Imbalance between subpopulations of regulatory T cells in COPD

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ABSTRACT

Background Recent evidence indicates that human regulatory T cells (Tregs) are composed of three distinct subpopulations: CD25++ CD45RA− resting Tregs (rTregs), CD25+++ CD45RA− activated Tregs (aTregs), which are suppressive, and CD25++ CD45RA− cytokine-secreting (Fr III) cells with pro-inflammatory capacity.

Objectives To evaluate the dynamic changes in circulating and pulmonary Treg subpopulations in smokers and patients with chronic obstructive pulmonary disease (COPD), and to explore their potential roles in COPD pathogenesis.

Methods Blood samples were obtained from 57 never-smokers, 32 smokers with normal lung function and 66 patients with COPD. Bronchoalveolar lavage (BAL) samples were taken from 12 never-smokers, 12 smokers and 18 patients with COPD. The proportions of Treg subpopulations and activated CD8 T cells were evaluated using flow cytometry.

Results In peripheral blood, increased proportions of rTregs, aTregs and Fr III cells were found in smokers compared with never-smokers, whereas patients with COPD showed decreased rTregs and aTregs, and significantly increased Fr III cells compared with smokers. The changes in Treg subpopulations, with an overall decrease in the (aTreg+rTreg):(Fr III) ratio, indicated that immune homeostasis favoured inflammation and correlated with enhanced CD8 T-cell activation (r=−0.399, p<0.001) and forced expiratory volume in 1 s (FEV1) % predicted value (r=0.435, p<0.001). The BAL (aTreg+rTreg):(Fr III) ratios displayed more robust correlations with FEV1 % predicted value (r=0.741, p<0.001) and activation of effector T cells (r=−0.763, p<0.001).

Conclusions The imbalance between the anti-inflammatory subsets (aTreg+rTreg) and the pro-inflammatory subset (Fr III) of Tregs may play an important role in COPD progression.

INTRODUCTION

The principal feature of chronic obstructive pulmonary disease (COPD) is abnormal inflammatory response of the lung to inhaled noxious gases or particles, especially to tobacco smoke. Accumulating evidence indicates that chronic inflammation and adaptive immunity play important roles in the development and progression of COPD. The inflammation in COPD extends beyond the lungs and includes regional lymph nodes and the systemic circulation. However, the regulation of inflammation in patients with COPD has not yet been fully elucidated.

What is the key question?

► Are phenotypically and functionally different subpopulations of regulatory T cells (Tregs) varied in chronic obstructive pulmonary disease (COPD) and potentially involved in the progression of inflammation?

What is the bottom line?

► The imbalance between the anti-inflammatory subsets and the pro-inflammatory subset of Tregs correlates with loss of lung function and immune activation in patients with COPD.

Why read on?

► This study provides evidence to support disturbed homeostasis of Treg subpopulations as a potential mechanism for persistent inflammation mediated by CD8 cells in COPD.
In most previous studies, Tregs have only been considered as a whole population. However, recent studies have demonstrated that human CD4\(^+\) CD25\(^+\) Foxp3\(^+\) Tregs are heterogeneous and comprise three distinct subpopulations, each with a precise phenotype and function. Apart from resting Tregs (rTregs, CD25\(^++\) CD45RA\(^-\)) and activated Tregs (aTregs, CD25\(^++\) CD45RA\(^-\)), which are suppressive in vitro, human CD4\(^+\) CD25\(^+\) Foxp3\(^+\) Tregs also possess CD25\(^++\) CD45RA\(^-\) cytokine-secreting T cells (Fr III) with pro-inflammatory capacity.\(^{21-25}\) This population lacks suppressive activity or has limited suppressive activity, but can produce interleukin (IL)-2, IL-17 and interferon (IFN)-\(\gamma\).\(^{21-25}\) which are important for T-cell activation and pulmonary inflammation.\(^{26,27}\) Recent studies revealed the clinical relevance of subpopulations of Tregs in patients with autoimmune diseases,\(^{21}\) HIV infection\(^{22}\) and diabetes.\(^{23}\)

The aim of this study was to explore whether there were abnormal distributions in the suppressive and/or the pro-inflammatory subpopulations of Tregs in the blood and the lung of patients with COPD and smokers by using this new identification strategy of Foxp3\(^+\) T-cell subsets, and whether the frequency of different Treg subsets was correlated with effector T-cell (CD8) activation and disease severity as defined by forced expiratory volume in 1 s (FEV\(_1\)). The findings should provide new insights into the potential mechanisms underlying persistent inflammation and adaptive immunity in COPD.

**MATERIALS AND METHODS**

**Study subjects**

Sixty-six patients with COPD and 34 smokers with normal lung function were recruited in Beijing Tongren Hospital, Capital Medical University, China. Fifty-seven never-smokers with normal lung function were also recruited as controls. Written informed consent was obtained and the local research ethics committee approved this study (TRECKT 2008-14). Subject baseline characteristics are summarised in table 1. A total of 112 patients with COPD were consecutively invited but 46 declined. Subjects with a smoking history of \(\geq 20\) pack-years and normal lung function (FEV\(_1\)/FVC \(\geq 70\%\)) were categorised as smokers. COPD diagnosis was established according to the definition supplied by the Global Initiative for Chronic Obstructive Lung Disease (GOLD) guidelines.\(^{28}\) Patients with COPD had FEV\(_1\)/forced vital capacity ratio \(\geq 70\%\) and FEV\(_1\)/FEV\(_1\) \(\geq 80\%\) of the predicted value post bronchodilators. All patients with COPD were clinically stable and had not experienced any exacerbations for \(\geq 3\) months preceding inclusion in the study. Participants with neoplasm, interstitial lung disease, autoimmune disease, diabetes, infection or other immune-related diseases were excluded.

**Flow cytometry**

Peripheral blood samples were collected in ethylenediaminetetraacetic acid treated tubes from each subject and were processed to measure peripheral blood mononuclear cells (PBMCs) for flow cytometry setup procedures. Blood samples were layered onto Ficoll-Paque Plus (Amersham Biosciences, Amersham, Bucks, UK), centrifuged (400 g for 20 min at 21°C), and PBMCs were harvested. Cells were washed once in divalent cation-free Hanks balanced salt solution at 300 g for 5 min at 4°C. PBMCs were resuspended and viable counts obtained.

**Data analysis**

Group data were expressed as mean and SEM or as median and IQR when appropriate. For data not distributed normally, comparisons between three groups were made using a one-way Kruskal–Wallis test (\(p<0.05\) was considered statistically significant). If this test indicated significance, the Mann–Whitney test was used for post hoc analysis for comparison between two groups, with corrections of p values according to Bonferroni (\(p<0.017\) was considered statistically significant). Correlation was assessed by calculating Spearman’s rank correlation coefficient. Here, \(p<0.05\) was considered statistically significant. Statistical analysis was performed using SPSS for Windows V16.0 (Chicago, Illinois, USA).

**RESULTS**

**Demographic characteristics of study population**

The characteristics of the patients with COPD, smokers and never-smokers with normal lung function are summarised in table 1. There was no difference between the groups in terms of...
age. The unequal sex ratio was mostly due to the much higher prevalence of COPD in men than in women in China. There was no significant difference in the smoking history of patients with COPD and smokers. Table 2 shows the main clinical and functional characteristics of participants who underwent bronchoscopy. The demographic characteristics of this study population were consistent with those who did not receive bronchoscopy.

**Table 2** Demographics and spirometry of participants who underwent bronchoscopy

<table>
<thead>
<tr>
<th></th>
<th>Never-smokers</th>
<th>Smokers</th>
<th>Patients with COPD</th>
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<tr>
<td>Subjects</td>
<td>n=12</td>
<td>n=12</td>
<td>n=18</td>
</tr>
<tr>
<td>Age (year)</td>
<td>63.3±3.9</td>
<td>65.8±2.8</td>
<td>66.5±4.2</td>
</tr>
<tr>
<td>Men/Women</td>
<td>10/2</td>
<td>10/2</td>
<td>14/4</td>
</tr>
<tr>
<td>Current/ex-smokers</td>
<td>0/0</td>
<td>9/3</td>
<td>8/10</td>
</tr>
<tr>
<td>Smoking history pack (year)</td>
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<td>34 (30–41)</td>
<td>38 (20–53)</td>
</tr>
<tr>
<td>FEV1% predicted</td>
<td>94.2±4.8</td>
<td>92.6±3.4</td>
<td>46.8±7.4</td>
</tr>
<tr>
<td>FEV1/FVC%</td>
<td>75.2±1.4</td>
<td>73.3±3.3</td>
<td>42.4±5.6</td>
</tr>
<tr>
<td>Inhaled corticosteroid use</td>
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<td>0</td>
<td>n=6</td>
</tr>
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Data are presented as median (IQR) for smoking history, mean±SD for all others.

COPD, chronic obstructive pulmonary disease; FEV1, forced expiratory volume in 1 s; FVC, forced vital capacity.

Dissection of Foxp3+ cells into three subsets with different function and phenotypic characteristics

As described previously, CD4+ Foxp3+ T cells were separated into three subpopulations by the expression of CD25 and CD45RA: rTregs (CD45RA+ CD25++, Fr I), aTregs (CD45RA- CD25++, Fr II) and cytokine-secreting subset (CD45RA-- CD25++, Fr III) (figure 1A). As shown in figure 1A, the degrees of Foxp3 expression in these fractions were proportional to CD25 expression. Moreover, rTregs expressed high levels of CD25, a marker for primary thymic emigrants, but expression was lost during their post-thymic peripheral expansion, as compared with never-smokers, the number of Foxp3+ IL-17-secreting FrIII cells and Foxp3+IFN-γ-secreting FrIII cells were slightly increased in smokers, but dramatically increased in patients with COPD (figure 3E, F). More importantly, the number of Foxp3+ IL-17-secreting FrIII cells strongly correlated with T helper 17 (Th17) cells (Foxp3+IL17+) (r=0.818, p<0.001; figure 3G).

**Disturbed homeostasis among subpopulations of circulating Tregs correlated with effector T-cell activation status and disease severity**

To illustrate further the balance between the suppressive and pro-inflammatory subpopulations, we calculated the ratio of (aTreg+rTreg):(Fr III) as expected, the (aTreg+rTreg):(Fr III) ratio was significantly decreased in patients with COPD (median 0.47) compared with smokers (median 0.77; p<0.0001) and never-smokers (median 0.75; p<0.0001) (figure 4A). No difference was found in the (aTreg+rTreg):(Fr III) ratio between the patients receiving and those not receiving inhaled corticosteroids (see online supplementary figure S2), which indicated that the differences in Treg subpopulations among never-smokers, smokers and patients with COPD were not due to corticosteroids. However, a definite conclusion could only be made by a prospective study to explore specifically the effect of corticosteroids on Tregs.

It has been previously demonstrated that patients with COPD exhibited enhanced CD8 T-lymphocyte activation, which was correlated with the disease severity as measured by FEV1. Moreover, it has been shown that CD8 T-cell activation could be suppressed by Tregs10 and promoted by IL-17.44 35 The decreased (aTreg+rTreg):(Fr III) ratio in patients with COPD prompted us to test whether the disturbed Treg homeostasis had any influence on CD8 T-cell activation and disease severity. The expression of CD28 (a costimulatory molecule), CD69 (an early marker transiently expressed on activated T cells), CD38 and HLA-DR (more general markers of T-cell activation) on CD8 T cells was evaluated. Similar to a previous study,33 patients with COPD showed elevated frequencies of CD8+HLA-DR+ (median 10.72%, 5.33% and 4.98% for patients with COPD, smokers and never-smokers, respectively, p<0.001) and CD8+CD38+ cells (median 14.95%, 8.40% and 8.24% for patients with COPD, smokers and never-smokers, respectively, p<0.001) (figure 4B,C). However, expression of...
CD28 and CD69 in CD8 T lymphocytes did not differ significantly between the groups (data not shown).

In line with previous reports that Tregs suppress CD8 T-cell activation, we found that the (aTreg+rTreg):(Fr III) ratios were inversely correlated with the frequencies of CD8+ HLA-DR+ and CD8+ CD38+ cells (r = −0.399, p < 0.001; r = −0.416, p < 0.001; figure 4E,F). More importantly, the (aTreg+rTreg):(Fr III) ratios were significantly correlated with FEV1 predicted values (r = 0.435, p < 0.001; figure 4D), which indicated that the imbalance between suppressive subpopulations and the cytokine-secreting population was correlated with effector T-cell activation and severity of COPD.

**Disturbed homeostasis among subpopulations of Tregs in BAL**

To clarify the homeostatic status of local Tregs, BAL samples were obtained from 12 never-smokers, 12 smokers and 18...
patients with COPD who were undergoing clinically investiga-
tional bronchoscopy. In line with a previous study,18 we found
that the majority of T regs in BAL were CD45RA−. Accordingly,
the percentage of rT regs in BAL was decreased markedly com-
pared with that in peripheral blood and was identical across all
three groups. However, aT regs and FrIII cells in BAL had a
similar pattern of variation in peripheral blood, that is, aT regs
decreased whereas Fr III cells increased in patients with COPD
compared with never-smokers and smokers (figure 5A). Next, we
calculated the (aT reg+rT reg):(Fr III) ratios in BAL to illustrate
the local balance between the suppressive and pro-in
flammatory subpopulations. Similar to the results from circulating T regs, we
found that (aT reg+rT reg):(Fr III) ratios were significantly lower
in BAL of patients with COPD compared with smokers and
never-smokers, suggesting that disturbed T reg homeostasis was
also present in the lung (figure 5B). More importantly, compared
with the blood (aT reg+rT reg):(Fr III) ratios, the BAL ratios
showed a stronger correlation with activation status of effector
T cells (CD8+ HLA-DR+: r=0.763, p<0.001; CD8+ CD69+
cells; r=0.713, p<0.001) and FEV1% predicted value (r=0.741,
p<0.001; figure 5C–E).

DISCUSSION
CD4+ Foxp3+ Tregs have been recognised as a negative regula-
tory population during immune responses.10 11 12 However,
phenotypic and function heterogeneity of human CD4+
Foxp3+ Tregs is a major obstacle for understanding their clinical
relevance. Dissecting CD4+ Foxp3+ cells into subsets, especially
defining the cytokine-producing population (Fr III), is one of
the striking findings of the studies on human CD4+ Foxp3+
Treg heterogeneity.21 24 25 Previous studies which identi-
ed Tregs as a whole did not find any significant difference in fre-
quencies of circulating Tregs in patients with COPD.17 18 Here,
based on this new definition of Treg subsets, we revealed signifi-
cantly decreased proportions of rTregs and aTregs and an
increased proportion of the cytokine-secreting non-Treg

Figure 2 Variations in Foxp3+ cell subpopulations under physiological and disease conditions. (A–C) The percentages of each circulating T-regulatory subset among CD4 T cells in never-smokers, smokers and patients with chronic obstructive pulmonary disease (COPD). (D–F) Number of each Foxp3+ subset per microlitre of peripheral blood in never-smokers, smokers and patients with COPD. (G) Representative data of flow cytometry profiles are shown. Horizontal lines indicate median values. A p value<0.017 was considered statistically significant. Fr I, CD25++ CD45RA+ resting T-regulatory cells (rTreg); Fr II, CD25+++ CD45RA− activated T-regulatory cells (aTreg); Fr III, CD25++ CD45RA− cytokine-secreting cells.
subpopulation in patients with COPD compared with smokers with normal lung function. More importantly, we linked the imbalance between these subsets with activation of CD8 T cells and the severity of COPD.

Despite a debate about their immune suppressive capacity, the inflammatory role of Fr III cells is well accepted due to their ability to produce IL-17 and IFN-γ. In smokers, we observed increased frequencies of three subpopulations, which suggested coexistence of anti-inflammatory and inflammatory responses. Strikingly, in comparison to smokers, patients with COPD exhibited increased proportions of Fr III cells and decreased proportions of rT regs and aT regs. This might reflect progression of inflammation and exhaustion of anti-inflammatory responses during disease progression.

Figure 3 In vitro functional activity of the Foxp3+ cell subpopulation in patients with chronic obstructive pulmonary disease (COPD).

(A) Suppression of T-cell proliferation by each subpopulation was assessed by carboxyfluorescein succinimidyl ester (CFSE) staining. Percentages of dividing cells were indicated. Data are representative of five independent experiments. (B and C) Intracellular staining of cytokines. Representative staining of intracellular Foxp3 versus interleukin 17 (IL-17) or interferon γ (IFN-γ) in never-smokers, smokers and patients with COPD after 5 h of stimulation with phorbol-12-myristate-13-acetate (PMA)/ionomycin and GolgiStop. Data are representative of 51 independent experiments. (D–F) Frequencies of Foxp3− IL17+ (D), Foxp3+ IL17+ (E) and Foxp3+ IFN-γ (F) among CD4 T cells in three groups. A p value<0.017 is considered statistically significant. The top bar in (D–F) is for the difference between the never-smokers and patients with COPD. (G) Proportions of IL-17-secreting T-regulatory cells correlated with T helper 17 cells (Foxp3− IL17+). A p value<0.05 was considered statistically significant. Fr I, CD25++ CD45RA+ resting T-regulatory cells; Fr II, CD25+++ CD45RA− activated T-regulatory cells; Fr III, CD25++ CD45RA− cytokine-secreting cells.
Moreover, we further described an imbalance between anti-inflammatory and pro-inflammatory subsets by measuring the (aTreg+rTreg):(Fr III) ratio. Despite the elevation of three tested subsets in smokers with normal lung function, the (aTreg+rTreg):(Fr III) ratio remained stable as in never-smokers, which indicated that immune response homeostasis remained intact, although inflammatory and anti-inflammatory mechanisms were activated. However, in patients with COPD, as indicated by a significantly decreased (aTreg+rTreg):(Fr III) ratio, the balance between subpopulations tilted in favour of the inflammatory response, which might have facilitated inflammation-related lung injury. More importantly, in line with a decreased (aTreg+rTreg):(Fr III) ratio, we found a positive correlation between the circulating (aTreg+rTreg):(Fr III) ratio and FEV1%, which further linked the immune imbalance with airflow limitation in patients with COPD. The stronger correlation between the BAL (aTreg+rTreg):(Fr III) ratio and FEV1% provided more evidence to support this link. From these findings we hypothesise that a decrease in the immunosuppressive Treg populations, together with enhanced pro-inflammatory responses, induced by long-term exposure to inhalation of particles or gases, for example, tobacco smoking, lead to persistent airway inflammation dominated by CD8 T cells. This persistent airway inflammation is believed to be involved in the progressive loss of lung function characteristic of COPD.

It has been shown that CD8 T cells predominate over CD4 T cells in the airways and lung parenchyma of patients with COPD. COPD severity is correlated significantly with the frequency of activated CD8 T cells in peripheral blood. Moreover, previous studies have demonstrated opposing roles for Th17 cells and Tregs in CD8 cell activation: Treg cells suppress the proliferation of activated CD8 T cells via a variety of mechanisms, whereas IL-17-secreting cells promote CD8 cell activation by inducing expression of IL-6, IL-8 and intracellular adhesion molecule 1. It has been shown that BAL samples from patients with COPD also exhibit a higher CD8 cell:Treg ratio than smokers. In this study, we revealed a negative correlation between the circulating (aTreg+rTreg):(Fr III) ratio and frequency of activated CD8 T cells, which indicated that such enhanced activation of CD8 T cells might have resulted from immune imbalance in patients with COPD. Moreover, circulating CD8 T cells in patients with COPD exhibited elevated frequencies of cells expressing CD38 and HLA-DR, two general markers for T-cell activation, but not a transient marker CD69, which further indicated that activation of CD8 T cells in patients with COPD was a result of chronic inflammation rather than acute activation. Interestingly, pulmonary CD8 T cells in patients with COPD exhibited elevated expression of CD69 and HLA-DR, suggesting ongoing activation of T cells at the site of inflammation.

In summary, this study provides further evidence for the role of adaptive immunity in COPD pathogenesis, and demonstrates that the balance between the subpopulations of previously described CD4+ Foxp3+ Tregs may contribute to the progression of inflammation in the lung. Of note, the correlations between the (aTreg+rTreg):Fr III ratio and activated CD8 T cells or FEV1% existed in BAL, and to a lesser extent, in peripheral blood, indicating a closer correlation between loss of lung function and local immune activation. Furthermore, our data extend local immune activation to systemic immune activation, which might facilitate our understanding of the underlying mechanisms for local and systemic inflammation in COPD. Future therapeutic strategies to control inflammatory responses in COPD may be directed at modulation of different subpopulations of CD4+ Foxp3+ cells to restore immune homeostasis.
Figure 5 The percentages of each Foxp3+ subset among CD4 T cells (A) and (aTreg+rTreg):(Fr III) ratios (B) in the bronchoalveolar lavage of never-smokers, smokers and patients with chronic obstructive pulmonary disease (COPD). Horizontal lines indicate median values. A p value<0.017 was considered significant. The (aTreg+rTreg):(Fr III) ratios correlated with CDB T lymphocyte activation status (C and D) and forced expiratory volume in 1 s (FEV1) predicted values (E) in patients with COPD. A p value<0.05 was considered statistically significant. Fr I, CD25++ CD45RA+ resting T-regulatory cells (rTreg); Fr II, CD25+++ CD45RA− activated T-regulatory cells (aTreg); Fr III, CD25++ CD45RA− cytokine-secreting cells.

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Contributors JH: contributed to recruiting the patients, performing all data collection, collecting and processing samples, and writing the manuscript. YS: contributed as primary investigator and was responsible for designing the study and writing the manuscript. YH and JH: performed laboratory-based assays. JZ, XL, PB and XZ: recruited the patients and collected clinical data. HZ: contributed as lead investigator and was responsible for designing the study, analysing the data and writing the manuscript. All authors read and approved the final manuscript.

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Competing interests None.

Ethics approval Ethics Committees, Beijing Tongren Hospital, Capital Medical University.

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Supplementary Appendix

Flow cytometry and cell count

Treg subpopulations were gated as shown in supplementary figure 1. These settings were applied for subsequent CD4$^+$ T cells analysis of 100,000 events. CD4$^+$ T-cell count was determined using a standard flow cytometry technique with a TruCOUNT tube (BD Biosciences). The absolute numbers of each subpopulation were calculated based on CD4$^+$ T-cell counts and their frequencies. Data acquired by FACS-Calibur (BD Biosciences) were analysed using FlowJo software (Tree Star, Ashland, OR, USA).

Cells for FoxP3 and cytotoxic T lymphocyte antigen (CTLA)-4 staining were prepared for intracellular flow cytometry with a “Fix and Perm” kit (e-Bioscience) following the manufacturer’s instructions. After permeabilisation and washing, cells were labelled with anti-Foxp3-PE (e-Bioscience) and anti-CTLA-4-APC (e-Bioscience). Corresponding isotype controls were used as staining controls (BD Biosciences and e-Bioscience). Intracellular cytokine elaborations were determined in PBMC sand stimulated for 5 h with phorbol myristate acetate (PMA; 5 ng/ml) and calcium ionomycin (500 ng/ml) in the presence of GolgiStop. Cells were fixed, permeabilised, and stained with Anti-hIFN-ɤ-FITC (BD Biosciences) and anti-hIL-17A-Percp-cy5.5 (BD Biosciences).

Cell culture and in vitro suppression assay

For in vitro suppression assay of different Treg subsets, CD4$^+$CD25$^-$ cells were purified by labelling with anti-human CD25-PE antibody (eBioscience) and anti-PE microbeads (Miltenyi Biotech, BergischGladbach, Germany) from healthy controls as responder cells. Carboxyfluorescein succinimidyl ester (CFSE)-labelled CD4$^+$CD25$^-$ responder cells (5×10$^4$) were cocultured with 1×10$^4$ unlabelled FrI (CD25$^{++}$CD45RA$^+$,
rTreg), FrII(CD25+++CD45RA−, aTreg) or Fr III (CD25+++CD45RA−) cells, respectively, in anti-CD3 (5 g/ml, OKT3 mAb; eBioscience) coated plates in the presence of soluble anti-CD28 (5 μg/ml; eBioscience) for 72–96 h. Proliferation of CFSE-labelled cells was assessed by flow cytometry and the percentage suppression was determined based on the percentage of dividing of CFSE-labelled cells as compared with the percentage of dividing CFSE-labelled cells when cultured alone.
Supplementary figure 1. Representative plots of flow cytometry used in BAL (A) and PBMC (B) analysis.
**Supplementary figure 2.** The effect of corticosteroid on subpopulations of Foxp3$^+$ T cells in COPD patients. The cross-sectional analysis showed that no difference was found between patients receiving and not receiving inhaled corticosteroid in terms of three subpopulations of Tregs. Horizontal lines indicate median values.