Captopril Prevents Experimental Autoimmune Myocarditis

Lisa M. Godsel, Juan S. Leon, Kegiang Wang, Jamie L. Fornek, Agostino Molteni and David M. Engman

J Immunol 2003; 171:346-352;
doi: 10.4049/jimmunol.171.1.346
http://www.jimmunol.org/content/171/1/346

Why The JI?

• Rapid Reviews! 30 days* from submission to initial decision
• No Triage! Every submission reviewed by practicing scientists
• Speedy Publication! 4 weeks from acceptance to publication

References

This article cites 63 articles, 15 of which you can access for free at:
http://www.jimmunol.org/content/171/1/346.full#ref-list-1

Subscription

Information about subscribing to The Journal of Immunology is online at:
http://jimmunol.org/subscription

Permissions

Submit copyright permission requests at:
http://www.aai.org/About/Publications/JI/copyright.html

Email Alerts

Receive free email-alerts when new articles cite this article. Sign up at:
http://jimmunol.org/alerts

The Journal of Immunology is published twice each month by
The American Association of Immunologists, Inc.,
1451 Rockville Pike, Suite 650, Rockville, MD 20852
Copyright © 2003 by The American Association of Immunologists All rights reserved.
Print ISSN: 0022-1767 Online ISSN: 1550-6606.
Captopril Prevents Experimental Autoimmune Myocarditis

Lisa M. Godsel, Juan S. Leon, Kegiang Wang, Jamie L. Fornek, Agostino Molteni, and David M. Engman

Captopril, an angiotensin-converting enzyme inhibitor, is widely used in the treatment of a variety of cardiomyopathies, but its effect on autoimmune myocarditis has not been addressed experimentally. We investigated the effect of captopril on myosin-induced experimental autoimmune myocarditis. A/J mice, immunized with syngeneic cardiac myosin, were given 75 mg/L of captopril in their drinking water. Captopril dramatically reduced the incidence and severity of myocarditis, which was accompanied by a reduction in heart weight to body weight ratio and heart weight. Captopril specifically interfered with cell-mediated immunity as myosin delayed-type hypersensitivity (DTH) was reduced, while anti-myosin Ab production was not affected. Captopril-treated, OVA-immunized mice also exhibited a decrease in OVA DTH. In myosin-immunized, untreated mice, injection of captopril directly into the test site also suppressed myosin DTH. Interestingly, captopril did not directly affect Ag-specific T cell responsiveness because neither in vivo nor in vitro captopril treatment affected the proliferation, IFN-γ secretion, or IL-2 secretion by Ag-stimulated cultured splenocytes. These results indicate that captopril ameliorates experimental autoimmune myocarditis and may act, at least in part, by interfering with the recruitment of cells to sites of inflammation and the local inflammatory environment. The Journal of Immunology, 2003, 171: 346–352.

Myocarditis, inflammation of the heart, is characterized by myocyte necrosis and degeneration with mononuclear cell infiltration in the presence or absence of fibrosis (1). In the U.S., ~2500 people develop myocarditis each year (2, 3), although the prevalence of this disease is probably underestimated (4, 5). Myocarditis may be caused by infections with bacteria, viruses, parasites, and fungi, as well as by drugs and toxins. Virally induced myocarditis is commonly caused by coxsackievirus infection in North America and Europe, and parasite-induced myocarditis is commonly caused by Trypanosoma cruzi infection in Latin America (1, 3, 5–7).

Treatments for myocarditis are directed toward reducing or eliminating the infectious agent and associated disease complications, such as congestive heart failure, cardiogenic shock, conduction abnormalities, dysrhythmias, and thromboembolism (8). These complications are typically treated with diuretics, digitalis, β blockers, and vasodilators, such as angiotensin II receptor antagonists and angiotensin-converting enzyme (ACE) inhibitors (9). One commonly prescribed ACE inhibitor is captopril, which binds to ACE via its peptide-binding pocket and inhibits the functions of ACE, particularly the formation of angiotensin II from angiotensin I and the breakdown of bradykinin (10). Among the many ACE inhibitors and angiotensin II receptor antagonists, captopril has been shown to modulate chemotaxis, motility, adhesion, differentiation, activation, and cytokine and chemokine production of immune cells (reviewed in Ref. 11). Captopril is effective at ameliorating many human cardiomyopathies (12, 13), although its direct effect on human myocarditis has not been addressed. The drug decreases inflammation, calcification, and fibrosis in several models of infectious myocarditis, including encephalomyocarditis virus (14–16), coxsackievirus B3 (17–19), and T. cruzi (20). However, the effect of captopril on experimental models of Ag-induced autoimmune myocarditis has not been addressed.

An established model of experimental autoimmune myocarditis (EAM) is induced in susceptible strains of mice upon immunization with the α H chain of cardiac myosin (21). EAM is histologically similar to human myocarditis, with myocyte swelling and necrosis accompanied by mononuclear cell infiltration and fibrosis. Studies have shown that EAM is a T cell-mediated disease, requiring both CD4+ and CD8+ subsets (22–26). B cells are not vital for Ag presentation in EAM, and autoantibodies are not necessary for the progression of myocarditis (22, 27, 28).

To study the effect of ACE inhibition on the development of autoimmune myocarditis, we administered captopril to A/J mice immunized with cardiac myosin. We found that captopril ameliorates myocarditis and decreases cell-mediated inflammatory responses found in EAM. These results demonstrate that captopril treatment is indeed an effective method for inhibiting autoimmune myocarditis, and although it decreases cell-mediated immune responses, it does not directly affect T cell function.

Materials and Methods

Experimental animals

Male A/J mice (The Jackson Laboratory, Bar Harbor, ME) were 6–8 wk of age at initiation of the experiments. DO11.10 BALB/c mice were a gift from S. Miller (Northwestern University, Chicago, IL). Mice were anesthetized by a single i.p. injection of 60 mg/kg sodium pentobarbital for each experimental manipulation. The use and care of mice were conducted in accordance with the guidelines of the Center for Comparative Medicine at Northwestern University.

Received for publication January 3, 2003. Accepted for publication April 17, 2003.

Copyright © 2003 by The American Association of Immunologists, Inc.
Preparation of myosin
Cardiac myosin H chains were purified according to the method of Shiv-erick et al. (29), with modifications as described (30).

Induction of autoimmune myocarditis
Mice were immunized with myosin (300 μg) in an emulsion of CFA (Difco, Detroit, MI) in a total volume of 0.1 ml. Mice received s.c. injections in three sites in the dorsal flank. Seven days later, mice were boosted in an identical manner.

OVA immunization
Mice were immunized with an emulsion of OVA (100, 75, 50, or 25 μg; Sigma-Aldrich, St. Louis, MO) in CFA in a total volume of 0.1 ml. Mice received s.c. injections in three sites in the dorsal flank. Seven days later, mice were boosted in an identical manner.

Captopril treatment regimen
Mice were given drinking water containing or lacking 75–100 μg/ml captopril from the day of immunization through the day of sacrifice. We tested a variety of doses of captopril and chose for the actual experiment the highest dose that gave a decrease in myosin-induced myocarditis without mortality. Administration of captopril at concentrations greater than 120 μg/ml in the water led to excessive mortality. The range of doses tested was chosen based on other reports (15, 31), with 2 mg/ml as the upper end dose (32). The amount of water consumed and the weights of the mice were monitored and the amount of captopril was adjusted so that the mice received ~25 mg captopril/kg body weight/day. Captopril stimulated water consumption in our mice, as reported (33), to 5–7 ml per mouse per day throughout the course of treatment.

Serum ACE activity
Serum ACE activity was determined by the spectrophotometric method of Cushman and Cheung (34) using the synthetic substrate hippuryl-L-histidyl-L-tyrosine. Serum was treated with HCl and ethyl acetate and dehydrated sample of 20 heart sections: overall agreement (0.82), significance of disease incidence and comparison of histologic scores were analyzed by Pearson’s χ2; Agreement of blinded observer histopathology scores was analyzed by weighted κ. Mean histologic scores ± SD, although statistically invalid, will be provided to aid the reader and to continue the convention of other autoimmune myocarditis papers. Values of p < 0.05 were considered significant.

Results
Captopril increases serum ACE levels
To study the effect of captopril on autoimmune-mediated inflammation and fibrosis, we added captopril to the drinking water of myosin-immunized and saline-immunized A/J mice. Each capto- pril-treated mouse received 25 mg drug/kg body weight per day. We confirmed that the captopril treatment was effective by assay- ing for increased levels of ACE in treated mice at day 21 postim- munization. Increased ACE levels result from the captopril-in- duced negative feedback loop of the renin-angiotensin system in which a decrease of angiotensin II stimulates the production of ACE (34). Captopril-treated myosin and saline-immunized mice had significantly (p < 0.001) higher levels of ACE than did untreated controls (Fig. 1). These results indicate that captopril was

![FIGURE 1. Captopril up-regulates serum ACE levels in myosin-immunized mice. At 21 days postimmunization, sera were collected and analyzed for serum ACE levels from four groups of mice: myosin immunized and captopril treated (Myosin/CFA + Captopril), myosin immunized (My- osin/CFA), saline immunized and captopril treated (PBS/CFA + Captopril), and saline immunized (PBS/CFA). *, p < 0.001 compared with the respective untreated group.](http://www.jimmunol.org/)
effective in blocking the production of angiotensin II by inhibiting ACE in treated mice. Increasing the captopril dose or prolonging captopril treatment resulted in elevated serum ACE levels (37–39).

**Captopril reduces cardiac hypertrophy in myosin-immunized mice**

Twenty-one days postimmunization, gross analysis of the hearts from captopril-treated mice revealed a significant decrease in the typical signs of myocarditis: hypertrophy, induration, and pallor. Captopril-treated, myosin-immunized mice resembled saline-immunized mice (Fig. 2). Hypertrophy was reduced in treated mice, as evidenced by body weight and heart weight measurements (Table I). Captopril significantly reduced the heart weight, body weight, and heart weight to body weight ratios in myosin-immunized mice. Interestingly, both the heart weight and the heart weight to body weight ratios of myosin-immunized, captopril-treated mice were equivalent to those of saline-immunized mice. Captopril did not significantly affect the heart weight or heart weight to body weight ratio in saline-immunized mice, suggesting that the reduction of these parameters in myosin-immunized, captopril-treated mice was due to reduction in hypertrophy.

**Captopril ameliorates myocarditis in myosin-immunized mice**

To investigate whether the reduction of hypertrophy reflected a lack of tissue inflammation, we performed histopathologic analysis of hearts excised from myosin- and saline-immunized mice 21 days postimmunization. Captopril significantly reduced the incidence (Table I) and severity (Fig. 2, Table II) of myocarditis in myosin-immunized mice. Specifically, captopril reduced inflammation, fibrosis, and necrosis in these animals. Restricting the analysis to only diseased hearts showed that disease severity in affected mice was reduced, although not to a statistically significant level (Table II).

**Captopril reduces Ag-specific DTH**

We hypothesized that the reduction in cardiac inflammation in captopril-treated, myosin-immunized mice was due to an effect on myosin-specific immunity, which mediates cardiac inflammation in these mice (36). We assayed myosin-specific cellular immunity and found that captopril significantly reduced myosin DTH in myosin-immunized mice (Fig. 3c). These results suggest that captopril affects T cell-mediated inflammation in vivo, explaining the reduction of inflammation and damage observed in hearts of the captopril-treated, myosin-immunized mice. To determine whether the reduction of DTH by captopril was due to a suppression of T cell responses and not due to a reflection of captopril’s cardioprotective role (i.e., less myocardial damage results in decreased myosin autoimmune response (21)), we assayed OVA DTH in OVA-immunized mice treated with captopril. Captopril significantly reduced OVA DTH in OVA-immunized mice (Fig. 3c). These results suggest that captopril can reduce inflammatory responses to both a self and foreign Ag, irrespective of myocardial damage. Captopril has been shown to reduce local inflammatory processes.

---

**Table I. Captopril treatment decreases disease incidence, heart weight, and heart weight to body weight ratio in mice with experimental autoimmune myocarditis**

<table>
<thead>
<tr>
<th>Group</th>
<th>Disease Incidence</th>
<th>Heart Weight (g)</th>
<th>Body Weight (g)</th>
<th>Heart Weight to Body Weight Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>Myosin/CFA + Captopril</td>
<td>6/30 (20%)*</td>
<td>0.087 ± 0.016**</td>
<td>21.1 ± 1.76**</td>
<td>3.97 × 10⁻³ ± 1.03 × 10⁻⁴***</td>
</tr>
<tr>
<td>Myosin/CFA</td>
<td>21/33 (64%)</td>
<td>0.110 ± 0.023***</td>
<td>22.8 ± 2.49</td>
<td>4.83 × 10⁻³ ± 1.65 × 10⁻⁴***</td>
</tr>
<tr>
<td>PBS/CFA + Captopril</td>
<td>0/11</td>
<td>0.084 ± 0.008</td>
<td>21.0 ± 2.22</td>
<td>4.03 × 10⁻³ ± 2.95 × 10⁻⁴</td>
</tr>
<tr>
<td>PBS/CFA</td>
<td>0/10</td>
<td>0.095 ± 0.011</td>
<td>22.8 ± 1.88</td>
<td>4.15 × 10⁻³ ± 2.86 × 10⁻⁴</td>
</tr>
</tbody>
</table>

* p = 0.001 compared with myosin/CFA.
** p < 0.05 compared with myosin/CFA.
*** p < 0.01 compared with PBS/CFA.

---

**Table II. Captopril treatment decreases inflammation, necrosis, and fibrosis in mice with experimental autoimmune myocarditis**

<table>
<thead>
<tr>
<th></th>
<th>Incidence</th>
<th>Necrosis</th>
<th>Fibrosis</th>
</tr>
</thead>
<tbody>
<tr>
<td>Captopril</td>
<td>+ **</td>
<td>+ **</td>
<td>+ **</td>
</tr>
<tr>
<td>PBS/CFA</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

---

**FIGURE 2.** Captopril prevents cardiac pathology in myosin-immunized mice. At 21 days postimmunization, hearts from the four groups described in Fig. 1 were analyzed grossly (Gross) and histopathologically by staining with H&E or Masson’s trichrome (Trichrome). Representative hearts and tissue sections are shown. Hearts from saline-immunized mice were indistinguishable from hearts from saline-immunized, captopril-treated mice (PBS/CFA + Captopril).
Prevention of myocarditis in myosin-immunized mice by restoring peripheral T cell tolerance to myosin is associated with a decrease in myosin-specific Ab levels (46, 47). We investigated whether captopril treatment affected humoral responses to myosin and OVA at day 21 postimmunization, and found that myosin-specific and OVA-specific Ab production was not significantly affected by captopril treatment (Fig. 4), suggesting that captopril does not affect humoral immunity in our model system.

**Ag-specific T cell proliferation and cytokine secretion are not affected in vivo or in vitro by captopril administration**

To determine whether the in vivo effects of captopril or Ag-specific cellular immunity are due to direct effects on T cell function, we measured the effect of captopril treatment in vitro on the Ag-specific stimulation of splenocytes derived from DO11.10 TCR transgenic mice in which the majority of T lymphocytes are specific for OVA. Splenocytes from untreated DO11.10 cultured with OVA exhibited strong proliferation and cytokine secretion in the presence or absence of captopril in the culture medium (Fig. 5). Splenocytes did not respond to myosin, a negative control. This prompted us to test splenocytes from captopril-treated OVA-immunized BALB/c mice. Splenocytes from mice receiving captopril for 21 days showed normal in vitro proliferation and cytokine secretion when stimulated by OVA or anti-CD3 (Fig. 6). These results suggest that captopril does not directly affect Ag-specific T cell responses.

**Discussion**

Captopril ameliorated autoimmune myocarditis, as evidenced by a reduction in cardiac hypertrophy and the incidence and severity of inflammation, necrosis, and fibrosis. Captopril also reduced in vivo cell-mediated inflammatory responses, as measured by a reduction of myosin- and OVA-specific DTH in Ag-immunized mice. This reduction in cell-mediated immunity by captopril was not due to a direct effect on T cells because these cells proliferated normally and secreted normal amounts of proinflammatory cytokines when necessary for the induction of DTH responses, including: deposition of extravasated fibrin (17), production of proinflammatory cytokines (40–42), recruitment of leukocytes (43, 44), and regulation of the renin-angiotensin system in dendritic cell function (45). Therefore, we tested whether captopril could suppress DTH locally or required systemic administration. In myosin-immunized, untreated mice, local injection of captopril into the DTH site also significantly decreased myosin DTH compared with controls (Fig. 3b). These results indicate that captopril can act locally to mediate its effects and that its reduction of DTH may be due to a direct effect on T cell function, trafficking of T cells, or a generalized suppression of the inflammatory environment.

**Captopril does not affect Ag-specific Ab production**

Prevention of myocarditis in myosin-immunized mice by restoring peripheral T cell tolerance to myosin is associated with a decrease in myosin-specific Ab production (36). Moreover, other studies suggest that captopril decreases bulk Ab levels (46, 47). We investigated whether captopril treatment affected humoral responses to myosin and OVA at day 21 postimmunization, and found that myosin-specific and OVA-specific Ab production was not significa-

![Image](https://example.com/figure3.png)

**FIGURE 3.** Captopril treatment inhibits DTH responses. *A*, Twenty-one days postimmunization, myosin-specific DTH was measured in 10 mice from the four groups described in Fig. 1 by a 24-h ear-swelling assay, as described in Materials and Methods. Error bars represent SEM. *B*, Twenty days postimmunization, untreated, myosin-immunized mice received ear injections of myosin plus 1 × 10⁻⁴ M captopril (Myosin/CFA + Captopril) or myosin alone (Myosin/CFA). Saline-immunized mice received ear injections of myosin plus 1 × 10⁻⁴ M captopril (PBS/CFA + Captopril) or myosin alone (PBS/CFA). Myosin-specific DTH was measured the following day, and bars represent the mean swelling of five mice per group. *, p < 0.01 compared with the myosin/CFA group. *C*, Eight mice per group were immunized and boosted with the indicated amounts of OVA (OVA/CFA) or saline (PBS/CFA). Four mice in each group received captopril (Captopril) or nothing (No Treatment) in their water. Twenty-one days postimmunization, OVA-specific DTH was measured in four mice from each group. *, p < 0.005. Error bars represent SEM.

![Image](https://example.com/figure4.png)

**FIGURE 4.** Captopril does not affect myosin-specific or OVA-specific Ab production. *A*, At 21 days postimmunization, sera from mice in the four groups described in Fig. 1 were analyzed by myosin-specific ELISA using isotype-specific secondary Abs. Bars represent the averages of 10 mice. *B*, At 21 days postimmunization, serum was collected and analyzed by OVA-specific ELISA using isotype-specific detecting Abs from four groups of mice: OVA immunized and captopril treated (OVA/CFA + Captopril), OVA immunized (OVA/CFA), saline immunized and captopril treated (PBS/CFA + Captopril), and saline immunized (PBS/CFA). Bars represent the mean OD₄₅₀ of 10 samples. Error bars represent SEM.
 removed from the animal and tested in vitro even when captopril was present in the culture medium. Interestingly, myosin- and OVA-specific Ab responses were not affected by captopril.

Our finding that captopril inhibits the development of experimental autoimmune myocarditis is supported by several studies showing the beneficial effects of captopril on human cardiomyopathies (12, 13), infection-induced experimental myocarditides (14–20), and experimental autoimmune disease models (48, 49). In addition, another ACE inhibitor, temocapril, reduces myocarditis in rats via redox regulation mechanisms involving thioredoxin, although the effect of this agent on the immune system is not known (50). Our data on the reduction of DTH responses by captopril are novel and are supportive of the drug’s role in suppressing inflammatory processes (reviewed in Ref. 11). Captopril reduced both heart weight and heart weight to body weight ratio almost to normal, as is true of other disease models (14–19, 51). This reduction is due to a decreased inflammation, myocyte necrosis, and consequent reparative fibrosis (Table II). Our data also indicate that captopril completely prevents myocarditis in some mice and reduces disease severity in those mice that did develop some disease (Table II). Although the reduction in disease severity in affected mice does not reach statistical significance, it may still be of clinical significance. We are currently addressing whether treatment of captopril at later times postdisease induction also reduces myocarditis, as is true of mice infected with coxsackievirus B3 (17, 18).

The precise mechanism by which captopril reduces autoimmune myocarditis remains to be determined. We initially hypothesized that captopril functions by inhibiting myosin-specific T cell responses. Although we found that captopril decreased myosin DTH in myosin-immunized mice (Fig. 3), we also found that captopril could work locally by reducing myosin DTH when injected into the DTH test site. In addition, the reduction in myosin DTH is not due to the cardioprotective role of captopril (less damage leading to decreased autoimmune response (21)), because captopril also reduced OVA DTH in OVA-immunized mice. These results suggest that captopril may suppress cell-mediated immunity against a self or foreign Ag irrespective of the presence of myocardial damage. We wondered whether the reduction in DTH induced by captopril was due to suppression of T cell function, as reported by other groups (42, 49). Instead, we found that captopril, whether administered in vitro or in vivo, had no effect on the proliferative capacity or cytokine secretion of splenocytes stimulated by Ag or by anti-CD3 (Fig. 5). Our results are in accordance with those showing that proinflammatory and anti-inflammatory cytokines secreted by human PBMCs are not affected by captopril administration (52). These results are also counter to those of other groups.
reporting that captopril enhances T cell function in their model systems (53–56). The main difference between our results and those of the other groups is that we tested the effect of captopril on Ag-specific T cell proliferation and cytokine secretion, while other groups addressed this question in an Ag-nonspecific manner (e.g., by Con A, LPS, and PHA responses, among others). We do not yet know the mechanism by which captopril affects T cell responsiveness in vivo. Some groups have suggested that differences in these effects could be due to duration of captopril exposure (57), dosage (52–54, 58), in vitro vs in vivo administration (54), and plasma levels of PGs and bradykinin (56, 59), among other possibilities. We are currently addressing these hypotheses in our model system.

If captopril does not directly affect T cell function, captopril may reduce inflammation and DTH by reducing recruitment of T cells to the site of antigenic stimulation or by altering the local inflammatory environment. These hypotheses are supported by our result that local injection of captopril into the DTH site reduced DTH. We are currently testing both hypotheses. Captopril has been shown to inhibit lymphocyte recruitment by decreasing chemotaxis in capillary endothelial cells (43) and neutrophils (44). The effects of captopril on chemokines have not been addressed, but there is mounting evidence that angiotensin II affects the activities of a number of chemokines, including RANTES (CCL-5), monocyte chemoattractant protein-1 (CCL-2), and macrophage-inflammatory protein 1-α (CCL-3) (reviewed in Ref. 11). Captopril also reduces local inflammatory processes necessary for the induction of DTH responses, including: deposition of extravasated fibrin (17); production of proinflammatory cytokines such as TNF-α (40, 41), IFN-γ (42), and IL-12 (42); and dendritic cell function (45).

Taken together, these results show that captopril significantly reduces experimental autoimmune myocarditis. Additional mechanisms of action of captopril could involve suppression of angiotensin II levels, enhancement of bradykinin levels, or a pharmacologic effect of captopril’s thiog group, among other mechanisms. Antagonists of angiotensin II receptors reduced encephalomyocarditis virus-induced myocarditis (16, 51, 60). The main difference between our results and those of the other groups is that we tested the effect of captopril on cardiac hypertrophy, in vivo and autoimmune myocarditis. J. Clin. Pharmacol. 38:295.


Captopril prevents autoimmune myocarditis


