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Immature lung TNFR2⁻ conventional DC 2 subpopulation activates moDCs to promote cyclic di-GMP mucosal adjuvant responses in vivoSamira Mansouri^{1,2}, Seema Patel², Divya S. Katikaneni², Steven M. Blaauboer¹, Wei Wang², Stefan Schattgen^{3,4}, Katherine Fitzgerald³ and Lei Jin²

Cyclic dinucleotides (CDNs), including cyclic di-GMP (CDG), are promising vaccine adjuvants in preclinical/clinical trials. The in vivo mechanisms of CDNs are not clear. Here we investigated the roles of lung DC subsets in promoting CDG mucosal adjuvant responses in vivo. Using genetically modified mice and adoptive cell transfer, we identified lung conventional DC 2 (cDC2) as the central player in CDG mucosal responses. We further identified two functionally distinct lung cDC2 subpopulations: TNFR2⁺pRelB⁺ and TNFR2⁻pRelB⁻ cDC2. The TNFR2⁺ cDC2 were mature and migratory upon intranasal CDG administration while the TNFR2⁻ cDC2 were activated but not mature. Adoptive cell transfer showed that TNFR2⁻ cDC2 mediate the antibody responses of CDG, while the TNFR2⁺ cDC2 generate Th1/17 responses. Mechanistically, immature TNFR2⁻ cDC2 activate monocyte-derived DCs (moDCs), which do not take up intranasally administered CDG. moDCs promote CDG-induced generation of T follicular helper- and germinal center B cells in the lungs. Our data revealed a previously undescribed in vivo mode of DCs action, whereby an immature lung TNFR2⁻ cDC2 subpopulation directs the non-migratory moDCs to generate CDG mucosal responses in the lung.

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INTRODUCTION

Adjuvants improve vaccine safety profiles and enhance, and shape, antigen-specific immune responses. Understanding the mode of action of adjuvants is key for the development of rationally designed modern vaccines. Recently, the small-molecule cyclic dinucleotides (CDNs) have emerged as a group of promising vaccine adjuvants in preclinical and clinical trials.¹ CDNs include the bacterial second messengers cyclic di-GMP (CDG), cyclic di-AMP, 3′/3′-cyclic GMP-AMP, and the mammalian second messenger 2′/3′-cyclic GMP-AMP.¹ CDG is the founding member and the most studied CDNs.² As a mucosal adjuvant, CDG does not cause acute toxicity in mice.¹ Furthermore, CDG is a more potent activator of Th1 and Th2 immune response than LPS, CpG oligonucleotides (ODN), or aluminum salt-based adjuvant in mice.³ Last, CDG-adjuvanted vaccines protect mice from H5N1 influenza,⁴ *Acinetobacter baumannii*,⁵ *Staphylococcus aureus*,⁶ *Klebsiella pneumoniae*,⁷ and *Streptococcus pneumoniae*.^{8,9} CDG also showed cancer vaccine adjuvant activity in animal models.^{10,11}

MPYS, also known as STING and MITA, is a receptor for CDNs¹² and a critical player in sensing cytosolic DNA.^{13,14} MPYS^{-/-} mice lose CDNs adjuvant activity.¹⁵ Additionally, tumor necrosis factor (TNF) signaling, not type I interferon (IFN) signaling, is essential for the adjuvant activity of CDG in vivo.^{15,16} Notably, when administered intranasally, CDG not only induced lung production of TNF,

interleukin-1β (IL-1β) but also the anti-inflammatory cytokine IL-10.¹⁷ Consequently, CDG adjuvant does not induce exaggerated inflammation responses in the lung.¹⁷ The precise in vivo mechanism by which TNF mediates CDG adjuvant activity in vivo is unknown.

DCs orchestrate vaccine adjuvant responses.¹⁸ They consist of developmentally and functionally distinct subsets that promote either immunogenic or tolerogenic immune responses.^{19–22} Murine lung DCs consist of three subsets: the CD103⁺ conventional DC (cDC1), the CD11b⁺CD24⁺CD64⁻ conventional DC (cDC2), and monocyte-derived CD11b⁺CD24⁻CD64⁺ DC (moDCs).²¹ Using MPYS^{fl/fl}CD11c^{Cre} mice, we previously showed that CDG adjuvant activity depends on MPYS expression in DCs.¹⁷ The lung DC subset mediating CDG adjuvant activity is unknown.

In this report, we revealed important heterogeneity in the lung cDC2 population and identified the cDC2 subpopulation that is responsible for CDG adjuvant effect. Surprisingly, the antibody responses of CDG adjuvant depends on an activated but immature TNFR2⁻ cDC2 subpopulation, which drive moDCs maturation to generate T follicular helper (Tfh) cells in the lung.

RESULTS

CDG directly targets lung cDC1 and cDC2 DCs mediate CDG adjuvant activity in vivo.¹⁷ There are three lung DC subsets: cDC1 (CD103⁺ CD24⁺ CD64⁻CD11b⁻), cDC2

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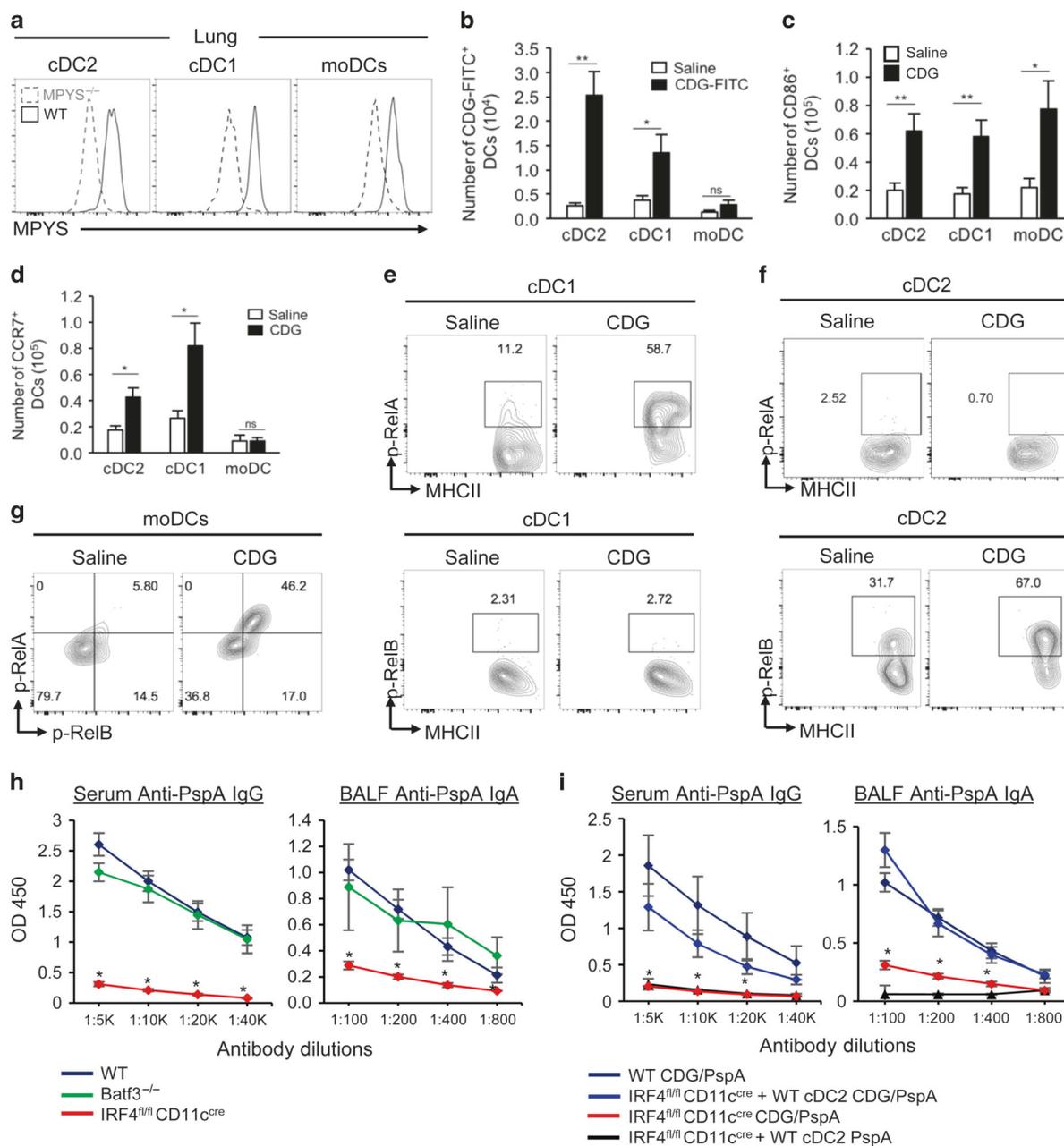


Fig. 1 cDC2 play a central role in mediating the adjuvant activity of CDG. **a** Flow cytometry analysis of MPYS expression in lung DC subsets. $n > 3$. **b** Absolute number of lung DC subsets in C57BL/6 mice administered (i.n.) with saline or 5 μ g FITC-CDG for 5 h. $n = 3$. **c** Absolute number of CD86⁺ lung DC in mice administered (i.n.) with saline or 5 μ g CDG for 16 h. $n > 3$. **d** Absolute number of CCR7⁺ lung DC in mice administered (i.n.) with saline or 5 μ g CDG for 16 h. $n > 3$. **e–g** Flow cytometry analysis of pRelA and pRelB in cDC1 (**e**), cDC2 (**f**), and moDCs (**g**) from mice treated with saline or CDG for 16 h. $n > 3$. **h** C57BL/6, *Batf3*^{-/-}, and *IRF4*^{fl/fl}CD11c^{cre} mice were immunized (i.n.) with two doses (14 days apart) of PspA or PspA plus CDG (5 μ g). Anti-PspA IgG in serum and IgA in BALF were determined by ELISA. $n > 3$. **i** *IRF4*^{fl/fl}CD11c^{cre} mice were adoptively transferred (i.n.) with lung cDC2 sorted from WT mice lung and immunized (i.n.) with PspA or CDG/PspA. Serum anti-PspA IgG and BALF IgA were determined by ELISA. $n = 3$. Graphs represent means \pm standard error from three independent experiments. The significance is represented by an asterisk (*) where $p < 0.05$ (unpaired Student's *t*-test)

(CD103⁻CD24⁺CD64⁻CD11b⁺), and moDCs (CD103⁻CD24⁻CD64⁺CD11b⁺)^{21,23–27} (Fig. S1). All DC subsets express the CDG receptor MPYS, which is an ER-resident protein (Fig. 1a). CDG has two phosphate groups preventing it from directly passing through the cell membrane. To determine which lung DC subset took up CDG, mice were intranasally administered with FITC-conjugated CDG and FITC⁺ lung cells were examined after 5 h. Among lung DCs, cDC1 and cDC2 had the highest percentage of CDG-FITC whereas moDCs had no CDG-FITC (Fig. 1b).

Alveolar macrophages take up CDG but are dispensable for CDG adjuvant activity

Alveolar macrophages (AM) (CD11c⁺MHC II^{int}) took up most of the fluorescent CDG in vivo (Fig. S2A). Unlike DCs, AM did not increase expression of CD86 following CDG treatment (Fig. S2B). To determine whether AM are required for CDG responses in vivo, we used the *MPYS*^{fl/fl}*LysM*^{cre} mice,¹⁷ which deleted MPYS expression in AM (Fig. S2C). The activation of lung DCs by CDG was unaltered in the *MPYS*^{fl/fl}*LysM*^{cre} mice (Fig. S2D). Importantly,

MPYS^{fl/fl}LysM^{cre} mice produced similar anti-pneumococcal surface protein A (PspA) antibody as the WT upon CDG/PspA immunization (Fig. S2E).

CDG differentially activates lung DC subsets in vivo

DCs subsets are functionally distinct. CDG increased CD86 and CCR7 expression in lung cDC1 and cDC2 (Fig. 1c, d).¹⁷ In addition, both cDCs migrate, bearing processed antigen, to the lung draining lymph nodes (dLNs) (Fig. S3A, B). However, we found that following intranasal CDG administration, cDC1 activated RelA (Fig. 1e) while cDC2 activated RelB (Fig. 1f). Notably, some cDC2 have constitutively activated RelB (Fig. 1f). To further demonstrate that CDG differentially activates lung DC subsets, we used the IRF4^{fl/fl}CD11c^{cre} and Batf3^{-/-} mice.

The development of cDC1 and cDC2 are controlled by transcriptional factors Batf3 and IRF4, respectively. IRF4^{fl/fl}CD11c^{cre} mice lack cDC2 in the lung (Fig. S1C)²⁸⁻³⁰ while Batf3^{-/-} mice lack cDC1 (Fig. S1D).^{31,32} We found that CDG-induced lung production of TNF, IL-1 β , and IL-12p70 were dramatically reduced in IRF4^{fl/fl}CD11c^{cre} mice but not in the Batf3^{-/-} mice (Fig. S3C). Conversely, CDG-induced MCP-1 production was largely absent in the Batf3^{-/-} mice but not in the IRF4^{fl/fl}CD11c^{cre} mice (Fig. S3C).

CDG indirectly activates moDCs

Although moDCs did not take up CDG, they increased expression of CD86 in response to intranasal administration of CDG (Fig. 1c). This was independent of MPYS expression in moDCs as moDCs in MPYS^{fl/fl}LysM^{cre} mice had normal levels of CD86 expression (Fig. S2D). Notably, activated moDCs did not increase CCR7 (Fig. 1d) and did not migrate to dLNs (Fig. S3B). Last, moDCs activated both RelA and RelB in response to CDG (Fig. 1g). We concluded that CDG indirectly activate moDCs and activated lung moDCs were not migratory.^{25,33}

cDC2 play a central role in mediating CDG adjuvant activity

We next asked which cDC subset mediates CDG adjuvant activity. IRF4^{fl/fl}CD11c^{cre} mice lack cDC2 in the lung^{28,29} (Fig. S1C). The cDC1 and moDCs were retained in the IRF4^{fl/fl}CD11c^{cre} mice (Fig. S1C). We examined CDG adjuvant activity in the IRF4^{fl/fl}CD11c^{cre} mice. Mice were intranasally administered with PspA alone or with CDG. PspA-specific Ab responses were examined in the blood and bronchoalveolar lavage fluid (BALF). Unlike the WT mice, CDG did not induce anti-PspA Abs in BALF and serum (Fig. 1h; S3D, E) from immunized IRF4^{fl/fl}CD11c^{cre} mice. Ex vivo recall assay in lung cells and splenocytes from immunized IRF4^{fl/fl}CD11c^{cre} mice also did not show PspA-specific Th1, Th2, or Th17 responses (Fig. S3F, G).

To further demonstrate that lung cDC2 mediate the adjuvant activity of CDG, we adoptively transfer (i.n.) WT lung cDC2 into IRF4^{fl/fl}CD11c^{cre} mice. The recipient IRF4^{fl/fl}CD11c^{cre} mice were then immunized with CDG/PspA. We found that adoptive transfer of WT cDC2 generated PspA-specific serum IgG and IgA in the IRF4^{fl/fl}CD11c^{cre} mice similar to the WT mice (Fig. 1i). We concluded that lung cDC2 are critical for CDG adjuvant activity.

In contrast to the IRF4^{fl/fl}CD11c^{cre} mice, Batf3^{-/-} mice mounted antigen-specific IgG and IgA responses in a manner comparable to the WT following CDG/PspA immunization (Fig. 1h; S3D, E). We concluded that cDC2 play a central role in mediating CDG adjuvant activity. Batf3^{-/-} mice had impaired Th1 responses following immunization (Fig S3F, G). Whether the defect is due to the lack of cDC1 remains to be determined since T cells also express Batf3.

TNFR2 is essential for CDG adjuvant activity

TNF signaling is critical for CDG adjuvant activity in vivo.^{15,16} TNF signals through two TNFR1 and TNFR2. TNFR1 binds transmembrane TNF (mTNF) and soluble TNF (sTNF) while TNFR2 only binds to mTNF.³⁴⁻³⁷ The lung DC compartment is not altered by the lack of either TNFR1 or TNFR2 (Fig. S4A, B). Consistent with the

previous report, we found that CDG induced reduced humoral and cellular immune responses in TNFR1^{-/-} mice (Fig. 2a; S4C-F). Surprisingly, CDG completely lost its adjuvant activity in TNFR2^{-/-} mice (Fig. 2a; S4C-F).

TNFR2 expression on lung cDC2 is required for its maturation cDC2 are critical for CDG adjuvant activity (Fig. 1). We next examined lung cDC2 maturation in the TNFR2^{-/-} mice. We found that CDG did not enhance CD86 or CCR7 expression in lung cDC2 of TNFR2^{-/-} mice in vivo (Fig. 2b; S5A). In comparison, CDG mediated CD86 and CCR7 expression on cDC1 of TNFR2^{-/-} mice in vivo (Fig S5A, B). Furthermore, blocking TNFR2 by mAb inhibited CDG-mediated CD86 expression on cDC2 in vivo (Fig. S5C). Last, adoptively transferred TNFR2-deficient cDC2 into IRF4^{fl/fl}CD11c^{cre} recipient mice failed to upregulate CD86 expression in response to intranasal CDG administration (Fig. 2c).

TNFR2⁺ lung cDC2 has constitutively activated RelB

We next examine TNFR2 expression on lung cDC2. We found that a population of lung cDC2 constitutively express TNFR2 (Fig. 2d). In contrast, TNFR2 expression was not detected on steady-state lung cDC1 though CDG dramatically increased TNFR2 expression (Fig. S5D). Steady-state lung cDC2 have a pRelB⁺ population (Fig. 1f). Interestingly, all the pRelB⁺ cDC2 are TNFR2⁺ (Fig. 2e, left panel). CDG further activate RelB in lung cDC2 upon CDG treatment (Fig. 1f). We found that all pRelB⁺ cells in activated cDC2 expressed TNFR2 (Fig. 2e, right panel) and all the TNFR2⁺ cDC2 are pRelB⁺ (Fig. 2f). Last, cDC2 in TNFR2^{-/-} mice lack pRelB, indicating that RelB activation requires TNFR2 signaling (Fig. 2g). Thus, TNFR2⁺ and pRelB⁺ lung cDC2 are the same population.

RelB in DCs is required for CDG-induced cDC2 maturation in vivo TNFR2 on lung cDC2 is required CDG-induced cDC2 maturation in vivo (Fig. 2c). We reasoned that RelB was required for CDG-induced cDC2 maturation too. We used RelB^{fl/fl}CD11c^{cre} mice to ablate RelB in DCs. RelB^{fl/fl}CD11c^{cre} mice have normal DC populations, with all subsets intact (Fig. S5E). In the absence of RelB in DCs, cDC2 failed to upregulate CD86 in response to CDG (Fig. 2h). cDC1, which do not activate RelB, upregulated CD86 (Fig. S5F). We concluded that CDG-induced lung cDC2 maturation depends on the cell-intrinsic signal of TNFR2-RelB.

TNFR2⁺ cDC2 are required for CDG-induced Th1 and Th17 responses but dispensable for the humoral responses

We next sought to determine if TNFR2 expression on cDC2 was needed for the adjuvant activity of CDG. Unexpectedly, even though adoptively transferred TNFR2-deficient cDC2 failed to upregulate CD86 in response to CDG (Fig. 2c), they induced serum anti-PspA IgG and IgA when transferred into IRF4^{fl/fl}CD11c^{cre} mice (Fig. 3a). In fact, the anti-PspA IgG and IgA in IRF4^{fl/fl}CD11c^{cre} mice receiving TNFR2-deficient cDC2 and WT cDC2 were comparable (Fig. 3a).

We then examined CDG adjuvant activity in the RelB^{fl/fl}CD11c^{cre} mice, which also lack mature cDC2. Upon immunization with PspA and CDG, RelB^{fl/fl}CD11c^{cre} mice produced normal levels of IgG and IgA (Fig. 3b). RelB^{fl/fl}CD11c^{cre} mice failed to induce Th1 and Th17 responses in the lung (Fig. 3c).

TNFR2 defines two functionally distinct subpopulations of lung cDC2

cDC2 is a heterogeneous population.^{21,32,38,39} We showed that lung TNFR2⁺pRelB⁺ cDC2 were mature and required for the Th1/Th17 responses but not humoral responses while the TNFR2⁻ cDC2 was not mature but mediates CDG-induced antibody response. We assessed whether TNFR2 expression could define functionally distinct lung cDC2 subpopulations.

Both cDC2 populations took up CDG in vivo (Fig. 4a). When adoptively transferred into MPYS^{-/-} mice, both produced lung



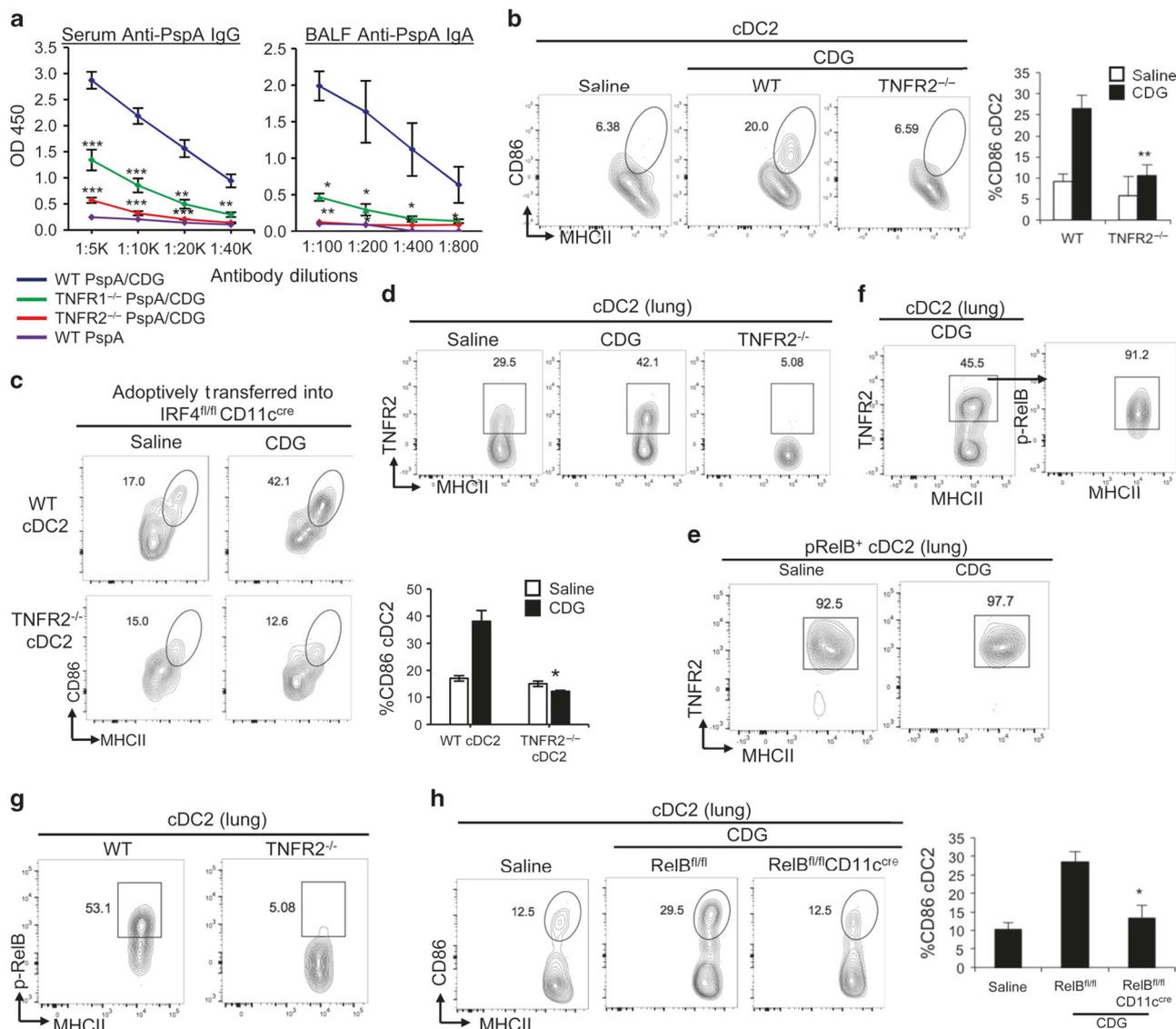


Fig. 2 cDC2 expression of TNFR2 is required for CDG-induced lung cDC2 maturation in vivo by activating RelB. **a** C57BL/6 (WT), TNFR1^{-/-}, and TNFR2^{-/-} mice were immunized (i.n.) with two doses of PspA or PspA plus CDG (5 μg). Serum anti-PspA IgG and BALF IgA were determined by ELISA. *n* = 3. **b** WT and TNFR2^{-/-} mice were treated (i.n.) with saline or CDG (5 μg) for 16 h. CD86 expression in lung cDC2 was determined by Flow cytometry. *n* = 3. **c** IRF4^{fl/fl}CD11c^{cre} mice were adoptively transferred (i.n.) with lung cDC2 sorted from WT or TNFR2^{-/-} mice lung. The recipient mice were administered (i.n.) with saline or CDG (5 μg) for 16 h. CD86 expression in lung cDC2 was determined by Flow cytometry. *n* = 3. **d** Flow cytometry analysis of TNFR2 expression on lung cDC2 in WT mice administered (i.n.) with saline or CDG for 16 h. *n* > 3. **e** Flow cytometry analysis of TNFR2 expression on pRelB⁺ cDC2 from mice treated with saline or CDG. *n* = 3. **f** Flow cytometry analysis of pRelB expression on TNFR2⁺ cDC2 from mice treated with CDG. *n* = 3. **g** Flow cytometry analysis of pRelB expression on cDC2 from WT and TNFR2^{-/-} mice. *n* = 3. **h** Flow cytometry analysis of CD86 expression on lung cDC2 in RelB^{fl/fl} and RelB^{fl/fl}CD11c^{cre} mice treated with CDG. *n* = 3. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

TNF (Fig. 4b). MPYS^{-/-} mice themselves do not respond to CDG.¹⁵ Consistently, adoptively transferred TNFR2⁺ cDC2 upregulated CD86 and CCR7 in response to CDG whereas TNFR2⁻ cDC2 failed to do so (Fig. 4c). Importantly, adoptive transfer of TNFR2⁺ cDC2 into MPYS^{-/-} (Fig. 4d; S6A, B) and IRF4^{fl/fl}CD11c^{cre} mice (Fig. 4e) failed to rescue antibody production. Consistent with the RelB^{fl/fl}CD11c^{cre} results (Fig. 3), TNFR2⁺ cDC2 were able to rescue Th1/Th17 responses in the IRF4^{fl/fl}CD11c^{cre} mice (Fig. 4f). TNFR2⁺ cDC2 also rescued Th2 response, in contrast to RelB^{fl/fl}CD11c^{cre} mice (Figs. 4f, 3c). We speculate that the ability of TNFR2⁺ cDC2 to mediate CDG-induced Th2 responses maybe redundant in vivo.

In contrast, adoptive transfer of TNFR2⁻ cDC2 completely restored antibody, but not Th, responses in MPYS^{-/-} (Fig. 4d; S6A,

B) and IRF4^{fl/fl}CD11c^{cre} mice (Fig. 4e, f). In fact, levels of anti-PspA IgG and IgA in IRF4^{fl/fl}CD11c^{cre} mice receiving TNFR2⁻ cDC2 were similar to the WT (Fig. 4e). We concluded that lung cDC2 can be divided into two functionally distinct subpopulations: TNFR2⁺ cDC2 and TNFR2⁻ cDC2. The TNFR2⁺ cDC2 are important for CDG-induced cellular immunity, while TNFR2⁻ cDC2 are responsible for CDG-induced humoral responses (Fig. 4g).

TNFR2⁺ and TNFR2⁻ lung cDC2 are derived from pre-cDC2 We further characterized these steady-state lung cDC2 populations. We found that the TNFR2⁺ cDC2 are positive for BTLA, PDL-1, arginase 1 (Arg1). The TNFR2⁺ cDC2 also have mixed expression of PD-L2 and CD301b (Fig. 5a). The lung TNFR2⁻ cDC2 expressed

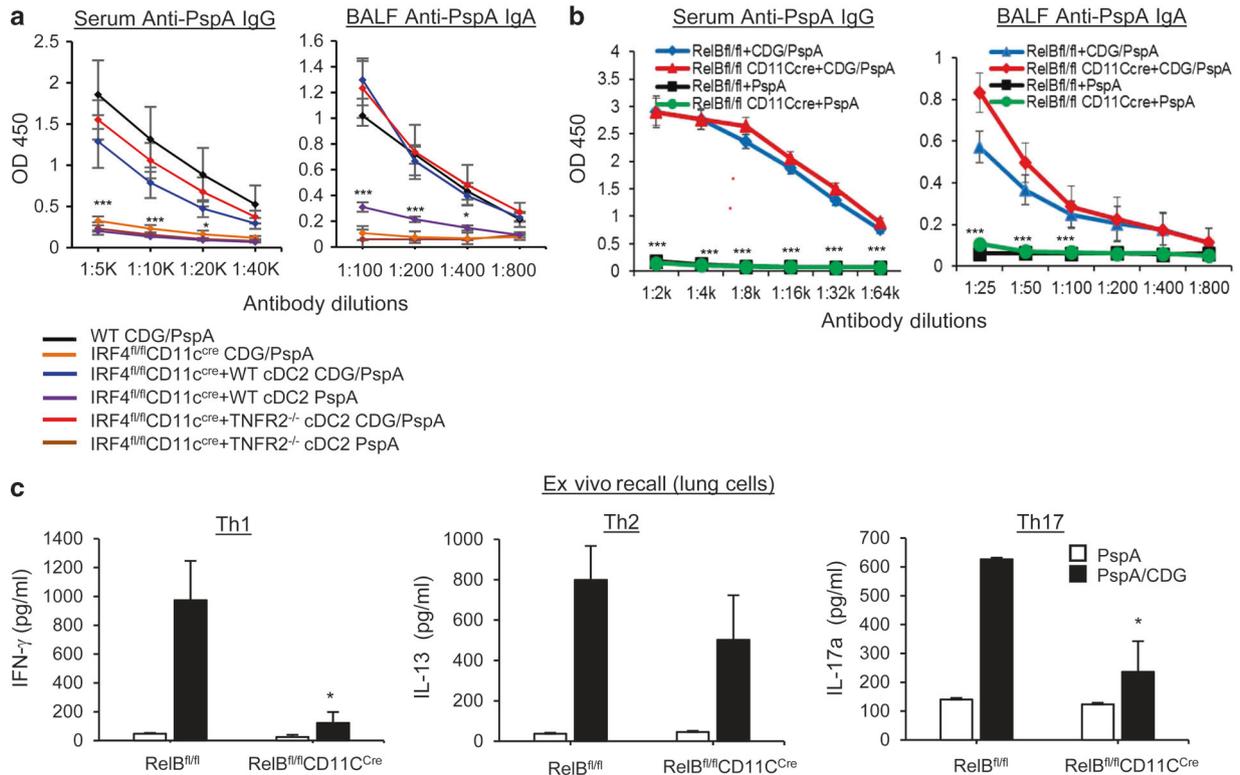


Fig. 3 cDC2 expression of TNFR2 and RelB is required for Th1 and Th17 responses, but dispensable for CDG-induced antibody response. **a** IRF4^{fl/fl}CD11c^{cre} mice were adoptively transferred (i.n.) with lung cDC2 sorted from WT or TNFR2^{-/-} mice lung and immunized (i.n.) with PspA or CDG/PspA. Serum anti-PspA IgG and BALF anti-PspA IgA were determined by ELISA. *n* = 3. **b** RelB^{fl/fl} and RelB^{fl/fl}CD11c^{cre} mice were immunized (i.n.) with CDG/PspA or PspA alone as before. Serum anti-PspA IgG and BALF anti-PspA IgA were determined by ELISA. *n* = 3. **c** Lung cells from immunized RelB^{fl/fl} and RelB^{fl/fl}CD11c^{cre} mice were stimulated with 5 μ g/ml PspA for 4 days in culture. Cytokines were measured in the supernatant by ELISA. *n* > 3. Graphs represent means \pm standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

CX3CR1 (Fig. 5a). Both populations express common cDC2 markers as SIRP α , CD26, IRF4, and Zbtb46 (Fig. 5a, b; S7A).^{40,41} Furthermore, both subpopulations of cDC2 were absent in Flt3^{-/-} mice (Fig. S7B–D). Last, TNFR2⁺ and TNFR2⁻ cDC2 are negative for cDC1 markers IRF8, XCR1 and not affected in Batf3^{-/-} mice confirming their identity as cDC2 (Fig. 5b; S7C, D).

To further establish that the lung TNFR2⁺ and TNFR2⁻ cDC2 subpopulations are cDC2, we adoptively transferred CD45.1 pre-cDC2 (refs. 40,42) into IRF4^{fl/fl}CD11c^{cre} mice (Fig. S8A–C).

CD45.1⁺ cells were identified in lung 5 days after transfer and displayed a cDC2 phenotype (Fig. 5d; S8C). Importantly, the CD45.1⁺ pre-cDC2 generated both TNFR2⁺ and TNFR2⁻ lung cDC2 in the recipient mice (Fig. 5d). The CD45.1⁺ TNFR2⁺ cDC2 expressed BTLA and PD-L1 and had mixed expression of PD-L2 and CD301b (Fig. 5e), similar to the resident TNFR2⁺ cDC2. The CD45.1⁺ TNFR2⁻ cDC2 only expressed CX3CR1 (Fig. 5e). We concluded that the lung TNFR2⁺ and TNFR2⁻ cDC2 arise from the cDC2 lineage and express distinct surface markers.

TNFR2⁺ and TNFR2⁻ lung cDC2 do not represent different activation states

We next asked if the TNFR2⁺ and TNFR2⁻ cDC2 populations represent different activation states of cDC2. We adoptively transferred CD45.1 lung TNFR2⁺ and TNFR2⁻ cDC2 into MPYS^{-/-} mice (Fig. S8D). The recipient mice were then activated by CDG (i.n.). Consistent with our previous observation (Figs. 3, 4), TNFR2⁻ cDC2 did not upregulate TNFR2 while TNFR2⁺ cDC2 maintained their expression of TNFR2 (Fig. 5f). CDG treatment did not affect PD-L1 expression either (Fig. 5f). Collectively, we concluded that lung cDC2 consist of two functionally and developmentally distinct subpopulations, TNFR2⁺ and TNFR2⁻ cDC2.

CDG activates TNFR2-deficient cDC2 in vivo to produce TNF

Question remains how the immature TNFR2⁻ cDC2 mediates CDG-induced antibody responses in vivo. We suspected that the TNFR2⁻ cDC2, though not mature, might still be activated by CDG in vivo. CDG induces TNF production in vivo that is essential for its adjuvant activity.^{15–17} CDG-induced TNF production in vivo mainly depending on MPYS expression in CD11c⁺ cells (Fig. 6a),¹⁷ specifically cDC2 as IRF4^{fl/fl}CD11c^{cre} mice had dramatically decreased lung TNF (Fig. S3C). We found that CDG induced lung TNF in TNFR2^{-/-} mice (Fig. 6b). Furthermore, cDC2 produced TNF in TNFR2^{-/-} mice (Fig. 6c). Deleting TBK1 in hematopoietic and endothelial lineages (TBK1^{fl/fl}Vav^{Cre}) dramatically reduced CDG-induced lung TNF production (Fig. 6d), suggesting TBK1 is needed for TNF production by CDG. Indeed, TBK1 was activated in the TNFR2^{-/-} cDC2 (Fig. 6e). Last, adoptive transferred TNFR2⁻ cDC2 produced lung TNF in MPYS^{-/-} lung (Fig. 4b). We concluded that although TNFR2⁻ cDC2 fail to mature, they were activated by CDG in vivo.

Adoptive transfer of WT monocyte restored CDG adjuvant activity in TNFR2^{-/-} mice

We next investigated how the activated, but immature, TNFR2⁻ cDC2 mediate CDG-induced antibody responses. First, we found that moDCs failed to upregulate CD86 in IRF4^{fl/fl}CD11c^{cre} mice following CDG treatment (Fig. 7a). The CD86 expression in Batf3^{-/-} mice was unaltered (Fig. 7b). Second, adoptively transferred TNFR2^{-/-} cDC2 induced CD86 expression on moDCs in IRF4^{fl/fl}CD11c^{cre} mice (Fig. 7c). Third, CDG induced CD86 expression on moDCs in RelB^{fl/fl}CD11c^{cre} mice (Fig. 7d). We concluded that cDC2, especially TNFR2⁻ cDC2, promote CDG-induced moDCs maturation in vivo.

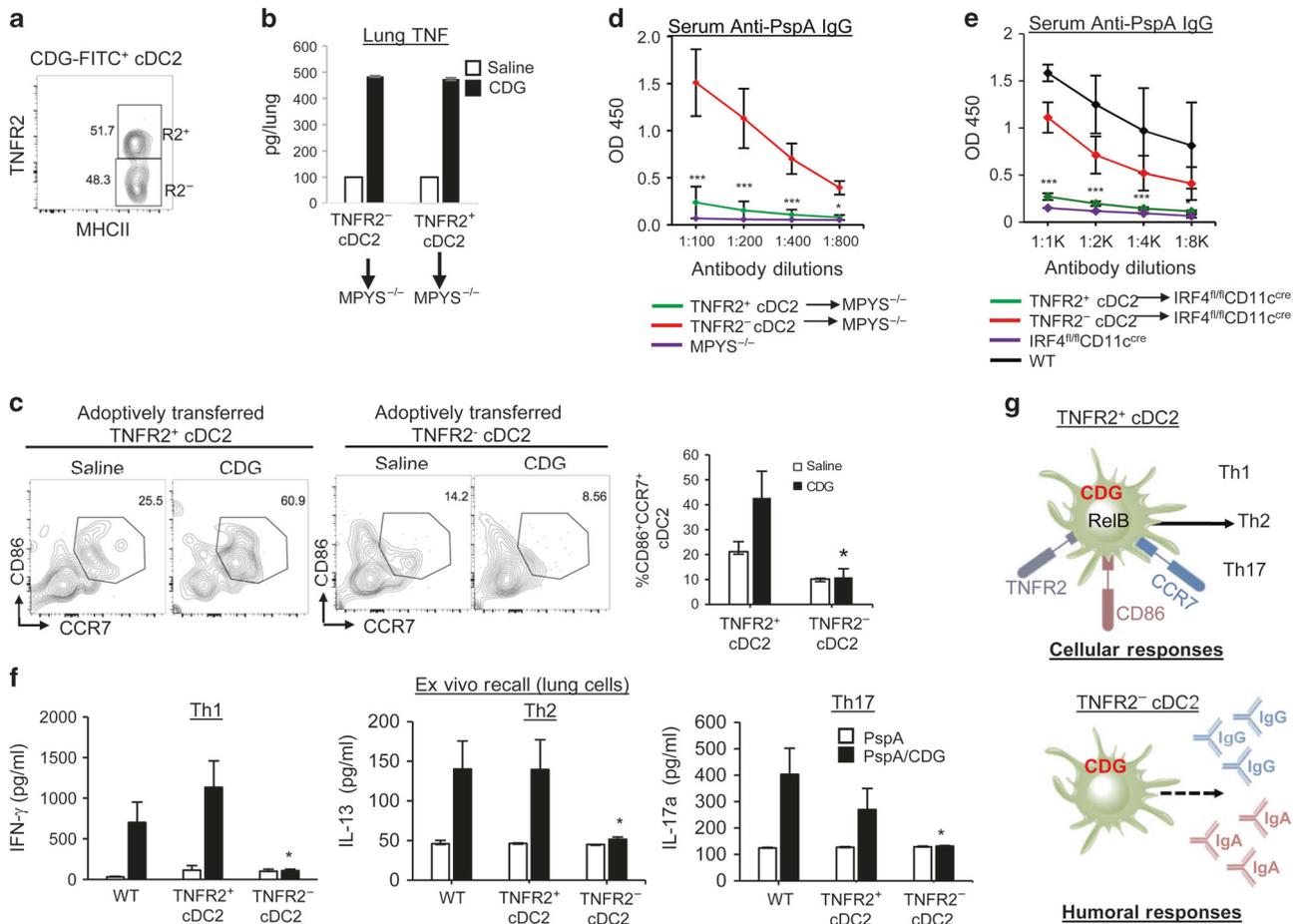


Fig. 4 Lung TNFR2^{-/-} cDC2 mediate CDG-induced humoral response. **a** Flow cytometry analysis of TNFR2 expression on lung CDG-FITC⁺ cDC2 from WT mice. *n* = 3. **b** Lung TNF production in CDG treated (i.n.) MPYS^{-/-} mice adoptively transferred with WT TNFR2⁺ or TNFR2⁻ lung cDC2. *n* = 3. **c** Sorted TNFR2⁺ and TNFR2⁻ lung cDC2 from WT mice were labeled with CFSE and adoptively transferred into the MPYS^{-/-} mice. Recipient mice were treated with CDG (i.n.) for 16 h. CD86 and CCR7 expression on CFSE-positive lung cells were examined by Flow cytometry. *n* = 3. **d** Sorted TNFR2⁺ and TNFR2⁻ lung cDC2 from WT mice were adoptively transferred into the MPYS^{-/-} mice. Recipient mice were immunized (i.n.) with PspA or CDG/PspA twice. Serum anti-PspA IgG were determined by ELISA. *n* = 3. **e** Sorted TNFR2⁺ and TNFR2⁻ lung cDC2 from WT mice were adoptively transferred into IRF4^{fl/fl}CD11c^{cre} mice. Recipient mice were immunized (i.n.) with PspA or CDG/PspA. Serum anti-PspA IgG were determined by ELISA. *n* = 3. **f** Lung cells from recipient IRF4^{fl/fl}CD11c^{cre} mice were stimulated with 5 μg/ml PspA for 4 days in culture. Cytokines were measured in the supernatant by ELISA. **g** A cartoon illustrating following CDG administration, TNFR2⁺ cDC2 activate RelB to induce Th1, Th2, and Th17 responses while TNFR2⁻ cDC2 mediate the antibody response. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

Adoptively transferred TNFR2^{-/-} cDC2 restored CDG responses in IRF4^{fl/fl}CD11c^{cre} mice (Fig. 3a). Yet, TNFR2^{-/-} mice had no CDG responses (Fig. 2a). We reasoned that TNFR2 expression on moDCs may be important for CDG responses in vivo. Indeed, we found that CDG induced TNFR2 on moDCs in WT mice (Fig. 7e) and moDCs from TNFR2^{-/-} mice did not upregulate CD86 in response to CDG in vivo (Fig. 7f). Last, adoptive transfer of WT monocytes into TNFR2^{-/-} mice restored CDG-induced IgG and IgA responses (Fig. 7g). Notably, adoptive transfer WT cDC2 into TNFR2^{-/-} mice did not restore CDG-induced antibody responses (Fig. 7h). We concluded that moDCs expression of TNFR2 is critical for its maturation and subsequent induction of CDG adjuvant response.

CDG induces mTNF expression on TNFR2^{-/-} cDC2 in vivo

Our data so far indicate that moDCs are matured by activated TNFR2^{-/-} cDC2. Furthermore, moDC maturation requires cell-intrinsic TNFR2 expression. Only mTNF can efficiently engage TNFR2.³⁶ Both TNFR2⁺ and TNFR2⁻ cDC2 produced TNF upon intranasal CDG treatment (Fig. 4b). We asked if the lung TNFR2^{-/-} cDC2 specifically expressed mTNF.

We intranasally administered CDG to WT mice for 16 h and detected cell surface mTNF expression using TNFR2-Fc recombinant protein (Fig. 8a). We found that the majority of lung mTNF⁺ DCs were cDC2 (Fig. 8b). Remarkably, TNFR2^{-/-} cDC2 were the main mTNF⁺ cDC2 cells in vivo while TNFR2⁺ cDC2 expressed little mTNF (Fig. 8c).

moDCs, not TNFR2^{-/-} cDC2, are very efficient in antigen processing in vivo

We next examined antigen processing in TNFR2^{-/-} cDC2 in vivo. WT mice were intranasally administered with CDG/DQ⁺-OVA.¹⁷ DQ⁺ cells were examined in lung cDC2 and moDCs (Fig. 8d). DQ⁺-OVA is a self-quenched conjugate of OVA exhibiting bright green fluorescence upon proteolytic degradation (DQ-Green). Furthermore, high concentration of digested fragments of DQ⁺-OVA accumulating in organelles form excimers that exhibit bright red fluorescence (DQ-Red). We found that DQ⁺ moDCs are mostly DQ-Red, indicating a high concentration of processed antigens in moDCs. Conversely, DQ⁺ cDC2 were DQ-Green (Fig. 8d). Strikingly, compared to the TNFR2⁺ cDC2 subpopulation, very few TNFR2⁻

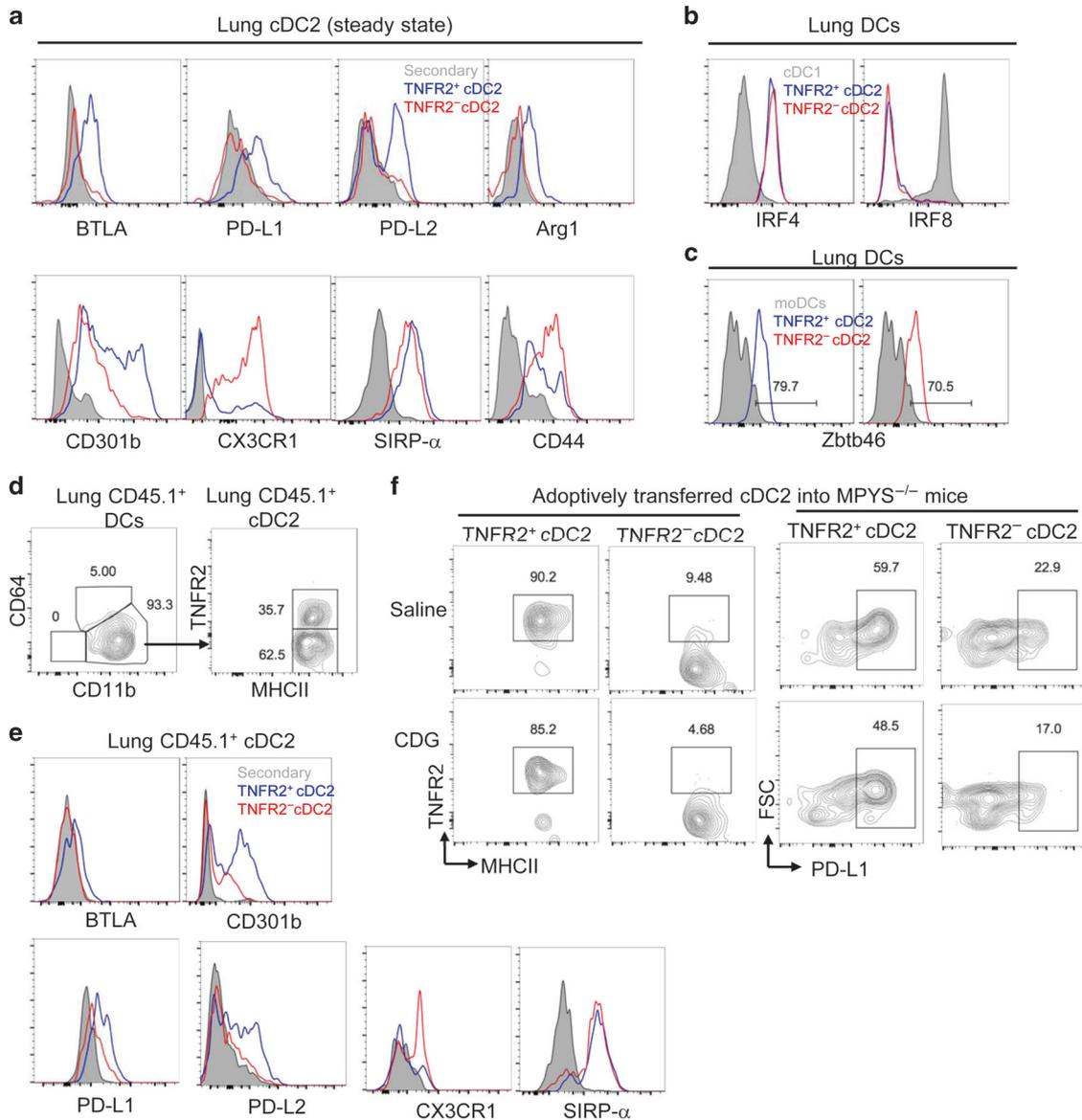


Fig. 5 Lung cDC2 consist of two distinct subpopulations. **a** Flow cytometry analysis of lung TNFR2⁺ vs TNFR2⁻ cDC2 at steady state. *n* = 3. **b, c** Flow cytometry analysis of IRF4 and IRF8 (**b**) and Zbtb46 (**c**) in TNFR2⁺ and TNFR2⁻ cDC2. *n* = 3. **d** Flow cytometry analysis in lungs of IRF4^{fl/fl}CD11c^{cre} mice reconstituted with CD45.1⁺ pre-cDC2. *n* = 3. pre-cDC2 were sorted from the bone marrow of B6.CD45.1 mice and transferred (i.n.) into IRF4^{fl/fl}CD11c^{cre} mice. *n* = 3. **e** Phenotypic analysis of CD45.1 TNFR2⁺ and TNFR2⁻ cDC2 transferred into IRF4^{fl/fl}CD11c^{cre} mice. *n* = 3. **f** Flow cytometry analysis of TNFR2 expression on cDC2 subpopulations transferred into MPYS^{-/-} mice treated with CDG (i.n.) for 16 h. *n* = 3

cDC2 subpopulation were DQ⁺ (Fig. 8d), suggesting that the TNFR2⁻ cDC2 either did not take up antigen or were not efficient at antigen processing. In comparison, all DQ⁺ moDCs were TNFR2⁺ cells (Fig. 8d) indicating TNFR2⁺ moDCs were indeed mature DCs.

moDCs promote CDG-induced Tfh and GC B cells generation in the lung
We next assessed how non-migratory moDCs (Fig. 1d; S3B)^{25,33} promote CDG-induced antibody responses. moDCs were efficient at antigen processing (Fig. 8d). We first asked if they presented antigen on cell surface. We intranasally administered C57BL/6 mice with CDG and E_a-OVA, and detected I-A^b/E_a⁺ cells with the YAE mAb. Indeed, CDG increased YAE⁺ moDCs in vivo (Fig 9a). Furthermore, the majority of YAE⁺ moDCs upregulated CD86 (Fig. 9b), indicating their potential to activate CD4⁺ T cells.

Tfh cells and GC B cells play central roles in promoting humoral responses. We found that 14 days after CDG/PspA immunization (i. n.), lungs from the WT mice had PD1⁺CXCR5⁺Bcl6⁺ Tfh cells and Bcl6⁺ GC B cells (Fig. 9c–e). In contrast, TNFR2^{-/-} mice were unable to generate lung Tfh or GC B cells (Fig. 9c, d). Importantly, adoptive transfer of WT monocytes into TNFR2^{-/-} mice restored the generation of Tfh and GC B cells in the lung (Fig. 9c, d). We concluded that moDCs promote CDG-induced Tfh and GC B cells generation in the lung.

moDCs are activated by TNFR2⁻ cDC2. Thus restoring TNFR2⁻ cDC2 in the IRF4^{fl/fl}CD11c^{cre} mice should restore Tfh cells. Indeed, we found that adoptive transfer of TNFR2⁻ cDC2, but not TNFR2⁺ cDC2, into IRF4^{fl/fl}CD11c^{cre} mice generated Tfh cells (Fig. 9e). Together, we propose that CDG activates TNFR2⁻ cDC2 that matures moDCs to generate Tfh and GC B cells promoting CDG-induced antibody responses in vivo (Fig 9f).

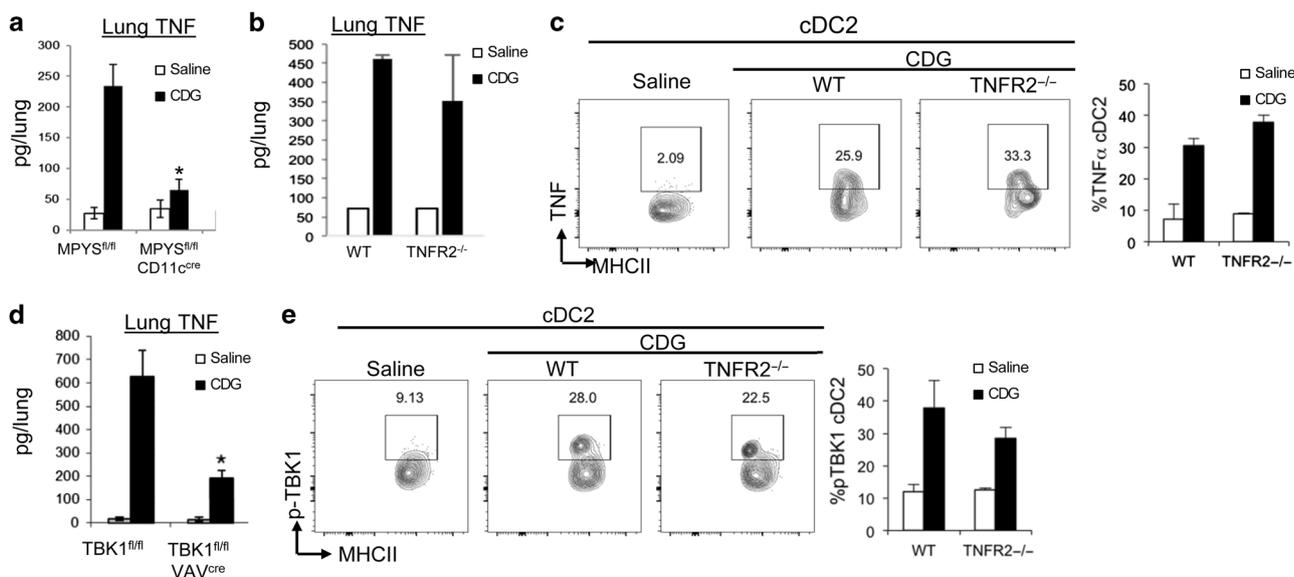


Fig. 6 CDG activates TNFR2⁻ cDC2 in vivo to produce TNF. **a, b** Indicated mice were administered (i.n.) with saline or CDG for 5 h. TNF production was measured in lung homogenates by ELISA. *n* > 3. **c** WT and TNFR2^{-/-} mice were treated with saline or CDG for 16 h. TNF in lung cDC2 was determined by an intracellular cytokine stain. *n* = 3. **d** TBK1^{fl/fl} and TBK1^{fl/fl}VAV^{cre} mice were administered (i.n.) with saline or CDG for 5 h. TNF production was measured in lung homogenates by ELISA. *n* = 3. **e** Flow cytometry analysis of p-TBK1 expression in lung cDC2 from WT and TNFR2^{-/-} mice treated with saline or CDG for 16 h. *n* = 3. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

DISCUSSION

In this report, we examined the mechanism by which lung DCs subsets mediate the mucosal adjuvant activity of CDG. The most exciting finding in this report is the identification of new lung cDC2 subpopulations and their unusual mode of action. cDC2 is a heterogeneous population.^{21,32,38,39} We found that steady-state lung cDC2 have two distinct subpopulations: TNFR2⁺pRelB⁺CX3CR1⁻ and TNFR2⁻pRelB⁻CX3CR1⁺. Functionally, these two cDC2 subpopulations mediate the cellular and humoral immune responses to CDG adjuvant, respectively. Developmentally, they derived from pre-cDC2 and do not represent different activation states of cDC2 in vivo.

Lung DC subsets are likely influenced by lung microenvironment.⁴³ In a large scale of phenotypic and transcriptional profiling of human tissues DC subtypes, Heidkamp et al.⁴³ found that the phenotype of DCs is predominantly determined by ontogeny in the lymphoid organs whereas the phenotype of DCs is heavily influenced by the microenvironment in barrier tissues. The lung TNFR2⁻ cDC2 express CX3CR1. Nakano et al.⁴⁴ showed that CX3CR1 promote pre-cDC migration to the lung at steady state. The lung TNFR2⁺pRelB⁺ cDC2 have not been described before. They have constitutively activated TNFR2-RelB signaling and lack mTNF themselves. We speculate that they react to modulatory signals (e.g. mTNF) from lung microenvironment that constitutively activates TNFR2-RelB. Tussiwand et al.³⁹ previously identified a Klf4-dependent SIRP- α ⁺CD24⁺Mgl2⁺ cDC2 subpopulation that is required for Th2 response. A subpopulation of TNFR2⁺pRelB⁺ cDC2 have high expression of Mgl2/CD301b. More studies are needed to determine if Klf4 is required for their development.

Intranasal administration of CDG leads to the maturation of the TNFR2⁺ cDC2 subpopulation, not the TNFR2⁻ cDC2 subpopulation. Unexpectedly, TNFR2⁻ cDC2 mediates the antibody responses of CDG. Why did not CDG activation mature lung TNFR2⁻ cDC2 in vivo? NF- κ B activation is essential for DC maturation. Different from cDC1 or TNFR2⁺ cDC2, CDG did not activate RelA or RelB in lung TNFR2⁻ cDC2 in vivo. CDG did induce p-TBK1 in lung TNFR2⁻ cDC2. TBK1 is critical for IRF3 activation and IFN β production.⁴⁵ However, it does not play a major role in NF- κ B activation in vivo.^{46,47} Previous studies, mostly done in vitro,

showed that STING/MPYS pathway activates NF- κ B, in particular, RelA.^{15,48} Our results here indicated that the ability of STING/MPYS to engage the NF- κ B pathway is cell-type specific. In this lung resident TNFR2⁻ cDC2, in vivo stimulation of STING/MPYS by CDG do not activate RelA or RelB.

How does the immature TNFR2⁻ cDC2 promote CDG adjuvant responses in vivo? Our monocyte adoptive transfer experiment in TNFR2^{-/-} mice showed that moDCs are critical for CDG adjuvant responses. moDCs do not directly take up intranasally administered CDG and STING expression in moDCs is dispensable. Instead, moDCs maturation requires TNFR2⁻ cDC2 and the expression of TNFR2 on moDC. Though we cannot rule out the possibility that mTNF on other cells interacts with TNFR2 on moDCs, we favor the model that mTNF on TNFR2⁻ cDC2 engages TNFR2 on moDC to induce its maturation and subsequent CDG antibody responses.

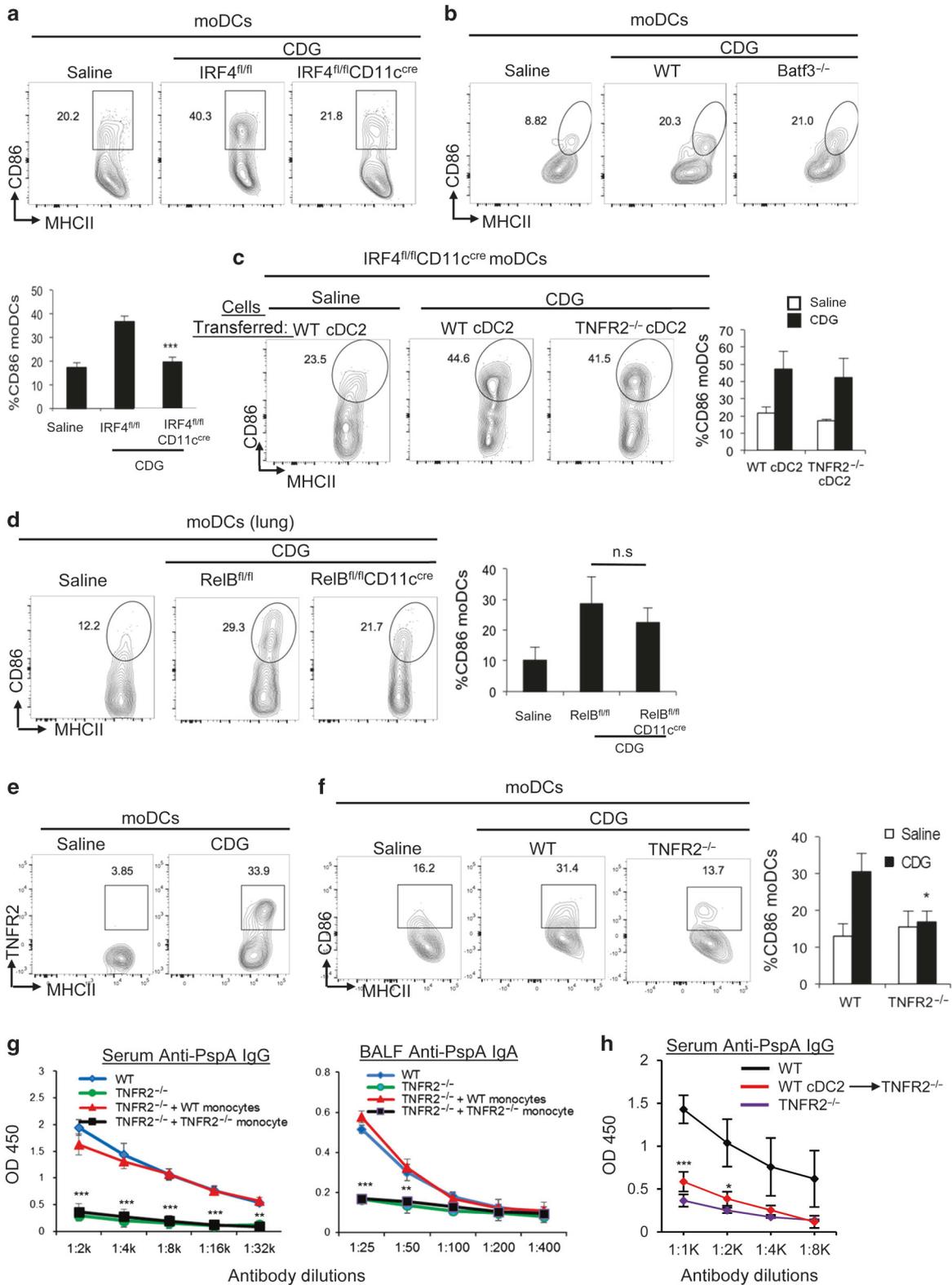
Lung moDCs are non-migratory.^{25,33} We showed that moDCs promote the generation of Tfh and GC B cells in lung suggesting the formation of the inducible bronchus-associated lymphoid tissue (iBALT). DCs are required for the formation of iBALT.^{49,50} The exact lung DC subset for iBALT induction is unknown. moDCs presented antigen, expressed co-stimulator, and activated RelA/RelB, which likely facilitate cytokine productions. We proposed that lung moDCs induce iBALT formation and promote CDG humoral responses.

In summary, we illustrated a previously unknown in vivo mode of action for CDG mucosal adjuvant, whereby a new lung TNFR2⁻ cDC2 subpopulation activated by CDG promoting the maturation of moDCs for the generation of Tfh cells. These findings will facilitate future mucosal vaccine development and DC research.

METHODS

Mice

Eight- to sixteen-week-old mice, both males and females, were used for experiments. All mice are on a C57BL/6 background. A detailed description of the lines can be found in the Supplemental Methods. Mice were housed and bred in the Animal Research Facility at the University of Florida. All experiments with mice were performed by the regulations and approval of the



Institutional Animal Care and Use Committee from the University of Florida.

Intranasal CDG immunization

A detailed description of intranasal vaccination and reagents can be found in the Supplemental Methods. Sera were collected

14 days after the last immunization. The PspA-specific Abs were determined by ELISA. To determine Ag-specific Th response, splenocytes and lung cells from PspA or CDG + PspA immunized mice were stimulated with 5 µg/ml PspA for 4 days in culture. Th1, Th2, and Th17 cytokines were measured in the supernatant by ELISA.

Fig. 7 TNFR2 expression on moDCs is required for CDG adjuvant activity. **a, b** WT, IRF4^{fl/fl}CD11c^{cre} (**a**) and Batf3^{-/-} (**b**) mice were treated (i.n.) with saline or CDG (5 µg) for 16 h. CD86 expression in lung moDC was determined by Flow cytometry. *n* = 3. **c** WT and TNFR2^{-/-} cDC2 were adoptively transferred into the IRF4^{fl/fl}CD11c^{cre} mice. The mice were treated with CDG (i.n.) for 16 h. CD86 expression on endogenous moDC was examined by Flow cytometry. *n* = 3. **d** Flow cytometry analysis of CD86 expression on lung moDCs in RelB^{fl/fl} and RelB^{fl/fl}CD11c^{cre} mice treated with CDG for 16 h. *n* = 3. **e** Flow cytometry analysis of TNFR2 expression on lung moDCs of WT mice treated (i.n.) with saline or CDG for 16 h. *n* = 3. **f** Flow cytometry analysis of CD86 expression on lung moDCs from WT or TNFR2^{-/-} mice treated (i.n.) with saline or CDG for 16 h. *n* = 3. **g** WT, TNFR2^{-/-}, or TNFR2^{-/-} mice receiving (i.n.) WT monocytes or TNFR2^{-/-} monocytes were immunized with CDG/PspA. Serum anti-PspA IgG and BALF anti-PspA IgA were determined by ELISA. *n* = 3. **h** WT cDC2 adoptively transferred into TNFR2^{-/-} mice were immunized with CDG/PspA. Serum anti-PspA IgG were determined by ELISA. *n* = 3. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

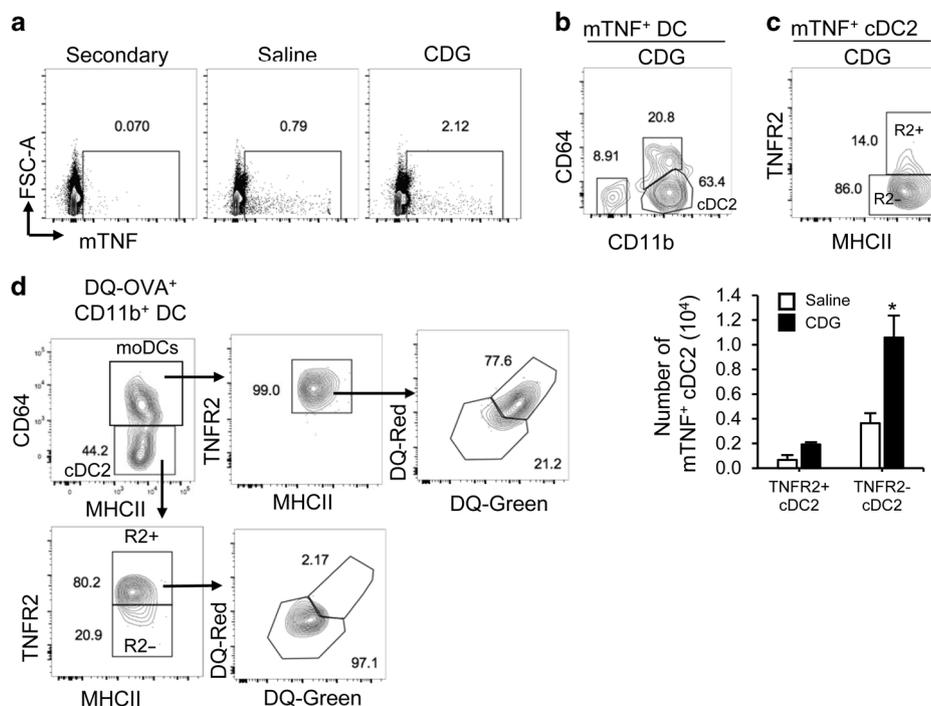


Fig. 8 TNFR2⁻ cDC2 express mTNF but have few processed antigen. **a** WT mice were administered with saline or CDG (5 µg) for 16 h. mTNF expression was determined by Flow cytometry using mouse TNFR2-Fc recombinant protein. *n* = 3. **b, c** Flow cytometry analysis of mTNF expression in lung DCs (**b**) and cDC2 (**c**) *n* = 3. **d** Flow cytometry analysis of antigen uptake and processing in lung CD11b⁺ DC from WT mice treated (i.n.) with DQ-OVA (20 µg) and CDG (5 µg) for 16 h. *n* = 3. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

Detection of lung cytokine production

Mice were intranasally administered 5 µg CDG, and then sacrificed after 5 h by CO₂ asphyxiation.¹⁷ Lungs were harvested and lung cytokines were determined in lung homogenates. A detailed description of lung homogenates preparation can be found in the Supplemental Methods.

Isolation of lung cells

Mice were intranasally administered with or without CDG (5 µg, vaccine-grade). After 20 h, the lungs were lavaged, perfused with ice-cold phosphate-buffered saline, and harvested. A detailed description of lung cell isolation can be found in the Supplemental Methods.

In vivo Ag uptake and processing

Mice were intranasally administered 20 µg DQTM-Ovalbumin (DQ-OVA) (Life Technologies, D12053) with or without CDG (5 µg, vaccine-grade). After 20 h, the lungs were lavaged, perfused, and harvested.

Flow cytometry and cell sorting

A detailed description of Flow antibodies used can be found in the Supplemental Methods. Cell sorting was performed on the BD FACSAriaIII Flow Cytometer and Cell Sorter. After sorting, dendritic cells were CFSE (carboxyfluorescein succinimidyl ester) labeled, according to the protocol from the manufacturer (Invitrogen).

Intracellular staining

The intracellular cytokine staining was performed using the Cytofix/CytopermTM kit from BD Biosciences (cat#555028). Briefly, mice were intranasally administered saline or cyclic di-GMP (5 µg, vaccine-grade). The single lung cell suspension was fixed in Cytofix/perm buffer (BD Biosciences) in the dark for 20 min at RT. Fixed cells were then washed and kept in Perm/wash buffer at 4 °C. Golgi-plug was present during every step before fixation.

Mouse cDC2 and monocyte purification

Primary mouse cDC2 (cat#18970A, Stemcell Technologies; cat# 480097, Biologend) were purified from lungs of naïve mice

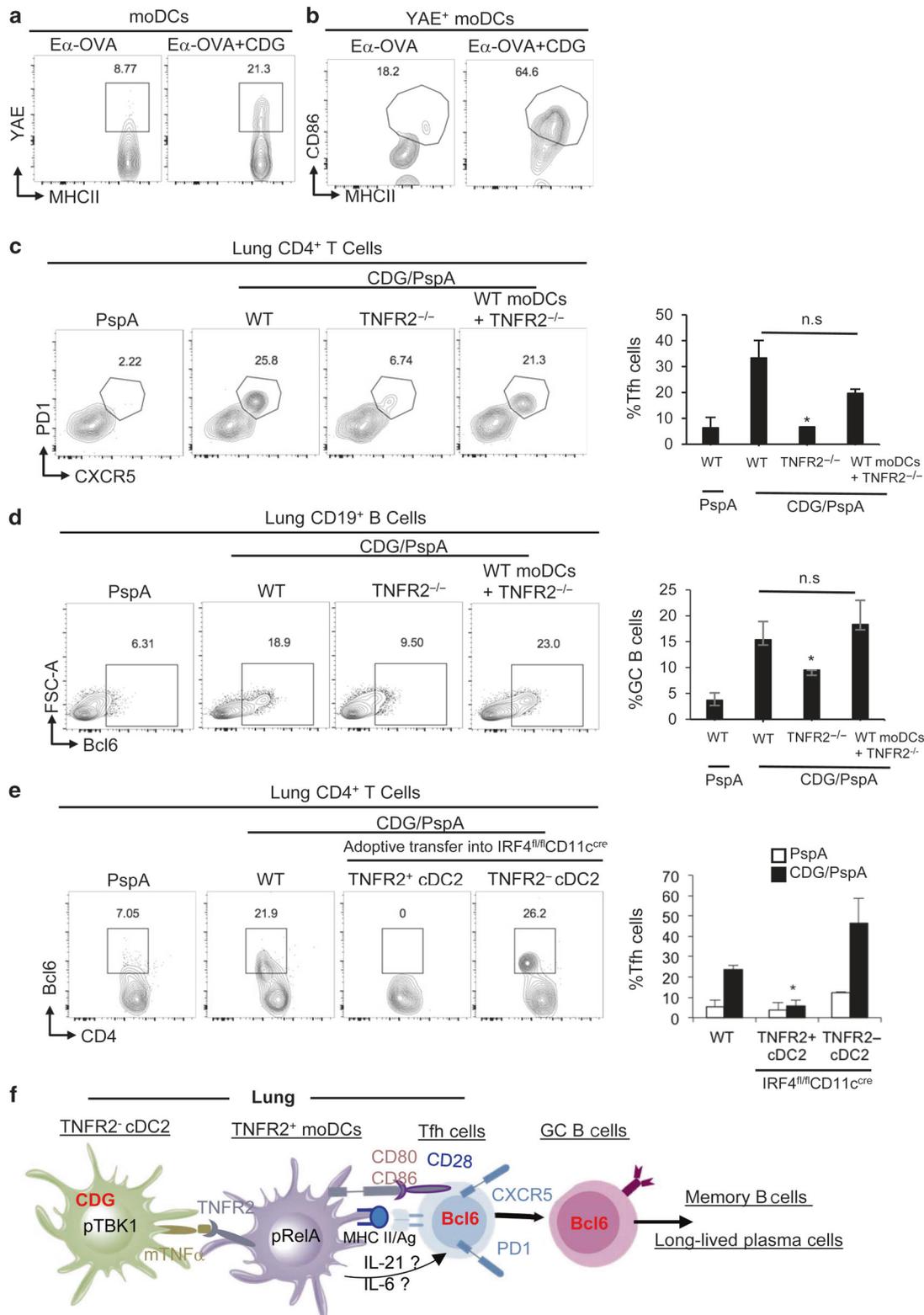


Fig. 9 moDCs promote CDG-induced Tfh and GC B cell generation in the lung. **a, b** WT mice were administered with Ea-OVA (10 μg) or Ea-OVA/CDG (5 μg) for 16 h. YAE⁺ moDCs (**a**) and CD86⁺YAE⁺ moDCs (**b**) were determined by Flow cytometry. *n* = 3. **c, d** WT, TNFR2^{-/-}, or TNFR2^{-/-} mice receiving (i.n.) WT monocytes were immunized with CDG/PspA. At Day 14, CD4⁺PD1⁺CXCR5⁺ Tfh (**c**) and CD19⁺Bcl6⁺ B cells (**d**) were determined in the lung by flow cytometry. *n* = 3. **e** TNFR2⁺ and TNFR2⁻ cDC2 were adoptively transferred into IRF4^{fl/fl}CD11c^{cre} mice and immunized with CDG/PspA. At Day 14, CD4⁺Bcl6⁺ Tfh were determined by flow cytometry. *n* = 3. **f** Model: following CDG administration, TNFR2⁻ cDC2 produced mTNF to activate moDCs, which will generate Tfh to mediate the antibody response. Graphs represent means ± standard error from three independent experiments. The significance is represented by an asterisk (*) where *p* < 0.05 (unpaired Student's *t*-test)

following the protocol according to the manufacturer. Mouse monocytes (cat#19861, Stemcell Technologies) were purified from the bone marrow of naïve mice following the protocol according to the manufacturer.

Adoptive transfer

Lung TNFR2⁺ and TNFR2⁻ cDC2 were sorted from the lungs of naïve donor mice with a FACSAriaIII flow cytometer. After sorting, dendritic cells were CFSE labeled, according to the protocol from the manufacturer (Invitrogen). Cells were administered intranasally into recipient mice. Twenty-four hours later of transfer, recipient mice were intranasally vaccinated with CDG (5 µg; Invivogen, cat# vac-cdg) adjuvanted PspA (2 µg; BEI Resources) or PspA alone.¹⁷ Recipient mice received two doses of transferred cells and were immunized at 14 days interval.

For in vivo reconstitution of cDC2, pre-cDC2 were sorted from the bone marrow of B6.CD45.1 naïve mice with a FACSAriaIII. pre-cDC2 were identified as Lin⁻MHCII⁻SiglecH⁻CD3⁻CD19⁻NK1.1⁻Ter119⁻CD11c⁺CD26⁺CD135⁺Ly6c⁺.⁴² In all, 250,000 cells were administered intranasally into recipient mice. DCs in the lung were analyzed on day 5 post transfer.

Statistical analysis

All data are expressed as means ± SEM. Statistical significance was evaluated using Prism 5.0 software to perform a Student's t-test (unpaired, two-tailed) for comparison between mean values.

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AUTHOR CONTRIBUTIONS

L.J. and S.M. designed the study, performed experiments, and wrote the manuscript. S.P., S.M.B., W.W., D.S.K., and S.S. performed the experiments. K.A. provided critical reagent and supervised S.S.

ADDITIONAL INFORMATION

The online version of this article (<https://doi.org/10.1038/s41385-018-0098-0>) contains supplementary material, which is available to authorized users.

Competing interests: The authors declare no competing interests.

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