Treatment with N-acetyl-sera-lysyl-proline prevents experimental autoimmune myocarditis in rats

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Nakagawa P, Liu Y, Liao TD, Chen X, González GE, Bobbitt KR, Smolarek D, Peterson EL, Kedl R, Yang XP, Rhaleb NE, Carretero OA. Treatment with N-acetyl-seryl-aspartyl-lysyl-proline prevents experimental autoimmune myocarditis in rats. Am J Physiol Heart Circ Physiol 303: H1114–H1127, 2012. First published August 24, 2012; doi:10.1152/ajpheart.00300.2011.—Myocarditis is an inflammatory disease of the heart muscle commonly associated with cardiotropic infections and has been linked to development of autoimmunity. N-acetyl-seryl-aspartyl-lysyl-proline (Ac-SDKP) is a naturally occurring tetrapeptide that prevents inflammation and fibrosis in hypertension and other cardiovascular diseases; however, its effect on autoimmune-mediated cardiac diseases remains unknown. We studied the effects of Ac-SDKP in experimental autoimmune myocarditis (EAM), a model of T cell-mediated autoimmune disease. This study was conducted to test the hypothesis that Ac-SDKP prevents autoimmune myocardial injury by modulating the immune responses. Lewis rats were immunized with porcine cardiac myosin and treated with Ac-SDKP or vehicle. In EAM, Ac-SDKP prevented both systolic and diastolic cardiac dysfunction, remodeling as shown by hypertrophy and fibrosis, and cell-mediated immune responses without affecting myosin-specific autoantibodies or antigen-specific T cell responses. In addition, Ac-SDKP reduced cardiac infiltration by macrophages, dendritic cells, and T cells, pro-inflammatory cytokines [interleukin (IL)-1α, tumor necrosis factor-α, IL-2, IL-17] and chemokines (cytokine-induced neutrophil chemoattractant-1, interferon-γ-induced protein 10), cell adhesion molecules (intercellular adhesion molecule-1, L-selectin), and matrix metalloproteinases (MMP). Ac-SDKP prevents autoimmune cardiac dysfunction and remodeling without reducing the production of autoantibodies or T cell responses to cardiac myosin. The protective effects of Ac-SDKP in autoimmune myocardial injury are most likely mediated by inhibition of T1 innate and adaptive immune cell infiltration and 2 expression of proinflammatory mediators such as cytokines, chemokines, adhesion molecules, and MMPs.

N-acetyl-seryl-aspartyl-lysyl-proline (Ac-SDKP) is a naturally occurring tetrapeptide released from thymosin β4 by prolyl oligopeptidase (7). Ac-SDKP is hydrolyzed almost exclusively by angiotensin-converting enzyme (ACE), and its plasma concentration is increased by ACE inhibitors (2, 7). The anti-inflammatory and anti-fibrotic effects of ACE inhibitors are known to be mediated in part by Ac-SDKP (28, 30). Hearts from rats overexpressing ACE have lower Ac-SDKP concentrations and increased fibrosis (31). Treatment with Ac-SDKP reduces cardiac inflammation and fibrosis in hypertension and in heart failure postmyocardial infarction (MI) (27, 29, 34, 44). In rats with myocarditis induced by intrapericardial galectin-3 (a proinflammatory lectin released by macrophages), Ac-SDKP prevented cardiac inflammation, fibrosis, hypertrophy, and dysfunction (24); on the other hand, in hypertension and MI, Ac-SDKP reduced both inflammation and fibrosis but failed to decrease hypertrophy or improve cardiac dysfunction (8, 29, 34, 44). While these data suggest Ac-SDKP protects against cardiac damage due to pressure overload or local inflammatory responses, we still do not know whether it prevents autoimmune-mediated cardiovascular diseases. To answer this question, we studied experimental autoimmune myocarditis (EAM) in rats, an animal model of human myocarditis (18). In this condition and also many other autoimmune diseases as well as chronic inflammation, infiltration by macrophages, dendritic cells, and T helper cells is a significant component of the process (37). Proinflammatory cytokines, chemokines, cell adhesion molecules, and matrix metalloproteinases (MMP) are all necessary for development of EAM (12, 16, 33). We tested the hypothesis that Ac-SDKP prevents autoimmune myocardial injury by modulating immune responses.

MATERIALS AND METHODS

Animals. Seven-week-old male Lewis rats (Charles River, Wilmington, MA) were housed in an air conditioned room with a 12:12-h light-dark cycle and given standard rat chow (0.4% sodium) and tap water. They were allowed 7 days to adjust to their new environment. Before all surgical procedures, butorphanol (2 mg/kg sc) was used to induce analgesia and pentobarbital sodium (50 mg/kg ip) for anesthesia. All protocols were approved by the Institutional Animal Care and Use Committee of Henry Ford Hospital.

Induction of EAM. EAM was induced in Lewis rats following Kitabayashi’s protocol (17). All rats were immunized at the beginning of the experiment (day 0) and again 7 days later (day 7). In each immunization, rats were anesthetized and intradermically injected with 1 mg of porcine cardiac myosin (Sigma, St. Louis, MO) emulsified with an equal volume of complete Freund’s adjuvant (CFA) supplemented with Mycobacterium tuberculosis H37RA.

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Experimental protocols. Rats were randomly divided into the following four groups: 1) controls, injected with CFA and infused with saline using an osmotic minipump (Alzet); 2) Ac-SDKP, injected with CFA and infused with Ac-SDKP (800 μg·kg⁻¹·day⁻¹); 3) EAM, injected with emulsified porcine myosin in CFA and infused with saline; and 4) EAM + Ac-SDKP, injected with emulsified porcine myosin in CFA and infused with Ac-SDKP (800 μg·kg⁻¹·day⁻¹).

Ac-SDKP infusion was started at day 0. Rats were killed at different time points depending on the parameter studied. At 2 wk postimmunization, we measured MMP activity. At 3 wk, total leukocyte infiltration, delayed-type hypersensitivity (DTH), autoantibody titers, antigen-specific T cell responses, T helper cell intracellular cytokines, dendritic cell infiltration, and myocardial expression of cytokines, chemokines, and adhesion molecules were measured. At 4 wk, we measured organ weight, blood pressure, cardiac function, collagen deposition, macrophage and T cell infiltration, and MMP activity.

Blood pressure and echocardiography. Systolic blood pressure (SBP) was measured by tail cuff in nonanesthetized rats before and 4 wk after immunization. After anesthetizing the rats, echocardiography and Doppler sonography using an Acuson Sequoia C 256 with a 15-MHz transducer were performed together with electrocardiography before and 4 wk after immunization. M-mode echocardiography was conducted first in the parasternal long-axis view to measure left ventricle (LV) dimensions and then in the anterior short-axis view to evaluate LV ejection fraction (LVEF). Transmitral Doppler inflow waves were used to measure peak early diastolic filling velocity (E wave), peak filling velocity at atrial contraction (A wave), and the ratio between them (E/A), assessing diastolic function as described previously (32). After determining the aortic root dimension (AoD) and systolic velocity-time integral (VTI), stroke volume was calculated according to the formula: stroke volume = (VTI)[(AoD/2)⁴] and cardiac output (CO) using the formula: CO = stroke volume × heart rate (HR). All Doppler spectra were recorded for five to seven cardiac cycles at a sweep speed of 200 mm/s.

Heart, lung, liver, kidney, thymus, and spleen weight. Four weeks after immunization, the rats were anesthetized and the heart stopped during diastole by injecting 15% potassium chloride solution, then excised, weighed, and expressed as the ratio of heart weight (HW) to body weight (BW). The lungs, liver, kidney, thymus, and spleen were also removed and weighed.

Histology. The LV was sectioned transversely into four slices from apex to base. The two middle slices (biventricular cross sections) were used for histological and immunohistochemical studies, and the base and apex were used for protein analysis. Five-micrometer sections were fixed in 10% formalin, embedded in paraffin, and inflammation estimated using hematoxylin-eosin staining. Sections were analyzed blindly by two investigators, and the extent of myocardial inflammation was graded according to the following four-tier system: grade 1 corresponding to cardiac necrosis/infiltration up to 10% of the cardiac section; grade 2, 11–20%; grade 3, 21–40%; and grade 4, >40% (43). Myocardial interstitial and perivascular collagen deposition, both markers of fibrosis, were quantified using picrosirius red (40). Microphotographs were taken at ×400 magnification using an Olympus IX81 microscope (Olympus America, Center Valley, PA) and DP70 digital camera. At least 100 images of the surface of each section were analyzed with an Olympus Microsuite Biological system. Interstitial collagen deposition was assessed by calculating the ratio of collagen to the entire section. Perivascular collagen was measured as the ratio of the surrounding fibrotic area to total vascular area. All measurements and analyses were carried out in a blind fashion.

DTH assay. Myosin DTH was quantified 3 wk after immunization based on swelling of the ear as described by Godsde et al. (11). Ear thickness was measured with a micrometer (serial no. 7323; Mitutoyo MTL, Aurora, IL). Ten micrograms of myosin in a solution of 0.16 M K₂PO₄, 0.01 M Na₂HPO₄, and 0.3 M KCl (pH 6.8) were injected intradermally into the dorsal surface of the ear using a 50- to 100-μl glass Hamilton syringe fitted with a 30-gauge needle, whereas 10 μg BSA in the same solution was injected in the opposite ear as a control. After 24 h, net swelling of the control ear (mm) was subtracted from the myosin-treated ear.

Anti-cardiac myosin autoantibody assay. Myosin-specific antibodies in the serum were measured by enzyme-linked immunosorbent assay (ELISA) 3 wk postimmunization as described by Wang et al. (42). Flat-bottom 96-well ELISA plates were coated with porcine cardiac myosin (10 μg/ml) by incubating them overnight at 4°C. After washing the plates two times with 0.05% PBS-Tween and blocking them with 1% BSA in PBS, serum diluted 1:5000 was first incubated overnight at 4°C; then goat anti- rat IgG conjugated to alkaline phosphatase (Sigma) was added, and samples were incubated for 1 h at room temperature and washed with PBS-Tween. Finally, paranitrophenylphosphate (Sigma) was added, halting the reaction at 10 min by adding 1 M sodium hydroxide and measuring optical density (OD) at 405 nm. Each sample was analyzed in duplicate.

Antigen-specific T cell proliferation and intracellular cytokines. Cells were collected from inguinal and popliteal draining lymph nodes 3 wk postimmunization, resuspended in prewarmed PBS/0.1% BSA at a final concentration of 1 × 10⁶ cells/ml and incubated with carboxyfluorescein diacetate, succinimidyl ester (CFSE) at a final concentration of 10 μM for 10 min. After the cells were washed two times with PBS, they were resuspended in T cell medium (RPMI 1640 containing 10% FBS, 50 μM 2-mercaptoethanol, 100 U/ml penicillin, and 100 μg/ml streptomycin) and placed in 96-well microtiter plates (Corning-Costar) preloaded with 5 × 10⁶ irradiated syngenic splenocytes pulsed with 50 μg/ml cardiac myosin for 24 h. Samples were incubated with 50 μg/ml porcine cardiac myosin for 6 days at 37°C in a humidified atmosphere containing 5% CO₂. After incubation, cells were stained with antibodies [APC-Cy7 anti-CD45, OX-1 (BioLegend); PE-Cy7 anti-CD8, OX-8 (eBioscience); PE-Cy5 anti-CD4, OX-35 (BD Biosciences); APC anti-CD25, OX-39 (eBioscience)] and fixed with 1% paraformaldehyde at room temperature for 20 min. Samples were analyzed using an LSR II flow cytometer (BD Biosciences) and Fluorescence-activated cell sorting (FACS) Diva software (version 6.1.3). Cell proliferation was calculated as the percentage of CD45⁺, CD4⁺, and CD25⁺ gated cells with reduced CFSE fluorescence intensity. For intracellular cytokine assay, 1 × 10⁶ lymph node cells were stimulated with 80 ng/ml phorbol 12-myristate 13-acetate plus 1 μg/ml ionomycin and 20 ng/ml brefeldin A for 4 h at room temperature. Intracellular fluorescent intensities were analyzed and expressed as the ratio of the fluorescent intensity of each subject to the corresponding unstimulated control. The stained cells were fixed, permeabilized, and stained with antibodies respectively for intracellular staining: CD4⁺, PE-Cy7; CD8⁺, APC-Cy7; and CD25⁺, APC-A750. Finally, cells were resuspended in 1% BSA in PBS and analyzed on a LSR II flow cytometer (BD Biosciences). The data were acquired using FlowJo software (Treestar). The results were expressed as geometric mean fluorescence intensities (GMFI).

Table 1. Effect of Ac-SDKP on heart rate and organ weight measured 4 wk after immunization

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>Ac-SDKP</th>
<th>EAM</th>
<th>EAM + Ac-SDKP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BW, g</td>
<td>325 ± 4 (12)</td>
<td>326 ± 4 (12)</td>
<td>305 ± 8 (13)</td>
<td>321 ± 8 (14)</td>
</tr>
<tr>
<td>Lungs/BW, mg/100 g</td>
<td>338 ± 22 (12)</td>
<td>367 ± 8 (12)</td>
<td>430 ± 16* (13)</td>
<td>377 ± 8.6# (14)</td>
</tr>
<tr>
<td>Liver/BW, g/100 g</td>
<td>3.66 ± 0.11 (8)</td>
<td>3.66 ± 0.16 (8)</td>
<td>3.79 ± 0.14 (10)</td>
<td>3.58 ± 0.08 (9)</td>
</tr>
<tr>
<td>Thymus/BW, mg/100 mg</td>
<td>137 ± 6 (12)</td>
<td>141 ± 7 (12)</td>
<td>165 ± 11* (14)</td>
<td>140 ± 6 (13)</td>
</tr>
<tr>
<td>Spleen/BW, mg/100 g</td>
<td>174 ± 7 (6)</td>
<td>182 ± 6 (6)</td>
<td>174 ± 5 (8)</td>
<td>174 ± 8 (7)</td>
</tr>
<tr>
<td>Kidney/BW, g/100 g</td>
<td>0.86 ± 0.06 (9)</td>
<td>0.81 ± 0.02 (12)</td>
<td>0.89 ± 0.03 (8)</td>
<td>0.81 ± 0.02 (7)</td>
</tr>
</tbody>
</table>

Values are means ± SE; nos. in parentheses are no. of animals analyzed/group. Ac-SDKP, N-acetyl-seryl-aspartyl-lysyl-proline; EAM, experimental autoimmune myocarditis; BW, body wt. *P < 0.05, EAM vs. control. #P < 0.05, EAM + Ac-SDKP vs. EAM.
controls and EAM rats treated with vehicle or Ac-SDKP (C0.01 and ** in controls and EAM rats treated with vehicle or Ac-SDKP (n).

Body weight (an indicator of hypertrophy) measured 4 wk after immunization.

LV mass, (mm³)/100 g BW 201

Table 2. Effect of Ac-SDKP on echocardiographic parameters measured 4 wk after immunization in rats with EAM

<table>
<thead>
<tr>
<th></th>
<th>Control (n = 12)</th>
<th>Ac-SDKP (n = 11)</th>
<th>EAM (n = 14)</th>
<th>EAM + Ac-SDKP (n = 13)</th>
</tr>
</thead>
<tbody>
<tr>
<td>PWT, mm</td>
<td>1.58 ± 0.06</td>
<td>1.65 ± 0.04</td>
<td>1.88 ± 0.08**</td>
<td>1.60 ± 0.06##</td>
</tr>
<tr>
<td>LV mass, (mm³)/100 g BW</td>
<td>201 ± 7</td>
<td>200 ± 6</td>
<td>247 ± 18*</td>
<td>188 ± 7##</td>
</tr>
<tr>
<td>SF, %</td>
<td>58.0 ± 1.4</td>
<td>58.7 ± 1.2</td>
<td>50.2 ± 1.6*</td>
<td>55.4 ± 1.3#</td>
</tr>
<tr>
<td>LVEF, %</td>
<td>81.5 ± 0.9</td>
<td>83.3 ± 0.6</td>
<td>66.7 ± 2.6**</td>
<td>77.8 ± 2.5##</td>
</tr>
<tr>
<td>E/A ratio</td>
<td>1.49 ± 0.04</td>
<td>1.45 ± 0.05</td>
<td>1.21 ± 0.07**</td>
<td>1.47 ± 0.04##</td>
</tr>
<tr>
<td>HR, beats/min</td>
<td>379 ± 10 (12)</td>
<td>383 ± 12 (11)</td>
<td>395 ± 9 (14)</td>
<td>388 ± 9 (13)</td>
</tr>
</tbody>
</table>

Values are means ± SE; n, no. of animals analyzed/group. PWT, posterior wall thickness; LV, left ventricle; BW: body weight; SF, shortening fraction; LVEF, ejection fraction; E/A, peak early diastolic filling velocity (E)peak filling velocity at atrial contraction (A); HR: heart rate. *P < 0.005 and **P < 0.001, EAM vs. control. #P < 0.05, ##P < 0.005, and ###P < 0.001, EAM + Ac-SDKP vs. EAM.
Fig. 2. **Left:** representative photographs of whole hearts taken 3 wk after immunization in controls and EAM rats treated with vehicle or Ac-SDKP. **Center:** representative images of heart sections stained with hematoxylin and eosin 3 wk after immunization in controls and EAM rats treated with vehicle or Ac-SDKP. **Right:** representative images of myocardial leukocyte infiltration (red: CD45^+^) 3 wk after immunization in controls and EAM rats treated with vehicle or Ac-SDKP.
and developed at 37°C for 12 h. After fixation and staining with Coomassie Brilliant blue G-250 (0.25%), the zymograms were destained with 10% (vol/vol) acetic acid, and bands were quantified by image analysis.

Data analysis. All data are expressed as means ± SE. Statistical significance of the data was analyzed by Kruskall-Wallis test followed by a Wilcoxon two-sample analysis or by ANOVA followed by Tukey’s test. A value of \( P < 0.05 \) was considered significant.

RESULTS

BW and organ weight. There were no significant differences in BW among groups 4 wk after immunization; however, lung and thymus weight both increased in rats with EAM. Ac-SDKP prevented the increase in lung weight but had no effect on the controls. Liver, spleen, and kidney weight were similar in all groups (Table 1).

SBP and cardiac function (echocardiography). By week 4, SBP was significantly decreased in the EAM group. Ac-SDKP prevented this decrease but had no effect on the controls (Fig. 1A). HW corrected by BW was significantly higher in the EAM group, but this increase was prevented by Ac-SDKP, whereas the control group showed no change (Fig. 1B). Rats with EAM had a significantly lower CO that was prevented by Ac-SDKP,

![Figure 3](http://ajpheart.physiology.org/)

Fig. 3. Left: myocardial interstitial (A) and perivascular (B) collagen deposition measured by picrosirius red staining 4 wk after immunization in controls and EAM rats treated with vehicle or Ac-SDKP. Right: quantitative data on interstitial (A) and perivascular (B) fibrosis, expressed as a percentage of the fibrotic area (n = 12–14). NS, not significant.
whereas the controls once again showed no change (Fig. 1C). In addition, LV mass and posterior wall thickness increased in the EAM group while LVEF, shortening fraction, and the ratio of transmitral Doppler E (early LV filling phase)-to-A (atrial contraction phase)-wave, an indicator of LV diastolic function, all decreased; and these abnormalities were prevented by Ac-SDKP. There were no differences in HR among groups (Table 2).

**Macroscopic and microscopic evaluation of the heart.** By week 3, discolored areas were observed in the hearts of EAM + vehicle but not EAM + Ac-SDKP or controls (Fig. 2, left). Only one rat in the EAM group had pericardial effusion. Macroscopic examination revealed inflammatory loci only in the EAM group (Fig. 2, center). Inflammatory score was increased in EAM compared with controls (EAM 2.20 ± 0.02 vs. control 1.14 ± 0.02 AU, p < 0.001), and this increase was significantly reduced in EAM + Ac-SDKP (EAM + Ac-SDKP: 1.49 ± 0.14 AU, p < 0.05 vs. EAM) (Fig. 2, center). The EAM group also showed increased infiltration by CD45+ leukocytes compared with the controls (319.3 ± 68.7 vs. 42.4 ± 3.2 cells/mm²; p < 0.001), and this increase was partially prevented by Ac-SDKP (146.1 ± 54.5 vs. 319.3 ± 68.7 cells/mm²; p < 0.05 vs. EAM). Ac-SDKP had no effect on the controls (48.5 ± 5.1 cells/mm²) (Fig. 2, right).

**Cardiac interstitial and perivascular collagen.** By week 4, cardiac interstitial and perivascular collagen deposition were both higher in the EAM group; this increase was prevented by Ac-SDKP, but it had no effect on the controls (Fig. 3, A and B).

**DTH.** Three weeks after immunization, we measured DTH by injecting cardiac myosin in the left ear, treating the right ear with an irrelevant protein (BSA) as a control. Whereas the right ear showed no change, a swollen red nodule was seen in the left ear of the EAM group. This increase in DTH was prevented by Ac-SDKP (Fig. 4A).

**Anti-cardiac myosin autoantibody assay.** At 3 wk, serum samples from rats with EAM showed increased autoantibodies. Ac-SDKP failed to prevent this increase and had no effect on the controls (Fig. 4B).

**Antigen-specific T cell proliferation and intracellular cytokines.** By week 3, incubation of lymph node cells with antigen (cardiac myosin) induced proliferation of T helper cells in the rats with EAM but not in the controls, and this increase was not prevented by Ac-SDKP (Fig. 5). Intracellular FACS analysis revealed that the Th2 subset (IL-4 positive) tended to increase in EAM rats treated with either vehicle or Ac-SDKP (although the difference was not statistically significant), whereas the Th1 subset (IFN-γ positive) remained unaffected. Three out of five rats in the EAM group had increased Th17 (IL-17 positive). Although EAM and EAM + Ac-SDKP were not significantly different, none of the rats in the EAM + Ac-SDKP group had increased levels of Th17 (Fig. 6).

**Cardiac infiltration by macrophages, dendritic cells, T helper cells, and cytotoxic T cells.** Myocardial ED-1-positive macrophages, CD4+ T helper cells, and CD8+ cytotoxic T cells were all increased in the EAM group at week 4, whereas CD11c-positive dendritic cells were significantly increased by 3 wk. Ac-SDKP prevented all of these increases save for the cytotoxic T cells but had no effect on the controls (Figs. 7 and 8).

**Expression of proinflammatory cytokines and cell adhesion molecules.** By week 3, cardiac protein expression of cytokines related to both innate (IL-1α, TNF-α) and adaptive (IL-17) immune responses as well as chemokines (CINC-1 and IP-10) was increased in the EAM group but prevented by Ac-SDKP. Ac-SDKP also lowered IL-2, which was not significantly increased in the EAM group (Fig. 9). Cell adhesion molecules L-selectin and ICAM-1 were also increased in the EAM rats and prevented by Ac-SDKP (Fig. 10A). Western blots of ICAM-1 protein showed similar results (Fig. 10B). Other inflammatory mediators such as CINC-3, IL-1β, IL-1ra, IL-6, LIX, MIP-1α, thymus chemokine, and tissue inhibitor of MMP-1 were also increased in the EAM group and prevented by Ac-SDKP (see Table 3). Ac-SDKP had no effect on any other inflammatory mediators in the control group.

**Metalloproteinase-2 and -9 activity.** By week 2, both MMP-2 and MMP-9 activity in the myocardium was higher in the EAM group, and Ac-SDKP prevented this increase (Fig. 11). However, MMP-9 returned to normal by week 4, whereas MMP-2 was undetectable (data not shown).

**DISCUSSION**

In Lewis rats immunized with cardiac myosin, Ac-SDKP prevented hypotension, cardiac remodeling (hypertrophy, inflammation, and fibrosis), and dysfunction. Using models of hypertension and MI, we showed that Ac-SDKP decreased cardiac macrophage infiltration, transforming growth factor-β expression, and fibrosis; however, it did not improve cardiac function or decrease hypertrophy (44). We also induced myocarditis by intrapericardial infusion of galectin-3 and found that Ac-SDKP not only lessened fibrosis and inflammation but also prevented cardiac dysfunction and hypertrophy (24). The ob-

Fig. 4. A: delayed-type hypersensitivity to porcine cardiac myosin measured 3 wk after immunization (expressed as mm of net ear swelling) in controls and EAM rats treated with vehicle or Ac-SDKP (n = 4–6). B: cardiac myosin-specific autoantibodies measured by enzyme-linked immunosorbent assay (ELISA) in serum samples collected 3 wk after immunization (n = 3).
servation that Ac-SDKP improved cardiac remodeling and function in galectin-3-induced myocarditis and EAM but not in hypertension and MI is probably related to the etiology and pathogenesis of remodeling and dysfunction. EAM is considered a T cell-mediated autoimmune disease (19), and the mechanism of cardiac damage differs from galectin-3-induced myocarditis. Galectin-3 is a lectin released by macrophages that induces local inflammation when infused in the pericardium, whereas EAM is induced by immunization with cardiac myosin, which causes the immune system to react against the heart’s own proteins; thus, in contrast to galectin-3-induced myocarditis, the autoimmune reaction observed in EAM depends on activation of not only the innate but also the adaptive immune system. We believe the findings presented here demonstrate for the first time that Ac-SDKP affords cardioprotection in a model of autoimmune-mediated heart disease. Four weeks after immunization, rats with EAM had significantly lower SBP, possibly because of reduced CO. Ac-SDKP prevented the decreases in both BP and CO, further supporting the hypothesis that the drop in SBP may have been secondary to decreased cardiac function. Yet, even with lower SBP, the rats with EAM had cardiac hypertrophy, suggesting that the remodeling and dysfunction were due to an autoimmune reaction independent of afterload. In immunized rats, echocardiography showed that Ac-SDKP prevented both systolic and diastolic function from decreasing while posterior wall thickness and LV mass were reduced, suggesting that Ac-SDKP prevented autoimmune-induced hypertrophy; moreover, both the lung congestion and HW corrected by BW support these observations. Therefore, we conclude that, in autoimmune-mediated

Fig. 5. A: representative histograms showing T helper cell proliferation in response to cardiac myosin in controls and EAM rats treated with vehicle or Ac-SDKP. Proliferation of T helper cells was seen as reduced carboxyfluorescein diacetate, succinimidyl ester (CFSE) fluorescence intensity on flow cytometry. B: quantitative data, expressed as %proliferating cells out of gated cells: CD45+, CD4+, and CD25+, which are markers of total leukocytes, T helper cells, and T cell activation, respectively.
myocardial injury, Ac-SDKP prevents not only cardiac inflammation and fibrosis but also hypertrophy along with systolic and diastolic dysfunction. It would be tempting to postulate that the reduced cardiac fibrosis was responsible for the improved diastolic dysfunction in the rats treated with Ac-SDKP; however, in an earlier study, we found that spontaneously hypertensive rats treated with Ac-SDKP had reduced cardiac fibrosis without improved hypertrophy or altered diastolic function despite decreased systolic function (8). Thus we believe prevention of systolic and diastolic dysfunction in animals with EAM treated with Ac-SDKP may be attributable to simultaneous protection against multiple pathogenetic factors, including hypertrophy, fibrosis, and inflammation.

Improved cardiac function and reduced hypertrophy were accompanied by decreased inflammation. The grade of inflammation observed in this study was comparable with other group’s reports (43). We previously showed that Ac-SDKP reduces mast cell and macrophage infiltration (24), and now we can report it also prevents dendritic cell and T helper cell infiltration; this is important because both are key components of the innate and adaptive arms of the immune system. Although Ac-SDKP did not reduce CD8⁺ T cells in the EAM group, it is well recognized that in these rats CD4⁺ are more important than CD8⁺ (6, 20, 26, 43). There is substantial evidence that innate immune cytokines such as TNF-α and IL-1 are crucial for the onset of autoimmune, so that resistant strains become susceptible when treated with IL-1 or TNF-α (21). TNF-rp 55 knockout animals do not develop EAM (3), and neutralization of TNF with monoclonal antibodies ameliorates the disease (38). In our study, the cardiac cytokine

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**Fig. 6.** Left: quantification of interferon-γ (IFN-γ)-positive (a) (A), interleukin (IL)-4 (B), and IL-17 (C) T helper cells in a population of lymph node cells under unstimulated (open triangles) and phorbol 12-myristate 13-acetate (PMA)/ionomycin-stimulated conditions (closed triangles) in controls and EAM rats treated with vehicle or Ac-SDKP. Right: figure showing gating strategy in a representative sample for the analysis of different T helper cell subsets in CD45⁺ and CD4⁺ events. Total leukocytes were gated on using CD45 expression and side scatter properties. Subsequently, CD45⁺ cells were gated on CD4⁺ and CD8⁺ cells, which were subsequently analyzed for IL-4, IFN-γ, and IL-17 expression.
expression profile revealed that, in EAM, Ac-SDKP prevented increases in cytokines related to innate (IL-1α and -β, IL-6, and TNF-α) and adaptive [IL-2, IP-10 (Th1 activation marker), and IL-17 (Th17 activation marker)] immune activation. Han et al. (13) determined that the Th1 response is associated with the initial cellular inflammatory stage of myocarditis, whereas Th2 predominates during the chronic stages when fibrosis is exacerbated; in turn, Baldeviano et al. (5) reported that Th17 is not required for myocarditis but essential for progression to dilated cardiomyopathy. We identified T subsets in the lymph nodes by FACS and found that Th1 was not altered in EAM 3 wk postimmunization; nevertheless, we cannot rule out the possibility that it is increased earlier than 3 wk. As we expected, Th2 and T17 subsets tended to be higher at 3 wk in
EAM; and, although Ac-SDKP had no effect on Th2, it tended to prevent an increase in Th17. Taken together, we speculate that the inhibitory effects of Ac-SDKP on Th17 and IL-17 expression may protect against postmyocarditis remodeling and progression to DCM during the chronic stage of the disease.

Ac-SDKP prevented expression of the chemokines CINC-1 and IP-10 in cardiac tissue.

Fig. 8. Left: representative images of myocardial T helper cell (red: CD4 positive) (A) and T cytotoxic infiltration (red: CD8 positive) (B) in controls and EAM rats treated with vehicle or Ac-SDKP 4 wk after immunization. Right: quantitative data, expressed as cells/mm² (n = 10–14).
posited as a critical mediator of neutrophil infiltration in rats during inflammation (14), whereas IP-10 is induced in many cells in response to interferon-γ (25) and is also seen in Th1-type inflammatory diseases where it is thought to play an important role in recruiting activated T cells into sites of inflammation (10).

It is also well-established that the recruitment of leukocytes to the inflammatory sites requires the binding to cell adhesion molecules. Treatment with Ac-SDKP reduced the protein expression of L-selectin and ICAM-1. It has been shown that expression of endothelial ICAM-1 is a prerequisite for target organ recognition by autoreactive T cells in CD4-mediated myocarditis as reported by Pummerer et al. (33).

MMPs are also considered crucial to recruitment of inflammatory cells and cardiac remodeling (15, 18, 39). Because Hishikari et al. (16) indicated EAM can be prevented by blocking MMPs, we studied the effect of Ac-SDKP on MMP activity. Measurement of MMP-2 and MMP-9 by zymography showed both enzymes were increased by 2 wk in the EAM group, and this increase was prevented by Ac-SDKP; thus, we believe Ac-SDKP may decrease infiltration by immune cells (and later cytokine production) in part by decreasing MMPs in addition to chemokines and cell adhesion molecules.

When we evaluated cell-mediated immunity by DTH, ear swelling was reduced in EAM rats treated with Ac-SDKP. Since Volkov et al. (41) demonstrated that adding Ac-SDKP to cultured T cells in vitro blocked the proliferation induced by concanavalin A, phytohemagglutinin, and pokeweek mitogen, and, since Ac-SDKP was initially described as a physiological negative regulator of hematopoietic stem cell proliferation (22), the decrease in DTH led us to hypothesize that Ac-SDKP blunts development of autoreactive T cells, possibly accompa-
Ac-SDKP PREVENTS EAM

H1125

Ac-SDKP acts at a different level by not preventing the development of autoreactive cells that initiate T cells or dendritic cells. Instead, Ac-SDKP decreases DTH by acting directly on macrophages rather than reducing TNF-α/H9251. Ac-SDKP has been shown to have direct effects on macrophages by and/or development of autoreactive T cells. Because Ac-SDKP is specifically degraded by ACE as supported by the observation that ACE inhibitors significantly increase Ac-SDKP in plasma and urine (1, 2), we believe increased Ac-SDKP may explain some of the beneficial effects of ACE inhibitors.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.

AUTHOR CONTRIBUTIONS


REFERENCES


Table 3. Additional inflammatory mediators measured 3 wk after immunization in heart homogenates from controls and EAM rats treated with vehicle or Ac-SDKP.

<table>
<thead>
<tr>
<th>Protein</th>
<th>Control</th>
<th>Ac-SDKP</th>
<th>EAM</th>
<th>EAM + Ac-SDKP</th>
</tr>
</thead>
<tbody>
<tr>
<td>CINC-2 α/β</td>
<td>0.24 ± 0.04</td>
<td>0.29 ± 0.12</td>
<td>0.57 ± 0.10</td>
<td>0.08 ± 0.05</td>
</tr>
<tr>
<td>CINC-3</td>
<td>0.82 ± 0.24</td>
<td>0.45 ± 0.13</td>
<td>1.46 ± 0.30</td>
<td>0.58 ± 0.21#</td>
</tr>
<tr>
<td>CNTF</td>
<td>0.45 ± 0.12</td>
<td>0.28 ± 0.08</td>
<td>0.55 ± 0.14</td>
<td>0.24 ± 0.07</td>
</tr>
<tr>
<td>Fractalkine</td>
<td>1.35 ± 0.30</td>
<td>1.11 ± 0.30</td>
<td>1.62 ± 0.37</td>
<td>1.10 ± 0.35</td>
</tr>
<tr>
<td>GM-CSF</td>
<td>1.32 ± 0.73</td>
<td>0.73 ± 0.32</td>
<td>0.91 ± 0.34</td>
<td>0.47 ± 0.16</td>
</tr>
<tr>
<td>IFN-γ</td>
<td>0.85 ± 0.20</td>
<td>0.69 ± 0.23</td>
<td>0.96 ± 0.21</td>
<td>0.87 ± 0.20</td>
</tr>
<tr>
<td>IL-1β</td>
<td>0.35 ± 0.11</td>
<td>0.20 ± 0.19</td>
<td>1.76 ± 0.35**</td>
<td>0.29 ± 0.07###</td>
</tr>
<tr>
<td>IL-1ra</td>
<td>0.30 ± 0.10</td>
<td>0.23 ± 0.10</td>
<td>19.96 ± 7.45*</td>
<td>0.30 ± 0.12#</td>
</tr>
<tr>
<td>IL-3</td>
<td>0.57 ± 0.16</td>
<td>0.56 ± 0.18</td>
<td>1.28 ± 0.28</td>
<td>0.29 ± 0.08</td>
</tr>
<tr>
<td>IL-4</td>
<td>0.50 ± 0.14</td>
<td>0.57 ± 0.16</td>
<td>0.60 ± 0.18</td>
<td>0.28 ± 0.10</td>
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<tr>
<td>IL-6</td>
<td>1.01 ± 0.23</td>
<td>0.71 ± 0.17</td>
<td>1.56 ± 0.21</td>
<td>0.72 ± 0.17#</td>
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<tr>
<td>IL-10</td>
<td>0.66 ± 0.20</td>
<td>0.49 ± 0.10</td>
<td>0.57 ± 0.11</td>
<td>0.67 ± 0.20</td>
</tr>
<tr>
<td>IL-13</td>
<td>0.70 ± 0.22</td>
<td>0.55 ± 0.16</td>
<td>1.01 ± 0.23</td>
<td>0.67 ± 0.17</td>
</tr>
<tr>
<td>LIX</td>
<td>1.16 ± 0.31</td>
<td>1.03 ± 0.24</td>
<td>19.61 ± 5.78*</td>
<td>1.02 ± 0.25##</td>
</tr>
<tr>
<td>MIG</td>
<td>0.84 ± 0.21</td>
<td>0.69 ± 0.15</td>
<td>3.29 ± 1.30</td>
<td>0.57 ± 0.15</td>
</tr>
<tr>
<td>MIP-1α</td>
<td>0.40 ± 0.21</td>
<td>0.19 ± 0.07</td>
<td>1.54 ± 0.23**</td>
<td>0.24 ± 0.09###</td>
</tr>
<tr>
<td>MIP-3α</td>
<td>0.55 ± 0.28</td>
<td>0.35 ± 0.08</td>
<td>1.14 ± 0.19</td>
<td>0.61 ± 0.32</td>
</tr>
<tr>
<td>RANTES</td>
<td>2.23 ± 0.55</td>
<td>1.97 ± 0.38</td>
<td>5.22 ± 1.71</td>
<td>2.29 ± 0.62</td>
</tr>
<tr>
<td>Thymus chemokine</td>
<td>37.33 ± 2.90</td>
<td>38.42 ± 5.66</td>
<td>53.09 ± 3.20</td>
<td>33.19 ± 5.01#</td>
</tr>
<tr>
<td>TIMP-1</td>
<td>0.52 ± 0.08</td>
<td>0.45 ± 0.09</td>
<td>66.30 ± 14.15**</td>
<td>1.06 ± 0.51###</td>
</tr>
<tr>
<td>VEGF</td>
<td>1.82 ± 0.64</td>
<td>1.98 ± 0.61</td>
<td>2.83 ± 0.50</td>
<td>1.24 ± 0.21</td>
</tr>
</tbody>
</table>

Values are means ± SE. CINC, cytokine-induced neutrophil chemoattractant; CNTF, ciliary neurotrophic factor; GM-CSF, granulocyte macrophage colony-stimulating factor; IFN, interferon; IL, interleukin; ra, receptor antagonist; LIX, lipopolysaccharide-induced CXC chemokine; MIG, MIP, macrophage inflammatory protein; RANTES, rapid upon activation normal T cell expressed and secreted; TIMP, tissue inhibitor of metalloproteinase; VEGF, vascular endothelial growth factor. *P < 0.005 and **P < 0.001, EAM vs. control. #P < 0.05, ##P < 0.005, and ###P < 0.001, EAM+Ac-SDKP vs. EAM.

Fig. 11. A: representative images showing matrix metalloproteinase (MMP)-9 (top) and MMP-2 (bottom) activity measured by zymography 2 wk after immunization in hearts of controls and EAM rats treated with vehicle or Ac-SDKP. Quantitative data on MMP-9 (B) and MMP-2 (C) activity are expressed as a percentage of control (n = 3–6).


