Original article

Aberrant expression of the negative costimulator PD-1 on T cells in granulomatosis with polyangiitis

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Abstract

Objective. Persistent T-cell activation is frequently observed in granulomatosis with polyangiitis (GPA, formerly known as Wegener’s granulomatosis). T-cell activation is usually balanced by negative costimulatory molecules. The negative costimulator programmed death receptor-1 (PD-1) and its relevance to T-cell immunity have not been studied so far in GPA. Thus it is the aim of the study to characterize the role of PD-1 in GPA.

Methods. Thirty-two patients suffering from GPA and 19 age-matched healthy controls (HCs) were enrolled. T-lymphocyte subsets from peripheral blood were analysed by flow cytometry for the expression of PD-1. The frequency of memory T cells and T cells producing pro-inflammatory cytokines was determined. Renal biopsies from GPA patients were stained for CD3 and PD-1.

Results. PD-1 expression was increased on T-helper cells (Th cells) from GPA patients as compared with HCs. In addition, parameters of persistent T-cell activation and production of pro-inflammatory cytokines were positively associated with numbers of PD-1+ Th cells in patients but not in HCs. Latent infection with CMV seemed to enhance PD-1 expression on CD4+ and CD4+CD25+ T cells. Interestingly, expression of PD-1 on CD4+CD25+T cells was inversely correlated with relapse rate. Importantly, lesional T cells were mostly lacking PD-1.

Conclusions. The expression of the negative costimulator PD-1 is altered in GPA and might counterbalance persistent T-cell activation.

Key words: ANCA, vasculitis, T cells, PD-1.

Introduction

Granulomatosis with polyangiitis (GPA, formerly known as Wegener’s granulomatosis) is an autoimmune vasculitis of small- to medium-sized vessels that is characterized by

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the presence of ANCA [1–4]. Granulomatous necrotizing inflammation of the upper/lower airways and rapidly progressive GN is usually observed. This disorder leads to acute organ failure and fatal prognosis if left untreated [5]. The adaptive and the innate immune system both contribute to disease mechanisms [6]. ANCA-triggered activation and degranulation of neutrophils causes endothelial injury and vasculitic damage [6]. Along with this, granulomatous necrotizing inflammation is found in affected organs. T cells are usually present in the inflammatory infiltrate [7, 8] and granuloma formation is T-cell dependent [9, 10]. Furthermore, determination of IgG subclasses suggests a T-cell-dependent class switch of B cells [11]. In line with these findings, several authors report abnormalities of the T-cell compartment in GPA. Persistent expansion and activation of T cells is a well-established finding [12–15]. In autoimmunity, breakdown of T-cell tolerance is a prerequisite [16, 17]. Inhibitory pathways
also involves organs outside the respiratory tract [28]. Upper and lower respiratory tract, whereas systemic disease
Localized disease was defined as GPA restricted to the
accordance with the criteria of the ACR and Chapel Hill
new-onset disease. The diagnosis of GPA was made in
with steroids, increased dose of maintenance therapy
was defined as new disease manifestation occurring after
Division of Clinical Immunology were recruited. A relapse
quiescent GPA visiting the outpatient clinic of the
control cohort. For the functional studies on PD-1 ligation,
ations, cancer or autoimmune diseases were enrolled as
9 males and 10 females) with no history of chronic infec-
tion during relapse of disease. Nineteen age-matched
disease and 3 of these 30 patients were sampled in add-
ing [27]. Given the role of T cells in GPA, we explored the
expression of PD-1 on T cells in relation to disease
pathogenesis.

**Methods**

**Patient cohort**

Thirty-two consecutive patients with GPA visiting the outpatient clinic of the Department of Nephrology or Department of Rheumatology and Clinical Immunology were enrolled (Table 1 and supplementary Table S1, available as supplementary data at *Rheumatology* Online). Fifteen of these patients were sampled and assessed twice. Thirty of 32 patients were measured with quiescent disease and 3 of these 30 patients were sampled in addition during relapse of disease. Nineteen age-matched healthy individuals [median age 55 (48-58) years; 9 males and 10 females] with no history of chronic infections, cancer or autoimmune diseases were enrolled as control cohort. For the functional studies on PD-1 ligation, five additional HCs and five consecutive patients with quiescent GPA visiting the outpatient clinic of the Division of Clinical Immunology were recruited. A relapse was defined as new disease manifestation occurring after a period in remission and requiring intensified treatment with steroids, increased dose of maintenance therapy or CYC. Two of 32 patients were sampled once with new-onset disease. The diagnosis of GPA was made in accordance with the criteria of the ACR and Chapel Hill Consensus [3, 4]. Detailed patient characteristics are given in Table 1 and supplementary Table S1, available as supplementary data at *Rheumatology* Online. Clinical data were obtained retrospectively based on the patient’s file records. CMV IgG antibody status was determined using the Enzygnost anti-CMV IgG Assay (Siemens Healthcare Diagnostics, Eschborn, Germany) according to the manufacturer’s instructions. Informed consent was obtained from each patient. The local ethical committee of the University Duisburg-Essen and the medical ethical committee of the University Hospital Maastricht approved the study.

**Flow cytometry: surface and intracellular staining**

Expression levels of the receptors including PD-1 were measured by four-colour surface staining on unstimulated lymphocytes from whole blood. Phycoerythrin (PE), FITC, peridinin chlorophyll protein (PerCP) and allophycocyanin (APC)-labelled antibodies with different specificity were used: CD3 (mouse IgG1, PerCP), CD4 (mouse IgG1, PerCP), CD25 (mouse IgG1, FITC), CD45RO (mouse IgG1, FITC), CD127 (mouse IgG1, APC; R&D Systems, Wiesbaden, Germany), CD-1 (mouse IgG1, PE), CD197 (CCR7, rat IgG2a, Alexa Fluor 647) and MultiTest CD3/CD8/CD45/CD4. All antibodies except CD127 were purchased from Becton Dickinson, Heidelberg, Germany. Appropriate isotype controls (Becton Dickinson) were used. Peripheral whole blood was stained with labelled mAbs for 20 min at room temperature followed by red blood cell lysis. Absolute numbers of T cells were determined using the TruCount system (Becton Dickinson). Intracellular cytokine staining was performed on Ficol-separated peripheral blood mononuclear cells (PBMC) of patients and HCs after mitogen stimulation. A surface staining was performed with anti-CD3, anti-CD4 or appropriate isotype controls followed by fixation and permeabilization (Cytotix/Cytoperm Kit, Becton Dickinson). Afterwards, intracellular staining with anti-IFN-γ or appropriate isotype controls was done. Analysis was performed with an FACS from Becton Dickinson. Effector memory T cells were defined as CD4+CD45RO+CCR7− (Temo), late differentiated effector memory T cells were defined as CD4+CD45RO−CD28− (CD28−) and activated T-helper cells (Th cells) were defined as CD4+CD25+ (Tact).

**T-cell cytokine and proliferation assays**

For intracellular IFN-γ stainings, cells were stimulated in the absence or presence of phorbol-12-myristate-13-acetate (PMA) (5 ng/ml) and ionomycin (1 µM) (Sigma-Aldrich, Seelze, Germany) for 4 h. Cytokine secretion was inhibited by Brefeldin A (Ebioscience, Frankfurt, Germany). PD-1 ligation studies were performed similar to Bertsias et al. [23] and Raptopoulou et al. [26]. Briefly, CD4+ T cells were isolated by negative selection (Rosette CD4+ T-cell Enrichment Kit, Stem Cell Technologies, Grenoble, France), stained with 1 µM 5,6-carboxy-fluorescein-succinimidyl ester (Molecular Probes, Invitrogen, Breda, The Netherlands) to track proliferation and stimulated for 72 h with immobilized anti-CD3 (0.25 µg/ml, clone

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**Table 1 Patients’ characteristics**

<table>
<thead>
<tr>
<th>Patients’ characteristics</th>
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</tr>
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<tbody>
<tr>
<td>Total, n</td>
<td></td>
</tr>
<tr>
<td>Age, median (IQR), years</td>
<td>62 (46-69)</td>
</tr>
<tr>
<td>Gender, female/male, n</td>
<td>14/18</td>
</tr>
<tr>
<td>PR3/MPO, n</td>
<td>29/3</td>
</tr>
<tr>
<td>Disease duration, median (IQR), months</td>
<td>71 (23-168)</td>
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<tr>
<td>Localized/systemic disease, n</td>
<td>8/24</td>
</tr>
<tr>
<td>Active disease, n</td>
<td>5</td>
</tr>
<tr>
<td>CMV anti-IgG, +/-</td>
<td>11/13</td>
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Localized disease was defined as GPA restricted to the upper and lower respiratory tract, whereas systemic disease also involves organs outside the respiratory tract [28].

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2G3, kind gift from Biomedical Research Institute, Diepenbeek, Belgium) in the presence or absence of immobilized human PDL-1 IgG chimera (R&D systems). After 72 h, the proliferation of cells was determined by flow cytometry. Suppression of proliferation was calculated as described in ref. [29].

Immunohistochemistry

Eight renal biopsies with diagnosed necrotizing crescentic GN (NCGN) from GPA patients were available and provided by the Department of Pathology, University Duisburg-Essen. Three biopsies were classified as focal NCGN and the other five as crescentic GN according to the histopathological classification of Berden et al. [30]. Moreover, five renal biopsies with minimal change GN (MCGN) were provided by the Department of Clinical and Experimental Immunology, Maastricht University Medical Center, The Netherlands. All specimens were fixed in 10% neutral buffered formalin and paraffin embedded. Sections 4 μm thick were deparaffinized in xylene and rehydrated in ethanol at different concentrations (100, 95, 70 and 50%). EDTA buffer pH 9.0 for heat-induced epitope retrieval was applied, followed by neutralization of endogenous peroxidase with 0.3% H2O2. Primary antibodies (CD3 obtained from DCS, Hamburg, Germany and PD-1 obtained from Becton Dickinson) and HRP-conjugated secondary antibodies (Zytomed) were incubated on slides (each for 30 min at room temperature. Tonsils were used as positive controls for CD3 and PD-1 staining [31]. Washing steps with PBS were performed after each incubation step. A DAB Substrate Kit (Zytomed) was used for visualization. Finally, the slides were counterstained with haematoxylin. CD3 and PD-1 expression in biopsies was scored in a similar fashion as described earlier [32]. Analysis was performed semi-quantitatively. A score ranging from 0 (0 = absence of mononuclear cell infiltration; 0.5 = scattered, positive cells present; 1 = few mononuclear cell infiltration; 2 = moderate mononuclear cell infiltration) to 3 (3 = severe mononuclear cell infiltration) was used for assessing the severity of cell infiltration. Serial sections were used to reveal colocalizations.

IF double staining

Tissues were prepared as indicated above. Primary antibodies against CD3 (rabbit IgG1, DCS) and PD-1 (mouse IgG1, Becton Dickinson) were used and incubated for 30 min at room temperature simultaneously. Secondary antibodies conjugated to Cy2 and Cy3 (Dianova, Hamburg, Germany) were applied for 30 min. Finally, the slides were mounted with Immuno Mount (Thermo Fisher, Kehl, Germany).

Results

Persistent T-cell activation in GPA patients with quiescent disease

Persistent T-cell activation was defined as expansion of CD25+ Th cells (CD4+CD25+) and/or effector memory Th cells (Tem, CD4+CD45RO+CCR7+) [14, 33]. GPA patients in remission showed an expanded CD25+ Th-cell population [GPA vs HC: 36 (25–46) vs 21 (16–27)%, P < 0.001, supplementary Table S2, available as supplementary data at Rheumatology Online] [34]. Likewise, an expansion of the Tem population was found [53 (40–68) vs 36 (32–45)%; P = 0.002]. Furthermore, GPA patients harboured an increased fraction of Th cells lacking CD28 [CD28null (0.7–11.4)% vs 0.9 (0.4–3.7)%; P = 0.06, supplementary Table S2, available as supplementary data at Rheumatology Online]. These results indicate persistent activation of T-cell-mediated immunity in patients in remission.

Increased PD-1 expression on Th cells in quiescent GPA is linked to persistent T-cell activation

Negative costimulation by PD-1 is thought to balance T-cell activation and maintain immune tolerance. Therefore PD-1 expression was analysed on circulating T cells from GPA patients with quiescent disease (Fig. 1 and supplementary Table S2, available as supplementary data at Rheumatology Online). Interestingly, the proportion of PD-1 expressing CD4+ T cells was increased as compared with HCs [9.8 (6.7–17.7)% vs 5.6 (3.4–8.7)%; P < 0.001, Fig. 1a]. As GPA patients showed a reduction in absolute CD4+ T-cell count, the absolute number of CD4+PD-1+ T cells was comparable in GPA patients and HCs [48 (31–76)% vs 45 (16–73) cells/μl; P > 0.05]. Disease extent had an impact on PD-1 expression on CD4+ Th cells; in systemic GPA, PD-1 expression tended to be higher as compared with localized GPA [12.8 (7.5–21.5)% vs 7.5 (6.2–8.6)%; P = 0.06]. There was a strong association between the relative number of PD-1+ Th cells and the presence of CD28null memory Th cells as well as Tem (%CD28null Th cells and %PD-1+ Th cells: n = 29, r = 0.71, P < 0.0001; Tem and %PD-1+ Th cells: n = 29, r = 0.67, P = 0.0002). No significant association of PD-1+ Th cells and CD28null memory T cells or Tem numbers was detected in HCs (%CD28null Th cells and %PD-1+ Th cells: n = 19, r = 0.12, P = 0.7; %Tem and %PD-1+ Th cells: n = 19, r = 0.44, P = 0.07). In GPA, the relative number of PD-1+ Th cells was also strongly correlated with T cells producing IFN-γ (%IFN-γ+ T cells and %PD-1+CD4+ T cells, GPA: n = 25, r = 0.72, P < 0.0001; HCs: n = 19, r = 0.46, P = 0.09). Interestingly, PD-1 expression was increased on IFN-γ+ T cells from GPA patients as compared with HCs [35 (31–38)% vs 22 (16–24)%; P = 0.02, n = 5 and n = 4, Fig. 1b]. Taken together, persistent T-cell activation in GPA seems to be linked to PD-1 expression.

Effect Th cells show enhanced expression of PD-1

Expansion of activated CD25+ Th cells is a specific feature of GPA [33, 34]. Therefore the presence of the negative
costimulator PD-1 was determined on the CD25+ and the CD25+/CD127low Th-cell subset. PD-1 expression on CD25+ Th cells was enhanced in GPA patients as compared with HCs [4.6 (3.2–7.3) vs 3.0 (1.2–3.9)%; \( P = 0.002 \), Fig. 1c], whereas the absolute cell count did not differ [8 (3–14) vs 7 (2–9) cells/\( \mu l \)]. Disease extent did not influence expression of PD-1 on CD25+ Th cells, as it was comparable in localized disease and systemic disease (data not shown). Further analysis revealed that PD-1+CD25+CD127low T cells (PD-1+ Tregs) were not different in GPA patients vs HCs, whereas PD-1+CD25+CD127high T eff cells were significantly increased [percentage of CD25+ Th cells: PD-1+ Tregs 1.74 (1.04–5.59) vs 1.32 (0.81–1.83)%; \( P > 0.05 \) and PD-1+ T eff 3.05 (1.97–4.36) vs 1.81 (0.85–2.41)%; \( P = 0.02 \)]. PD-1 expression on CD25+ Th cells remained stable over time in quiescent disease (see supplementary Fig. S1, available as supplementary data at Rheumatology Online).

CD4+CD25+ T cells from GPA patients showed increased expression of PD-1 when compared with HCs [13.3 (8.1–13.8) vs 5.9 (3.8–10.2)%; \( P < 0.002 \); absolute numbers did not differ significantly (supplementary Table S2, available as supplementary data at Rheumatology Online). In systemic GPA, PD-1 expression on CD4+CD25+ T cells tended to be enhanced as compared with localized GPA [16.1 (9.0–24.5) vs 9.0 (6.8–10.2)%; \( P = 0.05 \)].

Increased PD-1 expression on CD25+ and CD25– Th cells is maintained during active disease

Patients with active GPA (n=5, Table 1 and supplementary Table S1, available as supplementary data at Rheumatology Online) were assessed to elucidate if increased PD-1 expression is maintained during the acute phase of the disease. Patients with active GPA showed enhanced PD-1 expression on CD25+ Th cells as compared with HCs and was even higher in comparison with quiescent GPA [8.6 (7.8–12.3) vs 3.0 (1.2–3.9)%; \( P < 0.001 \), Fig. 1d and 8.6 (7.8–12.3) vs 4.6 (3.2–7.3)%; \( P = 0.02 \)]. PD-1 expression on CD25+ T cells did not differ between active GPA and quiescent GPA (data not shown).

Latent CMV infection in GPA associates with increased PD-1 expression on CD4+CD25– but not CD4+CD25+ T cells

As latent infection with CMV is described to drive expansion of T eff and also impacts PD-1 expression on T cells, the patient cohort was stratified according to CMV serostatus (Table 1) [35]. Interestingly, PD-1 expression on CD4+ and CD4+CD25+ T cells was higher in CMV+ patients as compared with CMV– patients [17.3 (14.2–49.7) vs 7.4 (5.4–8.3)%; \( P < 0.001 \) and 20.8 (15.1–36.8) vs 8.4 (6.4–10.2)%; \( P = 0.002 \), Fig. 2a and b]. CMV+ and CMV– patients did not differ regarding PD-1 expression on CD25+ Th cells.
expression on CD4+CD25+ T cells [5.4 (3.2–7.4) vs 4.6 (2.4–7.0)%, \( P = 0.45 \), Fig. 2c).

Relapse rate in GPA correlates with PD-1+CD25+ Th cells
Interestingly, PD-1+CD25+—but not PD-1+CD25− Th cells—showed a strong negative association with relapse rate (relapses per month of disease duration, PD-1+CD25+ T cells and relapse rate: \( r = -0.43 \), \( P = 0.03 \), \( n = 26 \), Fig. 3). Separate correlation analysis for PD-1+ Treg and PD-1+ T eff showed similar results (\( r = -0.5 \), \( P = 0.03 \) and \( r = -0.48 \), \( P = 0.03 \)).

PD-1-mediated suppression of T-cell proliferation is less efficient in GPA
In HCs, T-cell proliferation was suppressed in a PDL-1 dose-dependent fashion with maximal suppression at 5 μg/ml PDL-1. In four of five GPA patients, PD-1 ligation also resulted in suppression of T-cell proliferation at 5 μg/ml PDL-1, whereas in one patient no effect was seen. However, suppression was significantly more efficient in HCs when compared with GPA patients [43.3 (25.3–58.0) vs 13.4 (4.3–34.3)%, \( P = 0.03 \)].

Lesional T cells in GPA mostly lack PD-1 expression
The PD-1/PDL-1 pathway has a special role in maintaining tolerance and attenuation of the immune response. At active sites of inflammation, engagement of PD-1 via PDL-1 dampens T-cell activation and prevents tissue damage. To address the question if this pathway is also operative in GPA, eight renal biopsies of patients with GPA and NCGN were stained for the presence of PD-1+ cells and CD3+ T cells (Fig. 4 and supplementary Fig. S2, available as supplementary data at Rheumatology Online). Tonsil sections were used as positive control (supplementary Fig. S3, available as supplementary data at Rheumatology Online). PD-1 expression in NCGN was scarce and rare. Only single cells were found in one out of eight NCGN biopsies. The average PD-1 expression was scored with 0.03 (0.08). No expression was found in glomeruli. T-cell infiltration was found in all eight biopsies and was scored with an average of 0.85 (0.3). Serial sections revealed a lack of PD-1 expression in areas where T-cell infiltrates are present (Fig. 4). MCGN served as non-inflammatory kidney control tissue. Five different biopsies with MCGN were assessed and were completely lacking CD3+ T cells and PD-1 expression (Fig. 4). Given the scoring and the findings revealed by serial sections, it seemed that the majority of T cells infiltrating the kidney in NCGN lacked PD-1 expression.

Discussion
Our results demonstrate increased PD-1 expression on circulating CD4+ Th cells in GPA patients. PD-1 expression was associated with persistent activation of T cells

Fig. 2 PD-1 expression on circulating Th cells of CMV+ and CMV− GPA patients. (a) PD-1 expression on CD4+ and (b) CD4+CD25− T cells was higher in CMV+ patients as compared with CMV− patients. (c) CMV+ and CMV− patients did not differ regarding PD-1 expression on CD4+CD25+ T cells. The illustrated data are shown as medians (IQR). Significant differences by the Mann-Whitney U-test are indicated: *\( P < 0.05 \).
and latent CMV infection. Importantly, PD-1 expression on CD4+CD25+ T cells seemed to protect from relapses. However, PD-1-mediated inhibition of T-cell proliferation was less potent in GPA patients as compared with HCs. Lesional T cells in NCGN mostly lacked PD-1.

T-cell activation is inhibited by negative costimulatory molecules like cytotoxic T-lymphocyte antigen 4 (CTLA-4) and PD-1, which is an important mechanism of tolerance [17, 36]. More in detail, ligation of PD-1 inhibits the proximal signalling cascade pivotal for T-cell activation by attenuating phosphatidylinositol-3-kinase activation, which finally results in decreased cytokine production, decreased proliferation and decreased survival. As shown in animal models and in humans, breakdown of PD-1-mediated immune modulation leads to autoimmunity and uncontrolled T-cell responses [17, 36].

Persistent activation of T cells is consistently reported in GPA [13, 33, 34]. We observed increased PD-1 expression on T cells in GPA. PD-1 expression was positively correlated with expansion of memory T cells, CD28null T cells and T-cell activation and was enhanced on pro-inflammatory IFN-γ+ T cells in our GPA cohort but not in HCs. Thus persistent immune activation probably resulted in increased PD-1 expression to counteract T-cell activation [36, 37]. Patients with active disease and consequently highly activated immune system showed even more enhanced expression of PD-1+ Th cells as compared with patients in remission. This might reflect an attempt to terminate the ongoing immune response. Next to a balancing effect, chronic challenge with autoantigen or viral antigen might have caused up-regulation of PD-1 in the context of T-cell exhaustion [38]. Indeed, patients with latent CMV infection showed enhanced PD-1 expression on CD25+ T cells, suggesting that chronic challenge with viral antigen is related to up-regulation of PD-1 in GPA. Moreover, CMV infection has been associated with memory T-cell expansion in GPA [35]; this might explain the correlation between PD-1 expression and memory T-cell/CD28null T-cell expansion observed in our study.

In line with our findings, increased expression of a different inhibitory costimulator (CTLA-4 on T cells) was demonstrated in GPA previously by Steiner et al. [39]. In this study, GPA patients showed less strong up-regulation of this molecule in vitro upon mitogenic T-cell stimulation as compared with HCs. This might indicate insufficient CTLA-4-dependent balancing of immune activation in GPA. In our study, PD-1 expression was positively correlated with IFN-γ production and T-cell activation, pointing at a balancing effect. However, it has to be considered that the extent of PD-1 up-regulation in GPA is apparently not sufficient to limit and dampen immune responses. This is supported by our finding that PD-1-mediated suppression of T cells was less potent in GPA patients than in HCs. The cause for diminished PD-1-mediated suppression is not clear. The cytokine environment has a critical role on the outcome of PD-1-mediated inhibition, and IL-2 can counteract negative costimulation [40, 41]. Thus alterations of T-cell polarization and disturbances in cytokine levels reported in GPA might hamper the functionality of the PD-1/PDL-1 axis [6, 40]. Alternatively, it can be hypothesized that PD-1-mediated inhibition is impaired by enhanced responsiveness to specific cytokines (like IL-2) that are known to counteract PD-1/PDL-1 functionality. In line with this, the IL-2Rα chain is overexpressed in GPA patients as compared with HCs [6].

In contrast, decreased expression of PD-1 on circulating T cells is reported in other autoimmune diseases, such as MS and SLE [24, 25]. The pathogenesis of SLE or MS seems to be different from GPA, where T-cell-driven granuloma formation is a hallmark. Different genetic backgrounds might provide an explanation why PD-1 expression is low in SLE/MS and high in GPA. Some polymorphisms of the gene coding for PD-1 [programmed cell death-1 (PDCD1)] seem to be more common and specific for SLE or MS, whereas this has not been found in GPA. No differences between GPA patients and HCs have been detected regarding the distribution of PD1.3 and PD1.5 polymorphisms [23, 25, 27, 42, 43]. Accordingly, the PD1.3A polymorphism, which interferes negatively with transcription of the PDCD1 gene and seems to reduce its protein expression, is more frequently detected in SLE patients than in HCs [23].

Interestingly, CD25-PD-1+ Th cells were negatively associated with relapse rate. PD-1 ligation on activated T eff has been hypothesized to result in contra-conversion, meaning the conversion of T eff into anti-inflammatory T cells like Tregs [38]. Additionally, the PD-1/PDL-1 ligand interaction seems to impact the stability of T cell/dendritic cell (DC) interaction [44]. Moreover, ligation of PD-1 via PDL-1 expressed by endothelial cells is hypothesized to restrict extravasation of T cells [45]. Thus enhanced PD-1 expression on CD25+ effector T cells is likely to increase the threshold for immune activation. It might explain why patients with the lowest relapse rate have the highest...
**FIG. 4** Tissue sections were stained for CD3⁺ and PD-1⁺ cells by immunohistochemistry as stated before. Images are shown at a magnification of ×200 unless otherwise stated. Positive cells are depicted in brown. (a) Tonsil sections, serving as positive controls, were stained for CD3⁺ T cells and PD-1⁺ cells. (b) Renal biopsies with MCGN served as non-inflammatory control. Serial sections were stained for presence of CD3⁺ T cells and PD-1⁺ cells. Both are absent. (c) Renal biopsy with NCGN. Serial sections revealed CD3⁺ T-cell infiltration in the periglomerular area and in the tubulointerstitium. PD-1 expression is absent in these areas. (d) Renal biopsy with NCGN. The tubulointerstitium shows CD3⁺ T-cell infiltration. PD-1 expression is absent (×400 magnification).
PD-1 baseline expression on CD25+ Th cells. Unexpectedly, also patients with active GPA showed enhanced PD-1 expression on CD25+ T cells. As the cytokine milieu influences the efficacy of PD-1-mediated inhibition, negative costimulation by PD-1 can be overcome under inflammatory conditions [40, 41]. Furthermore, the ligands for the negative costimulator PD-1 but also for the positive costimulatory molecule CD28 are up-regulated on antigen-presenting cells under pro-inflammatory conditions [46]. It has also been demonstrated that positive costimulation via CD28 can override PD-1-mediated negative costimulation [41]. Therefore negative costimulation might be less potent during active disease due to competing positive costimulation.

Unlike reports on lesional PD-1 expression in RA, MS, SLE and SS [24–26, 47, 48], PD-1 was only rarely detected in renal biopsies of patients with GPA-associated NCGN. T cells were present in all of these NCGN biopsies but were mostly lacking PD-1. Therefore the PD-1 pathway might fail to regulate the T-cell response on tissue level sufficiently. The cognate ligand PDL-1 is usually expressed in renal tissue by tubular epithelial cells [49]. PDL-1 is considered to be important for regulating renal inflammation [49]. It has been demonstrated that T cells migrating to the kidney in NCGN [50]. Hypothetically, only PD-1+ effector memory T cells are capable of infiltrating renal tissue in GPA. Ligation of PD-1 by PDL-1 expressing endothelial cells might limit T-cell extravasation [45]. Alternatively, PD-1 might be down-regulated on T cells after migration.

In summary, we demonstrated increased PD-1 expression on circulating T cells in GPA, whereas T cells in renal lesions mostly lacked PD-1 expression. Increased PD-1 expression on circulating T cells might counterbalance persistent T-cell activation in GPA. However, PD-1-mediated inhibition seemed less potent in GPA patients than in HCs.

**Rheumatology key messages**

- Increased expression of the negative costimulator PD-1 on circulating T cells in GPA balances immune activation.
- The majority of lesional T cells lacks PD-1 expression.

**Supplementary data**

Supplementary data are available at *Rheumatology* Online.

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