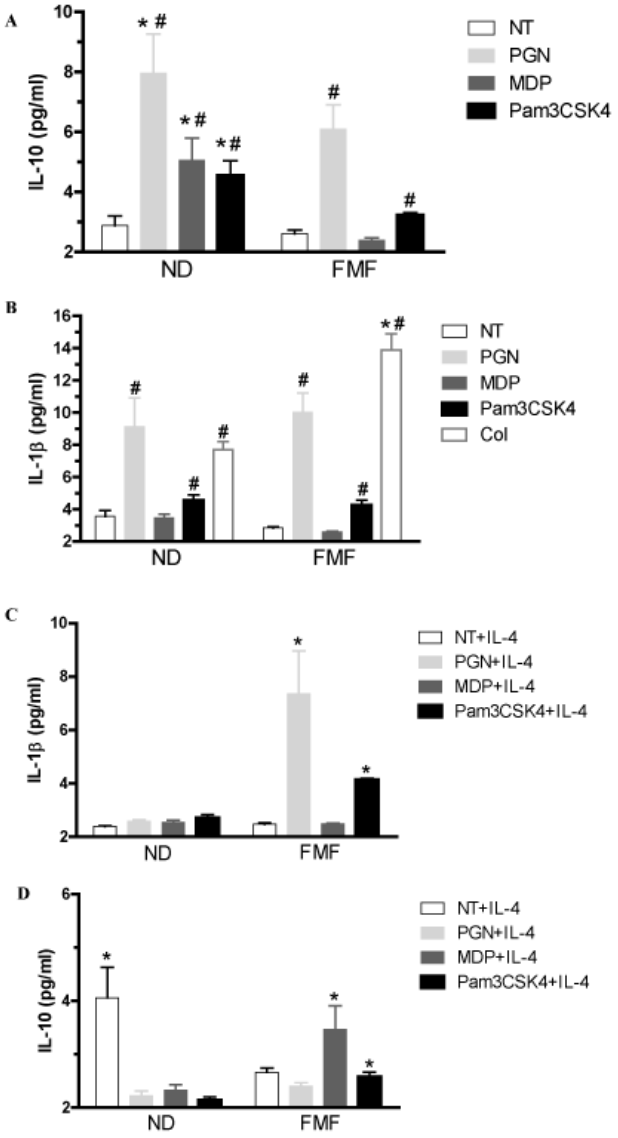

Figure 4: Influence of TLR- and NOD-agonists on monocyte IL-10 and IL-1β production in FMF patients. Peripheral blood monocytes were unstimulated (NT) or stimulated either with 2, 5 μg/ml PGN or Pam_3CSK4 or 5 μg/ml MDP for 3 days. IL-10 (A) and IL-1β (B) production by monocytes, isolated from ND and FMF patients ws determined by ELISA. To assess the versatility of monocytes activation, unstimulated or stimulated monocytes for 3 days were further incubated with 10 ng/ml IL-4 for an additional 3 days. Cell-free supernatants were decanted and IL-1β (C) and IL-10 (D) concentration in samples were determined by ELISA. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (*P_t or P_w<0.05) or comparing with NT (# P_p<0.05).

In contrast to IL-10, the production of IL-1β by monocytes stimulated with PGN or Pam_3CSK4 or MDP did not show any significant differences between ND and FMF patients. MDP induced a weak increase of IL-1β production by monocytes in ND, compared with FMF (Figure 4B). Interestingly, colchicine induced a statistically significant increase of IL-1β production by monocytes in both FMF (P_p<0.001) and ND (P_p<0.02). However, the production of IL-1β by colchicine-treated monocytes in FMF was significantly higher compared to ND (P_w<0.02).

Next, we study the production of IL-10 and IL-1β by PGN or Pam_3CSK4 or MDP pre-stimulated monocytes for 3 days and counter-stimulated with recombinant IL-4 for an additional 3 days. As shown in Figure 4C, the IL-1β production by IL-4-induced PGN- and Pam_3CSK4-pre-stimulated monocytes is significantly enhanced in FMF patients but not in ND (P_t<0.02). In contrast, the IL-10 production by unstimulated monocytes and future stimulated by IL-4 is significantly enhanced in ND (P_t<0.04) compared to FMF patients. The IL-10 production by IL-4-treated and Pam_3CSK4- or MDP-pre-stimulated monocytes is significantly enhanced in FMF patients, compared with ND (Figure 4D). Thus, in contrast to ND, monocytes from FMF patients failed to switch from a pro-inflammatory activated state to an anti-inflammatory phenotype, and still produced more IL-1β. Colchicine treatment could not restore the increased production of IL-1β in FMF, and only a combination of IL-4 and NOD2 ligand MDP could partially restore anti-inflammatory cytokine IL-10 production and versatitity of monocyte activation type switching.

Endotoxin tolerance induction by monocytes isolated from FMF patients

We studied how impaired versatility of pro-inflammatory activated monocytes in FMF patients caused disruptions in endotoxin tolerance induction. Monocytes, isolated from ND and FMF patients, were pretreated with LPS for 18 h or other TLR- and NOD-agonists, colchicine or IL-4 and cells were washed and subjected to another dose of LPS for 4 h and the production of IL-1β, IL-10, TNF-α and IFN-γ was subsequently assayed by ELISA.

We found that during the first 18 h of incubation, the production of IL-1β by TLR- and NOD- agonists- as well as IL-4- stimulated monocytes in FMF patients (Figure 5), was significantly higher than in ND (P_t< 0.03 for PGN, P_W<0.03 for MDP, P_t<0.002 for LPS and P_W<0.03 for IL-4 respectively). We observed that overnight LPS-treated monocytes, isolated from ND, develop tolerance to subsequent LPS challenges by declining the production of IL-1β (Figure 5B). In contrast, monocytes from FMF patients failed to induce LPS-homologous tolerance to the repeated action of LPS and produced equal amounts of IL-1β during repetitive LPS stimulation (Figure 5B). Colchicine pretreatment did not induce a hyporesponsive state of monocytes in FMF patients to LPS challenge. Similarly, PGN pretreatment failed to induce monocyte endotoxin cross tolerance after LPS re-stimulation in FMF patients (Figure 5A). However, in ND both PGN and colchicine pretreatment induced monocyte endotoxin tolerance by subsequent decreasing of IL-1β production by LPS re-stimulated monocytes (P_p<0.04, Figure 5A). Interestingly, MDP was found to be unable to induce IL-1β production by monocytes both in FMF patients and ND and induce endotoxin tolerance in FMF-patients as well (Figure 5). Similarly, IL-4 pretreatment caused endotoxin tolerance induction in FMF patients and ND monocytes to subsequent LPS restimulation, suggesting that monocytes alternative activation caused endotoxin-tolerance induction both in FMF and normal donors.

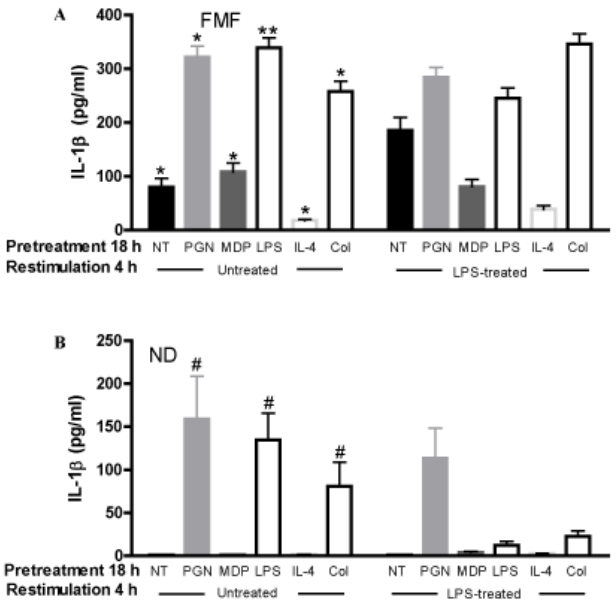

Figure 5: Influence of TLR- and NOD-agonists, colchicine and IL-4 on monocyte IL-1β production and endotoxin tolerance induction in FMF patients (A) and ND (B). Monocytes were pretreated with 100 ng/ml LPS or either with 2 μg/ml colchicine or 2.5 μg/ml PGN or 5 μg/ml MDP or 10 ng/ml recombinant IL-4 for 18 h, washed with LPS-free PBS and cultured for an additional 4 h in the presence of 1 μg/ml LPS. The production of IL-1β monocytes was subsequently assayed by ELISA. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (*P_t or P_w<0.05, ** P_t<0.002) or comparing pretreatment with LPS re-stimulation pairs (# P_p<0.05).

Next, we studied how monocytes, isolated from FMF patients and ND, responded to repeated action of LPS challenge by changing the production of IL-10 (Figure 6A). First, we compared the production of IL-10 by untreated and LPS-treated monocytes between ND and FMF patients at 18 h incubation. As it is shown in Figure 6A, IL-10 production by untreated monocytes in ND was significantly higher than in FMF patients (P_W<0.01). Surprisingly, LPS-induced production of IL-10 by monocytes at 18 h incubation were found to be significantly higher in FMF patients (P_W<0.04 and P_W<0.05, respectively) compared with ND. However, LPS-pretreated monocytes from FMF patients failed to produce a detectable level of IL-10 after 4 h LPS re-stimulation, while monocytes isolated from ND produced a detectable level of IL-10 during repeated action of LPS (comparing NT +LPS with the LPS+LPS parries, Figure 6A). We do not find statistically significant differences in IL-10 production by TLR4 and NOD2 agonists (LPS, PGN and MDP)- as well as IL-4- or colchicine-pretreated and LPS re-stimulated monocytes in FMF patients (data not shown).

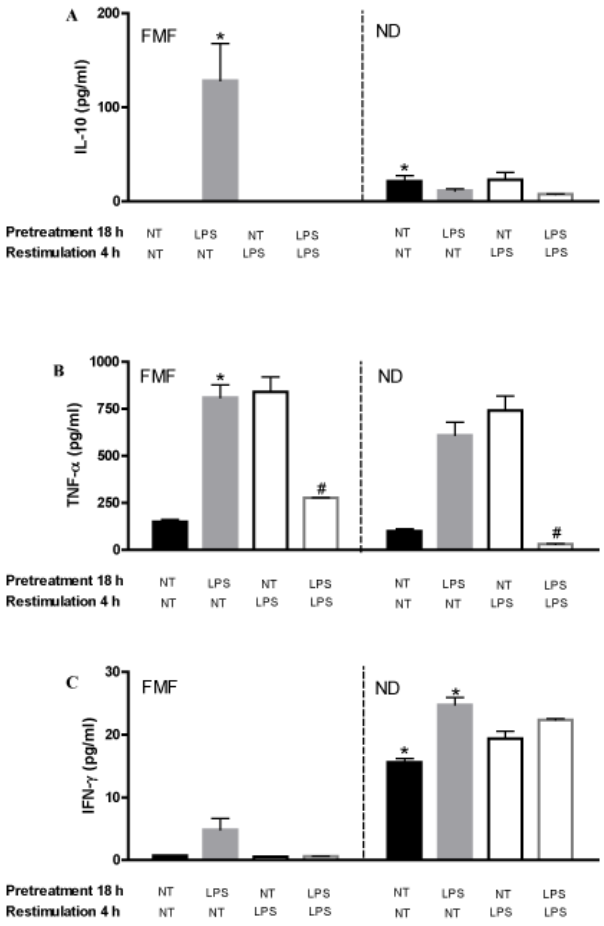

Figure 6: LPS homologous tolerance induction in patients with FMF and ND. Monocytes were pretreated with 100 ng/ml LPS for 18 h, washed with LPS-free PBS and cultured for an additional 4 h in the presence of 1 μg/ml LPS. The production of TNF-α (A), IL-10 (B) and IFN-γ (C) was subsequently assayed by ELISA. All data represent means ± SEM (error bars) and are significantly different comparing FMF with ND (*P_t or P_w<0.05, ** P_t<0.002) or comparing pretreatment with LPS re-stimulation pairs (# P_p<0.05).

LPS significantly increased overnight production of TNF-α in FMF patients (P_W<0.05) compared with ND (comparing NT+NT with NT +LPS parries accordingly, Figure 6B). We observed that monocytes, isolated from FMF patients and ND develop homologous tolerance to LPS challenge by declining production of TNF-α after overnight LPS treatment (comparing NT+LPS with the LPS+LPS parries, Figure 6B). However, 4 h LPS re-stimulation of monocytes, isolated from FMF patients caused only 3.0 fold reduction of TNF-α production, while in ND it caused up to 25.0 fold reduction of TNF-α production (P_W<0.05). Finally, we studied how monocytes, isolated from FMF patients and ND develop tolerance to LPS challenge by changing the production of IFN-γ after overnight LPS treatment (Figure 6C). It is unexpected that the unstimulated as well as LPS-induced overnight production of IFN-γ by monocytes in FMF patients statistically significantly declined (P_W<0.02) compared with ND. LPS significantly increased overnight production of IFN-γ by monocytes both in ND and FMF patients (comparing NT+NT with NT+LPS parries accordingly, Figure 6C), however, in ND the production of IFN-γ by stimulated monocytes statistically significantly increased compared with FMF patients (P_W<0.04 and P_W<0.01, respectively). Monocytes isolated from FMF patients failed to produce a detectable level of IFN-γ during the repeated action of LPS, while monocytes isolated from ND produced a higher level of IFN-γ during repeated action of LPS (comparing NT+LPS with the LPS+LPS parries, Figure 6C). Thus, the observed differences in monocyte cytokine production in response to repeated action of LPS could suggest that endotoxin tolerance induction is impaired in FMF patients due to down-regulation of IL-10 and IFN-γ production and up-regulation of IL-1β and TNF-α production by monocytes.

Discussion

The finding that FMF-associated mutations induce heightened sensitivity to endotoxin has important implications for understanding the nature of innate immune cell activation switching and the impaired resolution of inflammation during FMF. An anti-inflammatory cytokine IL-10 is associated with reduced immune responsiveness and control of the appropriate threshold for immune activation and host inflammatory response. Although there is a clear association between IL-10 and disease susceptibility, less is known regarding the cellular sources of IL-10 which mediate disease phenotypes. This is complicated by the fact that IL-10 is regulated by various receptor systems and is expressed by a wide array of cell types. In the case of autoinflammatory disease in particular, the anti-inflammatory properties of IL-10 create somewhat of a paradox. On the one hand, the initiation of inflammatory reactions is required for an effective response against pathogens, but if left unchecked, it can result in a huge inflammatory response. On the other hand, IL-10 expression can facilitate pathogen survival and the establishment of persistent infection [12,13,16]. Therefore, resolving the cellular sources and temporal/spatial expression profiles of IL-10 in FMF remains a priority.

Based on a large body of evidence, T cells are thought to be the main source of IL-10 *in vivo* and the critical role of T cell-derived IL-10 has been clearly demonstrated both in maintaining immune homeostasis and in enabling microbial persistence [22]. It is now accepted that IL-10 is expressed by subsets of all CD4 T helper populations including Th1, Th2, Th17 and Treg, which are a key source of IL-10 and play a central role in mediating inflammatory control functions [23]. In addition, it has been shown that the small population of the circulating $CD36^+$ peripheral blood lymphoid, but not monocytoid, cells constitutively producing IL-10 in healthy individuals are involved in the homeostatic regulation of innate immune response [21]. In agreement with this, we have shown here that, the lowered serum IL-10 level during FMF is correlated with down-regulation of circulating $CD36^+$ peripheral blood lymphoid cells, which constitutively produce IL-10. However, the major disagreement with published mouse and human studies is that the number of IL-10 synthesizing $CD36^+$ monocytes was found to be significantly higher than the $CD36^+$ lymphocytes in ND. We could not explain this by the CD36 surface expression differences between monocytes and lymphocytes [24] or between FMF and ND either. Indeed, the percentage of $CD36^+$ monocytes is significantly higher in FMF patients compared with ND and the total number of IL-10 synthesizing $CD14^+$ monocytes is significantly higher than the $CD3^+$ lymphocytes in FMF patients but not in ND. It is possible that the

IL-10 secretion rate in $CD36^+$ lymphocytes is higher than in $CD36^+$ monocytes, as it was originally shown using ELISPOT techniques [21].

Innate immune compartment is another potentially important source of IL-10 given that various cell types can be divided into distinct subpopulations based on IL-10 expression patterns. Most notably, monocytes, alternatively activated and type II macrophages, and DCs, including myeloid (but not plasmacytoid) DCs provide sources of IL-10 from the myeloid lineage [25,26]. Here we focused mainly on studying the production of IL-10 by monocytes and DCs in FMF patients, but not lymphocytes, based on the two reasons. First, it is well known that the *MEFV*-encoded pyrin is selectively expressed in monocytes and neutrophils, and participates in imflammasome activation, apoptosis, and secretion of IL-1β [5,6,27]. Second, the immunoregulatory function of myeloid- but not T-cell-derived IL-10 in many animal and human studies is well characterized during sepsis and the anti-inflammatory response to LPS [28-30]. The importance of IL-10 in such responses is particularly evident in the gut, where despite the large burden of commensal bacteria, there is a delicate balance of pro-inflammatory and anti-inflammatory cytokines which act in concert to maintain a steady state [31-33]. Here we demonstrated that the monocyte IL-10 production induced by LPS and other TLR and NLR-agonists, including PGN, Pam_3CSK4 and MDP is declined in FMF patients. Furtermore, the production of IL-10 was found to be diminished in both types of iDCs and mDCs, generated from FMF patients. Moreover, we found that DCs surface expression of co-stimulatory molecule CD86 is up-regulated in FMF, further suggesting that IL-10 antagonizes the expression of CD86 [34].

Do these data indicate that FMF is an IL-10-deficiency associated disease? Two data sets, obtained in this study suggested against this notion. First, the LPS-induced production of IL-10 by monocytes at 18 h incubation was found to be significantly higher in FMF patients, and second, the IL-10 production by IL-4-treated and Pam_3CSK4- or MDP-stimulated monocytes was significantly enhanced in FMF patients, compared with ND. Other studies also demonstrated that the serum IL-10 levels were not different in FMF patients with attacks and attack-free, and healthy controls [35]. In contrast, a significantly higher level of IL-10 in attack vs. control was confirmed by two independent groups of investigators [36,37]. In addition, a potentially important consideration in the analysis of human IL-10 expression is the well-described inter-individual variation in IL-10 production which is associated with single nucleotide polymorphisms in the IL-10 promoter [38,39]. However, there is no data available for FMF studies. These data may suggest that the diminished IL-10 production by monocytes is indirectly associated with mutation in *MEFV* and rather reflected the regulatory role of pyrin in IL-1β processing and release. Indeed, pyrin levels directly correlated with IL-1β processing in monocytes and macrophages in the context of endotoxin-induced activation and pyrin protein levels are down-regulated in monocytes as they mature into monocyte-derived macrophages [40]. These changes occur at the same time that IL-1β processing and release is also down-regulated. These data are in agreement with our observation that spontaneous and inducible production of IL-1β by monocytes at 18 h incubation were found to be significantly higher in FMF patients, while there is no significant differences observed between ND and FMF patients during the 3-day incubation period. Thus, pyrin may function to augment caspase-1 activation and IL-1β processing events in the early stages of innate immune response settings including IL-10 dependent regulatory pathways against of some pathogen (damage)-associated molecular patterns.

TLR- or NLR-mediated recognition of pathogen (damage)-associated molecular patterns initiates MyD88- or inflammasome-dependent signaling pathways correspondingly that orchestrates the production of pro-inflammatory cytokines by innate immune cells [41]. Even though these cytokines are crucial for host defense, excess pro-inflammatory cytokines give rise to systemic metabolic and hemodynamic disturbances that are harmful to the host. To avert these deleterious effects, IL-10 is also produced by stimulated monocytes or DCs [42], leading to Stat3 phosphorylation that has been correlated with the dampening of inflammatory response [43]. Upon encounter of monocytes or immature DCs with microbial, pro-inflammatory, or T cell-derived stimuli, characteristic phenotypic and functional changes are induced and cells recruit to sites of inflammation, a process referred to as pro-inflammatory (classical) activation of monocytes or maturation of DCs [44]. Mature DCs and activated monocytes exhibit reduced phagocytic activity and increased expression of co-stimulatory molecules, secreting large amounts of immunostimulatory cytokines [45]. However, some types of DCs or alternatively activated monocytes induce and maintain self-tolerance *in vivo*. Tolerogenic DCs, induced by various anti-inflammatory and immunosuppressive agents, are maturation-resistant or alternatively activated DCs that express low ratio of co-stimulatory surface molecules and are able to synthesize anti-inflammatory cytokines, including IL-10 and TGF-β1 [46]. The fact that LPS treatment of mature DCs in FMF patients, in contrast to ND, leads to the increased production of IL-10 indicated the high turnover potential for switching to the anti-inflammatory phenotype of mature DCs during the encounter to pro-inflammatory factors and may be associated with the characteristic self-limited inflammatory attack observed in FMF. In addition we observed that IL-10 production by DCs was restored after colchicine treatment which may indicate that tolerogenic DCs are induced in FMF patients but not in ND. However, we found that the surface expression of co-stimulatory molecules are not paralleled with the pattern of IL-10 production by differentially activated DCs and monocytes in FMF patients, further suggesting that cellular pro-inflammatory activation plasticity is altered in FMF and reduced the IL-10 production associated with impaired setting of feedback inhibition of the pro-inflammatory response. It has been shown that the increase of IL-10 and TGF-β1 in attack may play a compensatory and regulatory role with respect to proinflammatory cytokines and may contribute to the self-resolving nature of inflammatory attacks in FMF [36].

To address this hypothesis, we investigate here the impaired versatility of monocytes, obtained from FMF patients, by measuring the production of IL-10 and IL-1β after stimulation by pro- and anti-inflammatory agents, and after stimulation arrest or a further counter stimulation. In contrast to ND, monocytes from FMF patients failed to switch from a pro-inflammatory activated state to an anti-inflammatory phenotype and still produced more pro-inflammatory IL-1β and less IL-10, which may cause the impaired resolution of inflammation. Furthermore, this conclusion was confirmed by the observed impaired endotoxin tolerance and cross-tolerance induction in monocytes, obtained from FMF patients by measuring the production of IL-1β, IL-10, TNF-α and IFN-γ after pre-stimulation by NLR- or TLR-ligands and after re-stimulation with LPS. Again, in contrast to ND, monocytes from FMF patients failed to switch from a pro-inflammatory activated state to an anti-inflammatory phenotype in response to repeated action of LPS, suggesting that endotoxin tolerance induction is impaired in FMF patients due to down-regulation of IL-10 and IFN-γ production by monocytes. These data

agree with the findings that IL-10 not only antagonizes the expression of co-stimulatory molecules and the pro-inflammatory cytokines IL-1β, IL-6, IL-8, and TNF-α, but also induces endotoxin tolerance production of IFN-γ [16,17,47].

Previously, we had found that colchicine is able to restore impaired LPS-homologous tolerance induction (assayed by flow cytometry of monocytes, intracellularly synthesizing TNF-α), in FMF patients upon increasing the intracellular IL-4 synthesis and monocyte "alternative" activation [9]. In this study we observed that colchicine increased both IL-10 and IL-1β production by monocytes obtained from ND and FMF patients. However, the production of IL-1β by colchicine-treated monocytes in FMF was found to be higher and, vice versa, the production of IL-10 was significantly lower comparing with ND. In addition, colchicine failed to induce tolerance of monocytes to the repeated action of LPS (assayed by ELISA of monocytes IL-1β and IL-10 production), suggesting that colchicine alone is not sufficient to restore impaired endotoxin tolerance during FMF. It is known that taxol and colchicine, two drugs that affect microtubule structure and function, increase LPS-induced IL-1β by an increase in the production of the pro- IL-1β precursor molecule [48]. Suppressing this, we found that colchicine could not restore the polarization of IL-1β and IL-10 production in FMF, and only a combination of IL-4 and noninflammasome NLR (NOD2)- ligand MDP could partially restore the anti-inflammatory cytokine production and versatitity of monocyte activation switching. Moreover, MDP was found to be unable to induce IL-1β production by monocytes and IL-4, MDP-pretreatment were able to induce endotoxin tolerance in FMF patients. These results are in agreement with recent studies illustrating a role for chronic stimulation of NOD2 in mediating tolerance to bacterial products [49]. It is possible that pyrin represents a positive regulator in the context of LPS but a negative regulator of inflammation in the context of other types of intracellular infectious challenges, including MDP. Our future studies are directed at this question to understand further details of the regulatory role of noninflammasome NLR NOD2 in mechanisms required for inflammation resolution, which may underpin the development of new therapeutic approaches that can resolve FMF inflammation in directed and controlled ways. The finding that (NOD2)- ligand MDP differentially affects the monocyte activation program shift and endotoxin tolerance induction may have important implications for the treatment of FMF.

In conclusion, reduced IL-10 production by monocytes and dendritic cells is associated with the impaired setting of feedback inhibition of the pro-inflammatory response and caused impaired resolution of inflammation and endotoxin tolerance induction in response to repeated action of endotoxine. The IL-10 production by monocytes and dendritic cells and endotoxin tolerance induction are restored by NOD2- ligand MDP and partially by colchicine which may underpin the development of new therapeutic approaches that can resolve FMF inflammation in directed and controlled ways.

Acknowledgements

The International Science and Technology Center (ISTC Grant A-1580), and "Armenicum+" CJSC, Yerevan, Armenia, supported this study. We thank Professor Tamara Sarkisian PhD, Dr.Sc, Center of Medical Genetics and Primary Health, for her critical reading of the manuscript, Dr. Nazareth Seferian MD, for language revision and Honorary Doctor of NAS RA Levon A. Gevorkyan for his support of this study in the Armenicum Research Centre.

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