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

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1Hypertension and Vascular Research Division, Department of Internal Medicine, Henry Ford Hospital, Detroit, Michigan; 2Department of Biostatistics and Research Epidemiology, Henry Ford Hospital, Detroit, Michigan; and 3Integrated Department of Immunology, University of Colorado Denver and National Jewish Health, Denver, Colorado

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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 commonly associated with cardiotoxic 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 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 decreased 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 Kitabashy’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.
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), autoimmune 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])\(^2\) 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/infarction 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). Myocardial interstitial and perivascular collagen deposition, macrophage and T cell infiltration, and MMP activity.

<table>
<thead>
<tr>
<th>Table 1. Effect of Ac-SDKP on heart rate and organ weight measured 4 wk after immunization</th>
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<tr>
<td><strong>Control</strong></td>
</tr>
<tr>
<td>BW, g</td>
</tr>
<tr>
<td>Lungs/BW, mg/100 g</td>
</tr>
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<td>Liver/BW, g/100 g</td>
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<td>Thymus/BW, mg/100 mg</td>
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<td>Spleen/BW, mg/100 g</td>
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<td>Kidney/BW, g/100 g</td>
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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 (C): cardiac output measured by echocardiography 4 wk after immunization in

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

LV mass, (mm³)/100 g BW

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

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.

37°C and then washed, stained for surface markers, fixed with 1% paraformaldehyde at room temperature for 20 min, and suspended in permeabilization buffer. Intracellular markers were stained with a series of antibodies: FITC anti-interferon (IFN)-γ, DB-1 (Biolegend); PE anti-interleukin (IL)-4, OX-81 (BD Biosciences); and PerCP-Cy5.5 anti-IL-17, Tc11 (Biolegend). A BD Biosciences LSR II flow cytometer was used for all analyses.

Immunohistochemical staining. Six-micrometer frozen sections were immunostained with the appropriate antibody: anti-CD45 (total leukocytes), ED-1 (monocytes/macrophages), CD11c (dendritic cells), CD4 (T helper cells), or CD8 (T cytotoxic cells). Negative controls were processed in a similar fashion but were not treated with the primary antibody. Positive cells (red/dark brown staining) with clearly visible nuclei were counted in high-power fields and expressed as cells per square millimeter (9). All measurements and analyses were carried out in a blind fashion.

Proteomic array. Cross sections of the heart were homogenized in lysis buffer (PBS containing 1% Triton X-100, 10 µg/ml aprotinin, 10 µg/ml leupeptin, and 10 µg/ml pepstatin). Protein levels of 29 inflammatory mediators were measured in tissue homogenates using a proteomic array kit (R&D Biosciences, Minneapolis, MN); these included IL-1α and -β, tumor necrosis factor (TNF)-α, IL-2, interferon-γ-induced protein 10 (IP-10), cytokine-induced neutrophil chemoattractant-1 (CINC-1), macrophage inflammatory protein (MIP)-1α, intercellular adhesion molecule (ICAM)-1, and L-selectin. Data were expressed as arbitrary units (AU) representing the OD of the protein divided by the positive control.

Western blotting. Twenty micrograms of protein from heart extracts were subjected to 10% SDS-polyacrylamide gel electrophoresis (Invitrogen, Carlsbad, CA) under reducing conditions and transferred to polyvinylidene difluoride membranes (GE Healthcare, Piscataway, NJ). Each membrane was blocked with 5% nonfat milk for 1 h and incubated with anti-rat ICAM-1 (1:500; R&D Systems, Minneapolis, MN) or anti-GAPDH (1:50,000; Cell Signaling Technology, Danvers, MA) overnight at 4°C. The membranes were incubated for 60 min with the appropriate peroxidase-conjugated secondary antibody diluted 1:20,000 (Santa Cruz Technology, Santa Cruz, CA). ECL-plus chemiluminescense detection system reagents (Amerham Biosciences, Piscataway, NJ) to visualize the bands and Films were scanned with an Epson Perfection 3200 (Epson America, Long Beach, CA).

Metalloproteinase-2 and -9 activity in cardiac tissue homogenates. Gelatin zymography was performed 2 and 4 wk postimmunization as described by Zibadi et al. (45). Ten milligrams of cardiac tissue were washed with ice-cold saline and homogenized in 0.5 ml extraction buffer (pH 5.0) containing 10 mM cacodylic acid, 150 mM NaCl, 20 mM ZnCl2, 1.5 mM NaN3, and 0.01% Triton X-100. The homogenate was centrifuged, and the supernatant was applied to 10% polyacrylamide gel zymograms (Novex, Frankfurt, Germany). After electrophoresis at 125 V and 4°C for 90 min, the gels were washed two times with renaturing buffer (2.5% Triton X-100) at room temperature for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50 mM Tris·HCl, pH 8.0, 5 mM CaCl2, 0.2 M NaCl, and 0.02% Brij-35) for 30 min. The zymograms were then transferred to activity buffer (50
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,

![Graph](AJP-Heart Circ Physiol • doi:10.1152/ajpheart.00300.2011 • www.ajpheart.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 transmittal 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. Microscopic 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 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-
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.

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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 CD8⁷ T cells in the EAM group, it is well recognized that in these rats CD4⁷ are more important than CD8⁷ (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 autoimmunity, 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
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
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posed 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 pokeweed 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

Ac-SDKP PREVENTS EAM


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-β</td>
<td>0.35 ± 0.11</td>
<td>0.50 ± 0.19</td>
<td>1.76 ± 0.35**</td>
<td>0.29 ± 0.07##</td>
</tr>
<tr>
<td>IL-1α</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>
</tr>
<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>
</tr>
<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; CTNF, 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.


