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Suppression of Experimental Autoimmune Encephalomyelitis by Ghrelin

Michael-Mark Theil,*† Sachiko Miyake,2* Miho Mizuno,* Chiharu Tomi,* J. Ludovic Croxford,* Hiroshi Hosoda,‡ Julia Theil,†† Stephan von Hörsten,‡ Hiroaki Yokote,* Asako Chiba,* Youwei Lin,* Shinji Oki,* Takashi Akamizu,† Kenji Kangawa,‡ and Takashi Yamamura2*

Ghrelin is a recently identified gastric hormone that displays strong growth hormone-releasing activity mediated by the growth hormone secretagogue receptor. While this unique endogenous peptide participates in the regulation of energy homeostasis, increases food intake, and decreases energy expenditure, its ability to inhibit the production of proinflammatory cytokines in vitro indicates its role in the regulation of inflammatory process in vivo. Here we examine the effect of exogenous ghrelin on the development of experimental autoimmune encephalomyelitis (EAE), a representative model of multiple sclerosis. In the C57BL/6 mouse model of EAE induced by sensitization to myelin oligodendrocyte glycoprotein 35–55 peptide, we found that alternate-day subcutaneous injections of ghrelin (5 μg/kg/day) from day 1 to 35 significantly reduced the clinical severity of EAE. The suppression of EAE was accompanied by reduced mRNA levels of proinflammatory cytokines such as TNF-α, IL-1β, and IL-6 in the spinal cord, microglia in vitro. These results shed light on the new role of ghrelin in the regulation of inflammation with possible implications for management of human diseases. The Journal of Immunology, 2009, 183: 2859–2866.

Ghrelin does not only stimulate GH release, but it also increases food intake, regulates energy homeostasis, and decreases energy expenditure by lowering the catabolism of fat (4, 8, 9). Because of its orexigenic and adipogenic character, ghrelin may be potentially useful for the treatment of anorexia and cachexia (10, 11). Although the precise mechanisms remain to be clarified, the orexigenic activities of ghrelin may be mediated by another feeding regulatory hormone neuropeptide Y (NPY) via stimulation of Y1 and Y5 receptors (12). Furthermore, the antagonistic effect of ghrelin on leptin-induced decrease of food intake seems to be mediated by ghrelin-induced release of NPY and subsequent stimulation of the Y1 receptor (13).

Ghrelin has been shown to exhibit antiinflammatory functions against T cells and macrophages in vitro (14–16). The potential activity of ghrelin as an antiinflammatory reagent in vivo was shown in several animal models, including bowel disease (17), arthritis (16, 18), sepsis, and endotoxemia (16, 19, 20). Here we report that subcutaneous injections of ghrelin could significantly attenuate the clinical severity of the representative model of experimental autoimmune encephalomyelitis (EAE) induced in C57BL/6 (B6) mice by sensitization against myelin oligodendrocyte glycoprotein (MOG)35–55 peptide. Furthermore, we demonstrate that in vivo treatment with ghrelin significantly suppressed the mRNA levels of the proinflammatory cytokines TNF-α, IL-1β, and IL-6 in microglia and infiltrating T cells derived from the spinal cords of ghrelin-treated mice. Finally, we confirm that LPS-stimulated microglia and monocytes produced lower amounts of proinflammatory cytokines when they were pretreated with ghrelin in vitro. In conclusion, the present study indicates the potential use of ghrelin as an antiinflammatory drug to control human CNS pathology.

Materials and Methods

Mice and reagents

We used female B6 mice (CLEA Japan) between 6 and 10 wk of age in specific pathogen-free conditions. Animal care and use were in accordance with the Japanese Law on the Protection of...
Table I. Amino acid sequence of mouse ghrelin and des-acyl ghrelin

<table>
<thead>
<tr>
<th>Peptide</th>
<th>Amino Acid Sequence</th>
<th>Ser(^{a}) acylation</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ghrelin</td>
<td>GS...PKGQK...PKG...K</td>
<td>n-Octanoic acid</td>
<td>(4)</td>
</tr>
<tr>
<td>Des-acyl ghrelin</td>
<td>GS...PKGQK...PKG...K</td>
<td>n-Octanoic acid</td>
<td>(7)</td>
</tr>
</tbody>
</table>

\(^{a}\) The underlined letter S represents the third serine (Ser\(^{3}\)).
FACSARIA (BD Biosciences). The total RNA was extracted from the isolated cells and was subjected to reverse transcription and real-time PCR.

In vitro effect of ghrelin on microglia cells treated with LPS

Mononuclear cells were prepared from brains of untreated non-EAE mice incubated with Liberase Blendzyme 3 and DNase I as described above and were isolated on 40%-80% discontinuous Percoll gradients. Isolated cells were suspended in DMEM supplemented with 10% FCS and cultured in 96-well flat bottom plates at $2 \times 10^5$ cells/well in the presence of ghrelin ($10^{-8}$ M) overnight and later stimulated with LPS at different doses (0.01, 0.1 µg/ml). After 5 h of incubation at 37°C, supernatants were collected and the levels of TNF-α were detected by using a sandwich ELISA.

Statistical analysis

The differences in the clinical score between ghrelin-, des-acyl ghrelin-, and sham-treated groups were analyzed by the nonparametric Mann-Whitney U test. FACS analysis, real-time PCR, ELISA, and proliferation data were subjected to two-way ANOVA. In case of significant differences, a Fisher post hoc test was applied. Probability values of <0.05 were considered as statistically significant.

Results

Ghrelin inhibits EAE

To explore the modulatory effects of ghrelin on inflammatory demyelinating diseases, we employed a model of EAE actively induced in B6 mice with MOG$_{35-55}$. Although classical forms of demyelinating diseases, we employed a model of EAE actively induced in EAE are typically characterized by acute paralysis followed by partial recovery as a reflection of persistent inflammatory demyelination in the CNS (21, 22). In the first series of experiments, we injected 0.5, 5, or 50 µg/kg ghrelin to the mice every other day from day 1 to 35 postimmunization, while the control mice were injected with 0.9% saline. The results showed that the continuous injections of 5 µg/kg ghrelin suppressed most efficiently the clinical signs of EAE (Fig. 1A), whereas a lower (0.5 µg/kg) or a higher dose (50 µg/kg) showed only a marginal effect (data not shown). The treatment with 5 µg/kg ghrelin did not significantly alter either the onset or peak score of EAE. However, significant differences were noted in mean clinical score after day 25 postimmunization between the ghrelin-treated and the control mice (Fig. 1A).

Moreover, the effect of ghrelin on EAE was specific as des-acyl ghrelin, an acyl-modified ghrelin, which lacks the n-octanoic acid on the third serine, and consequently its binding ability to GHS-R (7) (Table I) had no modulatory effect on EAE at any concentration examined (Fig. 1B and Table II). Thus, the discrepant results obtained with ghrelin and des-acyl ghrelin indicate that ghrelin treatment would ameliorate the clinical course of EAE via activation of the GHS-R.

To further characterize the effects of ghrelin on EAE, we next examined if treatment lasting for a shorter duration may also be immunomodulatory in vivo. We injected 5 µg/kg ghrelin every day from day 1 to 10 postimmunization (roughly corresponding to the induction phase) or from day 11 to 20 (roughly corresponding to the effector phase). As shown in Fig. 1C, both protocols showed similar levels of disease suppression, although it was less notable than the continuous treatment from day 1 to 35 (Table II).

Ghrelin does not influence cellular infiltration into CNS

In the previous results on prophylactic or therapeutic treatment of EAE, clinical suppression of EAE was generally associated with a significant reduction of cellular infiltration in the CNS (23). To clarify if histological manifestation of EAE is also suppressed by ghrelin treatment, we treated MOG$_{35-55}$-immunized B6 mice with 5 µg/kg ghrelin or 0.9% saline every other day and prepared sections of spinal cords at the peak of disease (day 17 after immunization) (Fig. 2). Clinical signs were milder in the ghrelin-treated mice compared with saline-treated ones. However, histology of the spinal cord sections with H&E staining revealed equivalent levels of cellular infiltration in ghrelin- and saline-treated mice. To confirm this, we isolated mononuclear cells from spinal cords of the

Table II. Clinical scores of EAE treated with ghrelin or des-acyl ghrelin following different treatment protocols

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Incidence</th>
<th>Mean Day of Onset ± SEM</th>
<th>Mean Maximal Score ± SEM</th>
<th>Mean Cumulative Score ± SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle</td>
<td>8/8</td>
<td>16.38 ± 1.13</td>
<td>3.75 ± 0.33</td>
<td>55.44 ± 7.14</td>
</tr>
<tr>
<td>Ghrelin</td>
<td>7/8</td>
<td>17.86 ± 1.30</td>
<td>3.29 ± 0.33</td>
<td>36.71 ± 9.99</td>
</tr>
<tr>
<td>Des-acyl ghrelin</td>
<td>6/8</td>
<td>18.83 ± 2.55</td>
<td>3.67 ± 0.40</td>
<td>49.33 ± 12.99</td>
</tr>
<tr>
<td>Vehicle</td>
<td>6/8</td>
<td>18.00 ± 0.71</td>
<td>3.80 ± 0.44</td>
<td>49.05 ± 8.09</td>
</tr>
<tr>
<td>Ghrelin</td>
<td>7/8</td>
<td>15.14 ± 0.51</td>
<td>4.43 ± 0.07</td>
<td>50.43 ± 3.10</td>
</tr>
<tr>
<td>Ghrelin (1-10)</td>
<td>6/8</td>
<td>16.00 ± 0.73</td>
<td>3.17 ± 0.53</td>
<td>34.00 ± 7.25</td>
</tr>
<tr>
<td>Ghrelin (11-20)</td>
<td>7/8</td>
<td>16.29 ± 1.25</td>
<td>3.50 ± 0.45</td>
<td>38.72 ± 8.79</td>
</tr>
</tbody>
</table>

* The table shows the results of three separate experiments (n = 8 mice in each group of the three experiments).

* After induction of EAE with MOG$_{35-55}$, mice were treated in two different experiments following the standard protocol of every other day s.c. treatment with 5 µg/kg ghrelin or 5 µg/kg des-acyl ghrelin. The controls were injected with 0.9% saline (vehicle).

* Following an alternative protocol, we treated the mice from days 1–10 (induction phase treatment) or from days 11–20 (effector phase treatment) with 5 µg/kg ghrelin and in-between with 0.9% saline injections. Data represent mean ± SEM.
mice at the peak of disease and enumerated the number of the lymphoid cells. Notably, the total cell number was slightly elevated in the ghrelin-treated mice (1.40 × 10^6/mouse) compared with the saline-treated mice (1.05 × 10^6/mouse). To further analyze the effects of ghrelin on the formation of CNS inflammation, we evaluated the cellular composition of the CNS-derived lymphocytes by using FACS. Although there was a trend that CD4^+ T cell numbers are increased in the lesions of ghrelin-treated mice as compared with saline-treated mice (Fig. 3B). In parallel, we also examined the composition of lymphoid cells obtained from spleen, LN, and thymus. Again, we could not reveal any significant change in the subsets of lymphocytes in ghrelin-treated mice (data not shown). Concordant with the historical findings, these data imply that ghrelin did not ameliorate clinical EAE by reducing the numbers of inflammatory cells in the CNS, but rather by regulating the inflammatory potential of the CNS infiltrates.

Ghrelin does not inhibit the induction of MOG$_{35-55}$-reactive T cells

To elucidate the immunomodulatory mechanism of ghrelin, we examined the cytokine production and proliferative response of draining LN cells to MOG$_{35-55}$ that were obtained from MOG$_{35-55}$-sensitized mice treated for 10 days every day with ghrelin or saline. The LN cells were collected on day 11 after immunization and stimulated with MOG$_{35-55}$ in vitro. Accordingly, we harvested the supernatant and measured the levels of IFN-γ, IL-17, and IL-4 by using ELISA. Although the IL-4 concentration was under the detection level, IFN-γ and IL-17 were not different from saline-treated mice in the proliferative response of the draining LN cells to MOG$_{35-55}$. We also examined the frequency of CD4^+CD25^+FOXP3^+ regulatory T cells in the lymph nodes and spleens using flow cytometry and did not find significant differences between ghrelin-treated and saline-treated mice (data not shown). These results indicate that in vivo ghrelin treatment did not inhibit the induction of MOG$_{35-55}$-reactive T cells.

Ghrelin does not affect induction of pathogenic autoimmune T cells

To further confirm that MOG$_{35-55}$-reactive T cells are normally induced in ghrelin-treated mice, we evaluated if the ability of the MOG$_{35-55}$-sensitized lymphoid cells, obtained from MOG$_{35-55}$-immunized mice, to transfer EAE into naive mice could be affected by in vivo ghrelin treatment. To this aim, we immunized donor mice with MOG$_{35-55}$ and treated them every day with ghrelin or saline from immunization up to day 10. Next day, we pooled lymphocytes from spleen and LN and cultured them in the presence of MOG$_{35-55}$. Three days later, CD4^+ T cells were purified and injected into recipient mice as described in Materials and Methods. It was theoretically possible that in vivo ghrelin treatment does not
inhibit induction of MOG<sub>35-55</sub>-reactive T cells, but would prohibit the ability to cause EAE in vivo. In postulating that this could happen, CD<sup>4+</sup> T cells from ghrelin-treated donors should be less encephalitogenic than those from saline-treated mice. The results showed that transfer of activated CD<sup>4+</sup> T cells either derived from saline- or ghrelin-treated donors induced passive EAE in the recipients, showing approximately the same clinical course and severity (Fig. 4). Thus, it can be concluded that ghrelin treatment does not affect the induction of encephalitogenic MOG<sub>35-55</sub>-reactive CD<sup>4+</sup> T cells.

**Ghrelin decreases mRNA levels of proinflammatory cytokines in the CNS**

After demonstrating that ghrelin does not suppress the infiltration of inflammatory cells in the spinal cord, we wondered whether the cytokine milieu in the ghrelin-treated mice could be significantly altered. To answer the question, we analyzed the mRNA levels of pro- and antiinflammatory cytokines (IFN-γ, TNF-α, IL-1β, IL-6, IL-4, IL-10, and TGF-β) in the spinal cord, spleen, LN, and thymus of ghrelin- and saline-treated mice at the peak of disease (day 17) by using quantitative PCR. Although ghrelin treatment had no effect on the mRNA levels of IL-4, IL-10, and IFN-γ in the spinal cord, spleen, LN, and thymus (data not shown), we found significantly reduced levels of TNF-α (<i>p < 0.0015</i>), IL-1β (<i>p < 0.025</i>), and IL-6 (<i>p < 0.025</i>) in the spinal cord of ghrelin-treated mice, compared with saline-treated ones (Fig. 5A). In contrast, the level of TGF-β showed a trend for slight elevation in the spinal cord. We also found a diminished level of TNF-α mRNA (<i>p < 0.0001</i>) in the spleen of ghrelin-treated mice (Fig. 5B), whereas we saw no significant change in any of the cytokines that we measured in LN or thymus of ghrelin-treated mice (Fig. 5, C and D). Because TNF-α, IL-1β, and IL-6 mRNAs were selectively down-regulated in the spinal cord, we suspected that monocytes could be potential target cells in the ghrelin-mediated EAE suppression. This idea was consistent with the fact that ghrelin treatment did not inhibit the induction of MOG<sub>35-55</sub>-reactive T cells.

**Ghrelin suppresses the proinflammatory cytokine production of LPS-stimulated monocytes**

To verify the postulate that in vivo treatment with ghrelin may ameliorate EAE by targeting monocytes, we examined in vitro effects of ghrelin on the monocytic cell line RAW 264.7 that robustly produce proinflammatory cytokines when stimulated with LPS. The RAW 264.7 line cells were first exposed to various doses of ghrelin for 1 h and then stimulated with LPS. We harvested the supernatant 2 h later and measured the levels of TNF-α and IL-6 by ELISA. The results revealed that prior exposure to ghrelin would significantly suppress the production of TNF-α (<i>p < 0.02</i>) and IL-6 (<i>p < 0.05</i>) by LPS-stimulated RAW 264.7 cells in a dose-dependent manner (Fig. 6). The inhibitory effect of ghrelin was very potent, as in addition to the effects on LPS-stimulated monocytes, even the basal production of TNF-α (<i>p < 0.008</i>) and IL-6 (<i>p < 0.03</i>) was significantly reduced by in vitro ghrelin treatment. Given that in vivo treatment with ghrelin could suppress the...
clear cells from the brains of untreated mice. In untreated non-EAE whether ghrelin directly affects microglia, we isolated mononuclear cells from the brains of untreated mice. To test this hypothesis, we  

We next examined the effect of ghrelin on microglia. To test whether ghrelin directly affects microglia, we isolated mononuclear cells from the brains of untreated mice. In untreated non-EAE mice, most (~77%) of the brain mononuclear cells were CD11b+ cells, and the majority of CD11b+ cells (~95%) were considered as CD45low microglia cells. Among these mononuclear cells, CD19+ B cells were <0.1% and CD3+CD45+ T cells were 1–1.5%. We cultured the isolated mononuclear cells in the presence of ghrelin overnight and stimulated them with LPS in different doses for 5 h. The TNF-α levels in the culture supernatant were measured by using ELISA. In the presence of ghrelin, the TNF-α levels were significantly reduced (Fig. 8). These results suggest that ghrelin directly affects microglia by reducing the production of inflammatory cytokines.

Discussion
Starvation is known to have immunosuppressive effects (24–26). Although little was known about the mechanistic link between starvation and immunity, recent studies have shed light on the immunomodulatory potency of a range of feeding regulatory hormones such as leptin and NPY. For example, serum leptin is decreased after acute starvation in parallel with immunosuppression or Th2 bias, whereas exogenous leptin would correct the altered Th1/-Th2 balance toward Th1 (27, 28). In contrast, NPY is increased after starvation. Exogenous NPY would shift the Th1/Th2 balance toward Th2 and can ameliorate the severity of EAE (29). Interestingly, both peptide hormones are linked to ghrelin in an endocrine feedback system (30). Ghrelin itself is increased after

![Image](http://www.jimmunol.org/)
starvation, and it can potently stimulate the release of NPY in the CNS (12). Moreover, ghrelin shows antagonistic effects against leptin (31). Although the available data on the action of ghrelin on leptin or NPY may not be extrapolated to speculate about its role in the immune system, we decided to explore whether ghrelin may exhibit beneficial effects in the modulation of EAE. Furthermore, ghrelin was reported to have protective effects on endotoxic shock in rats (32). Additionally, the wide range of GHS-R expression within the immune cells strongly suggested the immunomodulatory potential of ghrelin (6). Considering its endocrine interactions, ghrelin becomes an interesting candidate for the in vivo modulation of EAE.

To evaluate the effects of ghrelin on the immune system in vivo, we used the representative EAE model induced with MOG35-55 in B6 mice. Subcutaneous injections of ghrelin significantly suppressed EAE severity, especially after the peak of disease, while the EAE onset occurred almost similarly in both ghrelin- and sham-treated mice. Priming phase treatment (days 1–10) as well as effector phase treatment (days 11–20) also showed disease-suppressing effects, suggesting a modulatory role of ghrelin during all phases of disease. The unacylated ghrelin form, des-acyl ghrelin, failed to suppress EAE, demonstrating that the disease suppression was mediated by the GHS-R.

The histological findings at day 17 were similar in all animals regardless of the applied treatment. The inflammatory cell infiltration and demyelination occurred in both groups, suggesting a ghrelin effect independent of cell trafficking at the peak of disease. Moreover, we found by FACS analysis that the number of mono-nuclear cells isolated from the spinal cord and their composition did not significantly alter among ghrelin- and sham-treated mice at the same time point. Our data showed no statistically significant changes in the examined cell subsets, which supported the histological findings of unaffected immune cell traffic to the CNS. This discrepancy between analogous inflammatory status in the spinal cord on the one hand and less severe disease on the other hand in ghrelin-treated mice was remarkable, suggesting cytokine regulation as the possible mechanism of EAE suppression.

Leptin and NPY both influence the Th1/Th2 balance in opposing directions (27–29). Since ghrelin is the most potent NPY-releasing hormone and NPY suppresses EAE by a Th2 bias (29), we examined whether ghrelin affects the Th1/Th2 balance similar to NPY and if its potential mechanism of EAE suppression is primarily mediated on immune cells or secondarily through NPY release. To investigate the effect of ghrelin on the cytokine balance, we measured the cytokine responses of MOG35-55-primed T cells from mice treated with ghrelin or saline. The evaluated IFN-γ, IL-17, and IL-4 levels as well as the proliferative response did not significantly alter between ghrelin- and sham-treated mice. Underlying these observations, we conclude that the suppression of EAE mediated by ghrelin does not affect the T cell-derived cytokine balance. To further address whether ghrelin acts via the NPY pathway, we determined the encephalitogenic potential of CD4+ T cells from ghrelin-treated mice to cause passive EAE in syngeneic recipients. We treated donor animals with ghrelin or saline for 10 days after priming with MOG35-55, and lymphoid cells from the mice were stimulated with MOG35-55. Three days later, CD4+ T cell blasts were isolated and transferred to naïve mice. The CD4+ T cells from ghrelin-treated mice did not differ from those from saline-treated mice in the ability to mediate passive EAE, indicating that ghrelin does not primarily affect induction of encephalitogenic CD4+ T cells in vivo. While NPY attenuates EAE by a Th2 bias of encephalitogenic CD4+ T cells (29), our findings likely suggest that ghrelin interacts independently of NPY in the amelioration of EAE.

To further clarify the mechanism of ghrelin-mediated EAE suppression, we examined the mRNA levels of several cytokines of ghrelin- and sham-treated mice at the peak of disease. Our data demonstrate significantly reduced levels of the proinflammatory cytokines TNF-α, IL-1β, and IL-6 in the spinal cord and lower levels of TNF-α in the spleen of ghrelin-treated mice. In contrast, the level of TGF-β showed a trend for slight elevation in the spinal cord. The importance of TNF-α for initiating and sustaining inflammation is well described, as well as its essential role in the development of acute EAE (33, 34). The proinflammatory role of IL-1β and IL-6 in the immunopathology of EAE is also generally accepted (35–38). Thus, the inhibition of TNF-α, IL-1β, and IL-6 must be considered as an important mechanism in the ghrelin-mediated EAE suppression.

Given the selective down-modulation of the proinflammatory cytokines, we suspected that monocytes could be potential target cells in the ghrelin-mediated EAE suppression. However, the analysis of infiltrating cells and residual microglia revealed that the suppression of proinflammatory cytokines was prominently led by microglia. A decreased expression of these cytokines was also observed in infiltrating T cells. Considering that the transfer of T cells obtained from ghrelin-treated mice induced a similar disease course compared with control mice, the reduction of proinflammatory cytokines in microglia might be important in the ghrelin-mediated suppression of EAE.

In conclusion, the present study demonstrates for the first time to our knowledge that the gastric hormone ghrelin suppresses actively induced EAE by inhibiting production of the proinflammatory cytokines TNF-α, IL-1β, and IL-6 with microglia as the main target cells. These findings support an antiinflammatory property of ghrelin, shedding light on its role in immune-endocrine interactions. Consequently, we speculate that ghrelin may serve as an antiinflammatory drug to control human CNS pathology involving the production of proinflammatory cytokines.

Disclosures
The authors have no financial conflicts of interest.

References


