CD28/B7 Deficiency Attenuates Systolic Overload-Induced Congestive Heart Failure, Myocardial and Pulmonary Inflammation, and Activated T Cell Accumulation in the Heart and Lungs

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Abstract—The inflammatory response regulates congestive heart failure (CHF) development. T cell activation plays an important role in tissue inflammation. We postulate that CD28 or B7 deficiency inhibits T cell activation and attenuates CHF development by reducing systemic, cardiac, and pulmonary inflammation. We demonstrated that chronic pressure overload–induced end-stage CHF in mice is characterized by profound accumulation of activated effector T cells (CD3+CD44high cells) in the lungs and a mild but significant increase of these cells in the heart. In knockout mice lacking either CD28 or B7, there was a dramatic reduction in the accumulation of activated effector T cells in both hearts and lungs of mice under control conditions and after transverse aortic constriction. CD28 or B7 knockout significantly attenuated transverse aortic constriction–induced CHF development, as indicated by less increase of heart and lung weight and less reduction of left ventricle contractility. CD28 or B7 knockout also significantly reduced transverse aortic constriction–induced CD45+ leukocyte, T cell, and macrophage infiltration in hearts and lungs, lowered proinflammatory cytokine expression (such as tumor necrosis factor-α and interleukin-1β) in lungs. Furthermore, CD28/B7 blockade by CTLA4-Ig treatment (250 μg/mouse every 3 days) attenuated transverse aortic constriction–induced T cell activation, left ventricle hypertrophy, and left ventricle dysfunction. Our data indicate that CD28/B7 deficiency inhibits activated effector T cell accumulation, reduces myocardial and pulmonary inflammation, and attenuates the development of CHF. Our findings suggest that strategies targeting T cell activation may be useful in treating CHF. (Hypertension. 2016;68:688–696. DOI: 10.1161/HYPERTENSIONAHA.116.07579.)

Key Words: congestive heart failure ■ heart ■ inflammation ■ leukocytes ■ lung ■ T-cell activation

The inflammatory response is believed to play an important role in the development of congestive heart failure (CHF). Increased myocardial leukocyte infiltration and elevated systemic and cardiac proinflammatory cytokine levels are commonly associated with CHF, and several of these factors, such as tumor necrosis factor-α and interleukin-1β, have been demonstrated to accelerate left ventricle (LV) hypertrophy, cardiac fibrosis, and LV dysfunction. In addition to inflammation of myocardial tissue, severe CHF results in profound leukocyte infiltration in the lungs of experimental animals and CHF patients, provoking the development of type-2 pulmonary hypertension that drives the transition from LV failure to right ventricular hypertrophy and failure.

T cell activation plays a central role in inflammation. T cell activation requires at least 2 signals to become fully activated. The first signal occurs after the engagement of T cell receptor by antigen-major histocompatibility complex peptides present on the surface of antigen-presenting cells. The second important signal is the engagement of costimulatory molecules (like CD28 or ICOS) on the T cell with one of the B7 proteins (B7.1 [CD80] and B7.2 [CD86]), which are also expressed on antigen-presenting cells. CD28 is a potent T-cell costimulator. Inhibition of CD28/B7 signaling with antibodies to CTLA4-Ig treatment (250 μg/mouse every 3 days) attenuated transverse aortic constriction–induced T cell activation, left ventricle hypertrophy, and left ventricle dysfunction. Our data indicate that CD28/B7 deficiency inhibits activated effector T cell accumulation, reduces myocardial and pulmonary inflammation, and attenuates the development of CHF. Our findings suggest that strategies targeting T cell activation may be useful in treating CHF.

Previous studies have demonstrated that CD4+ T cells accumulate in the LV of mice with CHF and contribute to the pathogenesis of CHF. In this study, we found that end-stage CHF is associated with profound infiltration and accumulation of activated effector T cells (CD3+CD44high cells) in the heart and lungs, as well as a significant increase in the percentage of effector memory CD4+ and CD8+ T cells (TEM; CD44highCD62Llow).
T cells) in the lungs. To demonstrate a role for CD28 function in CHF development, we tested the hypothesis that transverse aortic constriction (TAC)–induced LV failure and lung remodeling would be attenuated in CD28 or B7 knockout (KO) mice. Our findings indicate that genetic disruption of either CD28 or B7 protein significantly attenuates TAC-induced cardiac and pulmonary inflammation, lung remodeling, as well as LV hypertrophy and dysfunction. The beneficial effect of CD28 or B7 deletion was associated with a dramatic reduction of TAC-induced T cell activation in the heart and lungs.

Materials and Methods
Detailed methods are available in the online-only Data Supplement. Primary antibodies and primers used in this study are listed in Tables S1 and S2 in the online-only Data Supplement.

Mice and TAC Procedure

Animals and Experimental Design
CD28 KO (B6.129S2-Cd80tm1Shr Cd86tm2Shr/J; stock No 002666) and B7 KO (B6.129S4-Cd80tm1abo Cd86tm1abo/J; stock No. 003610) mice and C57BL/6j wild-type (WT) mice were obtained from Jackson Laboratory. The fusion protein CTLA4-Ig (abatacept, 250 μg), which inhibits CD28/B7 interactions, was administered intraperitoneally every 3 days beginning 1 day before TAC. An isotype control antibody human IgG was used as a vehicle control. Male mice 4 to 5 weeks of age were subjected to a procedure using a 27G needle to create the TAC, a model that mimics clinical systemic hypertension and aortic stenosis, as previously described. Data were collected 8 weeks after TAC. LV hypertrophy and cardiac function were assessed. Experimental studies were approved by the Institutional Animal Care and Use Committee at the University of Minnesota.

Data Analysis
A normality test (Shapiro–Wilk) provided by SigmaPlot was used to determine whether data were normally distributed. If the data were normally distributed, they were presented as mean±SEM. Student’s t test was used to test for differences between 2 groups. Two-way ANOVA followed by a Bonferroni correction post hoc test was performed. All pairwise P values are 2-sided. The null hypothesis was rejected at P<0.05.

Results
End-Stage CHF Caused a Significant Accumulation of Activated T Cells in Lungs
We examined T-cell activation and T-cell accumulation in hearts and lungs of mice with end-stage CHF produced by TAC. As shown in Figure S1A and S1B, ratios of LV weight and lung weight to body weight were increased 2.3-fold and 2.8-fold in CHF mice, respectively. Echocardiography showed that mice with TAC had a significant decrease of LV ejection fraction (EF; 36.0% in CHF versus 77.8% in control mice; Figure S1D–S1F). CD28 deficiency also attenuated the TAC-induced decrease of LVEF (32.1±3.2% in WT–control versus 64.5±14.3% in CD28 KO–control), increase of LV end-systolic diameter (4.1±0.2 mm in WT–control versus 2.5±0.6 mm in CD28 KO–control), and increase of LV end-diastolic diameter (4.9±0.1 mm in WT–control versus 3.8±0.9 mm in CD28 KO–control; Figure 1D–1F). CD28 deficiency significantly attenuated the TAC-induced increase of LV end-systolic pressure (18.4±3.4 mm Hg in WT–control versus 3.9±1.1 mm Hg in CD28 KO–control), decrease of LV maximum rate of decline of LV systolic pressure (dp/dtmin; 5997±827 mm Hg/s in WT–control versus 8038±1797 mm Hg/s in CD28 KO–control), and increase of LV minimum rate of decline of LV systolic pressure (dp/drmin; −5943±864 mm Hg/s in WT–control versus −8930±2005 mm Hg/s in CD28 KO–control; Figure 1G–1I). Moreover, CD28 deficiency reduced TAC-induced increases of myocardial atrial natriuretic peptide and β-myosin heavy chain.
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B7 Deficiency Attenuated TAC-Induced CHF Development

Because CD28 deficiency attenuated the TAC-induced LV hypertrophy and dysfunction, we used B7 KO mice to examine the effect of B7 deficiency on TAC-induced CHF. LV systolic pressure was comparable in WT and B7 KO mice under control conditions, as well as 8 weeks after TAC (Figure S8C and S8D). We found that B7 deficiency had no effect on the ratio of LV, left atria, or lung weight to body weight under control conditions (Figure 2A–2C; Table S4). Echocardiographic measurements showed that B7 deficiency did not affect LV function under control conditions (Figure 2D–2F).

B7 deficiency significantly attenuated the TAC-induced LV hypertrophy (6.9±0.5 mg/kg in WT-TAC versus 5.1±1.0 mg/kg in B7 KO-TAC), increase of left atria weight (0.64±0.16 mg/kg in WT-TAC versus 0.15±0.03 mg/kg in B7 KO-TAC), and increase of lung weight (8.6±1.1 mg/kg in WT-TAC versus 4.9±1.1 mg/kg in B7 KO-TAC; Figure 2A–2C; Table S4). Echocardiographic measurements showed that B7 deficiency significantly attenuated the TAC-induced decrease of LVEF (48.4±6.2% in WT-TAC versus 67.5±11.8% in B7 KO-TAC), increase of LV end-systolic diameter (3.4±0.4 mm in WT-TAC versus 2.4±0.4 mm in B7 KO-TAC), and increase of LV end-diastolic diameter (4.5±0.5 mm in WT-TAC versus 3.8±0.7 mm in B7 KO-TAC; Figure 2D–2F). In addition, B7 deficiency also attenuated the TAC-induced increase of LV end-diastolic pressure (21.3±6.1 mm Hg in WT-TAC versus 4.7±0.9 mm Hg in B7 KO-TAC), decrease of LV dP/dt max (5567±1426 mm Hg/s in WT-TAC versus 8730±218 mm Hg/s in B7 KO-TAC), and increase of LV dP/dt min (−5579±1491 mm Hg/s in WT-TAC versus −8788±1290 mm Hg/s in B7 KO-TAC; Figure 2G–2I). Moreover, B7 KO significantly reduced the TAC-induced increases of myocardial atrial natriuretic peptide and β-myosin heavy chain protein expression (Figure 2J–2L). These data indicate that B7 deficiency protects hearts against TAC-induced LV dysfunction and CHF.

CD28 or B7 Deficiency Inhibited CD3+ T-Cell Activation and Accumulation in Hearts and Lungs of Mice After TAC

To determine the effect of CD28/B7 signaling on T-cell activation and inflammation, we assessed changes in the percentage and (β-MHC) protein content (Figure 1J–1 L). Together, these data indicate that CD28 deficiency protects hearts against TAC-induced LV hypertrophy and CHF.
number of CD3+ T cells, activated effector T cells, and early activated T cells (CD3+CD69+ cells) in LV tissues and lungs using flow cytometry analysis. The gating strategies are presented in Figures S4 and S5. Under control conditions, CD28 or B7 KO significantly reduced the percentage of activated effector T cells in both LV tissues (11.3±0.9% in WT–control, 8.7±0.4% in CD28 KO–control, and 7.4±0.4% in B7 KO–control) and lungs (28.7±1.2% in WT–control, 21.0±1.7% in CD28 KO–control, and 22.3±1.0% in B7 KO–control). TAC significantly increased the percentage of activated effector T cells in lungs, but did not increase the percentage of these cells in LV tissues. Notably, CD28 or B7 deficiency significantly attenuated the TAC-induced increase of the percentage of activated effector T cells in lungs, but did not increase the percentage of these cells in LV tissues. Notably, CD28 or B7 deficiency significantly attenuated the TAC-induced increase of activated effector T cells in both LV tissues and lungs (54.2±5.2% in WT–control, 22.0±1.1% in CD28 KO–control, and 24.2±2.1% in B7 KO–control) and in LV tissues (11.5±0.6% in WT–control, 8.6±0.7% in CD28 KO–control, and 7.0±0.6% in B7 KO–control) after TAC (Figure 3A–3C). Moreover, CD28 or B7 deficiency considerably reduced TAC-induced accumulation of activated effector T cells in both LV tissues and lungs (Figure 3D). CD28 KO or B7 deficiency also significantly attenuated TAC-induced increases of early activated T cells in LV tissues and lungs (Figure S9). In addition, CD28 or B7 deficiency significantly attenuated TAC-induced increases in total CD3+ T cells in lungs (10.6±1.5×10^5 in WT–TAC, 5.9±0.96×10^5 in CD28 KO–TAC, and 6.3±0.35×10^5 in B7 KO–TAC), but did not significantly affect TAC-induced CD3+ T-cell accumulation in LV tissues (Figure 3E). Furthermore, CD28 or B7 deficiency had no effect on the total number of CD45+ cells in LV tissues (34.0±1.9×10^3 in WT–control, 28.1±0.7×10^3 in CD28 KO–control, and 37.3±6.0×10^3 in B7 KO–control) or lungs (3041±63×10^3 in WT–control, 2901±77×10^3 in CD28 KO–control, and 3130±111×10^3 in B7 KO–control) under control conditions. However, CD28 or B7 deficiency significantly attenuated TAC-induced increases of CD45+ cells in LV tissues (18.3±2.1–10^4 in WT–TAC, 9.0±1.3×10^4 in CD28 KO–TAC, and 10.9±0.66×10^4 in B7 KO–TAC) and lungs (683±85×10^4 in WT–TAC, 37.4±2.47×10^4 in CD28 KO–TAC, and 33.20±1.48×10^4 in B7 KO–TAC) (Figure 3F). Together, these data demonstrate that pressure overload causes T-cell activation in lungs in mice with end-stage CHF. CD28 or B7 deficiency is effective in attenuating CD3+ T-cell activation, as well as CD3+ T-cell and CD45+ cell accumulation in LV tissues and lungs in mice after TAC.

**CD28 or B7 Deficiency Attenuated TAC-Induced LV Fibrosis**

Inflammation causes cardiac fibrosis, which exacerbates LV hypertrophy and CHF development. As shown by Sirius red/
Fast green staining in Figure S10A and S10B, CD28 or B7 deficiency did not affect LV fibrosis under control conditions. However, CD28 or B7 deficiency significantly attenuated TAC-induced LV fibrosis. CD28 or B7 deficiency also significantly reduced TAC-induced increases in LV mRNA content of transforming growth factor-β, a profibrogenic cytokine associated with fibrosis development (Figure S10C). These data demonstrate that CD28/B7 signaling contributes to pressure overload–induced LV fibrosis.

CD28 or B7 Deficiency Inhibited TAC-Induced T-Cell Activation and Accumulation in Both CD4+ and CD8+ Subsets in Lungs

Because CD28 or B7 deficiency significantly attenuated the TAC-induced CD3+ T-cell activation and accumulation in lungs, we further determined the effect of CD28 or B7 deficiency on the activation and accumulation of CD4+ and CD8+ T cells. As shown in Figure 4A–4C and 4E, under control conditions, CD28 or B7 deficiency resulted in an ~50% decrease in the percentage of TEM within the CD4+ or CD8+ T-cell subset. TAC significantly increased the percentage of CD4+ and CD8+ TEM (2.2- and 1.8-fold, respectively). CD28 or B7 deficiency totally abolished the TAC-induced increases in the percentage of CD4+ TEM and largely reduced the increase in the percentage of CD8+ and CD3+ TEM (Figure 4A–4C and 4E; Figure S11A). In addition, CD28 or B7 deficiency markedly attenuated TAC-induced increases in CD4+, CD8+, and CD3+ TEM in lungs of mice (Figure 4D and 4F; Figure S11B). Moreover, CD28 or B7 deficiency abolished the TAC-induced increase in the percentage of early activated T cells in their corresponding CD4+ and CD8+ T-cell subset and their total numbers in lungs (Figure S12). CD28 or B7 deficiency also significantly reduced the TAC-induced increases in CD4+ and CD8+ activated effector T cells (Figure S13). These data indicate that CD28 or B7 deficiency is highly effective in inhibiting pressure overload–induced T-cell activation in both CD4+ and CD8+ subsets in lungs.

CD28 or B7 Deficiency Attenuated TAC-Induced Lung Macrophage Infiltration and Proinflammatory Cytokine Expression

Because activated T cells regulate macrophage function, we further determined whether CD28 or B7 deficiency affected the number of lung macrophages expressing the macrophage marker F4/80 (Figure S5). Under control conditions, the percentage and total number of macrophages were not altered in either CD28 KO or B7 KO mice (Figure 5A and 5B). TAC significantly increased the percentage and total number of
macrophages in the lung, which was notably reduced in CD28- and B7-deficient mice (Figure 5A and 5B). Furthermore, CD28 or B7 deficiency also significantly suppressed TAC-induced increases of lung mRNA levels of interleukin-1β, tumor necrosis factor-α, and monocyte chemoattractant protein-1 (Figure 5C–5E). These data demonstrate that CD28 or B7 deficiency is effective in attenuating TAC-induced lung macrophage infiltration and proinflammatory cytokine expression.

**CTLA4-Ig Attenuated TAC-Induced T-Cell Activation and LV Dysfunction**

To further determine whether inhibition of T-cell activation can attenuate CHF development, the fusion protein CTLA4-Ig, which attenuates CD28/B7 signaling, was administrated to the mice before TAC. TAC markedly increased LV systolic pressure after 8 weeks, which was comparable in CTLA4-Ig-treated and vehicle-treated mice (Figure S14A). CTLA4-Ig treatment significantly reduced the TAC-induced increases in the percentage of CD4+ TEM (17.1±0.9% in control, 22.7±1.4% in TAC–vehicle, and 14.2±1.7% in TAC-CTLA4-Ig; Figure S14B), as well as the percentage of CD4+CD69+ T cells in lungs (Figure S14C), indicating CTLA4-Ig treatment inhibited T-cell activation in our experimental setting.

CTLA4-Ig treatment significantly attenuated the TAC-induced LV hypertrophy (3.25±0.05 mg/kg in control, 5.66±0.21 mg/kg in TAC–vehicle, and 4.72±0.25 mg/kg in TAC+CTLA4-Ig; Figure 6A). Moreover, echocardiographic measurements showed that CTLA4-Ig treatment also attenuated the TAC-induced decrease of LVEF (74.6±1.2% in control, 52.4±5.3% in TAC–vehicle, and 70.9±1.5% in TAC-CTLA4-Ig) and increase of LV end-systolic diameter (2.2±0.1 mm in control, 3.0±0.3 mm in TAC–vehicle, and 2.2±0.1 mm in TAC-CTLA4-Ig; Figure 6B and 6C). LV end-diastolic diameter was not altered (Figure 6D). These data indicate that inhibition of CD28/B7 signaling by CTLA4-Ig treatment protects hearts against TAC-induced LV hypertrophy and dysfunction.

**Discussion**

This study demonstrated that LV failure produced by chronic pressure overload caused an increase in total number of activated effector T cells and TEM in the LV and lungs. Using CD28/B7 KO mice or CTLA4-Ig to block CD28/B7 interactions, we also demonstrated that intact CD28/B7 signaling contributed significantly to TAC-induced LV hypertrophy and dysfunction, lung remodeling, and right ventricular hypertrophy. CD28/B7 interaction strongly enhanced myocardial and pulmonary infiltration of activated T cells and CD45+ leukocytes and resulted in increased fibrosis and cytokine expression in these tissues. These findings suggest that T-cell activation contributes to CHF development and that inhibition of T-cell activation may be useful in attenuating CHF development and progression by suppressing inflammatory responses.

The increased T-cell accumulation in LV and lung tissues in CHF mice seems to be a result of increased antigen-specific T-cell recruitment as well as nonspecific T-cell recruitment secondary to the proinflammatory environment in these tissues. The increased adhesion molecules (such as E-selectin and P-selectin) and chemokines on the resident cells and the selectin ligands and chemokine receptors on T cells contribute to the T-cell accumulation in these tissues. Increased selectin ligands...
and chemokine receptors during T-cell differentiation are known to promote T-cell recruitment into the inflamed sites. In addition, antigen-presenting cells (such as dendritic cells and macrophages) might also enhance antigen-specific T-cell recruitment by presenting resident cell debris or through other signaling mechanisms. Recent studies from Dr Harrison and his associates have demonstrated that oxidized self-antigen(s) contributes to Angiotensin II–induced T-cell activation and hypertension in mice. In the context that oxidative stress is increased during CHF development, oxidized proteins in heart and lungs are likely the contributors to the TAC-induced T-cell activation. However, it is not clear what endogenous antigen(s) mediates T-cell activation in CHF.

CHF dramatically increased the total number and the percentage of activated effector T cells in the lungs. To our surprise, end-stage CHF caused only a mild increase in the total number of activated effector T cells in LV tissues and did not affect the percentage of these cells. The accumulation of activated effector T cells in LV tissues and lungs in mice with CHF indicates that these tissues emit TAC-induced signals that promote T-cell infiltration or promote tissue-specific T-cell priming during CHF development. The profound increase of leukocytes, macrophages, T cells, and activated T cells in the present study is consistent with our previous observation using the same CHF model. The significant increase of activated effector T cells in peripheral blood and spleen in CHF mice indicates that T-cell

Figure 5. CD28 or B7 deficiency attenuates transverse aortic constriction (TAC)–induced lung macrophage infiltration and proinflammatory cytokine expression. Data were collected from lungs of wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. A. Flow cytometry plots and quantitative data represent the percentage of macrophages (F4/80+) in the lung. B. Quantitative data of flow cytometry represent the total number of macrophages in the lung. C–E. Quantitative reverse transcription polymerase chain reaction (RT-PCR) results of interleukin (IL)-1β, tumor necrosis factor-α (TNF-α), and monocyte chemoattractant protein-1 (MCP-1) mRNA levels in lung lysates. n=5 to 6 per group. *P<0.05 vs control group; †P<0.05 vs TAC group of WT mice.

Figure 6. CD28/B7 blockade attenuates transverse aortic constriction (TAC)–induced cardiac hypertrophy and dysfunction. Data were collected from mice under basal conditions (Ctr) or treated with human-Ig (vehicle) or CTLA4-Ig under TAC conditions. A, The ratio of left ventricle (LV) and body weight of mice. B–D, Echocardiographic measurements of LV ejection fraction, LV end-systolic diameter, and LV end-diastolic diameter from hearts. *P<0.05 vs control group; †P<0.05 vs TAC group of vehicle mice.

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activation is a systemic response during CHF development. Our findings that CHF caused a significant increase in the percentage of activated effector T cells in the lungs, but unchanged percentage of these cells in the LV, suggest that T-cell activation has a greater impact on pulmonary inflammation than on LV inflammation in animals with end-stage CHF.

Because previous studies demonstrated that T cells contribute to the pathogenesis of CHF and that CD4+ T cells promote the transition from LV hypertrophy to heart failure,12,13 the dramatic increase in CD4+ TEM might promote TAC-induced CHF progression by modulating lung inflammatory responses. The reduced accumulation of TEM in LV tissues and lungs by CD28/B7 deficiency or CD28/B7 blockade after TAC is in agreement with the reports that T-cell activation contributes to tissue inflammation in other disease models, such as inflammatory responses in skin diseases,20 organ transplant–induced inflammation and rejection,21,22 and cardiovascular diseases, including hypertension and atherosclerosis.23,24 Our finding supports an important role of T-cell activation in CHF development and progression and a critical role for CD28/B7 signaling in regulating T-cell activation during CHF development.

Although CD28 or B7 deficiency completely abolished the TAC-induced increases in CD4+ TEM, we observed only a partial attenuation of the TAC-induced increases in CD8+ TEM in CD28 KO or B7 KO mice. The finding that CD28 or B7 deficiency led to a stronger inhibition of T-cell activation in CD4+ T cells than in CD8+ T cells is likely related to the constitutive expression of CD28 on CD4+ T cells and a relatively high abundance of CD28 expression on CD4+ T cells as compared with that on CD8+ T cells in mice.27 The finding that CD28 or B7 deficiency only partially inhibited the TAC-induced tissue inflammatory responses in LV tissues and lungs suggests that additional proinflammatory signaling pathways independent of CD4+ and CD8+ T-cell activation may also play important roles in CHF-associated inflammatory responses and CHF development.

The present study has several limitations. First, both CD28 and B7 deficiency significantly attenuated TAC-induced LV hypertrophy and dysfunction, as well as tissue inflammation. The dramatically reduced TAC-induced lung inflammation and remodeling in CD28- and B7-deficient mice is likely to be a collective effect of the reduced cardiac, pulmonary, and systemic T-cell activation in these mice. However, we are unable to determine the relative contribution of cardiac, pulmonary, and systemic T-cell activation in the CHF progression and lung remodeling. In addition, because global CD28 KO and B7 KO mouse strains were used for our study, some of the observed phenotypes may be a result of chronic adaptation to the global gene deletion. Furthermore, the present study could not determine whether the cardioprotective effects in CD28 KO and B7 KO mice are because of CD28 and B7 gene deletion in leukocytes or in other cell types.

In summary, we demonstrate that CD28/B7 signaling contributes significantly to chronic pressure overload–induced cardiac and pulmonary inflammation and the development of CHF. Our study suggests that strategies that target CD28/B7 signaling may be useful in treating CHF.

**Perspectives**

Congestive heart failure (CHF) is accompanied by increased leukocyte accumulation and increased inflammatory cytokine expression in hearts and lungs, which exacerbates the development and progression of CHF. The interaction of the CD28 coreceptor with B7 proteins regulates T-cell activation. In this article, we demonstrate that CD28 or B7 deficiency attenuates systolic overload–induced CHF development by reducing cardiac and pulmonary inflammation and remodeling. Our study provides direct evidence that strategies targeting T-cell activation may be useful in treating CHF.

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**Disclosures**

None.

**References**


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**Novelty and Significance**

**What Is New?**

- CD28/B7 deficiency inhibits effector T-cell accumulation, reduces myocardial and pulmonary inflammation, and attenuates the development of congestive heart failure.

**What Is Relevant?**

- Congestive heart failure development is associated with T-cell activation–involved inflammatory responses. Thus, inhibition of T-cell activation by blocking CD28/B7 signaling may be a promising strategy in treating congestive heart failure.

**Summary**

CD28/B7 signaling contributes to chronic pressure overload–induced cardiac and pulmonary inflammation and the development of congestive heart failure, suggesting that strategies targeting T-cell activation may be useful for congestive heart failure treatment.
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CD28/B7 deficiency attenuates systolic overload-induced congestive heart failure, myocardial and pulmonary inflammation, and activated T-cell accumulation in the heart and lungs

Short title: T-cell activation and congestive heart failure

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Materials and Methods

Animals and experimental design: CD28 KO (B6.129S2-Cd28tm1Mak/J, stock No. 002666) and B7 KO (B6.129S4-Cd80tm1Shr Cd86tm2Shr/J, stock No. 003610) mice and C57BL/6J wild-type (WT) mice were obtained from Jackson Laboratory. The fusion protein CTLA4-Ig (abatacept, 250 μg), which inhibits CD28/B7 interactions, was administered intraperitoneally every 3 days beginning 1 day before TAC. An isotype control antibody human IgG was used as a vehicle control. Male mice 4-5 weeks of age were subjected to a procedure using a 27G needle to create the transverse aortic constriction (TAC) as previously described. Data were collected 8 weeks after TAC. Left ventricle (LV) hypertrophy and cardiac function were assessed. Experimental studies were approved by the Institutional Animal Care and Use Committee at the University of Minnesota.

Echocardiography and evaluation of LV hemodynamics: Mouse echocardiographic images were obtained with a Visualsonics high-resolution Vevo 2100 system as previously described. For aortic and LV pressure measurement, a 1.2-F pressure catheter (Scisense Inc) was introduced through the right common carotid artery into the ascending aorta and then advanced into the LV for measurement of end-diastolic pressures and positive and negative LV rate of pressure development (dP/dt) as described previously.

Sample collection: Mouse heart and lung samples for protein analysis were flash frozen in liquid nitrogen, weighted on an electronic balance and stored in liquid nitrogen until transfer into a -80°C freezer. Samples for histological analysis were directly embedded in frozen blocks.

Western blotting: Samples of the LV and lung were lysed in complete RIPA buffer (10mM Tris-HCl pH 7.4, 150mM NaCl, 1% NP40, 0.1% sodium dodecyl sulfate (SDS), 1mM phenylmethylsulfonyl fluoride (PMSF) and 1x protease inhibitor cocktail (Roche)) and homogenized by Sonic Dismembrator 100 (Fisher Scientific). The protein concentration of tissue homogenates was measured using Bio-Rad Protein Assay, and equal amounts of soluble protein were separated on 10% polyacrylamide gels, transferred onto nitrocellulose membrane, and followed by routine western blot analysis. Antibody against atrial natriuretic peptide (ANP) was purchased from Peninsula Laboratories Inc.; Myosin heavy chain (slow skeletal muscle, β-MHC) was from Sigma and vinculin was from Santa Cruz Biotechnology, Inc.. All chemicals unspecified were obtained from Sigma.

Histological staining: Sections of 5 μm thickness were sliced. LV and lung fibrosis was stained using Sirius red and Fast green Stain Kit from Chondrex, Inc.. Fibrosis quantification was done by dividing the area of red staining by the total measured section area in digitized images. Samples from 5 mice were analyzed per group.

Flow cytometric analysis: Cells were isolated from LVs and lungs. Individual LVs were excised, cutted into small pieces, and enzymatically digested in 5 ml of collagenase digestion buffer (HBSS without Ca+/Mg+ (Life technologies), 1.5 mg/ml collagenase
type II (Worthington Laboratories)) at 37°C for 30 min with agitating, subsequently transferred into 5 ml of collagenase/dispassage digestion buffer (HBSS without Ca+/Mg+, 1 mg/ml collagenase/dispassage (Roche)) for another 20 min at 37°C with agitating, and then pressed against the bottom of a 100 µm strainer with the plunger of a 3 ml syringe. Individual lungs were excised, cut into small pieces, and enzymatically digested in 5 ml of digestion buffer (HBSS without Ca+/Mg+ (Life Technologies), 1 mg/ml collagenase (Roche)) at 37°C for 30 min with agitating, and then pressed against the bottom of a 100 µm strainer with the plunger of a 3 ml syringe. Single cells from tissues were washed through the strainer with 10 ml cold buffer (PBS + 0.5%BSA + 2 mM EDTA). After erythrocyte lysis using Red Blood Cell Lysing Buffer (Sigma), cells were counted using a hemocytometer. Single cells suspensions were pre-incubated with anti-mouse CD16/32 (clone 2.4G2) antibody to prevent non-specific binding of antibodies to FcRγ, followed by multi-staining with fluorescence directly conjugated primary antibodies (Table S1), accordingly. Dead cells were stained with propidium iodide staining solution. Samples were subjected to FACS Aria II analysis (BD Biosciences). All antibodies unspecified were obtained from BD Biosciences. Data were analyzed by FlowJo_V10 (FlowJo, OR) software. Values represent the mean of five independent experiments.

Quantitative real-time PCR: Total RNA from mouse LV and lung was extracted using Trizol reagent (Invitrogen), and 2 µg of total RNA was used for reverse transcription reaction using Reverse Transcription & cDNA Synthesis Kit-Advantage RT for PCR Kit (Clontech Laboratories) followed by quantitative PCR using FastStart Universal SYBR Green Master (Rox) (Roche Applied Science). Primer pairs used in this study are listed in Table S2. The relative amount of each gene in each sample was estimated by the ΔΔCT method. Results were normalized to 18S rRNA level.

References

### Table S1. Primary antibodies used in flow cytometric analysis

<table>
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<tr>
<th>Antibody</th>
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<th>Name of the Company</th>
<th>Catalog number</th>
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<td>BD Biosciences</td>
<td>553142</td>
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<td>30-F11</td>
<td>BD Biosciences</td>
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<td>PE/Cy7-conjugated anti-CD45</td>
<td>30-F11</td>
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<td>552848</td>
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<td>145-2C11</td>
<td>BD Biosciences</td>
<td>557596</td>
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### Table S2. Primers used in quantitative real-time PCR

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<td>5'-CTT CTG TCT ACTGAA CTT CGG G-3’</td>
<td>5'-CAG GCT TGT CAC TCG AAT TTT G-3’</td>
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<td>IL-1β</td>
<td>5'-TCC TGT GTA ATG AAA GAC GGC-3’</td>
<td>5'-ACT CCA CTT TGC TCT TGA CTT C-3’</td>
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<td>TGF-β</td>
<td>5'-CCT GAG TGG CTG TCT TTT GA-3’</td>
<td>5'-CGT GGA GTT TGT TAT CCT TGC TG-3’</td>
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<td>MCP-1</td>
<td>5'-GCA TCC ACG TGT TGG CTC A-3’</td>
<td>5'-CTC CAG CCT ACT CAT TGG GAT CA-3’</td>
</tr>
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<td>18s</td>
<td>5'-TCG AGG CCC TGT AAT TGG AA-3’</td>
<td>5'-CCC TCC AAT GGA TCC TCG TT-3’</td>
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Table S3. Anatomic data for WT and CD28 KO mice under control and TAC conditions

<table>
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<tr>
<th>Parameters</th>
<th>WT-Ctr</th>
<th>CD28 KO-Ctr</th>
<th>WT-TAC</th>
<th>CD28 KO-TAC</th>
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</thead>
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<tr>
<td>Number of mice</td>
<td>15</td>
<td>9</td>
<td>15</td>
<td>9</td>
</tr>
<tr>
<td>Bodyweight (g)</td>
<td>26.7 ± 0.67</td>
<td>25.2 ± 0.86</td>
<td>28.2 ± 0.56</td>
<td>26.7 ± 0.76</td>
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<td>Left ventricular (LV) weight (mg)</td>
<td>95.9(88.9-101.2)</td>
<td>93.4(87.9-103.2)</td>
<td>218.5(198.9-227.9)*</td>
<td>140.3(132.8-160.4)*†</td>
</tr>
<tr>
<td>Left atria (LA) weight (mg)</td>
<td>3.6(3.2-4.3)</td>
<td>3.7(3.4-4.5)</td>
<td>16.9(9.4-27.2)*</td>
<td>5.1(3.1-5.3)*†</td>
</tr>
<tr>
<td>Lung mass (mg)</td>
<td>141.3(135.3-152.3)</td>
<td>148.7(146.8-158.7)</td>
<td>228.8(169.9-404.9)*</td>
<td>180.7(179.6-181.1)*†</td>
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<td>Right ventricular (RV) weight (mg)</td>
<td>24.0(22.6-26.1)</td>
<td>24.7(23.4-27.1)</td>
<td>36.7(31.2-44.1)*</td>
<td>24.6(23.5-27.6)†</td>
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<tr>
<td>Ratio of LV weight to body weight (mg/g)</td>
<td>3.6(3.5-3.8)</td>
<td>3.8(3.5-4.1)</td>
<td>7.5(7.0-8.5)*</td>
<td>5.8(5.6-6.1)*†</td>
</tr>
<tr>
<td>Ratio of LA weight to body weight (mg/g)</td>
<td>0.15(0.13-0.17)</td>
<td>0.17(0.16-0.19)</td>
<td>0.57(0.32-1.14)*</td>
<td>0.20(0.13-0.21)†</td>
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<td>Ratio of lung weight to body weight (mg/g)</td>
<td>5.5(4.9-5.9)</td>
<td>6.2(5.7-6.7)</td>
<td>7.7(5.7-15.8)*</td>
<td>7.0(6.5-7.7)†</td>
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<tr>
<td>Ratio of RV weight to body weight (mg/g)</td>
<td>0.9(0.8-1.0)</td>
<td>1.0(0.9-1.1)</td>
<td>1.3(1.1-1.6)*</td>
<td>1.1(1.0-1.2)†</td>
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<tr>
<td>Tibial length (mm)</td>
<td>17.5 ± 0.07</td>
<td>17.3 ± 0.18</td>
<td>17.7 ± 0.05*</td>
<td>17.6 ± 0.09*</td>
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<tr>
<td>Ratio of LV weight to tibial length (mg/mm)</td>
<td>5.6(5.3-5.8)</td>
<td>5.4(5.2-6.5)</td>
<td>12.3(11.3-12.7)*</td>
<td>8.0(7.6-9.0)*†</td>
</tr>
<tr>
<td>Ratio of LA weight to tibial length (mg/mm)</td>
<td>0.23(0.19-0.24)</td>
<td>0.25(0.21-0.26)</td>
<td>0.94(0.53-1.55)*</td>
<td>0.29(0.18-0.34)†</td>
</tr>
<tr>
<td>Ratio of lung weight to tibial length (mg/mm)</td>
<td>8.2(7.9-8.6)</td>
<td>8.4(8.1-9.2)</td>
<td>12.8(9.6-22.3)*</td>
<td>9.2(8.1-10.3)†</td>
</tr>
<tr>
<td>Ratio of RV weight to tibial length (mg/mm)</td>
<td>1.38(1.31-1.48)</td>
<td>1.42(1.36-1.61)</td>
<td>2.06(1.76-2.48)*</td>
<td>1.41(1.33-1.56)†</td>
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</table>

Data are presented as mean ± SEM when normally distributed. Data are presented as median (quartile1-quartile3) when not normally distributed. *p<0.05 as compared with corresponding control conditions; † p<0.05 as compared with WT mice under the TAC condition.
Table S4. Anatomic data for WT and B7 KO mice under control and TAC conditions

<table>
<thead>
<tr>
<th>Parameters</th>
<th>WT-Ctr</th>
<th>B7 KO-Ctr</th>
<th>WT-TAC</th>
<th>B7 KO-TAC</th>
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<tbody>
<tr>
<td>Number of mice</td>
<td>15</td>
<td>15</td>
<td>15</td>
<td>9</td>
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<tr>
<td>Bodyweight (g)</td>
<td>26.8 ± 0.42</td>
<td>27.1 ± 0.59</td>
<td>28.0 ± 0.67</td>
<td>32.2 ± 1.04*†</td>
</tr>
<tr>
<td>Left ventricular (LV) weight (mg)</td>
<td>96.2(89.1-101.9)</td>
<td>94.8(88.4-101.5)</td>
<td>214.2(175.5-227.2)*</td>
<td>174.1(132.9-188.2)*†</td>
</tr>
<tr>
<td>Left atria (LA) weight (mg)</td>
<td>3.7(3.2-4.2)</td>
<td>3.2(2.9-3.7)</td>
<td>17.8(6.9-40.3)*</td>
<td>5.1(3.3-5.8)*†</td>
</tr>
<tr>
<td>Lung mass (mg)</td>
<td>146.2(140.2-153.5)</td>
<td>150.1(146.2-162.7)</td>
<td>250.9(183.8-439.4)*</td>
<td>177.2(154.6-194.1)†</td>
</tr>
<tr>
<td>Right ventricular (RV) weight (mg)</td>
<td>23.7(22.1-24.3)</td>
<td>24.9(23.1-26.5)</td>
<td>38.8(30.0-44.4)*</td>
<td>27.3(26.3-28.8)†</td>
</tr>
<tr>
<td>Ratio of LV weight to body weight (mg/g)</td>
<td>3.6(3.5-3.7)</td>
<td>3.6(3.3-3.8)</td>
<td>7.8(5.9-8.9)*</td>
<td>5.3(4.2-6.5)*†</td>
</tr>
<tr>
<td>Ratio of LA weight to body weight (mg/g)</td>
<td>0.14(0.12-0.16)</td>
<td>0.13(0.12-0.15)</td>
<td>0.58(0.23-1.50)*</td>
<td>0.15(0.10-0.19)†</td>
</tr>
<tr>
<td>Ratio of lung weight to body weight (mg/g)</td>
<td>5.6(5.1-5.7)</td>
<td>5.8(5.5-6.1)</td>
<td>8.1(6.3-18.1)*</td>
<td>5.7(5.4-6.3)†</td>
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<tr>
<td>Ratio of RV weight to body weight (mg/g)</td>
<td>0.87(0.82-0.91)</td>
<td>0.94(0.86-0.98)</td>
<td>1.31(1.02-1.67)*</td>
<td>0.87(0.76-0.92)†</td>
</tr>
<tr>
<td>Tibial length (mm)</td>
<td>17.4 ± 0.06</td>
<td>17.5 ± 0.10</td>
<td>17.9 ± 0.05*</td>
<td>18.0 ± 0.08*</td>
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<tr>
<td>Ratio of LV weight to tibial length (mg/mm)</td>
<td>5.5(5.2-5.9)</td>
<td>5.4(5.1-5.8)</td>
<td>12.2(9.8-12.7)*</td>
<td>9.7(7.4-10.5)*†</td>
</tr>
<tr>
<td>Ratio of LA weight to tibial length (mg/mm)</td>
<td>0.19(0.18-0.24)</td>
<td>0.18(0.16-0.21)</td>
<td>0.99(0.38-2.23)*</td>
<td>0.28(0.18-0.33)†</td>
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<tr>
<td>Ratio of lung weight to tibial length (mg/mm)</td>
<td>8.4(8.1-8.8)</td>
<td>8.6(8.4-9.2)</td>
<td>14.0(10.4-24.4)*</td>
<td>8.9(8.1-10.1)†</td>
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<tr>
<td>Ratio of RV weight to tibial length (mg/mm)</td>
<td>1.34(1.28-1.38)</td>
<td>1.42(1.34-1.51)</td>
<td>2.21(1.70-2.44)*</td>
<td>1.49(1.48-1.61)†</td>
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Data are presented as mean ± SEM when normally distributed. Data are presented as median (quartile1-quartile3) when not normally distributed. *p<0.05 as compared with corresponding control conditions; † p<0.05 as compared with WT mice under the TAC condition.
Figure S1. End-stage congestive heart failure (CHF) exhibits increased activated T-cell accumulation in Hearts and Lungs. Data were collected from mice under control (Ctr) and CHF conditions. A and B, The ratio of left ventricle (LV) and lung weight to body weight of mice. C, Echocardiographic measurements of LV ejection fraction from hearts. D and E, Flow cytometry plots and quantitative data represent the percentage of CD3+CD44+ cells in LV tissues and lungs. F, Flow cytometry quantitative data represent the number of CD3+ T cells in whole LV tissues and lungs. G, Flow cytometry quantitative data of CD45+ cells in LV tissues and lungs. n=8 per group.

*P<0.05 vs control group.
Figure S2. End-stage congestive heart failure (CHF) exhibits an increased spleen weight and increased percentage of activated CD4+ T-cells in splenocytes. Data were collected from mice under control (Ctr) and CHF conditions. A, Flow cytometry plots and quantitative data represent the percentage of CD4+ and CD8+ T-cells in splenocytes. B, Flow cytometry plots and quantitative data represent the percentage of CD44hiCD62Llo T-cells (effector memory T cells, TEM) within the CD4+ population of splenocytes. C, The ratio of spleen weight to body weight of mice. n=8 per group. *P<0.05 vs control group.
Figure S3. End-stage congestive heart failure (CHF) exhibits an increased percentage of activated CD4+ T-cells in peripheral blood cells. Data were collected from mice under control (Ctrl) and CHF conditions. **A**, Flow cytometry plots and quantitative data represent the percentage of CD4+ and CD8+ T cells in peripheral blood cells. **B** and **C**, Flow cytometry plots and quantitative data represent the percentage of CD44^high^CD62L^low^ T cells (effector memory T cells, TEM) and CD44^low^CD62L^high^ T cells (naive T cells) within the CD4+ or CD8+ population of peripheral blood cells. n=8 per group. ^*^P<0.05 vs control group.
Figure S4. For flow cytometric analysis, single cells from the digested LV were stained with directly conjugated primary antibodies according to the manufacturer’s instructions, followed by staining with PI and then subjected to FACS Aria II analysis. Cells that were negative for PI staining were identified as living cells and analyzed.
Figure S5. For flow cytometric analysis, single cells from the digested lung were stained with directly conjugated primary antibodies according to the manufacturer’s instructions, followed by staining with PI and then subjected to FACS Aria II analysis. Cells that were negative for PI staining were identified as living cells and analyzed.
Figure S6. For flow cytometric analysis, single cells from the spleen were stained with directly conjugated primary antibodies according to the manufacturer’s instructions, followed by staining with PI and then subjected to FACS Aria II analysis. Cells that were negative for PI staining were identified as living cells and analyzed.
Figure S7. For flow cytometric analysis, single cells from peripheral blood were stained with directly conjugated primary antibodies according to the manufacturer’s instructions, followed by staining with PI and then subjected to FACS Aria II analysis. Cells that were negative for PI staining were identified as living cells and analyzed.
Figure S8. Left ventricular (LV) systolic pressure was significantly increased by transverse aortic constriction (TAC) to a similar level in wild-type (WT) and CD28 or B7 knockout (KO) mice. Data were collected from mice under control conditions (Ctr) or 8 weeks after TAC. A and B, Hemodynamics of LV systolic pressure and mean aortic pressure from hearts of WT and CD28 KO mice. C and D, Hemodynamics of LV systolic pressure and mean aortic pressure from hearts of WT and B7 KO mice. *P<0.05 vs control group.
Figure S9. CD28 or B7 deficiency inhibits transverse aortic constriction (TAC)-Induced CD3⁺ T-cell early activation in the left ventricle (LV) and lung. Flow cytometry data were collected from wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. A to C, Flow cytometry plots and quantitative data represent the percentage of CD3⁺CD69⁺ T cells (early activated T cells) within the CD3⁺ T-cell population of LV tissues and lungs. D, Quantitative data represent total numbers of CD3⁺CD69⁺ T cells in LV tissues and lungs. n=5-6 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of WT mice.
Figure S10. CD28 or B7 deficiency attenuates transverse aortic constriction (TAC)-induced left ventricle (LV) fibrosis. Data were collected from wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. A and B, Representative images and quantitative data of Sirius red/Fast green staining for detection of fibrosis in LV tissues. C, Quantitative RT-PCR results of TGF-β mRNA levels in LV lysates. n=5 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of WT mice.
Figure S11. CD28 or B7 deficiency inhibits transverse aortic constriction (TAC)-induced CD3+ T-cell activation and accumulation in the lung. Flow cytometry data were collected from wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. A, Flow cytometry plots and quantitative data represent the percentage of CD3+CD44^hi^CD62L^lo^ T cells (effector memory T cells, TEM) within the CD3+ population of lungs. B, Total numbers of CD3+CD44^hi^CD62L^lo^ T cells in lungs. n=5-6 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of WT mice.
Figure S12. CD28 or B7 deficiency inhibits transverse aortic constriction (TAC)-induced CD4+ and CD8+ cell early activation and accumulation in the lung. Flow cytometry data were collected from wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. 
A, Flow cytometry plots and quantitative data represent the percentage of CD4+CD69+ T cells within the CD4+ population of lungs. B, Total numbers of CD4+CD69+ T cells in lungs. C, Flow cytometry plots and quantitative data represent the percentage of CD8+CD69+ T cells within the CD8+ population of lungs. D, Total numbers of CD8+CD69+ T cells in lungs. n=5-6 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of WT mice.
Figure S13. CD28 or B7 deficiency inhibits transverse aortic constriction (TAC)-induced CD4⁺ and CD8⁺-cell activation and accumulation in the lung. Flow cytometry data were collected from wild-type (WT) and CD28 or B7 knockout (KO) mice under control conditions (Ctr) or 8 weeks after TAC. A, Flow cytometry plots and quantitative data represent the percentage of CD4⁺CD44<sup>hi</sup> T cells within the CD4⁺ population of lungs. B, Total numbers of CD4⁺ CD44<sup>hi</sup> T cells in lungs. C, Flow cytometry plots and quantitative data represent the percentage of CD8⁺ CD44<sup>hi</sup> T cells within the CD8⁺ population of lungs. D, Total numbers of CD8⁺ CD44<sup>hi</sup> T cells in lungs. n=5-6 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of WT mice.
Figure S14. CD28/B7 blockade inhibits transverse aortic constriction (TAC)-induced CD4+ T-cell activation in the lung. Data were collected from mice under basal conditions (Ctr), or treated with human-Ig (vehicle) or CTLA4-Ig under TAC conditions. A, Hemodynamics of left ventricular systolic pressure of mice. B, Flow cytometry plots and quantitative data represent the percentage of CD44highCD62Llow T cells within the CD4+ population of lungs. C, Flow cytometry plots and quantitative data represent the percentage of CD69+ T cells within the CD4+ population of lungs. n=3-6 per group. *P<0.05 vs control group; #P<0.05 vs TAC group of vehicle mice.