Mineralocorticoid Receptor Deficiency in T Cells Attenuates Pressure Overload–Induced Cardiac Hypertrophy and Dysfunction Through Modulating T-Cell Activation

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Abstract—Although antagonists of mineralocorticoid receptor (MR) have been widely used to treat heart failure, the underlying mechanisms are incompletely understood. Recent reports show that T cells play important roles in pathologic cardiac hypertrophy and heart failure. However, it is unclear whether and how MR functions in T cells under these pathologic conditions. We found that MR antagonist suppressed abdominal aortic constriction–induced cardiac hypertrophy and decreased the accumulation and activation of CD4+ and CD8+ T cells in mouse heart. T-cell MR knockout mice manifested suppressed cardiac hypertrophy, fibrosis, and dysfunction compared with littermate control mice after abdominal aortic constriction. T-cell MR knockout mice had less cardiac inflammatory response, which was illustrated by decreased accumulation of myeloid cells and reduced expression of inflammatory cytokines. Less amounts and activation of T cells were observed in the heart of T-cell MR knockout mice after abdominal aortic constriction. In vitro studies showed that both MR antagonism and deficiency repressed activation of T cells, whereas MR overexpression elevated activation of T cells. These results demonstrated that MR blockade in T cells protected against abdominal aortic constriction–induced cardiac hypertrophy and dysfunction. Mechanistically, MR directly regulated T-cell activation and modulated cardiac inflammation. Targeting MR in T cells specifically may be a feasible strategy for more effective treatment of pathologic cardiac hypertrophy and heart failure. (Hypertension. 2017;70:137-147. DOI: 10.1161/HYPERTENSIONAHA.117.09070.) *Online Data Supplement

Key Words: cardiac hypertrophy ■ heart failure ■ mineralocorticoid receptor ■ T cells ■ T-cell activation

Pathologic cardiac hypertrophy is a maladaptation of the heart responding to conditions such as chronic hypertension and myocardial infarction.1 The pathologic remodeling of the heart is often associated with deleterious disorders, including cardiac fibrosis, chronic inflammatory response, and cardiac dysfunction, leading to heart failure, which remains to be a leading cause of mortality and morbidity around the world.2 Better understanding of the underlying pathophysiology and development of novel strategies are in need to achieve better outcome in treating pathologic cardiac hypertrophy and heart failure.

T cells have emerged as an important cellular compartment for targeting pathologic cardiac hypertrophy and heart failure.3,4 In particular, recent data have revealed that activation of T cells plays a fundamental role in pressure overload (POL)–induced cardiac hypertrophy and heart failure. Deletion of T-cell receptor alpha, an important component of signal 1 of T-cell activation, reduces cardiac fibrosis, hypertrophy, and inflammation, as well as improves cardiac function and survival in a mouse model of POL.5 Similarly, deletion or blockade of CD28 or B7, essential components of signal 2 of T-cell activation, attenuates POL-induced cardiac hypertrophy, heart failure, cardiac inflammation, and T-cell accumulation.6 Interestingly, CD4+ T cells, but not CD8+ T cells, are critical in the transition from cardiac hypertrophy to heart failure in response to POL.7 Therefore, it may be a feasible strategy to identify key molecules that regulate T-cell function and that ultimately intervene in cardiac hypertrophy and heart failure.

Mineralocorticoid receptor (MR) is an important drug target for treating heart failure. Clinical trials have
convincingly demonstrated the beneficial effects of MR antagonists for heart failure patients. Similar results were observed in murine models of cardiac hypertrophy and heart failure. However, the usage of MR antagonists, spironolactone and eplerenone, remains suboptimal at least partially because of their side effects. Delineating the underlying mechanisms may facilitate better usage of spironolactone and eplerenone and help to develop new generation of MR antagonists.

Studies in recent years have shed some light on the cellular and molecular mechanisms of how MR functions in the setting of cardiac hypertrophy and heart failure, although they remain to be incompletely understood. Cardiomyocyte MR deficiency improves cardiac dysfunction in a mouse model of myocardial infarction. Although MR deletion in cardiomyocyte protects end-stage heart failure induced by POL, it has no effect on cardiac hypertrophy or fibrosis in this model. Macrophage MR deficiency attenuates cardiac hypertrophy and remodeling in various mouse models of POL, including aortic constriction and treatment with NG-nitro-l-arginine methyl ester/angiotensin II or deoxycorticosterone/salt. Mechanistically, MR in macrophages has been demonstrated to control macrophage polarization. However, the function of T-cell MR in pathologic cardiac hypertrophy and heart failure has not been explored.

In this study, we set out to determine whether and how MR in T cells affects pathologic cardiac hypertrophy and dysfunction. We first study the impacts of eplerenone on pathologic cardiac hypertrophy and T-cell activation. Then, we used T-cell MR knockout (TMRKO) mouse model to further establish the roles of T-cell MR in cardiac hypertrophy, fibrosis, dysfunction, and cardiac inflammation. Subsequently, we determine the effects of TMRKO on T-cell accumulation and activation in the heart. Finally, we explore the direct influence of MR on T-cell activation in vitro.

**Methods**

**Animals and Surgeries**

TMRKO mice were generated by crossing floxed MR mice with CD4-Cre mice as previously described. Male C57BL6/J mice were purchased from SLAC Laboratory Animal Co. Eplerenone was mixed in regular rodent chow (2 g/kg; SLAC Laboratory Animal Co.) and administrated 3 days before surgeries until the end of experiments to deliver a dosage of ∼200 mg/kg/d. Abdominal aortic constriction (AAC) was performed according to previous report. Briefly, male mice (8–12 weeks old) were anesthetized with 2% isoflurane inhalation. Silk sutures (6–0) were used to ligate abdominal aortas for another 4 days. The needle was then removed immediately. For sham operation, sutures were removed above both renal arteries. The needle was then removed immediately. For sham operation, sutures were removed above both renal arteries. For AAC, mice were anesthetized with 2% isoflurane and received aortic constriction with a blunted 27G needle above both renal arteries.

**Statistical Analysis**

The results were presented as means±SE and analyzed using Prism (GraphPad Software). Multiple comparisons were tested with 2-way analysis of variance followed by Bonferroni posttests. Pairwise comparisons were analyzed by Student’s t test. Results were considered significantly different if P values were ≤0.05.

**Results**

**Eplerenone Inhibits AAC-Induced Cardiac Hypertrophy and T-Cell Activation**

Similar to previous reports, eplerenone significantly decreased ventricular weight-to-body weight ratio in mice 1 week after AAC, illustrating suppression of cardiac hypertrophy (Figure S1A in the online-only Data Supplement). We then analyzed cardiac T cells using flow cytometry (Figure S1B). AAC markedly induced accumulation of both CD4+ and CD8+ T cells in the heart, and this was substantially inhibited by eplerenone treatment (Figure 1A). In addition, activated T cells (CD69+) were upregulated in hypertrophic hearts, and eplerenone decreased CD69+ T cells in both CD4+ and CD8+ subpopulations (Figure S1C; Figure 1B and 1C).

Recent data have indicated the involvement of memory T cells in pathologic cardiac remodeling. Moreover, effector memory T cells (TEM, CD44hiCD62Llow) are the main source of inflammatory cytokines, such as IFNγ. We further analyzed this T-cell subpopulation using flow cytometry (Figure S1D). Eplerenone significantly decreased the accumulation of both CD4+ and CD8+ TEM cells in heart samples after AAC (Figure 1D and 1E). Furthermore, eplerenone suppressed both CD4+ IFNγ+ and CD8+ IFNγ+ T cells (Figure S1D through S1F). Eplerenone did not significantly alter blood pressure under AAC (Figure S2). These results indicated that eplerenone suppressed cardiac hypertrophy at least partially through its impacts on T cells, independently of its effects on blood pressure.

**T-Cell MR Deficiency Attenuates AAC-Induced Cardiac Hypertrophy and Fibrosis**

To further test whether blockade of MR in T cells specifically would affect cardiac hypertrophy, TMRKO mice was generated. Ventricular weight-to-body weight ratio demonstrated significantly less cardiac hypertrophy in TMRKO mice than in littermate control mice 1 and 6 weeks after AAC (Figure 2A). Hematoxilin and eosin staining of cross sections of left ventricles showed significantly decreased cardiomyocyte size in TMRKO mice after AAC (Figure 2B; Figure S3A). Picrosirus red staining showed that TMRKO effectively decreased AAC-induced cardiac fibrosis (Figure 2C; Figure S3B). Consistently, quantitative reverse transcriptase polymerase chain reaction analysis revealed that cardiac expression of fetal genes, such as natriuretic peptide A (ANP), natriuretic peptide B (BNP), and cardiac myosin heavy chain β (JMHC), was significantly inhibited in TMRKO mice after AAC (Figure 2D). Cardiac expression of fibrosis-related genes, such as collagen I, collagen III, connective tissue growth factor precursor (CTGF), and transforming growth factor β (TGFβ1), was also inhibited in TMRKO mice after AAC (Figure 2E). Telemetric...
monitoring\textsuperscript{23} showed no difference in either systolic or diastolic blood pressure between littermate control and TMRKO mice after AAC (Figure S4), excluding the influence of different pressure to the heart.

**T-Cell MR Deficiency Attenuates AAC-Induced Cardiac Dysfunction**

Chronic POL eventually leads to cardiac dysfunction. Therefore, we evaluated the effects of TMRKO on cardiac
function using echocardiography. Four weeks after AAC, both end-systolic and end-diastolic left ventricular diameter and volume were augmented in littermate control mice, and these parameters were all attenuated in TMRKO mice (Figure 3A through 3D). Consistently, left ventricular fractional shortening and ejection fraction were both significantly mitigated in TMRKO mice after AAC (Figure 3E and 3F). These results supported that T-cell MR deficiency was beneficial to cardiac function under pathologic conditions.

T-Cell MR Deficiency Decreases AAC-Induced Cardiac Inflammatory Response

Inflammation plays critical roles in pathologic cardiac remodeling. We next determined whether TMRKO affected cardiac inflammation. Accumulation of myeloid cells in the heart was first analyzed using flow cytometry (Figure S5). Both monocytes/macrophages (CD11b+ Ly6G−) and neutrophils (CD11b+ Ly6G+) were decreased in TMRKO hearts 1 week after AAC (Figure 4A). Furthermore, Ly6C+ inflammatory monocytes were decreased in TMRKO mice after AAC (Figure 4B). Immunofluorescence staining further confirmed the diminished cardiac accumulation of neutrophils (Gr-1+) and macrophages (CD68+) in TMRKO mice (Figure 4C and 4D). Finally, quantitative reverse transcriptase polymerase chain reaction results demonstrated that expression of F4/80 and inflammatory genes, including IL-1β (interleukin-1β), RANTES (regulated on activation, normal T-cell expressed and secreted), and MCP-1 (monocyte chemoattractant protein-1), was substantially suppressed in TMRKO hearts after AAC, further supporting the attenuated cardiac inflammatory response (Figure 4E).
T-Cell MR Deficiency Decreases AAC-Induced T-Cell Accumulation and Activation in the Heart

We next explored how MR deficiency affected T cells in the process of cardiac hypertrophy. Flow cytometric analysis showed that AAC-induced cardiac accumulation of both CD4+ T cells and CD8+ T cells was markedly mitigated in TMRKO mice compared with littermate control mice (Figure 5A). Numbers of both CD4+/CD69+ and CD8+/CD69+ T cells were significantly decreased in hearts of TMRKO mice after AAC (Figure 5B and 5C). Further, CD4+ TEM cells were sharply decreased in heart samples from TMRKO mice after AAC (Figure 5D). There was also a tendency of reduction of CD8+ TEM cells in hearts of TMRKO mice after AAC (Figure 5E).

In addition, TMRKO significantly suppressed the number of CD4+ IFNγ+ T cells in hypertrophied hearts (Figure S6A) and to a less extent, the number of CD8+ IFNγ+ T cells (Figure S6B). These results suggested that the activation of T cells, especially CD4+ T cells, was downregulated by T-cell MR deficiency in the setting of pathologic cardiac hypertrophy.

MR Regulates T-Cell Activation In Vitro

Previous data have shown that CD4+ T cells, rather than CD8+ T cells, play a dominant role during POL-induced cardiac hypertrophy and dysfunction. Therefore, we paid attention particularly to CD4 T cell in our experiment. Elevated expression of IL-2 and increased expression of cell surface molecules, such as CD44, CD69, and CD25, are important markers of T-cell activation. Quantitative reverse transcriptase polymerase chain reaction results showed that MR antagonist spironolactone effectively inhibited the expression of IL-2 in naive splenic CD4+ T cells stimulated by anti-CD3 antibodies (Figure S7A). Flow cytometric analysis demonstrated that spironolactone repressed anti-CD3–induced elevation of CD4+CD44+ population (Figure S7B). Expression of CD69 and CD25 in CD4+ T cells was also suppressed by spironolactone (Figure S7C and S7D). Nonetheless, spironolactone also decreased the expression of CD44 and CD69 in CD8+ T cells (Figure S8).

Consistently, TMRKO largely recapitulated the effects of spironolactone on the expression of IL-2 (Figure 6A) and the percentage of CD4+CD44+, CD4+CD69+, and CD4+CD25+ populations in naive CD4+ T cells under the stimulation of anti-CD3 antibodies (Figure 6B through 6D). Furthermore, TMRKO markedly inhibited the secretion of inflammatory cytokines, including IFNγ and IL-6, in activated CD4+ T cells (Figure 6E). During T-cell activation, NFATc2 (nuclear factor of activated T cells, cytoplasmic 2) is dephosphorylated and translocated into nucleus to initiate IL-2 transcription. Western blotting results showed that TMRKO noticeably decreased the amount of dephosphorylated NFATc2 after stimulation with anti-CD3 antibodies for 1 and 2 hours (Figure 6F).

On the contrary, overexpression of MR in naive CD4+ T cells using lentivirus (Figure S9A) significantly upregulated the expression of IL-2 as demonstrated by quantitative reverse transcriptase polymerase chain reaction (Figure S9B) and the percentage of CD4+CD44+ and CD4+CD69+ population as demonstrated by flow cytometric analysis (Figure S9C and S9D).

To further confirm our results in fully activated T cells, MR antagonist–treated, TMRKO, and MR-overexpressed CD4+ T cells were stimulated with the combination of anti-CD3 and anti-CD28 antibodies. Consistently, MR inhibition and TMRKO downregulated, whereas overexpression of MR upregulated IL-2, CD44, and CD69 (Figure S10). Flow cytometric analysis demonstrated that TMRKO did not affect proliferation of CD4+ T cells (Figure S11).
Although functions of MR in several other cell types have been elucidated in pathologic cardiac hypertrophy and heart failure, the roles of MR in T cells have not been illuminated. Through this study, we demonstrated that eplerenone and TMRKO attenuated POL-induced cardiac remodeling and dysfunction in parallel with attenuated cardiac inflammation, as well as decreased T-cell accumulation and activation in the heart. Moreover, in vitro results illustrated direct regulation of T-cell activation by MR.

This study implies that MR blockade in T cells is a feasible approach to treat pathologic cardiac hypertrophy and heart failure. MR deficiency in T cells was sufficient to suppress POL-induced cardiac hypertrophy, cardiac fibrosis,
Figure 5. T-cell mineralocorticoid receptor (MR) deficiency decreases abdominal aortic constriction (AAC)-induced T-cell accumulation and activation in the heart. A, Flow cytometric analysis of T cells in heart samples from littermate control (LC) and T-cell MR knockout (TMRKO) mice undergoing sham operation or AAC. n=5:5:15:14. B, Flow cytometric analysis of CD4+ CD69+ T cells in heart samples. n=5:5:13:12. C, Flow cytometric analysis of CD8+ CD69+ T cells in heart samples. n=5:5:13:12. D, Flow cytometric analysis of CD4+ effector memory T cells (CD4+ CD44high CD62Llow) in heart samples. n=8:8:10:10. E, Flow cytometric analysis of CD8+ effector memory T cells (CD8+ CD44high CD62Llow) in heart samples. n=8:8:10:10. *P<0.05, **P<0.01, ***P<0.001.
and cardiac dysfunction, as well as cardiac inflammation in mice. Particularly, TMRKO completely abrogated parts of the phenotype 1 week after POL, indicating that MR in T cells may be more important than MR in other cellular compartments in the early stage of cardiac remodeling. MR deletion in other cell types, such as cardiomyocytes, also manifests protection against cardiac remodeling, mostly in the later stage rather than the early stage of the process. It is conceivable to target MR in T cells specifically to circumvent the side effects of systemic MR blockade. An early study engineered a chimeric major histocompatibility complex class II to deliver doxorubicin to CD4+ T cells through specific binding of T-cell receptor. Similar approach could be exploited to deliver MR antagonists to specifically target T cells and treat pathologic cardiac hypertrophy and heart failure with fewer side effects in expectation. Higher dosage is also plausible when better efficacy is desired.

Figure 6. Mineralocorticoid receptor (MR) regulates T-cell activation in vitro. A, Quantitative reverse transcriptase polymerase chain reaction (QRT-PCR) analysis of IL-2 (interleukin-2) gene expression in naive CD4+ T cells isolated from littermate control (LC) and T-cell MR knockout (TMRKO) mice without stimulation (unstimulated) or stimulated with anti-CD3 for 24 h. B, Flow cytometric analysis of CD44 in naive CD4+ T cells isolated from LC and TMRKO mice. C, Flow cytometric analysis of CD69 in naive CD4+ T cells. D, Flow cytometric analysis of CD25 in naive CD4+ T cells. E, Enzyme-linked immunosorbent assay (ELISA) of IFNγ (interferon-γ) and IL-6 in culture media from naive CD4+ T cells. F, Western blotting analysis of NFATc2 (nuclear factor of activated T cells, cytoplasmic 2) in naive CD4+ T cells. Data represent 3 independent experiments. **P<0.01, ***P<0.001.
We have provided evidence to show the direct role of T-cell MR in regulation of T-cell activation, particularly in the setting of pathologic cardiac remodeling. MR signaling has been shown to regulate the number of circulating T cells in human subjects. Spironolactone decreases the expression of IL-17 and increases that of forkhead box P3 in a rat model of hypertension, indicating that MR blockade downregulates Th17, while it upregulates Treg polarization. Intriguingly, earlier data suggest that aldosterone and spironolactone modulate the function of dendritic cells, which affect T-cell activation and polarization. However, the direct role of MR in CD4+ T cells has not been vigorously investigated. Our in vivo results illustrated that MR deficiency in T cells markedly suppressed the accumulation and activation of T cells in hypertrophied hearts. In vitro results further elaborated a direct regulatory role of MR on activation of CD4+ T cells, using specific knockout antagonism. Moreover, our data indicated that NFATc2 was a connecting point mediating the functions of MR in CD4+ T cells, although the molecular machinery needed further exploration.

Our data have also revealed that inflammation is an important link between MR signaling in T cells and pathologic cardiac remodeling. Inflammation is at the center stage of pathologic cardiac remodeling and heart failure. Previous reports have shown that lessened T-cell activation is correlated with diminished cardiac inflammation in the setting of POL. We presented that TMRKO mice manifested reduced cardiac inflammation in parallel with improved cardiac remodeling, as well as decreased T-cell accumulation and activation in the heart after POL. Particularly, cardiac expression levels of inflammatory cytokines, as well as accumulation of neutrophils and monocytes/macrophages, were both suppressed by T-cell MR deficiency. These data together supported the importance of inflammation in mediating the impacts of T-cell MR signaling.

MR deficiency and its influence on T-cell activation may modulate interactions between T cells and myeloid cells, contributing to the attenuated cardiac inflammation and ultimately the improved cardiac remodeling and dysfunction. Interactions between T cells and myeloid cells are essential in modulating inflammatory tissue microenvironments. CD8+ T cells infiltrate preceding accumulation of macrophages in inflamed adipose tissue and play critical roles in obesity and insulin resistance. In spontaneous autoimmune myocarditis, CD4+ T cells are assumed to orchestrate the cardiac pathology through recruiting and activating macrophages. A more recent study has exemplified the importance of reciprocal interactions between T cells and macrophages in angiotensin II–induced cardiac inflammation and remodeling. It would be reasonable that MR deficiency in T cells modulated interactions between T cells and myeloid cells in the setting of POL. However, the exact mechanisms remain to be interrogated. Either direct or cytokine-facilitated interactions between T cells and myeloid cells may mediate the effects of MR deficiency and T-cell activation on infiltration and phenotypic alterations of macrophages and neutrophils and consequently on cardiac inflammation, as well as ultimately on cardiac remodeling and dysfunction.

Perspectives
We have revealed that MR blockade, particularly in T cells, ameliorates AAC-induced cardiac hypertrophy and dysfunction. MR directly regulates T-cell activation, reflecting that MR blockade decreases activation and accumulation of T cells in the heart, likely contributing to the suppressed inflammation and cardiac protection of MR antagonism or deficiency. These results support that T-cell MR may at least partially mediate the beneficial effects of MR antagonists. Furthermore, the study provides knowledge basis for targeting MR in T cells specifically to circumvent side effects of systemic MR blockade and achieve better outcomes for treating pathologic cardiac hypertrophy and heart failure.

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Disclosures
None.

References


What Is New?

- Both genetic deficiency and pharmacologic inhibition of mineralocorticoid receptor (MR) attenuate cardiac remodeling and accumulation and activation of T cells in the heart. MR directly regulates T-cell activation.

What Is Relevant?

- MR antagonists are widely used for patients with heart failure. Our findings indicate that MR in T cells has detrimental effects during pathologic cardiac hypertrophy and dysfunction. Targeting MR in T cells specifically may be a feasible approach for treating patients with heart failure.

Summary

Pathologic cardiac hypertrophy is a major cause of heart failure. Targeting T cells represents a new approach for treating pathologic cardiac hypertrophy and heart failure. In the current study, we investigate whether MR influences T-cell activation to regulate pathologic cardiac hypertrophy. We illustrate that MR deficiency in T cells attenuates pressure overload–induced cardiac hypertrophy, fibrosis, dysfunction, and inflammation. Both MR deficiency and antagonists reduce T-cell accumulation and activation in hypertrophied hearts. In vitro, both MR antagonism and deficiency suppress activation of T cells, whereas MR overexpression elevates activation of T cells. These findings have revealed novel functions of MR in modulating T-cell activation and in regulating pathologic cardiac hypertrophy. It is conceivable to specifically target MR in T cells and to treat pathologic cardiac hypertrophy and heart failure more effectively.
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Mineralocorticoid receptor deficiency in T cells attenuates pressure overload-induced cardiac hypertrophy and dysfunction through modulating T cell activation

Running Title: T cell MR regulates cardiac hypertrophy

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Online Methods

Cardiac hypertrophy estimation and sample collection. Mice were sacrificed one or six weeks after AAC and cardiac size was assessed as before. Ventricular weight to body weight ratio (VW/BW, mg/g) was used as an indicator of cardiac hypertrophy. Ventricles were dissected. Parts of ventricles close to the base of the heart were fixed in 4% paraformaldehyde solution for paraffin section and those close to cardiac apex were embedded in O.C.T. for frozen sections. Left ventricles were separated and frozen in liquid nitrogen for further analyses.

Echocardiographic analysis. Four weeks after surgeries, cardiac function was evaluated using echocardiography (Vevo2100 Imaging System, VisualSonics). Mice were anesthetized using isoflurane. Hearts were imaged in two-dimensional LV long-axis view. M-mode frames were recorded at the papillary muscle level. Ejection fraction and fractional shorting were calculated. The procedure and analysis were performed by an investigator who was blinded to the experimental groups.

Histological analysis. Paraformaldehyde-fixed ventricle samples were embedded in paraffin and 7μm sections were stained with hematoxylin and eosin (H&E) or 0.1% picrosirius red. Cardiomyocyte crosssectional areas were measured as previously described. Fibrotic staining was quantified as a percentage of positively stained areas to the total areas examined. O.C.T.-embedded ventricle samples were sliced and 10μm sections were fixed in cold acetone for 15 minutes. The frozen sections were subsequently used for immunofluorescence staining. Gr-1 (BD Biosciences, 557445) was used to detect neutrophils and CD68 (Abd Serotec, MCA1957GA) to detect macrophages. All quantifications were conducted by an investigator who was blinded to the experimental groups.

Analysis of gene expression. Total RNA was isolated using Trizol (Invitrogen) and reverse transcription kits (Takara) were used to synthesize cDNA. QRT-PCR was carried out on an ABI 7900 using SYBR green to detect PCR products. Relative expression of each gene was determined by normalizing to GAPDH for ventricular samples and ml19 or 18s for CD4+ T cells.

Flow cytometry. Mice were sacrificed one week after AAC and immediately perfused through inferior vena cava with 1xPBS until hearts became pale. Whole ventricles were then separated, weighed, cut into pieces, and put into digestion solution in C tubes (Miltenyi Biotec). The digestion solution contained Collagenase II (Worthington, 1.5mg/ml), Collagenase IV (Worthington, 1.5mg/ml), and DNase I (AppliChem, 60U/ml) in HBSS. Samples with digestion solution were first mechanically dissociated using gentleMACS Dissociator system, followed by incubation at 37°C for 30 minutes, and next dissociated again. Single cell suspensions were filtered through cell strainer (BD Biosciences, 70μm) and then used for flow cytometric staining. Antibodies used for flow cytometry were: Fc block (BD Biosciences, 553142), CD45-PE-Cy7 (eBioscience, 25-0451-81), CD3-PE (eBioscience, 12-0031-81), CD4-FITC (eBioscience, 11-0043-82), CD4-eFluor450 (eBioscience, 11-0042-80) CD8-APC (eBioscience, 17-0081-81), CD8-5-PerCP-Cy5.5 (eBioscience, 45-0081-80) CD69-eFluor450 (eBioscience, 48-0691-80), CD25-PE-Cy7 (eBioscience, 25-0251-81), CD25-PerCP-Cy5.5 (eBioscience, 45-0251-80), CD11b-FITC (eBioscience, 11-0112-82), Ly6G-APC (BD Biosciences, 560599), Ly6C-APC (BD Biosciences, 128018), F4/80-eFluor450 (eBioscience, 48-4801-80), CD44-PerCP-Cy5.5 (eBioscience, 45-0441-80), CD44-APC (eBioscience, 17-0441-81) CD62L-FITC (eBioscience, 11-0621-82), interferon gamma (IFNγ)-PE (eBioscience, 12-7311-81) and IFNγ-APC (eBioscience, 17-7311-81).

T cell isolation and treatment. Naive CD4+ T cells and CD8+ T cells were isolated from spleens using negative selection kit (Miltenyi, 130-104-453; Stem cell, 19853A). To activate T cells, anti-CD3
antibodies (eBioscience, 2ug/ml) were coated on plates and anti-CD28 antibodies (eBioscience, 2ug/ml) were added directly into culture media. The culture media for T cells consisted of 90% RPMI 1640, 10% FBS, 1% penicillin-streptomycin and 1% β-mercaptoethanol. For experiments with spironolactone (Selleck, S4054), T cells were incubated in culture media containing spironolactone (5μM) for 1h before further stimulation. For proliferation assay, CD4+ T cells were labelled by CFDA, SE (Thermo Fisher, C34554), and then stimulated by plate-coated anti-CD3 antibodies (5μg/ml) and anti-CD28 antibodies (2μg/ml) for 72h before detection by flow cytometry.

**Enzyme-Linked Immunosorbent Assay (ELISA).** Cell culture media were collected from CD4+ T cells with or without stimulation by anti-CD3 antibodies for 24h. IFNγ and interleukin (IL)-6 were measured by ELISA kits (Mouse IFN-gamma Quantikine ELISA Kit, MIF00; mouse IL-6 Quantikine ELISA Kit, M6000B, R&D) according to the manufacturer’s instructions.

**Lentivirus packaging and infection.** Mouse MR-flag was subcloned into pHAGE plasmid and introduced into 293FT cells together with lentivirus packaging plasmids using Lipofectamine 2000 (Life Technologies). Media containing lentivirus were harvested 48 hours and 72 hours after transfection, combined and filtered through 0.22 filters, and condensed by ultracentrifugation. CD4+ T cells were used for further treatment 36 hours after lentivirus infection.

**Protein extraction and western blotting analysis.** CD4+ T cells were collected in unstimulated state or after stimulated by anti-CD3 antibodies for 1h and 3h. Cells were then lysed with lysis buffer containing phenylmethanesulfonyl fluoride. Samples were separated by SDS-PAGE and analyzed by immunoblotting. Antibodies used for western blotting were: NFA Tc2 (Santa Cruz, sc-7296X), GAPDH (KangChen Bio-tech, KC-5G4).

Online Figure S1. MR antagonist inhibits AAC-induced cardiac hypertrophy and T cell activation. (A) Ventricular weight to body weight ratio (VW/BW) of C57BL6/J mice undergone sham operation or abdominal aortic constriction (AAC) and fed with or without eplerenone (Epl). n=7:9:10. (B) Gating strategy for flow cytometric analysis of T cells in heart samples. Cardiac tissue suspension was labeled with various antibodies. CD45+ SSc^low cells, which included T cells, were identified. After doublet exclusion, T cells were selected by CD3+. Then T cell subsets were separated by CD4
and CD8. (C) Gating strategies for CD69 positives T cells in heart samples. (D) Gating strategies for memory effector T cells (CD44\textsuperscript{hi}CD62L\textsuperscript{low}) in heart samples. (E) Gating strategies for IFN\textgamma positive T cells in heart samples. (F) Flow cytometric analysis of CD4\textsuperscript{+} IFN\textgamma\textsuperscript{+} T cells in heart samples after AAC. n=4:5:5. (G) Flow cytometric analysis of CD8\textsuperscript{+} IFN\textgamma\textsuperscript{+} T cells in heart samples after AAC. n=4:5:5. *P<0.05, **P<0.01, ***P<0.001.

**Online Figure S2**

Telemetric monitoring of systolic (A) and diastolic blood pressure (B), and heart rate (C) of wild type (WT) C57BL6/J mice after AAC and fed with or without eplerenone (Epl) (n=4-5). Data were collected 1 week after AAC.
Online Figure S3. T cell mineralocorticoid receptor (MR) deficiency attenuates AAC-induced cardiac hypertrophy and fibrosis. (A) Representative H&E staining of cross sections of left ventricles. Scale bar: 25μm. (B) Representative picrosirius red staining of cross sections of left ventricles. Scale bar: 50μm.
Online Figure S4. Telemetric monitoring of systolic (A) and diastolic blood pressure (B), and heart rate (C) of LC and TMRKO mice after AAC (n=4-5). Data were collected 1 week after AAC.

Online Figure S5. Gating strategy for flow cytometric analysis of myeloid cells in heart samples. Cardiac tissue suspension was prepared and labeled. CD45+ cells, including myeloid and T cells, were identified. Doublets were excluded by FSC-W vs. FSC-A. Then monocytes/macrophages and neutrophils were separated by CD11b and Ly6G. CD11b+ Ly6G− monocytes/macrophages were further analyzed by Ly6C, which identifies inflammatory monocytes (CD11b+ Ly6C hi).
Online Figure S6. T cell MR deficiency mitigates AAC-induced accumulation of IFNγ-producing T cells in heart samples. (A) Flow cytometric analysis of CD4+ IFNγ+ T cells in heart samples. n=6:6:9:9. (B) Flow cytometric analysis of CD8+ IFNγ+ T cells in heart samples. n=6:6:9:9. *P<0.05, **P<0.01, ***P<0.001.
Online Figure S7. MR antagonist inhibits activation of CD4⁺ T cell. (A) QRT-PCR analysis of IL-2 gene expression in naive CD4⁺ T cells without stimulation (unstimulated) or stimulated with anti-CD3 and treated with vehicle (Veh) or spironolactone (Spiro) for 24h. (B) Flow cytometric analysis of CD44 in naive CD4⁺ T cells. (C) Flow cytometric analysis of CD69 in naive CD4⁺ T cells. (D) Flow cytometric analysis of CD25 in naive CD4⁺ T cells. Data represent three independent experiments. *P<0.05, ***P<0.001.
Online Figure S8. MR antagonist inhibits activation of CD8⁺ T cells. (A) Flow cytometric analysis of CD44 in CD8⁺ T cells without stimulation (unstimulated) or stimulated with anti-CD3 and treated with vehicle (Veh) or spironolactone (Spiro) for 24h. (B) Flow cytometric analysis of CD69 in CD8⁺ T cells. without stimulation (unstimulated) or stimulated with anti-CD3 and treated with vehicle (Veh) or spironolactone (Spiro) for 12h. Data represent three independent experiments. ***P<0.001.
Online Figure S9. MR overexpression promotes T cell activation. (A) QRT-PCR analysis of MR gene expression in naive CD4⁺ T cells infected with control lentivirus (Control) or MR overexpression lentivirus (MROV). (B) QRT-PCR analysis of IL-2 gene expression in control and MROV naive CD4⁺ T cells with or without stimulation by anti-CD3 for 12h. (C) Flow cytometric analysis of CD44 in control and MROV naive CD4⁺ T cells. (D) Flow cytometric analysis of CD69 in control and MROV naive CD4⁺ T cells. Data represent three independent experiments. *P<0.05, **P<0.01, ***P<0.001.
Online Figure S10
Online Figure S10. MR regulates activation of T cells under co-stimulation by anti-CD3/anti-CD28. (A) QRT-PCR analysis of IL-2 gene expression in naive CD4⁺ T cells without stimulation (unstimulated) or stimulated with anti-CD3/anti-CD28 and treated with vehicle (Veh) or spironolactone (Spiro) for 24h. (B) Flow cytometric analysis of CD44 in naive CD4⁺ T cells. (C) Flow cytometric analysis of CD69 in naive CD4⁺ T cells. (D) QRT-PCR analysis of IL-2 gene expression in naive CD4⁺ T cells isolated from spleens of LC and TMRKO mice with or without stimulation by anti-CD3/anti-CD28 for 24h. (E) Flow cytometric analysis of CD44 in naive CD4⁺ T cells from LC and TMRKO mice. (F) Flow cytometric analysis of CD69 in naive CD4⁺ T cells from LC and TMRKO mice. (G) QRT-PCR analysis of IL-2 gene expression in control and MROV naive CD4⁺ T cells with or without stimulation by anti-CD3/28 for 24h. (H) Flow cytometric analysis of CD44 in control and MROV naive CD4⁺ T cells. (I) Flow cytometric analysis of CD69 in control and MROV naive CD4⁺ T cells. Data represent three independent experiments. *P<0.05, **P<0.01, ***P<0.001.

Online Figure S11

Online Figure S11. T cell MR deficiency does not affect proliferation of CD4⁺ T cells. Flow cytometric analysis of Carboxyfluorescein Diacetate Succinimidyl Ester (CFSE) in CD4⁺ T cells with or without stimulation by anti-CD3 and anti-CD28 for 72h. Data represent three independent experiments.