Allergen specific Treg upregulated by lung-stage schistosome infection alleviates allergic airway inflammation via inhibiting IgE secretion

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Short title:

Lung-stage schistosome infection alleviates asthma via Treg inhibiting IgE.

Abstract

Schistosome infection showed protective effects against allergic airway inflammation (AAI). However, controversial findings exist especially regarding the timing of helminth infection and the underlying mechanisms. Moreover, most previous studies focused on understanding the preventive effect of schistosome infection on asthma (infection before allergen sensitization), while its therapeutic effects (infection after allergen sensitization) were rarely investigated. In this study, we investigated the therapeutic effects of schistosome infection on AAI using a mouse model of OVA induced asthma. To explore how the timing of schistosome infection influences its therapeutic effect, the mice were percutaneously infected with cercaria of *Schistosoma japonicum* at either 1 day before OVA induced asthma attack (infection at lung-stage during AAI) or 14 days before OVA induced asthma attack (infection at post lung-stage during AAI). We found that lung-stage schistosome infection significantly ameliorated OVA-induced AAI, whereas post lung-stage infection showed no therapeutic effect. Mechanistically, the lung-stage schistosome infection significantly upregulated the frequency of Treg, especially OVA specific Treg, in lung tissue, which negatively correlated with the level of OVA specific IgE. Depletion of Treg *in vivo* counteracted the therapeutic effect. Furthermore, transcriptomic analysis of lung tissue showed that lung-stage schistosome infection during AAI shaped the microenvironment to favor Treg induction. In conclusion, our data showed that lung-stage schistosome infection could relieve OVA induced asthma in a mouse model. The therapeutic effect was mediated by the upregulated OVA specific Treg which suppressed IgE production and Th2 cytokine secretion.

69 Our results may facilitate the discovery of a new therapy for AAI.

70

71 **Key words:** *Schistosoma japonicum*, Schistosome, Infection, Allergic airway

72 inflammation, Asthma, Helminth therapy, Treg, IgE

Author Summary

Asthma is an increasingly common disease especially in industrialized countries, which is still lack of an optimal therapy. The protective effect of schistosome infection against allergic asthma has been shown in previous studies, which represents a promising candidate immune intervention approach. However, controversial findings exist especially regarding the timing of helminth infection and the underlying mechanisms. In this study, we demonstrate that lung-stage schistosome infection could upregulate the frequency of allergen specific Treg, which significantly alleviated OVA induced allergic airway inflammation via inhibiting the production of IgE and Th2 cytokines. Our results proved the therapeutic effect of schistosome infection on allergic asthma. Moreover, we highlighted that lung-stage infection is essential for inducing allergen specific regulatory T cells in lung, which is the key mediator of the observed therapeutic effect. These findings shed new light on exploiting helminths or their derivatives to treat asthma and other allergic diseases.

Introduction

The prevalence of asthma has increased dramatically in the past three decades [1, 2], which represent a great health burden especially in developed countries [3, 4]. Atopic asthma is the most common form of asthma, which is an immunological disorder disease characterized by inflammation of the airways and lungs triggered by allergen with marked Th2 responses, overactive immunoglobulin IgE production, mucus hypersecretion and large amount of eosinophils influx to airways [5].

The exact social and environmental factors that lead to hyper-reactive immune disorder is still not fully understood. A leading theory behind the rapid rising of allergy and asthma rates is the “hygiene hypothesis”, which suggests that the decreasing incidence of infections in western countries is the origin of the increasing incidence of both autoimmune and allergic diseases [6]. The hypothesis was supported by an observation showing that westernized lifestyle linked with significantly higher prevalence of atopic disease [7]. A putative explanation to this phenomenon is that the overall reduction in common Th1-inducing (bacterial, viral and parasitical) infections resulting in a decreased ability to counterbalance Th2-polarized allergic diseases [8-10]. Following this lead, a variety of experimental studies have proved that helminth infection can down-regulate host immunity and immunopathology in allergy and other immune disorders[11-13]. Schistosome was one of the parasites that has been found to have protective effects for autoimmune diseases and allergies like arthritis and asthma [14-16]. These explorations hold great

promise to identify a new and better therapy for atopic asthma, which may avoid the adverse effects of current treatments [17-19].

Schistosome is an ancient parasite affecting more than 230 million people in 78 tropical and subtropical countries [20]. During the life stages in the definitive hosts, the trematode invades its mammalian hosts through the skin firstly, migrates from skin to lung, then develops and matures in liver, finally resides mesenteric venules. Although it has been shown by multiple studies that schistosome could abate allergic airway inflammation (AAI), the understanding of underlying mechanisms remains limited. Most previous studies focused on testing the preventive effect (infection before allergen sensitization) of schistosome infection against allergic asthma. And under this setting, controversial results have been reported regarding both the timing of infection (acute versus chronic) [21-23] and the effector component (egg versus worms) [24-26], which reflects the complexities of schistosome life cycle and its immune regulatory components. Moreover, contradictory results were also reported regarding the roles of regulatory T cells in schistosome mediated protection. Some studies showed that Treg was an important effector in schistosome mediated protection against asthma [21, 23, 26-28], while a more recent study showed that the protection was independent of Treg [24].

Unlike previous studies which focused on testing the preventive effect (infection before allergen sensitization) of schistosome infection against allergic asthma, the primary goal of this study was to investigate the therapeutic effect of schistosome infection on asthmatic inflammation

(infection after allergen sensitization) and to clarify the underlying mechanism. To this aim, the mice were percutaneously infected with cercaria of *Schistosoma japonicum* at either 1 day before OVA induced asthma attack (infection at lung-stage during AAI) or 14 days before OVA induced asthma attack (infection at post lung-stage during AAI). We found that only lung-stage schistosome infection could upregulate the frequency of allergen specific Treg, which significantly alleviated AAI via inhibiting IgE production and inflammatory cytokine secretion.

Results

Lung-stage schistosome infection ameliorated OVA-induced AAI in a murine model

A mouse model of OVA-induced AAI was adopted to test the therapeutic effect of schistosome infection on allergic asthma (Fig 1A & 1B). Compared to the control group, mice in the OVA group showed significant infiltration of inflammatory cells in BALFs (Fig 1C & 1D), which resembled the main clinical feature of AAI [29]. Moreover, after schistosome infection, the results showed lung-stage infection significantly reduced the infiltration of inflammatory cells, especially eosinophils (Fig 1C), while post lung-stage infection did not (Figure 1D). Histopathological examination further confirmed the above findings by showing that lung-stage infection significantly suppressed the OVA-induced eosinophil-rich leukocyte infiltration and mucus hypersecretion (Fig 1E), whereas post lung-stage infection showed no obvious therapeutic effect (Fig 1F).

Lung-stage schistosome infection inhibited IgE production and suppressed Th2 cytokine secretions

IgE is the key factor mediating the pathological immune responses that lead to allergic asthma [30]. To further characterize the therapeutic effects of schistosome infection, we measured the total and OVA specific IgE in serum of mice. The results showed that lung-stage infection significantly downregulated both the total and OVA specific IgE to levels comparable with DXM treated mice (Fig 2A & 2B). In contrast, post lung-stage infection tended to elevate the

total and OVA specific IgE levels despite no significant difference was reached (Fig 2C & 2D). Moreover, we also measured a panel of cytokines and chemokines in BALFs and found that lung-stage infection altered the cytokine/chemokine secretion pattern induced by aerosolized OVA challenge (Fig 3A & S1 Fig). More specifically, IL-5 and Eotaxin were reduced to levels similar with DXM treatment (Fig 3B). On the contrary, post lung-stage infection increased IL-4 and IL-5 secretion (Fig 3B).

Lung-stage schistosome infection upregulated the frequencies of regulatory T cells (Treg) especially OVA specific Treg in lung

Treg was suggested to be the key factor of *S. mansoni*-mediated protection against allergic airway inflammation [21]. Herein, we first assessed the frequencies of Treg ($CD4^+CD25^+Foxp3^+$ Treg) in spleen and lung. As shown in Figure 4A, compared to the OVA control, lung-stage infection significantly upregulated the frequency of Treg both in lung and spleen (Fig 4A), whereas post lung-stage infection only slightly improved the proportion of Treg in spleen (Fig 4B). To further illustrated that the influences of schistosome on OVA induced AAI were allergen specific or non-specific immune response, OVA specific naïve $CD45.1^+$ $CD4^+$ T cells were transferred into $CD45.2^+$ recipient mice. The frequencies of total Treg, $CD45.1^+$ Treg (OVA specific), and $CD45.2^+$ Treg (OVA non-specific) were detected in lung and lung draining lymph nodes (LDLNs). Interestingly, we found that the frequency of OVA specific Treg ($CD45.1^+$ Treg) in lung increased by more than 3 folds after schistosome infection ($P < 0.001$), while that in LDLNs didn't show any

199 significant changes (Fig 5B & 5C). However, the frequency of endogenous
200 Treg (CD45.2$^+$ Treg) in lung was not significantly improved, while that in
201 LDLNs showed a slight increased (Fig 5B & 5C). The proportion of total Treg
202 was increased in lung and LDLNs (Fig 5B & 5C).
203
204 Besides, we also found that the ratio of OVA specific CD4$^+$ IL-4$^+$ T versus CD4$^+$
205 IFN-γ$^+$ T cells significantly decreased after lung-stage schistosome infection
206 (S2 Fig), suggesting that specific CD4$^+$ T cell responses from Th2 toward Th1
207 shifted responses.
208
209 **The therapeutic effect of lung-stage schistosome infection was Treg**
210 **dependent**
211 Significant negative correlations between the frequency of Treg and OVA
212 specific IgE or IgG (Fig 6) were observed, indicating that the therapeutic effect
213 of schistosome infection on AAI might be mediated by Treg. To elucidate the
214 role of Treg, we performed *in vivo* depletion using anti-mouse CD25 antibody
215 (Fig 7A). Our data showed that Treg depletion (OVA+INF+αCD25 group)
216 aggravated OVA induced AAI compared to isotype control group. Inflammatory
217 cell infiltration, mucus secretion (shown by PAS staining) and OVA specific IgE
218 production significantly increased after Treg depletion (Fig 7).
219
220 **Lung-stage schistosome infection moulded the microenvironment to**
221 **facilitate the generation of Treg**
222 To find out factors that contributed to the induction of Treg upon lung-stage
223 schistosome infection, we performed the transcriptomic profiles of the lung

224 tissues from the schistosome infected and non-infected mice post OVA
225 challenge. The results showed that 203 genes were upregulated and 279
226 genes were downregulated in the lung-stage schistosome infection group (Fig
227 8A & Data file S1). GO analysis of DEGs showed that the top 3 terms of
228 significantly enriched ($P < 0.05$) is mainly distributed in the T cell activation, the
229 leukocyte proliferation and the regulation of leukocyte proliferation (Fig 8B)
230 pathways. And panther analysis showed that 84 DEGs are relate to immune
231 system process (S3 Fig) and 70 of them were downregulated (Data file S1).
232 Further analysis showed that 3 genes (CD46, Epor, and Klra17) reported to
233 promote Treg response were upregulated [31-33] and 8 genes (Clec7a, CCR6,
234 Spi-B, ABCG1, ADA, Ctsk, Ctss, and Ptgir) reported to inhibit Treg response
235 were downregulated [34-41] (Fig 8C & Table 1) in schistosome infected mice.
236 We postulated that lung-stage schistosome infection generated a
237 microenvironment facilitating Treg development in lung (Fig 8C).
238
239 In addition, we found that 8 genes (DOCK2, IRF4, Rac2, Lgals3, H2-Oa,
240 Pdcd1lg2, Sash3, and Mzb1) related to B cell function or differentiation [42-49]
241 were also downregulated after schistosome infection (Table 2), which might
242 potentially contribute to the inhibition of IgE response. Genes related to lung
243 development (FOXF1, ANO9, TRIM6, MMP27, Epor, Gata1, and Serpina)
244 [50-52] and cell integrity (Villin and CRB1)[53, 54] were found to be
245 upregulated too, which indirectly supported the observed therapeutic effect of
246 schistosome infection (Table 2).

Discussion

The eradication of helminths (and other pathogens) is suggested to have resulted in over-activated immune response, which might be the cause of the increasing prevalence of allergic and autoimmune disorders especially in developed and urbanized countries [55-57]. The therapeutic effect of parasitic infection against allergies and autoimmune disease have been extensively explored especially after the hygiene hypothesis was introduced into this field [58]. Among which, the immunoregulation of schistosome is best illustrated [14, 21, 59].

In this study, to investigate how the timing of schistosome infection influence the development of allergic asthma, we compared the therapeutic effect of two phase of schistosome infection: lung-stage and post lung-stage. We found that lung-stage schistosome infection significantly relieved OVA-induced allergic airway inflammation, but post lung-stage infection showed no therapeutic effect. Within lung-stage infection (3-7 days post infection), schistosomula transformed from cercaria was completely located in lung tissue of the host [60], which might modulate the local immune response to abate OVA induced AAI. We postulated that this might be the reason that made the therapeutic effect of lung-stage infection superior to post lung-stage infection. And indeed, we found that lung-stage infection significantly upregulated Treg response in lung.

Multiple factors such as worm species, timing, intensity and chronicity of infection, as well as host genetics have been investigated to illustrate the

mechanisms of helminth mediated the regulation of host immunity [61]. Nonetheless, the relationship between helminths and asthma still remains. Mechanistic studies reported contradictory results, for example, one study showed that *S. mansoni*-mediated suppression of allergic airway inflammation was patency dependent and mediated by infection-induced Treg [21], while another study showed that protection mediated by *S. mansoni* egg was independent of either Treg or Breg [24]. In current study, we found that lung-stage schistosome infection occurred during OVA induced asthma attack could upregulate the frequency of Treg and suppressed OVA specific IL-4 response. Upregulation of Treg by schistosome infection has been reported by few previous studies [21, 62], however, to our knowledge, this is the first proof showing that the lung-stage schistosome infection can upregulate allergen OVA specific Treg.

To elucidate the role of Treg in schistosome infection mediated alleviation of AAI, we first analyzed the relationship between Treg and OVA specific IgE and found that the frequency of Treg in lung negatively correlated with OVA specific IgE. Furthermore, by *in vivo* depletion of Treg, we found that the decrease of IgE secretion was Treg dependent. IgE acts as the major mediator resulting in the allergic airway inflammation [63]. Our result proved that the therapeutic effect of schistosome infection on AAI was mediated by a Treg dependent inhibition of IgE, which was consistent with a previous report showing that the preventive effect of chronic *S. mansoni* infection against later AAI was also Treg dependent [21].

Mechanisms underlying the induction of Treg or Breg by egg related antigens have been reported [64, 65]. However, we did not find out the exact active molecules of schistosome that led to the upregulation of Treg in this study. Nonetheless, we think that it is very likely the observed therapeutic effect was a collective result of multiple components of schistosome, as previous studies showed multiple enzymes released by schistosomula could regulate host immunity [66, 67]. We plan to acutely define these components in future.

Instead of identifying effector antigens, in this study, we tried to understand how the lung-stage schistosome infection influence local immune responses in lung. To do so, we performed transcriptomic comparison between lung tissues of schistosome infected and non-infected mice. The results showed, after lung-stage schistosome infection, most genes related to immune response were downregulated (70/84), implying the general immune state in lung tended to be downregulated by schistosome infection. Among these genes, we found that 3 genes (CD46, Epor, and Klra17) reported to promote Treg response were upregulated and 8 genes (Clec7a, CCR6, Spi-B, ABCG1, ADA, Ctsk, Ctss, and Ptgir) reported to inhibit Treg response were downregulated in schistosome infected mice, suggesting that schistosome infection generated a milieu facilitating Treg induction in lung. In the meantime, we also observed some molecules reported to facilitate the function of B or plasma cells were downregulated, which was consistent with our finding that IgE response was suppressed.

Collectively, our study showed that lung-stage schistosome infection established a regulatory environment in lungs, which can help to relieve OVA induced AAI in mouse model. Although the exact mechanism about Treg upregulation remains elusive, our data clearly showed that lung-stage schistosome infection can improve the frequency of allergen specific Treg and the latter can directly suppress IgE production. The encouraging results highlight the value of lung-stage schistosome infection as a potential therapy for allergic asthma. And identifying the effector molecules is especially of interesting, as it will make this therapy more practical.

Methods

OVA-induced allergic airway inflammation and schistosome infection

Female BALB/c mice (6- to 8-week-old) were randomly divided into six groups in this experiment, which are OVA-induced AAI (OVA) group, OVA-induced AAI with lung-stage schistosome infection (OVA+INF, lung-stage) group, OVA-induced AAI with post-lung stage infection (OVA+INF, post lung-stage) group, OVA-induced AAI with dexamethasone (DXM) treatment (OVA+DXM) group, as well as infection (INF) group and normal (NOR) group. The mice were sensitized by injecting 10 μg of alum-adjuvanted ovalbumin (OVA; Cat# 77120 and 77161, Thermo Fisher, US) intraperitoneally on day 0 and day 14. Subsequently, to induce AAI, the mice were challenged with aerosolized OVA (1% in PBS) for 30 minutes in the chamber of a Medical Compressor Nebulizer (DEDAKJ, Germany) on days 21–24 (Fig 1A and 1B). The mice of the normal control and schistosome infection control groups were challenged with phosphate buffer solution (PBS). To test the therapeutic effect of infection on OVA induced AAI, mice were infected with 15 cercaria of *S. japonicum* at either 1 day before OVA induced asthma attack (infection at lung-stage during AAI) or 14 days before OVA induced asthma attack (infection at post lung-stage during AAI).

Bronchoalveolar lavage collection and cell counting

Mice were euthanized 48 h after the last aerosolized OVA challenge (day 26), and bronchoalveolar lavage fluids (BALFs) were collected as previously reported method [68]. Briefly, after euthanasia, tracheotomy was carried out and an arteriovenous indwelling needle (20G; BRAUN, Germany) was inserted

357 into the trachea. Lavages were collected by washing the lung twice with 0.3 ml
358 PBS. Cells in BALFs were harvested after centrifugation and the supernatants
359 were stored at -80°C for cytokine detection. Cell pellet was fixed with
360 paraformaldehyde (4%) and stained with a Haematoxilin-Eosin (H&E). A total
361 of 1000 cells from multiple fields were examined for each slide. Counts of total
362 cells, eosinophils, macrophage, neutrophils, and lymphocytes were performed
363 on blinded samples, as described previously [69].
364

365 **Lung histopathology**

366 Lung tissues were fixed in 4% phosphate buffered formaldehyde overnight,
367 then embedded in paraffin and cut for haematoxylin-eosin (H&E) and periodic
368 acid-Schiff (PAS). Images of the stained sections were captured with a NIKON
369 DS-U3 microscope (NIKON, Japan). Lung inflammation and the intensity of
370 goblet cell metaplasia was assessed and scored 0-4 by two blinded,
371 independent investigators, as described previously [70].
372

373 **Determination of total and OVA-specific IgE in serum**

374 The level of total and OVA specific IgE in serum were measured using enzyme
375 linked immunosorbent assay (ELISA). Briefly, Maxisorp 96-well microtiters
376 plates (Thermo Fisher Scientific, USA) were coated with rat monoclonal
377 anti-mouse IgE antibody for total IgE detection (1: 1000; Cat# ab99571,
378 Abcam, UK) or 10 µg/ml ovalbumin for OVA specific IgE (Cat# A5503, Sigma,
379 US) 100 µl/well, respectively, in carbonate-bicarbonate buffer, pH 9.6, for
380 12–16 hours at 4°C. Then the plates were blocked for at least 2 hours at 37°C

with 100 μl/well of PBS plus BSA (1%). After wash, 100 μl serum diluted with PBST (1: 40 for total IgE; 1: 5 for OVA specific IgE) were added to each well and incubated at 37°C for 2 hours. Next, HRP labeled goat anti-mouse IgE antibody were diluted with PBST (1: 2000; Cat# ab99574, Abcam, UK) and added to each well at 100 μl/well. After 2 hours incubation at 37°C, the plates were washed with PBST for 5 times. Finally, color was developed by addition of 100 μl/well of TMB (Cat# PA107, TIANGEN, China) and after incubating at room temperature for maximal 30 minutes, the reaction was stopped with 5% sulfuric acid (50 μl/well). Optical density (OD) values were determined at 450 nm using the multi-mode microplate readers (BioTek, USA). The concentration of total IgE was then calculated according to the standard curve.

Cytokine detection in BALFs

Levels of IL-4, IL-5, IL-13, IL-10, Eotaxin and IFN-γ in BALFs were measured using a custom-made Bio-Plex Pro Reagent Kit V (6-plex customization) (Cat# MHSTCMAG-70K, Wayen Biotechnologies, China) according to the manufacturer's instructions. The fluorescence labeled beads was detected using a corrected Bio-Plex MAGPIX system (Bio-Rad, Luminex Corporation, Austin, TX, USA) and the cytokine concentrations were calculated using Bio-plex manager 6.1 (Bio-Rad).

Lymphocytes isolation from lung tissues

After collection, lung tissues were washed 3–4 times with Roswell Park Memorial Institute (RPMI) medium, minced to tiny pieces, and then digested in 0.1% type IV collagenase (Cat# C8160, Solarbio, China) solution at 37°C for

30 min. Digested lung tissues was filtered through a 70 μm cell strainer and erythrocytes were lysed with a Red Blood Cell Lysis Buffer (Cat# R1010, Solarbio, China).

Flow cytometry assay

Single cells suspension were stained with a panel of surface mAbs in FACS buffer (PBS containing 2 mM EDTA and 0.5% bovine serum albumin) for 30 min on ice, including FITC-conjugated anti-CD4 (Clone# 88-8111-40, eBioscience, USA), APC-conjugated anti-CD25 mAb (Clone# 88-8111-40, eBioscience, USA), SuperBright645-conjugated anti-CD45.1 (Clone# 64-0453-82, eBioscience, USA) and Pe-cyanine7-conjugated anti-CD45.2 (Clone# 25-0453-82, eBioscience, USA). Subsequently, cells were fixed with fix/perm buffer (Clone# 88-8111-40, eBioscience, USA) on ice for 20 min, and then stained with mAbs targeting intracellular markers in a Perm/wash buffer for 30 min on ice. For the detection of Treg, PE labeled anti-Foxp3 mAb (Clone# 88-8111-40, eBioscience, USA) was used. And for detecting OVA specific IL-4 and IFN-γ secretion, isolated lymphocytes were initially stimulated for 16 h with 5 ug/ml OVA peptide (323-339) (China peptides, China) and then stained with mAbs Perp-cy5.5 conjugated anti-CD3 (Clone# 145-2C11, eBioscience, USA) and FITC conjugated anti-CD4 (Clone# 88-8111-40, eBioscience, USA) for 30 min on ice. Subsequently, cells were fixed with fix/perm buffer (Clone# 88-8111-40, eBioscience, USA) on ice for 20 min. Then PE conjugated anti-IL-4 (Clone# 12-7041-81, eBioscience, USA) or APC conjugated anti-IFN-γ (Clone# 17-7311-81, eBioscience, USA) for 30 min on ice. Finally, after two washes, all cells were resuspended in PBS containing

1% paraformaldehyde and subject to flow cytometry analysis (Cytometer LX, Beckman).

Adoptive Transfer of naïve CD4$^+$ T cells

Naïve CD4$^+$ T cells of CD45.1$^+$ OT II mice were purified using EasySep Mouse Naïve CD4$^+$ T Cell Isolation Kit (Cat# 19765, StemCell, USA) according to the manufacturer's protocol. The purity of isolated cells was checked by flow cytometry and was confirmed to be > 85%. Freshly purified naïve CD4$^+$ T cells were suspended in PBS and injected intravenously into CD45.2$^+$ congenic C57BL/6 recipient mice, 1 × 10^6 cells/mouse. The induction of AAI and schistosome infection were performed as described above.

In vivo depletion of Treg

Anti-CD25 antibody clone PC61 has been widely used to deplete Tregs for characterizing Treg function *in vivo* [71]. 100 μg/mouse anti-CD25 antibody (Cat# 16-0251-85, Clone# PC61.5, eBioscience, USA) or isotype IgG (Cat# 16-4301-85, Clone# eBRG1, eBioscience, USA) were dissolved with 150 μl sterile PBS and injected intravenously into the mice 21 days post OVA sensitization. A second shot of 50 μg /mouse antibodies was given on day 23 post OVA sensitization (Fig 7A). After depletion, the mice were randomly divided into two groups: OVA+INF+αCD25 and OVA+INF+IgG. OVA sensitization, aerosol challenge and schistosome infection were performed as described above.

RNA sequencing

Total RNA was extracted from lung tissues by using Trizol reagent (Cat# 15596026, Invitrogen). RNA purity was checked using the Nano Photometer spectrophotometer (IMPLEN, CA, USA). RNA integrity was assessed using the RNA Nano 6000 Assay Kit of the Bioanalyzer 2100 system (Agilent Technologies, CA, USA). 1 μg total RNA from each sample was used to construct the sequencing library using Poly(A) mRNA Capture Module (Cat# RK20340, Abclonal, USA) and Fast RNA-seq Lib Prep Module for Illumina (Cat# RK20304, Abclonal, USA). Index codes were added to attribute sequences of each sample. Then the libraries were sequenced on Illumina Novaseq platform (2 × 150 bp). Total 7 samples, 3 from OVA group and 4 from OVA+INF group, were sequenced in one lane, producing more than 30 million reads per library.

Differential expression genes (DEGs) analysis and functional enrichment analysis

Sequencing quality was evaluated by FastQC software (http://www.bioinformatics.babraham.ac.uk/projects/fastqc/). Poor quality reads and adaptors were trimmed by Trimmomatic software (Released Version 0.22, www.usadellab.org/cms/index/php?page = trimmomatic), and only reads longer than 50 bp were used for further analysis. The high-quality reads were mapped to mouse genome (mouse BALB/cJ) downloaded in Ensembl database. The HTseq [72] were used to quantify gene expression

and R DEseq2 package [73] were employed for differential expression analysis. Only genes with FDR adjusted *P*-value < 0.05 and absolute value of fold change > 2 were considered as DEGs. Functional enrichment of GO terms and KEGG analyses of DEGs were conducted by R cluster Profiler package [74] with FDR correction. Significantly enriched GO terms and KEGG pathways were identified with corrected *P* value < 0.05. DEGs related pathways enrichment terms were performed with the Panther Classification System (http://pantherdb.org/).

RNA sequencing data are deposited in the SRA database, SRA accession number: PRJNA609083.

Ethics Statement

All experiments and methods were performed in accordance with relevant guidelines and regulations. Mice experiments were carried out at National Institute of Parasitic Disease, Chinese Center for Disease Control and Prevention (NIPD, China CDC) in Shanghai, China. All animal experiment protocols used in this study were approved by the Laboratory Animal Welfare & Ethic Committee (LAWEC) of National Institute of Parasitic Diseases (Permit Number: IPD-2016-7).

Statistical analysis

All statistical analyses were performed using GraphPad Prism 8.0 (GraphPad Software, Inc., San Diego, CA, USA). The data of quantitative variables were presented as mean ± standard error of mean (SEM). *P* < 0.05 was considered

503 statistically significant.

504 Supporting information

505 **S1 Fig.** Comparisons of concentrations of IL-13, IL-10, IL-17A and IFN-γ in
506 BALF. FI indicated fluorescence intensity. Data were shown as Mean ± SEM. *,
507 $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.
508 (TIF)

509 **S2 Fig.** The influences of Lung-stage schistosome infection on OVA specific
510 IFN-γ and IL-4 response after OVA challenge.
511 (A) Gating strategy of flow cytometry. (B) Frequencies of OVA specific
512 CD3+CD4+IL-4+ T cells, CD3+CD4+IFN-γ+ T cells and their ratios in lung and
513 LDLN. Data were shown as Mean ± SEM, n = 8. *, $P < 0.05$; **, $P < 0.01$ and
514 NS, not significant.
515 (TIF)

516 **S3 Fig.** Panther pathway analysis of DEGs between lung-stage schistosome
517 infected mice and no-treatment control mice post OVA challenge.
518 (TIF)

519

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Conflict of interest

The authors declare that they have no relevant conflicts of interest.

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Figures and figure Legends

Fig. 1.

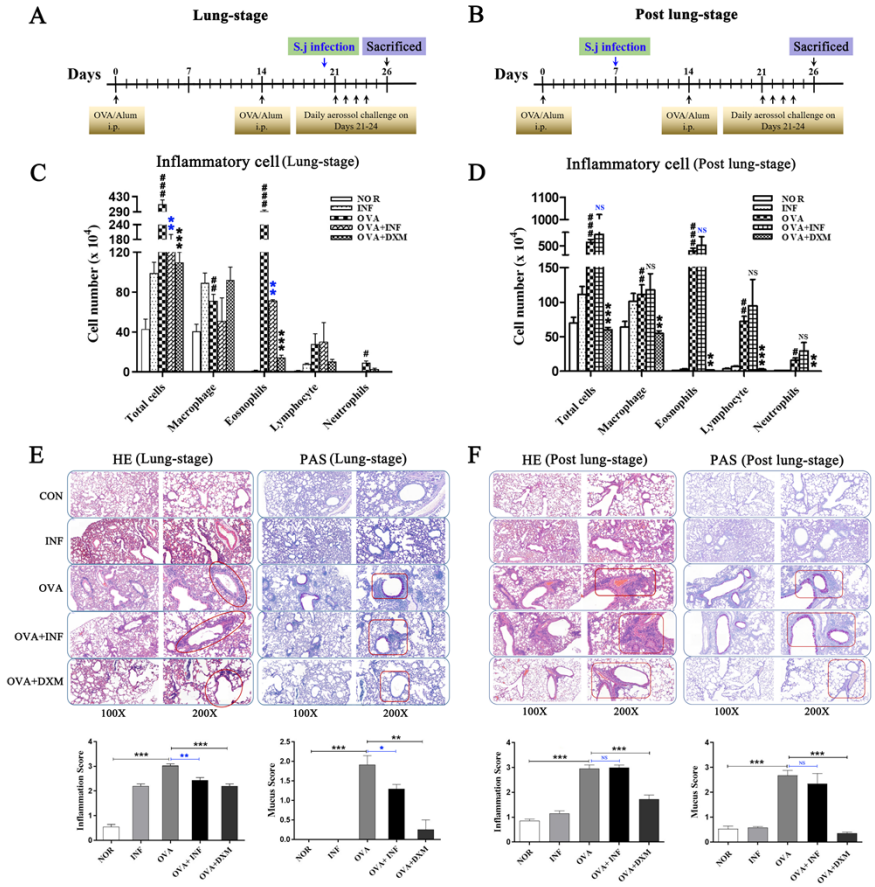

Fig. 1. Lung-stage schistosome infection alleviated the attack of OVA-induced AAI, whereas post lung-stage infection did not. Experimental design of OVA induced AAI treated with either lung-stage (**A**) or post lung-stage (**B**) schistosome infection. (**C & D**) Comparisons of inflammatory cell infiltration in BALF of mice after OVA challenge. (**E & F**) Representative images of H&E and PAS staining of lung tissue after OVA challenge. Statistical analysis of inflammation score and mucus secretion score were also shown in (**E**) and (**F**), respectively. NOR, normal mice (without OVA sensitization and challenge); INF, mice without OVA sensitization and challenge but infected with schistosome; OVA, mice with OVA sensitization and challenge but without schistosome infection; OVA + INF, mice sensitized and challenged with OVA and treated with schistosome infection; OVA + DXM, mice sensitized and challenged with OVA and treated with dexamethasone. Data were shown as mean ± SEM, n = 5. *, $P < 0.05$; **, $P < 0.01$; NS, not significant by the one-way analysis of variance (ANOVA) with Tukey test. #; ##; ### indicated $P < 0.05$; < 0.01; < 0.001, respectively, OVA versus NOR (C & D). *, **, *** indicated $P < 0.05$; < 0.01; < 0.001, respectively, OVA+INF or OVA+DXM versus OVA (C & D).

938 **Fig. 2.**
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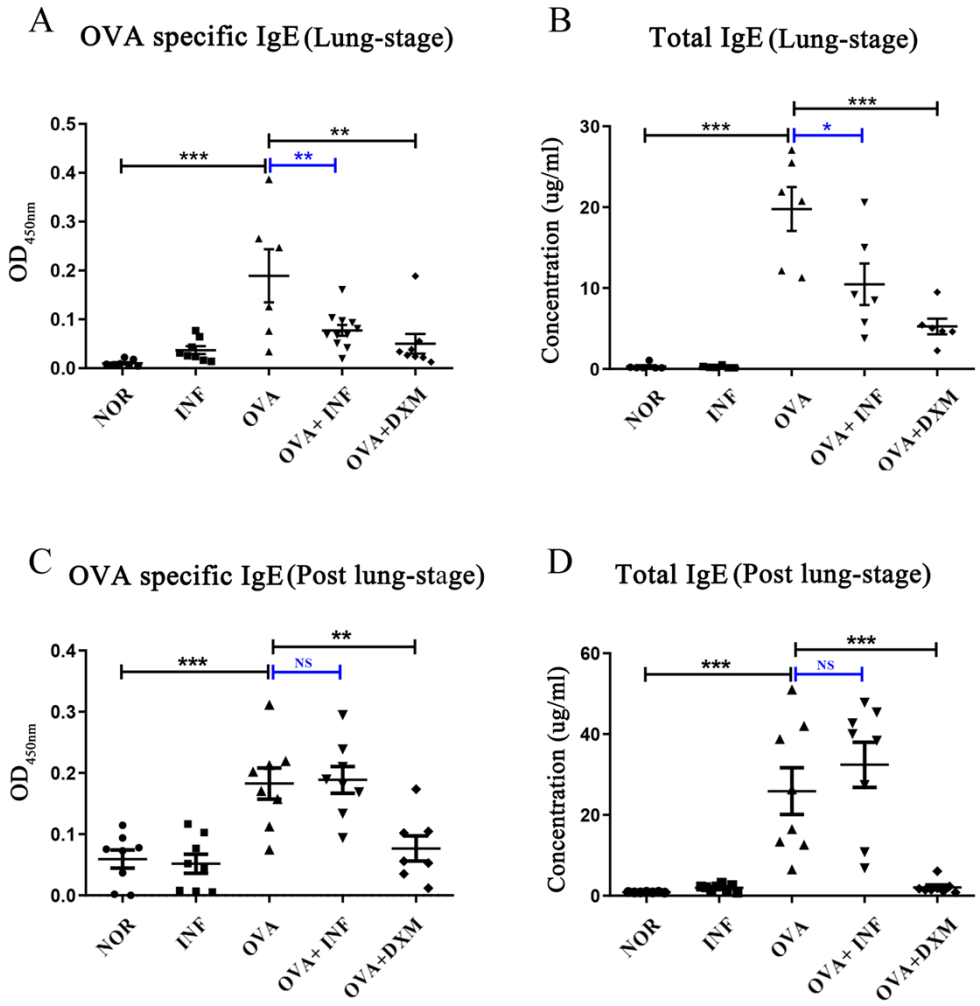

940 **Fig. 2. Lung-stage schistosome infection suppressed both the total and**
941 **OVA specific IgE after OVA challenge, whereas post lung-stage infection**
942 **did not.**
943 (**A & C**) OVA specific IgE in each group were measured by ELISA after
944 treatment with schistosome infection. (**B & D**) The concentration of total IgE in
945 mouse serum were compared among all groups after OVA challenge. Data
946 were shown as Mean ± SEM, n = 5. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; NS,
947 not significant.
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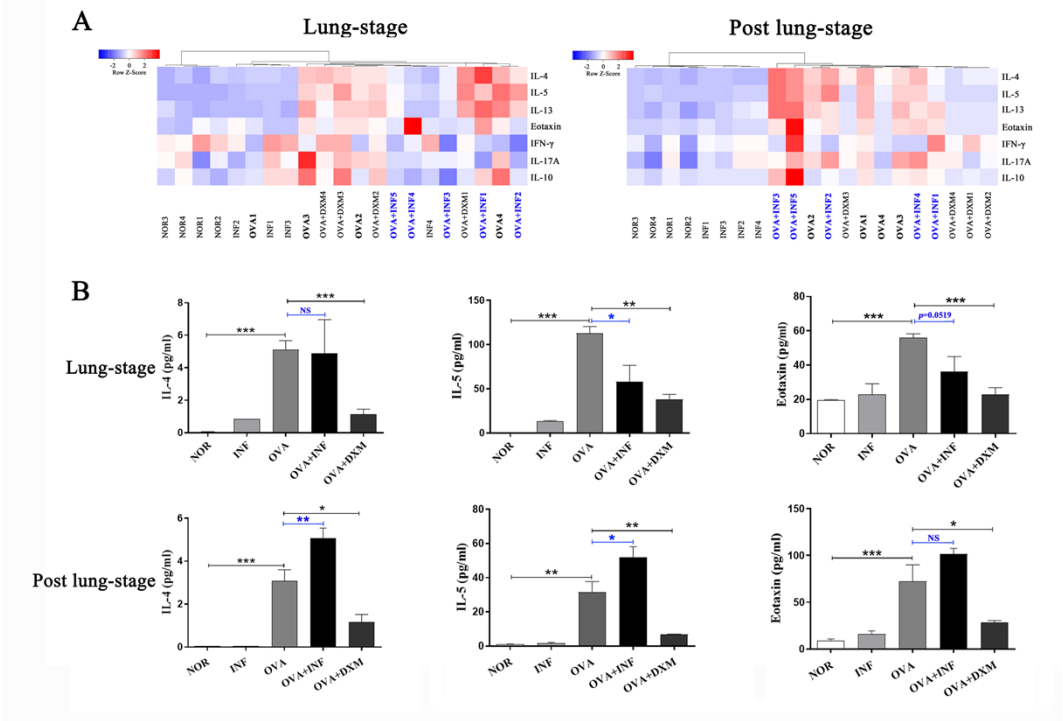
952 **Fig. 3.**



953
954 **Fig. 3. Lung-stage schistosome infection inhibited Th2 cytokine**
955 **secretion after OVA challenge, while post lung-stage infection did not.**
956 **(A)** Heatmaps of multiple cyto-/chemokines of mice treated with lung-stage
957 schistosome infection (left) and post lung-stage schistosome infection (right)
958 after OVA challenge. (**B**) Concentrations of IL-4, IL-5 and Eotaxin in BALFs
959 were compared among all groups. Data were shown as Mean ± SEM, n = 5. *,
960 $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; NS, not significant.
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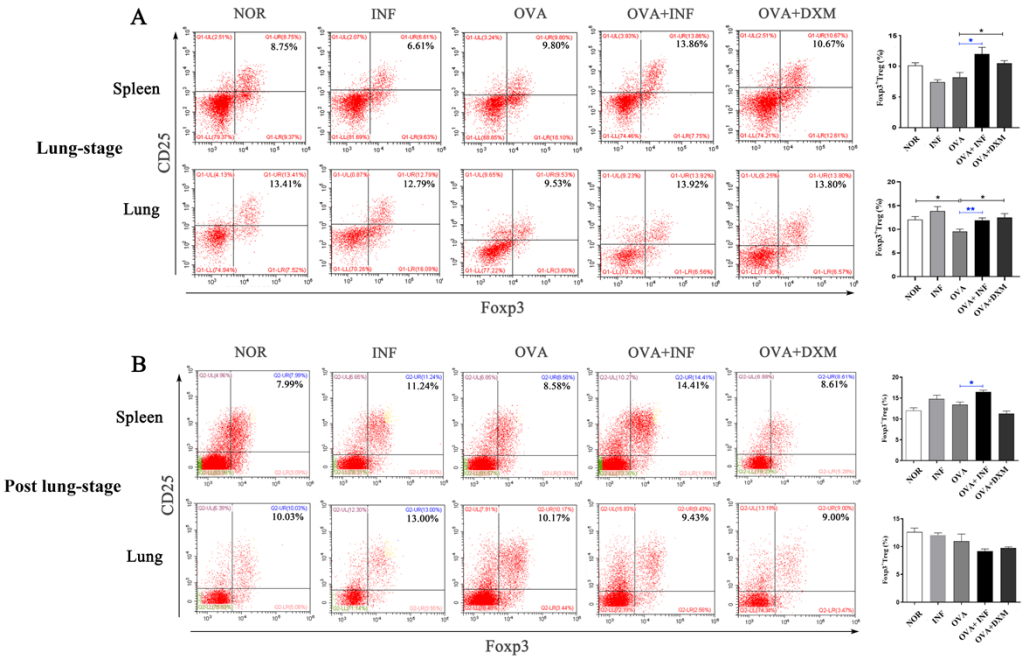
970 **Fig. 4.**



971
972 **Fig. 4. Lung-stage schistosome infection upregulated Treg frequency in**
973 **lung and spleen after OVA challenge.**
974 (**A & B**) Comparisons of Treg frequencies ($CD4^+CD25^+Foxp3^+$ Treg) in lungs
975 and spleens among all groups. Representative data of flow cytometry analysis
976 for each group were shown together with statistical comparisons. Data were
977 presented as Mean ± SEM, n = 5. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$.
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Fig. 5.

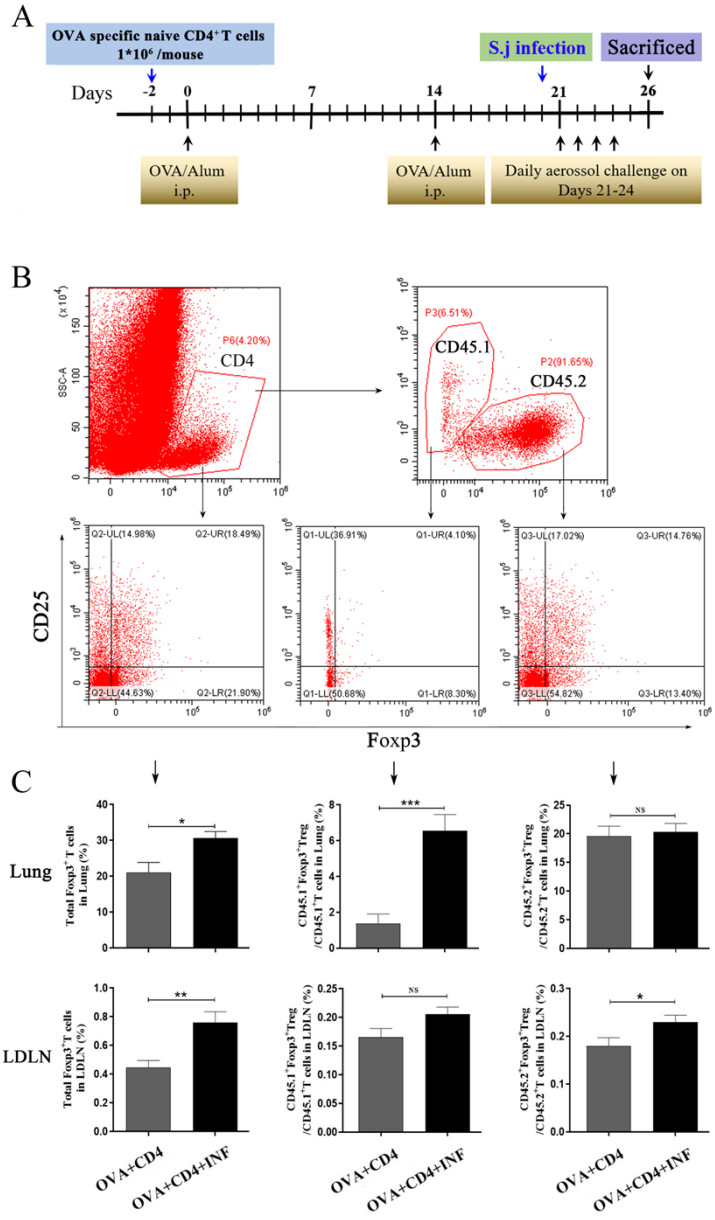
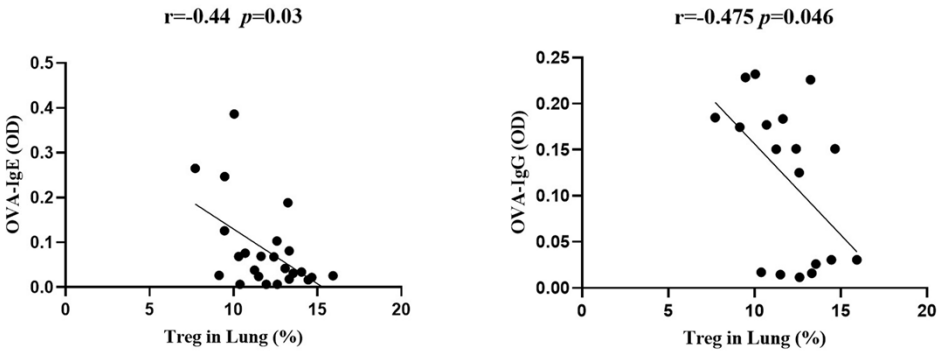


Fig. 5. Lung-stage schistosome infection upregulated OVA specific Treg after OVA challenge.

(A) Design of experiment for testing the therapeutic effect of lung-stage schistosome infection on OVA induced AAI after adoptive transfer of OVA specific naïve $CD4^+$ T cell. (**B & C**) Gate strategy and statistical comparisons of flow cytometry analysis for total Treg, $CD45.1^+$ Treg (OVA specific) and $CD45.2^+$ Treg in lung and lung draining lymph nodes (LDLN). Data were shown as Mean ± SEM, n = 8. *, $P < 0.05$; **, $P < 0.01$; ***, $P < 0.001$; NS, not significant.

1000 **Fig. 6.**



1001
1002 **Fig. 6. The frequency of Treg in lung negatively correlated with OVA**
1003 **specific IgE and IgG.** Correlation analysis between Treg frequency in lung
1004 and the OD values of OVA specific IgE (left) and IgG (right) in serum.
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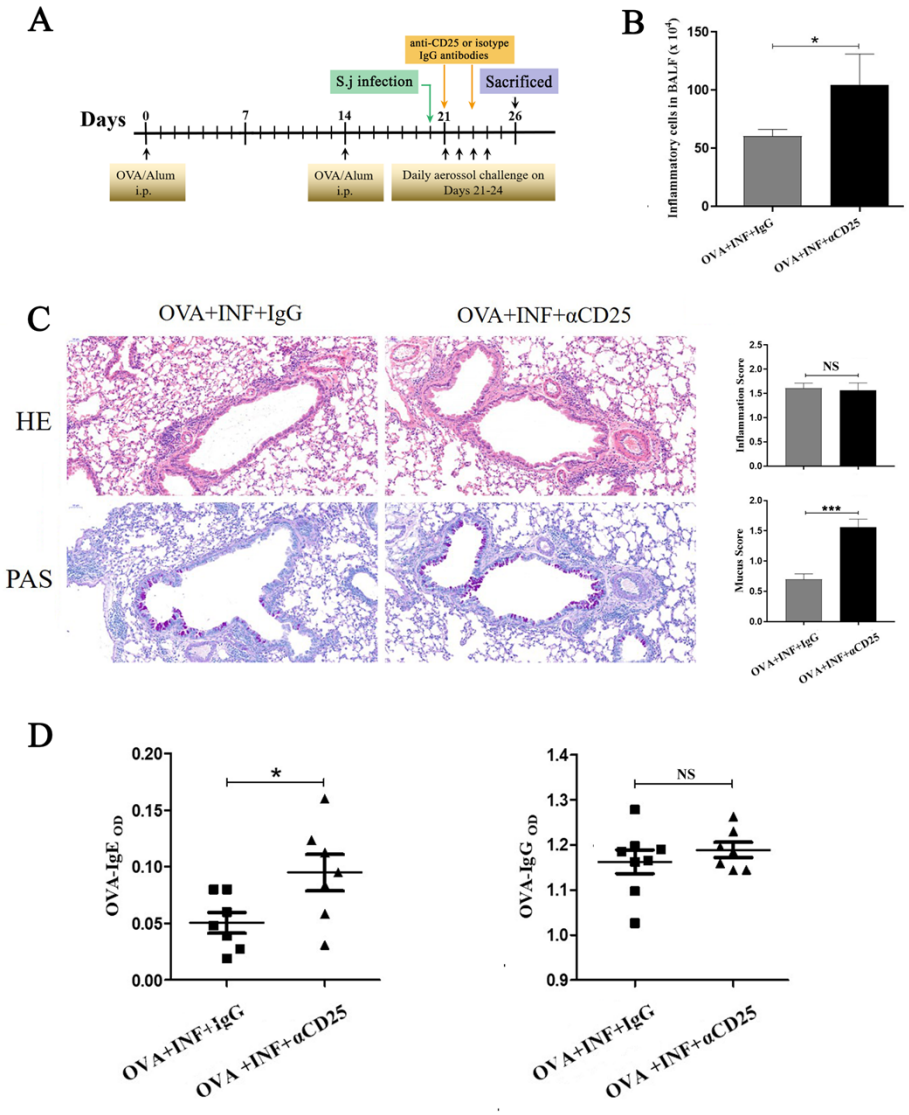
1019 **Fig. 7.**



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1021 **Fig. 7. *In vivo* depletion of Treg counteracted the therapeutic effect of**
1022 **lung-stage schistosome infection on OVA-induced AAI**.
1023 (**A**) Design of experiment for testing the role of Treg in the therapeutic effect
1024 mediated by lung-stage schistosome infection. (**B**) Comparisons of
1025 inflammatory cell counts in BALF between lung-stage schistosome infected
1026 mice treated with either anti-CD25 antibody or isotype control IgG. (**C**) Lung
1027 histopathology analysis of lung-stage schistosome infected mice treated with
1028 either anti-CD25 antibody or isotype control IgG. Upper, H&E staining; lower,
1029 PAS staining. (**D**) Comparisons of OVA specific IgE and IgG between Treg
1030 depleted and control mice. Data were shown as Mean ± SEM, n = 8. *, $P <$
1031 0.05; ***, $P < 0.001$.
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Fig. 8.

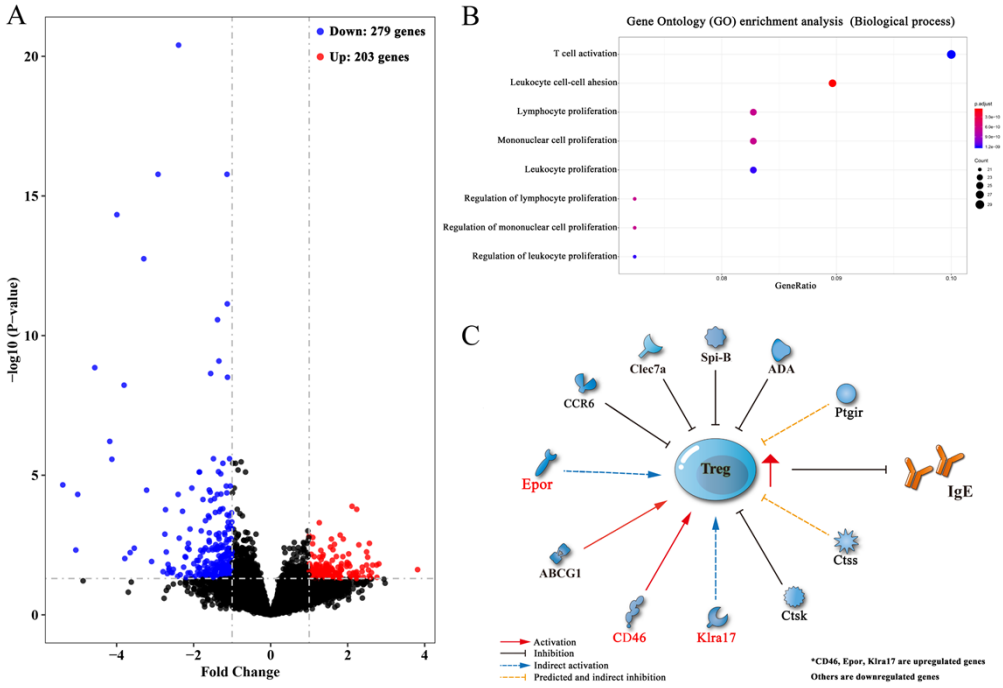

Fig. 8. Transcriptomic analysis of differentially expressed genes (DEGs) between lung tissues of OVA-induced asthmatic mice treated with and without lung-stage schistosome infection.
(**A**) Volcano plot of detected gene transcription profile in lung tissues of OVA-induced asthmatic mice treated with lung-stage schistosome infection compared with no-treatment control mice after OVA challenge. (**B**) The top 8 functional enrichment pathways of Gene ontology (GO) analysis for biological process in DEGs ($P < 0.05$). (**C**) Predicted gene network that might promote the generation of Treg in DEGs.

Tables and captions

Table 1. DEGs reported to promote or inhibit Treg response.

Classification	Name	Short name	GeneID	Log_2Foldchange	Adj *p*-value	Reference
Upregulate and promote Treg	CD46 antigen, complement regulatory protein	CD46	17221	1.52	0.015635106	31
	Erythropoietin receptor	EPOr	13857	1.26	0.000502759	32
	Killer cell lectin-like receptor, subfamily A, member 17	Klra17	170733	1.81	0.00139324	33
Downregulate and inhibit Treg	Chemokine (C-C motif) receptor 6	CCR6	12458	-1.82	0.004889779	34
	C-type lectin domain family 7, member a	Clec7a	56644	-1.27	0.016544002	35
	Spi-B transcription factor	Spi-B	272382	-1.03	0.008667091	36
	Adenosine deaminase	ADA	11486	-1.45	6.94E-05	37
	ATP binding cassette subfamily G member 1	ABCG1	11307	-1.11	0.024201953	38
	Cathepsin K	Ctsk	13038	-1.30	0.000166352	39
	Cathepsin S	Ctss	13040	-1.44	0.000215072	40
	Prostaglandin I receptor	Ptgir	19222	-1.05	0.007454223	41
Downregulate and promote Treg	Programmed cell death 1 ligand 2	Pdcd1lg2	58205	-1.85	0.020944852	75
	Interleukin 2 receptor, beta chain	IL-2Rβ	16185	-1.31	0.02093114	76
	CD 5 antigen	CD5	12507	-1.06	0.035912699	77
	CD52 antigen	CD 52	23833	-1.19	0.001160938	78
	C-type lectin domain family 4, member a2	DCIR	26888	-1.34	0.001202901	79
	Lipocalin 2	LCN2	16819	-1.57	4.03219E-05	80

Table 2. DEGs reported to facilitate B cell or plasma cell, lung development and cellular morphology.

Classification	Name	Short name	GeneID	Log_2Foldchange	Adj *p*-value	Reference
Related to inhibiting IgE production	Dedicator of cyto-kinesis	DOCK2	94176	-1.059783027	0.013672224	42
	Interferon regulatory factor 4	IRF4	16364	-1.399178091	0.020943206	43
	Rac family small GTPase 2	Rac2	19354	-1.073471112	0.019595199	44
	Lectin, galactose binding, soluble 3	Lgals3	16854	-1.240144306	3.75E-06	45
	Histocompatibility 2, O region alpha locus	H2-Oa	15001	-1.349647201	0.001621659	46
	Programmed cell death 1 ligand 2	Pdcd1lg2	58205	-1.8532719	0.020944852	47
	SAM and SH3 domain containing 3	Sash3	74131	-1.00163088	0.005576389	48
	Marginal zone B and B1 cell-specific protein 1	Mzb1	69816	-1.854756211	7.72E-06	49
Related to Lung development or development	Foxf1 adjacent non-coding developmental regulatory RNA	FOXF1	68790	1.028879446	0.042391573	NCBI
	Anoctamin 9	ANO9	71345	1.104812889	0.04292976	50
	Tripartite motif-containing 6	TRIM6	94088	1.104616713	0.043674764	51
	Matrix metallopeptidase 27	MMP 27	234911	2.088654169	0.041785907	52
	Erythropoietin receptor	Epor	13857	1.263048651	0.000502759	NCBI
	GATA binding protein 1	Gata 1	14460	1.821382745	0.04829584	NCBI
	Serine (or cysteine) peptidase inhibitor, clade A (alpha-1 antiproteinase, antitrypsin), member 7	Serpina7	331535	2.231550156	0.028961618	NCBI
Related to cell morphology or membrane integrity	Villin	Villin	22349	1.077160094	0.026732286	53
	Crumbs family member 1, photoreceptor morphogenesis associated	CRB1	170788	2.51928641	0.008667091	54

Data file S1. DEGs between OVA and OVA+INF groups and their classifications. (See supplementary materials)