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Enhancement of nickel elution by lipopolysaccharide-induced inflammation

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ABSTRACT

Background: Implantations of metallic biomedical devices into bodies are increasing. The elution of Ni ions from these devices can lead to metal allergies. However, the molecular mechanisms of the elution have not been fully examined. Furthermore, it is not clear whether infection and inflammation affect the corrosion of metals.
Objective: We examined whether the elution of Ni from metal wires and plates was enhanced by inflammation *in vivo* and *in vitro*.
Methods: A Ni or SUS316L wire was implanted subcutaneously in the dorsum of mice. Lipopolysaccharide (LPS) was injected at the site immediately following the implantation. After 8, 24, and 72 h, the tissue around the wire was excised. RAW 264 cells were seeded on a Ni plate and incubated for 24 h in medium containing LPS. The amount of Ni in the tissue or conditioned medium was determined fluorometrically.
Results: The release of Ni ions from the wire was significantly increased from 8 to 72 h, and further increased by LPS. LPS also enhanced the release of Ni ions by the cells, but only when they were attached to the Ni plate. Chloroquine, bafilomycin A_1 and amiloride markedly inhibited the effects of LPS.
Conclusion: The activation of inflammatory cells on metals enhanced the elution of Ni probably via the release of protons at the interface of the cells and material.

1. Introduction

Implantations of biomedical devices to treat diseases and organ insufficiencies are increasing as populations age [1]. Most devices for the replacement of hard tissues, including artificial hip joints, bone plates and dental implants, comprise metallic biomaterials because of their reliable mechanical performance [2,3]. Corrosion-resistant and ductile, nickel (Ni) is contained in various alloys, including stainless steels, Ni–Cr and Ni–Ti. However, Ni is also the most common contact allergen among metals [4]. Allergies to Ni, classified as Type IV allergies [5], are initiated by the release of Ni ions from alloys. Ni bound to soluble proteins [4] or to proteins on antigen-presenting cells [6] is recognized as an antigen. The antigen-presenting cells then activate T cells and induce an increase in the number of Ni-specific, IFN-γ-producing $CD4^+$ and $CD8^+$ effector T cells [7]. It is difficult to prevent Ni allergies by inhibiting these immune responses. A more practical approach might be to block the elution of Ni ions from biomaterials. However, the molecular mechanisms of this elution have not been fully examined. Furthermore, although the inflamed sites become acidic, it is not clear whether infection and inflammation affect the corrosion of metals.

In general, the release of Ni ions from alloys is tested in solutions [8,9]. However, as biodevices are implanted for long periods of time, one should test the release of metal ions from alloys in tissues to assess the risk of inducing metal allergies. There is little evidence that the release of metal ions from alloys *in vivo* is similar to that *in vitro*.

To reveal the mechanisms of Ni-induced inflammation and allergy, several animal models have been developed. The injection of Ni ions into sensitized animals was found to cause allergic inflammation including ear swelling [8–10], footpad edema [11] and the proliferation of lymph node cells [12]. Tolerance to nickel sensitization was also examined in these animals [9]. Recently, Sato et al. found that the co-administration of lipopolysaccharide (LPS), a stimulator of innate immune responses [13], effectively enhanced sensitization to Ni [10]. Sensitization using Ni ions plus LPS will promote research into how metal allergies are evoked. In contrast to models using Ni ions, we induced inflammation in mice using a Ni

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wire [14]. In this model, Ni wire but not Fe, Al and Co wires induced necrosis of the surrounding tissues. The implantation of the Ni wire elicited the increase in plasma exudation 8 h after the implantation and prostaglandin and histamine mediated the responses, indicating that Ni ions were released within a few hours [14].

LPS mimics the inflammation induced by an infection, which can occur when a biomedical device is implanted [15,16]. Therefore, it is possible that the injection of LPS enhances the elution of Ni ions from metals. In this study, using Ni wire-induced inflammation model and a novel *in vitro* system, we examined the mechanisms responsible for the elution of Ni.

2. Materials and methods

2.1. Animals

Male C57BL/6 mice, specific pathogen free and weighing 22–25 g, were purchased from SLC (Shizuoka, Japan). The mice were treated in accordance with procedures approved by the Animal Ethics Committee of Tohoku University, Japan.

2.2. Materials

A Ni wire (>99%, ϕ 0.8 mm), a SUS316L wire (ϕ 1 mm), and a Ni plate (>99%, thickness: 0.05 mm) were purchased from Nilako Co., Tokyo, Japan. Lipopolysaccharide (LPS) was purchased from Sigma–Aldrich (St. Louis, MO) and amiloride, chloroquine, and bafilomycin A_1 were from Wako Pure Chemical Ind. (Osaka, Japan).

2.3. Implantation of the Ni wire into mice

A nickel wire and a SUS316L wire were cut into 5 mm lengths and sterilized by soaking in ethanol. Mice were anesthetized and a length of wire was implanted subcutaneously in the dorsum using a 13G implant needle (Natsume Co., Tokyo, Japan). A hundred microliters of LPS solution (1 μg/ml) or saline was injected into the site immediately after the implantation. The mice were sacrificed at the indicated time and then the skin tissue (diameter: 14 mm) on the wire was excised. The skin samples were minced with scissors in 500 μl of Milli Q water and left at 4 °C overnight. The extract was centrifuged at 15,000 rpm for 20 min, and the supernatant was used to determine Ni concentrations as described below.

2.4. Determination of Ni concentrations by fluorometry and ICP-AES

Samples were diluted with Milli Q water, and Newport Green DCF [17] was added (150 μl per tube: 0.75 μM) to 850 μl of diluted sample. Fluorescence intensity was determined with excitation and emission wavelengths of 505 and 535 nm, respectively, with the use of a Fluorometer F-2000 (Hitachi High-Technologies Corporation, Japan). The Ni concentrations of some samples were determined by inductively coupled plasma atomic emission (ICP-AES) with an ICPS-8000 (Shimadzu System Development Corporation, Japan).

2.5. Macroscopic and histochemical analyses

Mice were sacrificed 0, 8, 24, or 72 h after the implantation. Tissue (14 mm in diameter) including epidermis, dermis and subcutaneous tissue on the wire was then excised and weighed. The wires obtained were washed with phosphate-buffered saline and then with an ice-cold lysis buffer (20 mM HEPES, pH 7.4, 1% (v/v) Triton-X 100, 10% (v/v) glycerol) to remove attached cells. The surface of wires was observed by scanning electric microscope (S-3200N, Hitachi, Japan).

2.6. Incubation of the Ni wire in vitro

A Ni wire was incubated in 50 μl of Milli Q water, saline, or mouse serum at 37 °C for 8 h. Then, the amount of Ni eluted was determined as described above.

2.7. Cell culture and stimulation

RAW 264 cells, mouse macrophage cell lines, were cultured at 37 °C under 5% CO_2–95% air in phenol red-free Eagle's minimal essential medium containing 10% (v/v) fetal bovine serum, penicillin G potassium (15 μg/ml), and streptomycin sulfate (50 μg/ml). The cells were suspended at the indicated numbers in the same medium, and 200 μl of the cell suspension was added to a Ni plate (25 mm^2) in each well of a 96-well cluster dish. Two hours later, LPS was added at the indicated concentrations and the cells were further incubated at 37 °C for 24 h or the period indicated. To prevent them attaching to plates, the cells were seeded first, and 2 h later, the Ni plate was placed in a sloping position into each well.

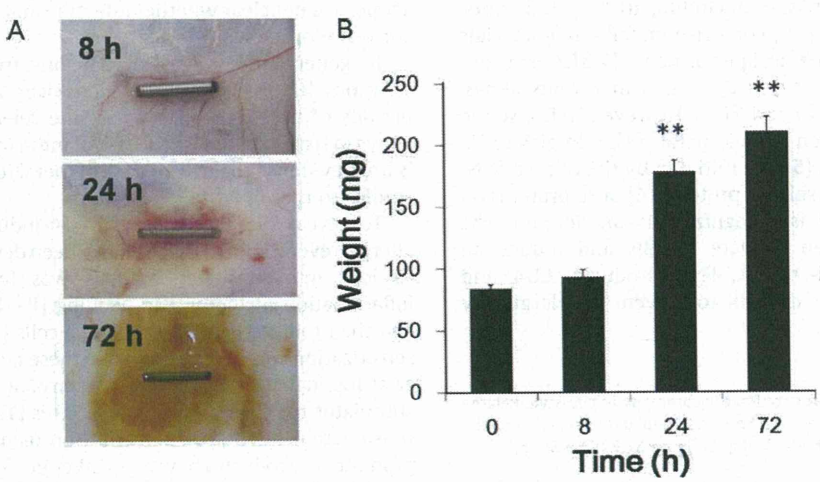

Fig. 1. Ni wire-induced inflammation. (A) A Ni wire was implanted subcutaneously in the dorsum of each mouse. The mice were sacrificed 8, 24 and 72 h after the implantation, and the skin around the wire was photographed. (B) The skin tissue (diameter: 14 mm) on the wire was excised and the weight of tissue was measured. The values are means for four mice with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. the 0 h group.

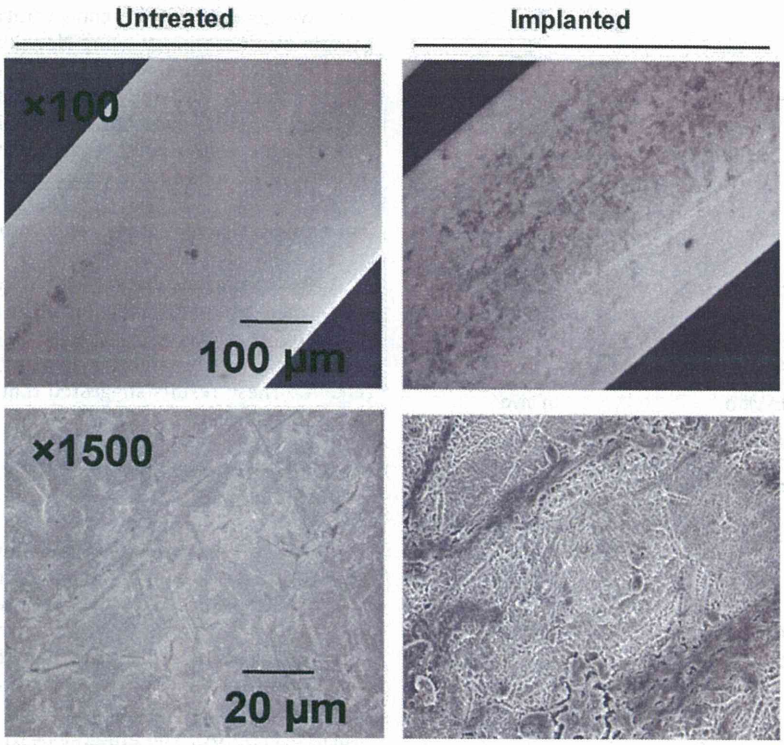

Fig. 2. Erosion of the surface of Ni wire. The surface of an untreated Ni wire (left) and an implanted Ni wire 72 h after implantation (right) was analyzed by scanning electron microscope.

2.8. Drug treatment

The V-ATPase inhibitor bafilomycin A_1 [18] was dissolved in DMSO, and the lysosome inhibitor chloroquine [19], and the Na^+/H^+ exchanger (NHE) inhibitor amiloride [20,21], were dissolved in autoclaved water, and diluted with the medium. The cells were incubated at 37 °C for 10 min in 1 ml of medium containing bafilomycin A_1 (1 nM), amiloride (100 μM), or chloroquine (10 μM) and then stimulated with LPS as described above. The final concentration of DMSO was 0.1% (v/v).

2.9. Statistical significance

The statistical significance of the results was analyzed with Dunnett's test or the Student–Newman–Keuls test for multiple comparisons. The results were confirmed by at least three independent sets of experiments.

3. Results

3.1. Metal wire-induced inflammation

A Ni wire was implanted subcutaneously into the dorsum of C57BL/6 mice and the response was observed 8, 24 and 72 h later. Consistent with our previous study, the wire caused extreme inflammation and bleeding (Fig. 1A). As an index of edema formation of tissues, the weight of skin tissues (14 mm in diameter) including epidermis, dermis and subcutaneous tissue on the wire was determined. The skin weight on the wire was

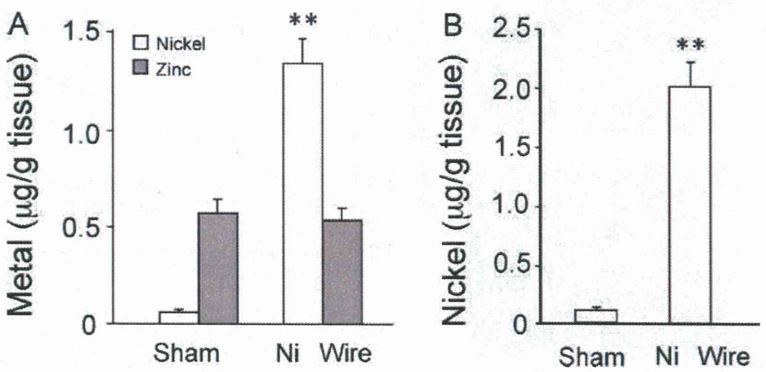

Fig. 3. Determination of the amount of Ni ions in tissues. (A) Skin tissue (diameter: 14 mm) was excised 8 h after the implantation of the Ni wire or sham treatment, and minced in 500 μl of deionized water. The concentrations of Ni and Zn ions in the supernatant were determined by ICP-AES. Values are the means for four mice with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. the corresponding sham control group. (B) The concentrations of Ni in the same samples were determined by fluorometry. Values are means for four mice with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. the sham group. The coefficient of the correlation between the concentrations of Ni ions determined by fluorometry (B) and by ICP-AES (A) was 0.996.

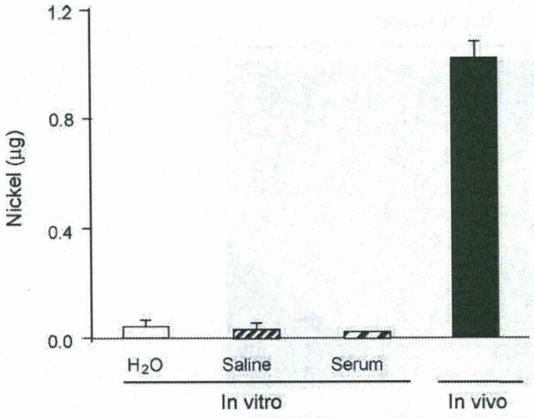

Fig. 4. Comparison of the release of Ni ions from a Ni wire *in vivo* and in solutions. A Ni wire was incubated at 37 °C for 8 h in 50 μl of H_2O, saline and serum. Then, Ni ions in the solution were quantified by fluorometry. The amount of Ni ions in the tissue 8 h after the implantation was determined as described in Fig. 3, and described as "*in vivo*". The values are the means of the four samples with S.E.M. shown by vertical bars.

significantly increased at 24 and 72 h (Fig. 1B), indicating that plasma leakage was induced by the Ni wire.

3.2. Corrosion of the wire

The corrosion of the implanted wire was analyzed with a scanning electron microscope. The untreated wire was smooth (Fig. 2, left panels) but the wire obtained 72 h after the implantation showed numerous traces of corrosion (Fig. 2, right panels), indicating that Ni ions had been released.

3.3. Quantitative analysis of the elution of Ni

A Ni wire was implanted subcutaneously in the dorsum and the skin tissue on the wire was excised 8 h later and homogenized. To evaluate quantitatively the release of Ni from the wire, the amounts of Ni ions, and Zn ions, as an internal control, in the supernatant of the skin tissue-homogenate were quantified by ICP-AES (Fig. 3A). The amount of Ni ions in the tissue was increased, although that of Zn ions was unchanged. Then we determined the concentration of Ni ions in the same sample by fluorometry using Newport Green DCF. As shown in Fig. 3B, the measurement of the Ni concentration in the control skin was not disturbed by Zn ions and the values showed a good correlation with those obtained by ICP-AES ($r = 0.996$). Therefore, in the experiment that followed, we determined the amount of Ni ions in the tissue by fluorometry.

3.4. Elusion of Ni ions in vivo and in solution

A Ni wire was incubated at 37 °C for 8 h in an aliquot of water, saline, or serum of C57BL/6 mice. The concentrations of Ni ions in the aliquots of water, saline and serum were only small as compared with the amount detected in the tissue homogenate (Fig. 4). These results suggested that Ni was eluted much more easily *in vivo* than *in vitro*.

3.5. Enhancement of the release of Ni from Ni- and SUS316L-wire in vivo by LPS

Using the wire-implanted mice, we found that the release of Ni ions was detectable at 8 h and increased to at least 72 h after the implantation. LPS (1 μg/100 μl saline) or saline (100 μl) was injected into the same site immediately after the implantation. Histological analysis disclosed that the wire's presence induced the infiltration of inflammatory cells, such as neutrophils and macrophages, in the tissue and LPS remarkably enhanced this process (Fig. 5A). The amount of Ni ions in the tissue samples from the LPS-treated group was significantly increased compared with that for the saline-treated group. The difference was significant at 8 and 24 h after the implantation (Fig. 5B).

Then we examined whether Ni was eluted from SUS316L, which is used as biomedical device. When SUS316L-wire was implanted subcutaneously in the dorsum of the mice, only a little elution of Ni ions was observed at 72 h after the implantation. As consistent with Ni wire, the elution of Ni from SUS316L wire was enhanced by the injection of LPS (Fig. 6).

3.6. Enhancement of the release of Ni ions from a metal plate by activated macrophages

Because macrophages are involved in the first line of defense in the inflammatory and immune response to foreign materials in

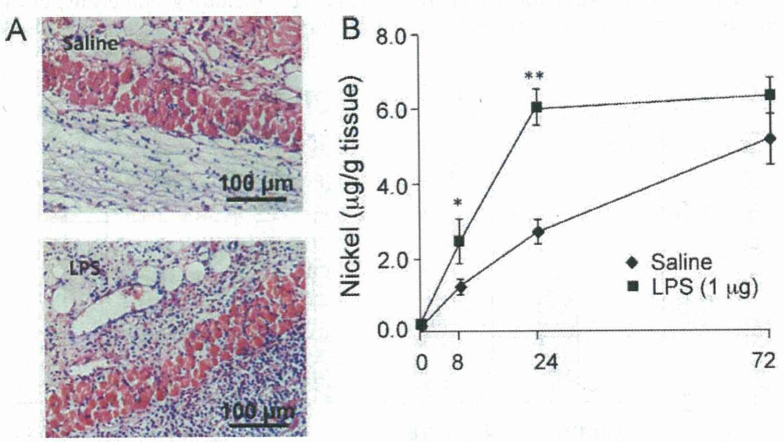

Fig. 5. Increase in the release of Ni ions by LPS-induced inflammation. (A) A Ni wire was implanted subcutaneously in the dorsum of each mouse. LPS (1 μg, bottom) or vehicle (saline, top) was injected into the site immediately after the implantation. Twenty-four hours after the implantation, the mice were sacrificed and the skin on the wire was dissected. Sections of tissue were prepared and stained with hematoxylin–eosin. (B) The skin tissue (diameter: 14 mm) on the wire was excised 8, 24 and 72 h after the implantation of Ni wires and the Ni ions in the tissue were quantified by fluorometry. Values are means for five mice with the S.E.M. shown by vertical bars. Statistical significance: $^*P < 0.05$, $^{**}P < 0.01$ vs. the saline group at the corresponding point.

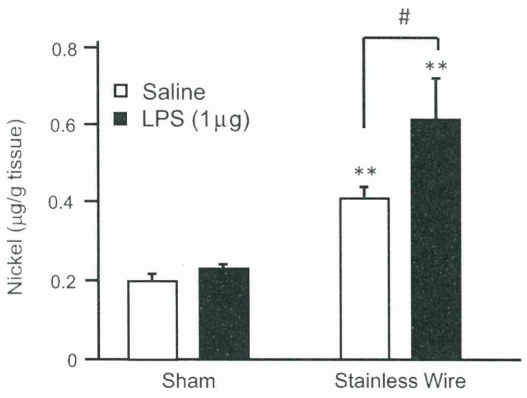

Fig. 6. Increase in the release of Ni ions from SUS316L by LPS. A SUS3167L-wire was implanted subcutaneously in the dorsum of each mouse. LPS (1 μg, closed columns) or vehicle (saline, open columns) was injected into the site immediately after the implantation. Seventy-two hours after the implantation, the mice were sacrificed and the skin tissue (diameter: 14 mm) on the wire was excised. The Ni ions in the tissue were quantified by fluorometry. Values are means for five mice with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. the corresponding sham group, and $^{\#}P < 0.05$ between groups indicated.

many tissues, we examined whether these cells induced the release of Ni ions from metals by using a mouse macrophage cell line RAW 264. RAW 264 cells were seeded on a Ni plate (25 mm^2) and incubated for 24 h in the presence or absence of LPS (1 μg/ml). Although few Ni ions were released when the plate was incubated in medium alone, the amount increased in the presence of the cells (Fig. 7A). Interestingly, the stimulation of the cells with LPS significantly increased the release of Ni ions in a concentration- and time-dependent manner (Fig. 7B and C). These results suggested that the activated cells enhanced elution of Ni ions from the plate.

3.7. Change in pH of the conditioned medium

To clarify whether the elusion of Ni ions from plates was caused by acidification of the medium, the pH of the conditioned medium was determined. The pH of the conditioned medium collected after the 24-h incubation decreased dependent on the number of cells (Fig. 8A) but was not affected by the addition of LPS (Fig. 8B). These findings indicated that the acidification of the medium was induced by the respiratory metabolism of cells and was not the main cause to induce Ni elution.

3.8. Requirement of cell attachment to the metal

We examined whether the attachment of cells to the metal plate was required for LPS-induced enhancement of the release of Ni ions. The cells were incubated for 24 h either attached or unattached to the Ni plate, and the concentration of ions released was determined. In the absence of LPS, there was no difference in the release of Ni ions between the attached and unattached cultures (Fig. 9). However, LPS-induced enhancement of the elution was observed when the cells were attached

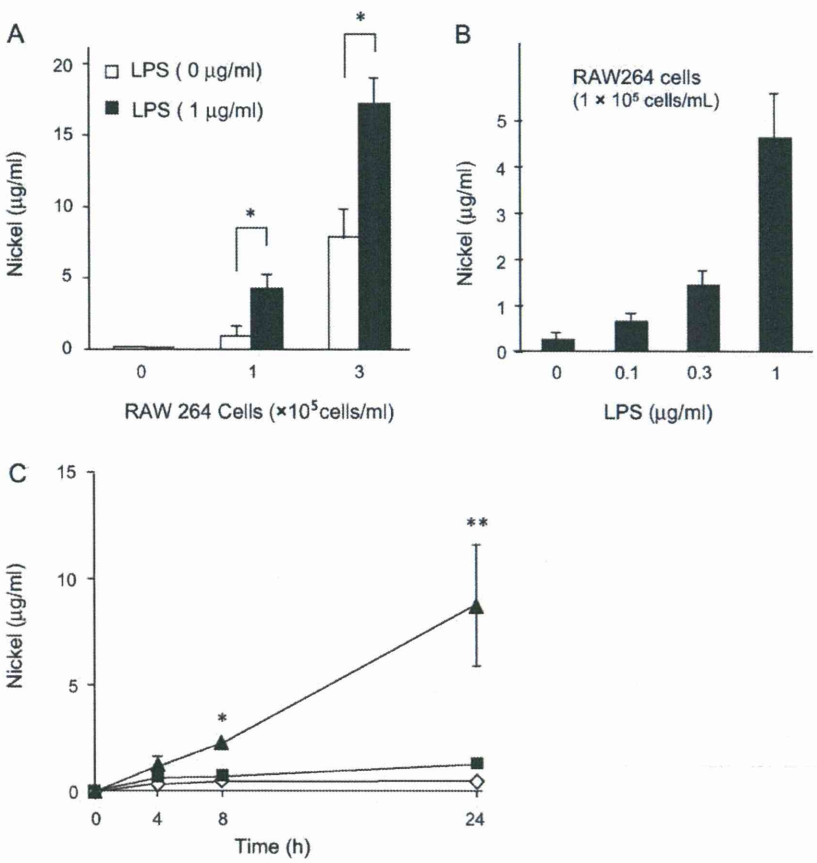

Fig. 7. Enhancement of elution of Ni ions from a Ni plate by LPS-stimulated RAW 264 cells. (A) The cells (1 or 3 × 10^5 cells/ml, 0.2 ml) seeded on a Ni plate (25 mm^2) were incubated for 24 h in the presence (closed columns) or absence (open columns) of LPS (1 μg/ml). The concentration of Ni ions in the supernatant was determined. (B) The cells (1 × 10^5 cells/ml, 0.2 ml) seeded on a Ni plate were incubated for 24 h in medium containing LPS (0.1, 0.3 and 1 μg/ml). (C) The cells (1 × 10^5 cells/ml, 0.2 ml) seeded on a Ni plate were incubated for 4, 8, and 24 h in medium containing LPS (1 μg/ml). Values are the means of five determinations with the S.E.M. shown by vertical bars. Statistical significance: $^{*}P < 0.05$, $^{**}P < 0.01$ vs. the corresponding LPS (0 μg/ml) group.

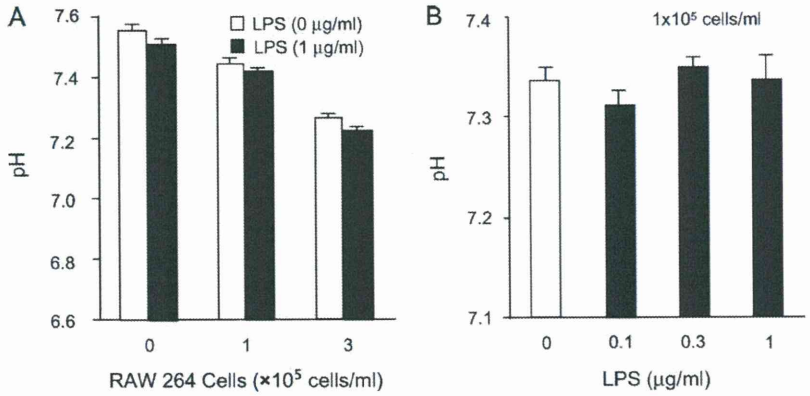

Fig. 8. Changes of pH in the culture medium of LPS-stimulated RAW 264 cells. The cells (1 and 3 × 10^5 cells/ml, 0.2 ml) seeded on a Ni plate (5 mm^2) were incubated for 24 h in the presence (closed columns) or absence (open columns) of LPS (1 μg/ml). The pH of the culture medium was determined with a pH meter. (B) The cells (1 × 10^5 cells/ml, 0.2 ml) seeded on a Ni plate (5 mm^2) were incubated for 24 h in medium containing LPS (0.1, 0.3 and 1 μg/ml). Values are the means for five determinations with the S.E.M. shown by vertical bars.

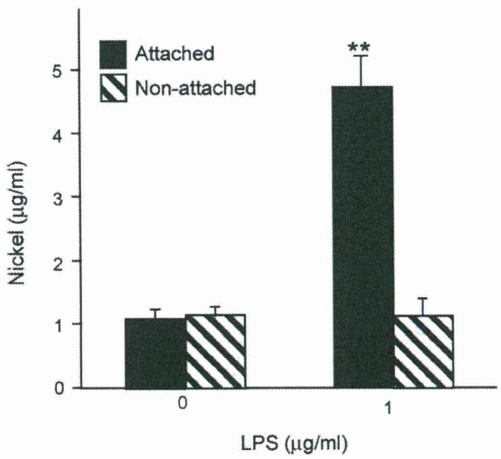

Fig. 9. Requirement of cell attachment for enhancement of the elution of Ni ions from Ni plates by LPS-stimulated RAW 264 cells. The cells (1 × 10^5 cells/ml, 0.2 ml) seeded on (attached condition) or under a Ni plate (non-attached condition) were incubated for 24 h in the presence or absence of LPS (1 μg/ml). The concentration of Ni in the culture medium was determined. Values are the means for five determinations with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. the corresponding LPS (−) group.

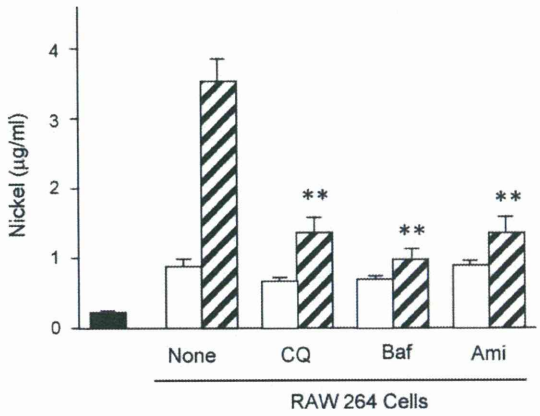

Fig. 10. Effects of inhibitors on the elution of Ni ions from Ni plates by RAW 264 cells. The cells (1 × 10^5 cells/ml, 0.2 ml) were seeded on a Ni plate (5 mm^2) and incubated for 24 h in medium containing chloroquine (CQ; 10 μM), amiloride (Ami; 100 μM) and bafilomycin A_1 (Baf; 1 nM) in the presence (hatched columns) and absence (open columns) of LPS (1 μg/ml). The closed column indicates that the Ni plate was incubated in the medium alone. The concentration of Ni in the supernatant was then determined. Values are the means for five determinations with the S.E.M. shown by vertical bars. Statistical significance: $^{**}P < 0.01$ vs. unstimulated RAW 264 cells, $^{\#\#}P < 0.01$ vs. LPS control.

to the plate (Fig. 9), indicating that the attachment of cells to plate was required to increase the release of Ni ions.

3.9. *Effects of inhibitors on the release of Ni ions from the plates*

The cells were incubated for 24 h on the Ni plate in the presence of the lysosome inhibitor chloroquine (10 μM), the V-ATPase inhibitor bafilomycin A_1 (1 nM), or the Na^+/H^+ exchanger (NHE) inhibitor amiloride (100 μM), and the concentration of Ni ions in the medium was determined. These inhibitors failed to reduce the release of Ni ions in the absence of LPS, but apparently inhibited it in the presence of LPS (Fig. 10). In the absence of the Ni plate, these inhibitors did not affect the viability of the cells (data not shown). These findings suggested that the release of H^+ by the cells was induced by the stimulation with LPS and caused the release of Ni ions from the plate.

4. Discussion

In this study, using two newly established models to assess the corrosion of Ni *in vivo* and *in vitro*, we found that inflammatory cells accelerated the release of Ni ions from the surface of the metal.

We developed a fluorometric method to determine Ni concentrations in tissue homogenate using Newport Green DCF, an indicator of Zn and Ni ions [17]. The Ni content obtained by the fluorometric assay well correlated with that obtained by ICP-AES, indicating the physiological concentration of Zn ions to be negligible in the fluorometric assay. In this study, we employed wires and plates made of >99% Ni to maximize the release of Ni from alloys. Therefore, the fluorometric assay was a convenient way to determine the concentration of Ni ions. For biomedical alloys such as stainless steel and nitinol, ICP-AES or ICP-MS should be used to assess the release of several metal ions at the same time. Such models are now under investigation.

Interestingly, when the wire was incubated at 37 °C for 8 h in water, saline, or mouse serum, only a little Ni was released. However, Ni ions were released more easily when the wire was implanted subcutaneously in mice, indicating the release to be highly dependent on the activation of cells around the wire. The increase in the concentration of Ni ions around the wire was already evident at 8 h after the implantation and well-correlated with the increase in vascular permeability [14]. Wataha et al. determined the concentration of Ni using a laser-ablation technique in tissue collected 7 days after implantation and demonstrated that the

distribution of the ions correlated well with the extent of necrosis in a Ni wire-implantation model in rats [22]. Therefore, it was likely that the eluted Ni ions caused local inflammation. The finding that the release of Ni ions into tissue was significantly increased by the injection of LPS suggested that the activation of inflammatory cells was involved in the corrosion of the wire. This notion was confirmed *in vitro* using RAW 264 cells. Namely, although little Ni was released from the plate in the medium alone, a significant increase in the elution was elicited in the presence of the cells, and apparently enhanced by the addition of LPS.

This *in vitro* model was useful for clarifying the molecular mechanisms by which activated inflammatory cells elute metals. LPS and inflammatory cytokines such as IL-1 activated V-ATPase and NHE in macrophages [23,24]. The unstimulated cells released a few Ni ions in both attached and unattached cultures and the release was little affected by the three inhibitors. The LPS-enhanced elution of Ni ions was observed only when the cells were attached to the metal and was markedly inhibited by chloroquine, bafilomycin A_1 and amiloride. Similar findings were observed regarding the resorption of bone by osteoclasts [25–27]. Osteoclasts attach to the bone and form a specialized compartment, the sealing zone, in which the resorption of bone is induced. Osteoclasts acidify the space using V-ATPase [28,29]. Because chloroquine neutralizes the acidity and the inhibitor of V-ATPase blocked the acidification, both inhibitors potently suppress bone resorption [30,31]. In addition, the NHE inhibitor also inhibited bone resorption and acidification [32], although the molecular mechanisms involved are not completely clear. However, amiloride inhibits the LPS-induced activation of cells [33,34]. Taken together, the molecular mechanisms of the elution of Ni might be similar to those behind the resorption of bone by osteoclasts. Recently, it was reported that macrophages create the acidic extracellular compartment to aggregated lipoproteins, which was inhibited by bafilomycin A_1 [35]. Thus, macrophages also form the acidic compartment via V-ATPase in various inflammatory processes. These findings suggest that the LPS-stimulated cells on Ni plates form a compartment and acidify it via V-ATPase and NHE, resulting in the elution of Ni ions.

Metal allergy is a concern when using metallic biomedical devices. Since we usually intake Ni ions from foods, the increase in the concentration of Ni ions in plasma might not be enough to induce Ni-allergy. There is a possibility that additional factor such as the exposure to LPS was required to elicit the sensitization of Ni [10]. On the other hand, in the Ni-sensitized persons, the elution of Ni ions from biomedical devices causes Ni-allergy. The most effective way to avoid it is to block the release of metal ions from biomaterials. However, there has been no system to assess the corrosion of metals under inflammatory conditions. We established *in vivo* and *in vitro* models for assessing the release of Ni from metal. In these models, the activation of cells such as macrophages apparently enhanced the corrosion of Ni. Thus, to assess the safety of biomaterials, the release of metal ions under inflammatory conditions should be evaluated. Our models might be useful tools for this purpose. Notably, the *in vitro* model might reflect the elution of Ni at sites of inflammation *in vivo*.

In conclusion, the elution of Ni ions from metal devices was promoted by inflammatory cells attached to the surface and inflammation as well as infection might augment the elution by enhancing the efflux of proton into the sealing zone as is the case for bone resorption.

Acknowledgements

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Mini Review

Assessment of the release of nickel from biomaterials in vivo and in vitro: enhancement by lipopolysaccharide

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Biodevices are implanted for long periods of time, so the release of metal ions from alloys should be tested in tissues to assess the risk of inducing metal allergies. However there is little evidence that the release of metal ions from alloys *in vivo* is similar to that *in vitro*. We implanted metal wires in mice and determined the concentration of metal ions in tissue to analyze the mechanisms responsible for metal allergies. The release of ions from the Ni wire was detected within 8 h and attained a plateau 72 h after the implantation. Furthermore, it was significantly increased by an injection of LPS. The results indicated that the release of Ni was apparently enhanced by inflammatory responses. We also established an *in vitro* assay system using the murine macrophage cell line RAW 264. The addition of LPS apparently increased the amount of Ni released into the medium, indicating the activation of the cells to have enhanced the elution of ions from the Ni plate. Our *in vitro* model using LPS-stimulated RAW264 cells might reflect the elution of Ni in inflamed tissue.

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Key words:
Nickel release, lipopolysaccharide, in vivo model, in vitro model, RAW264 cells

Introduction

Implantations of biomedical devices to treat diseases and organ insufficiencies are increasing as populationage [1]. Most devices for the replacement of hard tissues, including artificial hip joints, bone plates and dental implants, comprise metallic biomaterials because of their reliable mechanical performance [2-3]. Corrosion-resistant and ductile[3] nickel (Ni) is contained in various alloys, including stainless steels, Ni-Cr and Ni-Ti. However, Ni is also the most common contact allergen among metals[4-5]. Allergies to Ni, classified as Type IV allergies [4-6], are initiated by the release of Ni ions from alloys and the forming of Ni-binding proteins, which are recognized as antigens by antigen-presenting cells such as dendritic cells (DC) and macrophages [4]. These cells then activate T cells and induce an increase in the number of Ni-specific, IFN-γ-producing $CD4^+$ and $CD8^+$ effector T cells[4-6]. It is difficult to prevent Ni allergies by inhibiting these immune responses. A more practical approach might be to block the elution of Ni ions from biomaterials. However, the molecular mechanisms of this elution have not been fully examined.

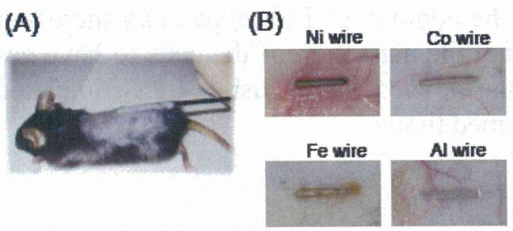

Fig. 1. Metal wire-implanted mice
A metal wire was implanted subcutaneously in the dorsum with an implant needle (A). The mice were sacrificed 72 h after the implantation and the skin around the wire was photographed (B, modified from ref. 17).

In general, the release of Ni ions from alloys is tested in solutions. For example, Okazaki *et al.* determined the release of metal ions from SUS316L stainless steel and Co–Cr–Mo casting alloy immersed in α-medium, PBS (−), calf serum, 0.9% NaCl, artificial saliva, 1.2 % L-cysteine, 1 % lactic acid and 0.01 % HCl for 7 days [7]. As biodevices are implanted for long periods of time, one should test the release of metal ions from alloys in tissues to assess the risk of inducing metal allergies. However, there is little evidence that the release of metal ions from alloys *in vivo* is similar to that *in vitro*.

Animal models of Ni-induced allergy and inflammation

To reveal the mechanisms of Ni-induced inflammation and allergy, several animal models have been developed. The injection of Ni ions into sensitized animals was found to cause allergic inflammation including ear swelling[8-10], footpad edema[12] and the proliferation of lymph node cells[8, 12]. Tolerance to nickel sensitization was also examined in these models[9, 11]. However, it is much more difficult to induce an allergy to Ni than to a proteinous antigen. In general, a high concentration of Ni or an oxidized form of the ion such as Ni (III) or Ni (IV) is required to trigger inflammation or an allergy[8]. Recently, Sato et al. found that the co-administration of lipopolysaccharide (LPS), a stimulator of innate immune responses, effectively enhanced sensitization to Ni [10]. Sensitization using Ni ions plus LPS will promote research into the evocation of Ni allergies. In addition, the toxicity of Ni particles to lung was assessed by injecting intratracheally in rats and mice[13-15]. The Ni particles induced the infiltration of leukocytes in bronchalveolar lavage fluid and production of tumor necrosis factor-α in this model[15]. Wataha *et al.* implanted a Ni wire into the subcutaneous space of rats and analyzed Ni concentrations in tissues and necrosis[16]. According to the methods described by Wataha et al., we implanted a metal subcutaneously in the dorsum of mice using an implant needle (Fig. 1A). We examined the effects of Ni and Co wires because Ni and Co were well-known metals inducing metal allergy. In addition, the Fe and Al wires were used as the control to clarify the nonspecific inflammation induced by the implantation of wires. The Ni wire caused extreme inflammation but the Co, Fe, and Al wires did not (Fig. 1B), indicating that Ni ions are easily released and cause inflammation[17]. In this model, the Ni wire-induced inflammation was assessed as the increase in vascular permeability, which was determined by the leakage of Evans blue[17]. The implantation of Ni wire also induced the expression of cyclooxygease-2 and histidine decarboxylase in the surrounding tissues[17].

Quantitative analysis of ions release from the implanted Ni wire

Analytical techniques like inductively coupled plasma-atomic emission spectrometry (ICP-AES) and ICP-Mass spectrometry (MS) are used for the detection of metals in solution. Wataha *et al.* analyzed Ni concentrations in tissues around the Ni wire 48 h, 96 h and 7 days later using laser-ablation (LA)-ICP-MS [16]. They found that the Ni caused severe inflammation and necrosis, and that its distribution in tissues correlated well with the inflammation. They appeared that greater than 25 μg/g of Ni in tissue was necessary to elicit severe inflammation with necrosis. In *in vitro* experiments using fibroblasts, endothelial cells, and monocytes, 10-50 μg/ml of Ni ions cause total suppression of mitochondrial function [18-20]. However, the concentration at which Ni ions induce Ni allergy has not been determined. Therefore, the quantitative analysis of the release of Ni ions from materials *in vivo* is required to assess the safety of biomaterials. We developed a fluorometric assay to determine Ni concentrations using Newport Green. Thierse et al. examined the binding of Ni to membranes of human Raji B cells by flow cytometry with Newport Green [21]. The use of Newport Green will reveal where Ni binds to protein as well as its concentration in tissues. Using the Ni wire-implanted mice described above, we determined the concentration of Ni in tissue and found that the release of Ni ions was detectable within 8 h and attained a plateau 72 h after the implantation. Vascular permeability around the wire also increased from 8 h post-implantation [16]. Interestingly, when the wire was incubated at 37 ℃ for 8 h in water, saline, or mouse serum, very little Ni was released. Thus, Ni ions were released more easily *in vivo* than in the solutions, indicating the release to be highly dependent on the responses of cells around the wire.

Enhancement by lipopolysaccharide of the release of Ni ions *in vivo*

The implantation of biomedical devices can cause infections and bacteria-induced inflammation. Although the inflamed sites become acidic, it is not clear whether the infection and inflammation affect the elution of Ni. So we examined the involvement of inflammatory responses in the release of Ni *in vivo*. LPS (1 μg/ 200 μL saline) was injected subcutaneously around the wire at the time of implantation. The release of Ni ions into tissue was significantly increased by the injection of LPS compared to an injection of the vehicle only. These results clearly indicated that the release of Ni was enhanced by the inflammatory responses. Thus, the elution of metal ions was induced by the attached cells on the surface of alloys and enhanced by inflammatory stimuli. These findings suggested that the release of metal ions from biomaterials in buffers might not reflect that in tissues. Thus, our metal-wire implant model might be used to assess the safety of biomaterials in normal tissues and in the inflammatory conditions.

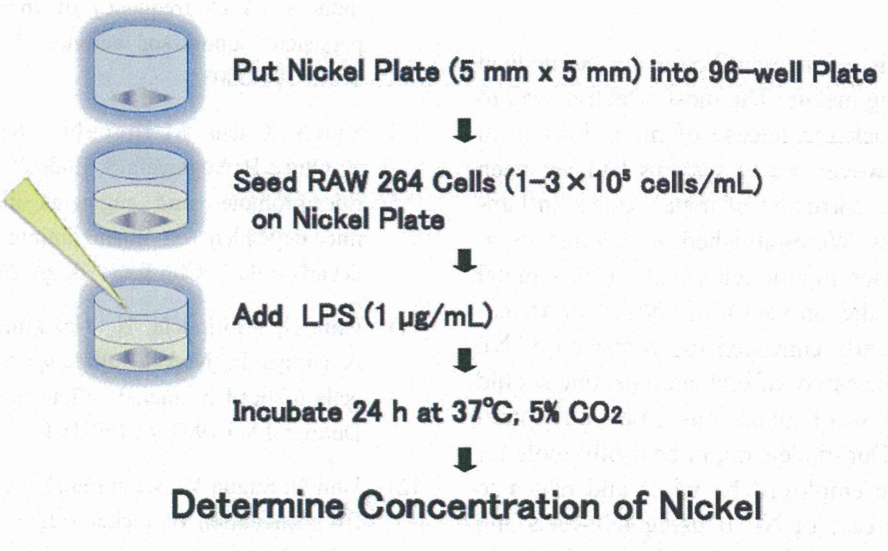

Fig. 2. ***In vitro*** **assay system for Ni release from the plate**

In vitro system for the assessment of Ni release at inflamed sites

The effects of inflammatory responses to infections on the release of Ni from alloys have not been analyzed *in vitro*. The finding that LPS enhanced the release of ions from a Ni wire implanted in mice, however, indicates that the corrosion of metals should be tested under condition similar to those in inflamed tissue. Consequently, we established an *in vitro* assay system using the murine macrophage cell line RAW 264 as the inflammatory cells activated by LPS (Fig. 2). RAW 264 cells were seeded on a Ni plate (5 mm square) and incubated for 4, 8 and 24 h in the presence or absence of LPS. Although little Ni was released from the plate in the medium alone, a significant increase occurred in the presence of the cells. LPS (0.1 to 1 μg/mL) significantly enhanced the release of Ni into the medium in concentration- and time-dependent manners, indicating that the activation of RAW 264 cells enhanced the elution of ions from the plate. These findings suggested our *in vitro* model using LPS-stimulated RAW264 cells to be a novel system reflecting the elution of Ni at the site of inflammation.

Our findings indicated that the interaction of the cells with metals on its surface is important to release of metal ions. However, it has not been disclosed that the molecular mechanisms by which activated inflammatory cells elute metal ions from the surface of metals. Our *in vitro* model using macrophages is useful to analyze the mechanisms.

Conclusion

Metal allergy is a concern when using biomedical devices containing metals. The most effective way to avoid it is to block the release of metal ions from biomaterials. However, assay systems had not been able to assess the corrosion of metals under inflammatory conditions. We established *in vivo* and *in vitro* models for assessing the release of Ni from metal. In these models, the activation of cells such as macrophages apparently enhanced the corrosion of Ni. Thus, to assess the safety of biomaterials, one should evaluate the release of metal ions under inflammatory conditions. Our models might be useful tools for this purpose. We employed Ni wires and plates to maximize the release of Ni. If using ICP-APS and ICP-MS within our models, the release of various metal ions from biomedical alloys could be assessed at the same time.

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Mini Review

Induction of thymic stromal lymphopoietin by chemical compounds in vivo and exacerbation of allergy

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Exposure to several chemical compounds in the environment might worsen allergies. However, it remains unclear which chemicals except for contact-sensitizing compounds modify inflammatory and immune responses and how. Thymic stromal lymphopoietin (TSLP), an IL-7-like cytokine produced mainly by epithelial cells, plays important roles in the initiation of allergic inflammation. We found that the painting of xylene on ear lobes induced production of TSLP and exacerbated the picryl chloride-induced allergic dermatitis. Thus, there are chemical compounds in the environment which do not have contact-sensitizing activity but cause the production of TSLP and on exacerbation of allergic dermatitis.

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TSLP, organic solvent, exacerbation of allergic dermatitis

Introduction

Atopic dermatitis is an allergic inflammatory disease characterized by intense pruritus, chronic eczematous plaques, and relapsing inflammation induced by repeated exposure to the antigen. In the inflamed skin, infiltration by eosinophils, the number of mast cells, and Th2-type immune responses are generally increased[1,2]. It is important to prevent exacerbation of the inflammation, from scratching for example, which can destroy the barrier function of skin and worsen the dermatitis. In addition, exposure to chemical compounds in the environment might exacerbate allergies. However, it remains unclear which chemicals other than contact-sensitizing compounds modify inflammatory and immune responses and how. Therefore, it is necessary to establish a suitable experimental model to identify chemical compounds which worsen allergic dermatitis and to clarify the molecular mechanisms involved.

Experimental models of allergic dermatitis

At present, there are several animal models of dermatitis with atopic dermatitis-like skin lesions. For example, repeated epicutaneous exposure to contact-sensitizing compounds such as 2,4,6-trinitro-1-chlorobenzene[3-5] and paraphenylenediamine[6], or dust mite allergen[7] results in chronic contact hypersensitivity. NC/Nga mice have also been used as a model of atopic dermatitis[8-10]. The contact hypersensitivity induced by contact-sensitizing compounds is caused by Th1-dominant inflammation[3,5]. Importantly, the repeated application of such compounds leads to responses different from those induced by a single challenge. Repeated treatment with antigenic compounds shifted the cytokine milieu from Th1 to Th2, resulting in increased infiltration of eosinophils and mast cells, and the induction of immediate- and late-phase responses[3-6]. However, the molecular mechanisms responsible for the shift in the milieu are still unclear. Here we established a novel model of chronic allergic dermatitis in which antigen-nonspecific inflammation shifts the cytokine milieu to a Th2-dominant reaction[11]. Namely, 12-*O*-tetradecanoyl 13-acetate (TPA) was painted twice on the ear lobes of PiCl-sensitized mice to induce antigen-nonspecific inflammation. The mice were then challenged with PiCl painted on the same ear lobe[11]. This model showed features similar to those observed in patients with atopic dermatitis: the formation of crust, epidermal hyperplasia and vigorous infiltration by leukocytes including eosinophils[11]. The application of TPA induced a shift in the cytokine milieu from a Th1- to a Th2-type profile, resulting in an exacerbation of the PiCl-induced allergic dermatitis[11]. Thus, this model would be suitable for studying the mechanisms by which antigen-nonspecific inflammation worsens allergic dermatitis.

Role of Thymic stromal lymphopoietin (TSLP) in the exacerbation of allergies

TSLP, an IL-7-like cytokine produced mainly by epithelial cells[12] and mast cells[13], plays important roles in the initiation of allergic inflammation[14]. TSLP production is increased at inflamed sites in patients with severe asthma[15], atopic dermatitis[16], and allergic rhinitis[17]. The allergic inflammation in an animal model of asthma was significantly suppressed in TSLP receptor-deficient mice[18]. In addition, the intratracheal administration of anti-TSLP receptor significantly reduced infiltration of eosinophils, hyperplasia and Th2 cytokine production[19]. Lung-specific expression of TSLP induced asthma-like airway inflammation[20], and skin-selective expression and the intradermal injection of TSLP induced atopic dermatitis[21,22]. Thus, an excess of TSLP is enough to cause allergic inflammation.

In our model, the application of TPA to the ear lobe of the PiCl-sensitized mice markedly increased the level of TSLP mRNA at 4 h[11]. Thus TPA-induced production of TSLP might be one of the mechanisms responsible for the shift forward a Th2-dominant response.

Effects of chemicals in the environments on TSLP production and allergic dermatitis

The first cells to interact with chemical compounds in the environment are the epithelial cells of the respiratory system, digestive tract and skin. Therefore, it is likely that chemicals which attach to epithelial tissues induce TSLP production by epithelial cells, promoting Th2-type reactions and worsening the allergic inflammation. Consequently, we assayed the activity of various chemical compounds, which are detected in the indoor environment, to induce TSLP production in ear lobes of mice. Among the organic solvents tested, xylene and related compounds such as 1,2,4-trimethylbenzene significantly induced the

production of TSLP protein. Interestingly, the activity to induce TSLP production was highly dependent on the position of methyl groups on the benzene ring. Namely, *m*-xylene induced much more extensively the production of TSLP than did *o*-xylene. These findings suggested that xylene triggered TSLP production by binding to a specific protein in a structure-dependent manner, and not through physical and/or chemical toxicity.

When painted on the ear instead of TPA, xylene enhanced the PiCl-induced thickening of the ear and IL-4 production. Importantly, the xylene-induced enhancement of these responses was reversed in TSLP receptor-knockout mice, suggesting that xylene exacerbated the PiCl-induced allergic inflammation via production of TSLP.

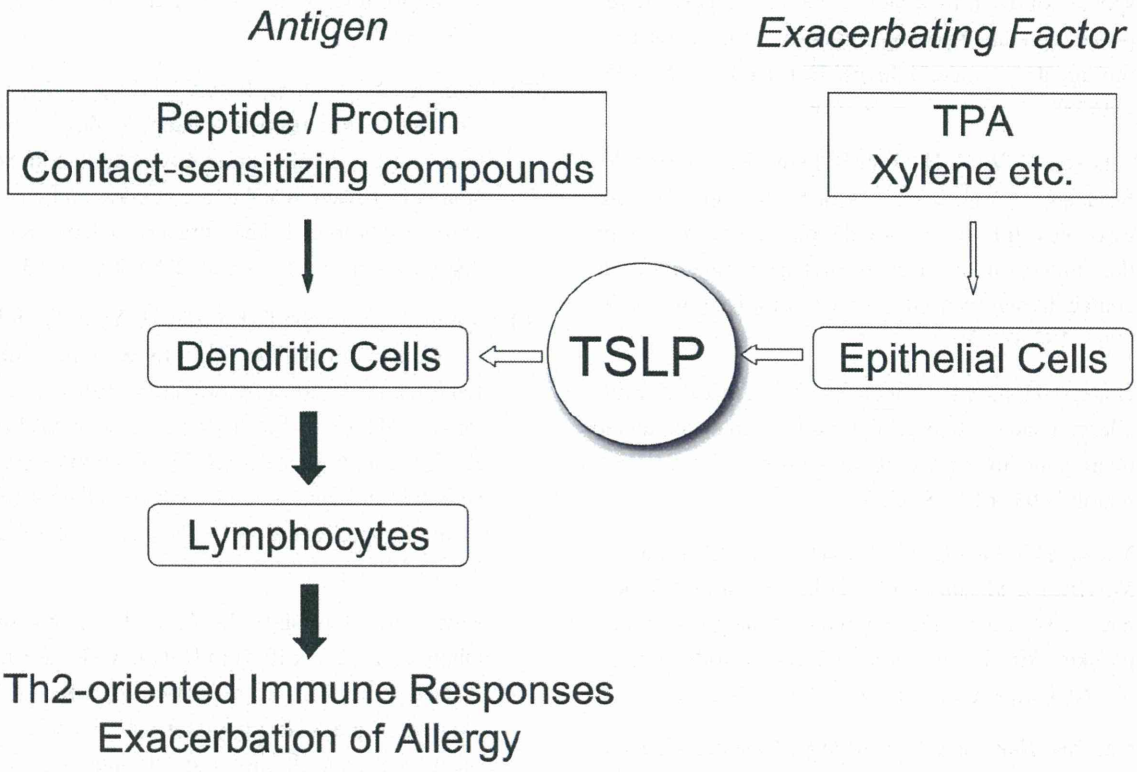

Fig. 1. Modification of allergies by exacerbating factors through production of TSLP.

Conclusion

Exogenous peptides/proteins and contact-sensitizing compounds act as antigens to induce allergies. However, the antigenicity of xylene itself has not been reported. Here we indicated that xylene, as well as TPA, exacerbated antigen-induced allergic inflammation via TSLP production (Fig. 1). Thus, there are chemicals in the environment which do not have contact-sensitizing activity but cause the production of TSLP and an exacerbation of allergic dermatitis. Our models would be useful to detect such compounds.

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Suppression of Intracellular Calcium Levels and Inhibition of Degranulation in RBL-2H3 Mast Cells by the Sesquiterpene Lactone Parthenolide

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Abstract

Pretreatment with parthenolide for 60 min inhibited the antigen-induced degranulation of RBL-2H3 mast cells; the IC_{50} value being 4.5 ± 0.4 μM. The inhibition was not due to suppression of the phosphatidylinositol 3-kinase pathway because the antigen-induced phosphorylation of Akt was not inhibited by parthenolide. The antigen-induced increase in intracellular calcium levels was prevented by parthenolide, suggesting that parthenolide inhibited the antigen-induced degranulation by suppressing an increase in intracellular calcium levels. In support of this, parthenolide was found to prevent ionomycin-induced degranulation by inhibiting an increase in intracellular calcium levels. Therefore, parthenolide inhibits the degranulation of mast cells by preventing an increase in intracellular calcium levels.

Key words

Tanacetum parthenium (L.) Sch. Bip. · Asteraceae · parthenolide · RBL-2H3 mast cells · degranulation · β-hexosaminidase · intracellular calcium

Abbreviations

DMSO:	dimethylsulfoxide
DNP-HAS:	dinitrophenol-conjugated human serum albumin
$[Ca^{2+}]i$:	intracellular calcium
MAPK:	mitogen-activated protein kinase
MTT:	3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide
PI3K:	phosphatidylinositol 3-kinase

Supporting information available online at http://www.thieme-connect.de/ejournals/toc/plantamedica

In the course of searching for new inhibitors of mast cell degranulation, we found that parthenolide (**Fig. 1**), a sesquiterpene lactone isolated from the herb feverfew (*Tanacetum parthenium* [L.] Sch. Bip. [Asteraceae]), inhibited the antigen-induced degranulation of a rat basophilic leukemia cell line, RBL-2H3 [1].

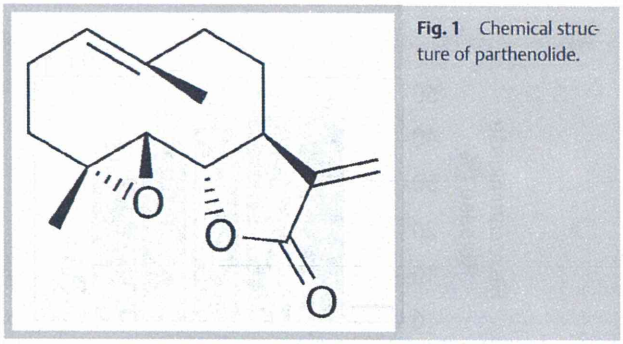

Fig. 1 Chemical structure of parthenolide.

Parthenolide is reported to have anti-inflammatory activities, including inhibition of the formation of edemas generated by 12-*O*-tetradecanoylphorbol 13-acetate in mouse skin [2] and by carrageenin in rats and mice [3,4]. It was also reported to suppress immune glomerulonephritis [5], gastric ulcers [6], migraines [7], myocardial reperfusion injury [8], and bladder inflammation [9]. These effects are attributable to the inhibition of nuclear factor-κB (NF-κB) [10]. However, the activation of NF-κB is not involved in the signaling pathway for the antigen-induced degranulation of mast cells. In this study, we examined the mechanism of action of parthenolide.

When IgE-sensitized RBL-2H3 cells were incubated in medium containing the antigen dinitrophenol-conjugated human serum albumin (DNP-HSA; 50 ng/mL) and various concentrations of parthenolide, significant inhibition of mast cell degranulation was induced only at 30 μM (**Fig. 2A**). However, a 60-min preincubation with parthenolide before the antigen challenge enhanced the inhibitory activity of parthenolide. Significant inhibition was observed at 1 to 30 μM in a concentration-dependent manner (**Fig. 2B**). At 30 μM, parthenolide almost completely inhibited the antigen-induced degranulation (**Fig. 2B**). The IC_{50} value was calculated to be 4.5 ± 0.4 μM. The phosphatidylinositol 3-kinase (PI3K) inhibitor wortmannin (100 nM) also inhibited the antigen-induced degranulation (**Fig. 2A** and **B**). The maximum inhibitory effect was obtained with 60 min preincubation (data not shown). At such concentrations, parthenolide did not exhibit cytotoxicity after 4 h (**Fig. 1S**). Therefore, the inhibition of the antigen-induced degranulation by parthenolide is not due to cytotoxicity. Subsequent experiments were conducted with 60 min preincubation with parthenolide. Wortmannin (100 nM) inhibited the phosphorylation of Akt (**Fig. 3**), but parthenolide (30 μM) did not (**Fig. 3**). Therefore, the inhibition of the antigen-induced degranulation by parthenolide is not mediated through the suppression of the PI3K pathway. Degranulation induced by the calcium ionophore ionomycin (1 μM) and A23187 (1 μM) was also inhibited by parthenolide at up to 30 μM in a concentration-dependent manner. However, the degranulation induced by these compounds was not completely suppressed by parthenolide (30 μM) or wortmannin (100 nM) (**Fig. 4A** and **B**). To clarify the mechanism of action of parthenolide, its effects on intracellular calcium ($[Ca^{2+}]i$) levels were examined. Fluorescence intensity in the suspended cells was increased by the antigen (**Fig. 5B**), and treatment with parthenolide at 1 to 30 μM sup-