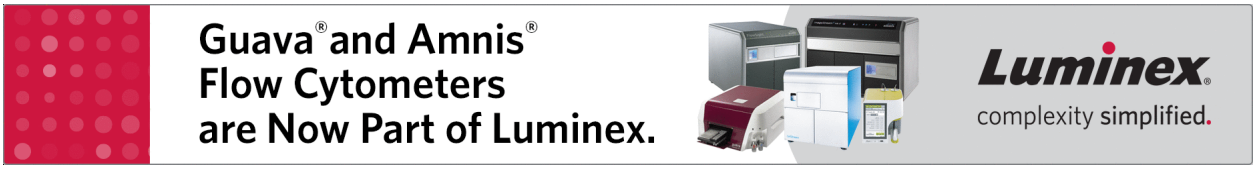

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Involvement of Nicotinic Acetylcholine Receptors in Suppression of Antimicrobial Activity and Cytokine Responses of Alveolar Macrophages to *Legionella pneumophila* Infection by Nicotine[1]

Kazuto Matsunaga, Thomas W. Klein, Herman Friedman, and Yoshimasa Yamamoto[2]

Although nicotine is thought to be one of the major immunomodulatory components of cigarette smoking, how nicotine alters the host defense of the lung and, in particular, immune responses of alveolar macrophages, which are critical effector cells in the lung defense to infection, is poorly understood. Nicotinic acetylcholine receptors (nAChRs) are the receptor for nicotine and may be involved in the modulation of macrophage function by nicotine. In this study, therefore, nicotine-induced suppression of antimicrobial activity and cytokine responses of alveolar macrophages mediated by nAChRs to *Legionella pneumophila*, a causative agent for pneumonia, were examined. The murine MH-S alveolar macrophage cell line cells expressed the messages for α4 and β2 subunits of nAChRs, but not α7 subunits, determined by RT-PCR. The nicotine treatment of MH-S alveolar macrophages after infection with *L. pneumophila* significantly enhanced the replication of bacteria in the macrophages and selectively down-regulated the production of IL-6, IL-12, and TNF-α, but not IL-10, induced by infection. These effects were completely blocked by a nonselective antagonist, *d*-tubocurarine, for nAChRs, but not by a selective antagonist, α-bungarotoxin, for α7-nAChRs. Furthermore, the stimulation of nAChRs with another agonist, 1,1-dimethyl-4-phenylpiperazinium iodide, showed the same effects, which were blocked by the antagonist *d*-tubocurarine, on the bacterial replication and cytokine regulation with that of nicotine. Thus, the results revealed that nAChRs, the major exogenous ligands of which are nicotine, are involved in the regulation of macrophage immune function by nicotine and may contribute to the cigarette-induced risk factors for respiratory infections in smokers. ***The Journal of Immunology*****, 2001, 167: 6518–6524.**

It is widely accepted that cigarette smoking is one of the risk factors for respiratory infections (1–3). In fact, pneumonia caused by *Streptococcus pneumoniae*, the most common causative bacteria of community-acquired pneumonia, is accelerated by smoking (4). Pneumonia caused by other bacteria, such as *Legionella* and *Mycobacterium*, also frequently occurs in smokers (1, 2, 5). However, the specific biological mechanisms by which exposure to cigarette smoke increases the risk of infection are poorly understood.

Nicotine, a small organic alkaloid synthesized by tobacco plants, is the addictive component of cigarette (6). The size and lipophilic characteristics of nicotine allow for a small amount to directly cross cell membranes, without interception by a receptor (6), even though its primary effects are via receptor mediation. This small alkaloid acts as an agonist at the nicotinic acetylcholine receptors (nAChRs)[3] found mainly in the central and peripheral nervous systems and on many other tissue cells throughout the body, including immune cells (7, 8). Even though the most frequent way to acquire nicotine is via cigarette smoking and even though nAChRs are the receptor for nicotine, the involvement of this receptor in the cigarette smoking-induced alterations of immune cell function, particularly alveolar cells, has not yet been well investigated. It has been briefly reported that the effect of nicotine on airway epithelial cells triggering GM-CSF release is via stimulation of nAChRs (9). Nicotine appears to be one of the major immunomodulatory components of cigarettes, because it has been shown that the treatment of human PBMC with nicotine significantly inhibited the production of IL-2, TNF-α, and IFN-γ in response to anti-CD3 stimulation (10). The suppression of LPS-induced murine splenocyte production of IL-6, TNF-α, and IFN-γ by concurrent nicotine treatment has also been demonstrated (11, 12).

The activation of macrophages to suppress bacterial growth in the cells is an essential effector mechanism for the resolution of respiratory infection caused by bacteria such as *Legionella pneumophila* (13–15). Several cytokines such as IL-6, IL-10, IL-12, and TNF-α are produced by macrophages in response to infection and may be involved in the regulation of bacterial growth in the cells (16–19). Thus, the modulation of production of such key cytokines by macrophages may eventually affect the outcome of infection. However, there has been no reported study showing how nicotine alters the host defense of the lung, particularly immune responses of alveolar macrophages, which are critical effector cells in the lung defense to infection. In the present study, the mechanism of nicotine-induced suppression of antimicrobial activity and possible involvement of nAChRs in the modulation of immune function caused by nicotine was examined using an in vitro *L. pneumophila* infection model with MH-S alveolar macrophage cell line cells (20).

Department of Medical Microbiology and Immunology, University of South Florida College of Medicine, Tampa, FL 33612

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[2] Address correspondence and reprint requests to Dr. Yoshimasa Yamamoto, Department of Medical Microbiology and Immunology, University of South Florida College of Medicine, 12901 Bruce B. Downs Boulevard, Tampa, FL 33612. E-mail address: yyamamot@hsc.usf.edu

[3] Abbreviations used in this paper: nAChRs, nicotinic acetylcholine receptors; α-BGTX, α-bungarotoxin; AYE, ace yeast extract; BCYE, buffered charcoal yeast extract; DMPP, 1,1-dimethyl-4-phenylpiperazinium iodide; d-TC, *d*-tubocurarine; RT, reverse transcription.

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Materials and Methods

nAChR agonists and antagonists

nAChR agonists, nicotine hydrogen bitartrate and 1,1-dimethyl-4-phenylpiperazinium iodide (DMPP), and antagonists, α-bungarotoxin (α-BGTX) and *d*-tubocurarine (d-TC), were purchased from Sigma (St. Louis, MO), dissolved in pyrogen-free water, and sterilized by filtration with a membrane. All reagents were diluted for working concentrations with RPMI 1640 containing 10% heat-inactivated FCS (HyClone Laboratories, Logan, UT).

Bacteria

L. pneumophila M124, serogroup 1, was originally obtained from a case of fatal legionellosis (21). The bacteria were cultured on buffered charcoal yeast extract (BCYE) medium (BD Biosciences, San Diego, CA) for 3 days at 37°C. The bacterial suspensions were prepared in pyrogen-free saline, and the concentration of bacteria was determined by spectrophotometry.

Alveolar macrophages

The MH-S murine alveolar macrophage cell line purchased from the American Type Culture Collection (Manassas, VA) was used in this study. The cells were maintained in 10% FCS-RPMI 1640. The MH-S cells were adhered to 24-well tissue culture plates at a concentration of 5×10^5 cells/ml for 2 h in 5% CO_2 at 37°C. The resulting cell monolayers were washed with HBSS, supplied with 10% FCS-RPMI 1640 without antibiotics, and then used for experiments.

Macrophage infection

The macrophage monolayers were infected with *L. pneumophila* (infectivity ratio, 10 bacteria/cell) at 37°C in 5% CO_2 for 30 min, washed to remove nonphagocytized bacteria, and incubated in RPMI 1640 containing 10% FCS without antibiotics. The cultures were then incubated for up to 48 h at 37°C in 5% CO_2.

Macrophage treatment

The macrophage cultures infected with bacteria were treated with varying concentrations of either nicotine (0.1–100 μg/ml) or DMPP (0.1–100 μM) for up to 48 h at 37°C in 5% CO_2. In some experiments, macrophage cultures infected with bacteria were pretreated with either α-BGTX (100 nM) or d-TC (10 μM) 15 min before nAChR agonist treatment; then cell monolayers were incubated with either nicotine or DMPP for up to 48 h at 37°C in 5% CO_2. The concentrations of nAChR agonists and antagonist used were previously confirmed to be an appropriate concentration showing stimulation and blocking of nAChRs (22–25).

Macrophage viability assay

The effect of nAChR agonists and antagonists on MH-S cell viability was determined by the viable cell number count and tetrazolium colorimetric methods. In brief, 24 h after treatment of macrophages with agonists or antagonist, the cells were washed with HBSS and then detached with trypsin-EDTA (Sigma). The cells were resuspended with RPMI 1640 containing 10% FCS and pipetted to homogenize the cell suspensions. The number of viable cells was determined with 2% trypan blue in a hemocytometer. For the tetrazolium colorimetric assay, the cells were incubated with a tetrazolium compound provided in the assay kit (CellTiter 96 AQ_{ueous} Non-Radioactive Cell Proliferation Assay; Promega, Madison, WI) in accordance with the manufacturer's manual.

Viable bacteria in cell cultures (CFU assay)

The number of viable bacteria (CFU) in cell lysates was determined by standard plate counts on BCYE medium, as described previously (26). After incubation, the cell monolayers were lysed with 0.1% saponin, and the number of viable bacteria in the lysates was determined.

Antimicrobial activity

To evaluate direct in vitro anti-*L. pneumophila* activity of nicotine, a culture of *L. pneumophila* in bacterial medium with nicotine was performed. In brief, ACE yeast extract broth medium (27) with or without varying concentrations of nicotine was dispensed to culture flasks and then inoculated with *L. pneumophila* at the final concentration of 5×10^3 bacteria/ml. After incubation for 24 or 48 h at 37°C, the number of viable bacteria (CFU) in the culture broth was determined by standard plate counts on BCYE medium.

ELISA

The amount of IL-6, IL-10, IL-12 p40/p70, and TNF-α protein in the culture supernatants of macrophage cultures was determined by sandwich ELISA using matched Ab pairs and protein standard for ELISA (BD PharMingen, San Diego, CA; IL-6, IL-10, IL-12 p40/p70) and Duoset ELISA development system (R&D Systems, Minneapolis, MN; TNF-α). Concentrations were calculated from the standard curve performed for each cytokine protein.

RT-PCR

Total RNA was extracted from cells by the microspin technique with RNeasy Mini Kit (Qiagen, Valencia, CA) in accordance with the manufacturer's manual. Reverse transcription (RT) of total RNA (1 μg) was performed with avian myeloblastosis virus transcriptase in a commercial reaction mixture (Reverse Transcription System; Promega). The resulting cDNA was subjected to PCR with primers for nAChR α4, α7, and β2 subunits. The primers used were designed from GenBank cDNA sequences using a website program, Primer 3 (http://www.path.cam.ac.uk/cgi-bin/primer3.cgi). The sequences of primer for nAChR α4 were 5′-ATC CTG ACA TCA CCT ACG CC-3′ (sense) and 5′-GGT GGT GTA CAT TGA GCA CG-3′ (antisense). The sequences of primer for nAChR α7 were 5′-CAT TCC ACA CCA ACG TCT TG-3′ (sense) and 5′-TGA GCA CAC AAG GAA TGA GC-3′ (antisense). The sequences of primer for nAChR β2 were 5′-TGT ATT TCT GTG CTG CTG GC-3′ (sense) and 5′-CAC GCT AGT GAC GAT GGA GA-3′ (antisense). The PCR was performed in a Minicycler (MJ Research, Watertown, MS) for 40 cycles, 57°C annealing temperature. PCR products were analyzed on an ethidium bromide-stained 2% agarose gel. The specificity of PCR was confirmed by oligonucleotide sequencing of PCR products (MWG, High Point, NC).

Statistical analysis

Statistical analysis was performed with a paired Student *t* test.

Results

Effect of nAChR agonists and antagonists on macrophage viability

To determine the toxicity of both nAChR agonists and antagonists on macrophages, the cells were incubated with various concentrations of either nAChR agonists (nicotine, 0.1–100 μg/ml; DMPP, 0.1–100 μM) or antagonists (α-BGTX, 1–100 nM; d-TC, 0.1–10 μM) for 24 h, and then the viability of macrophages was assessed

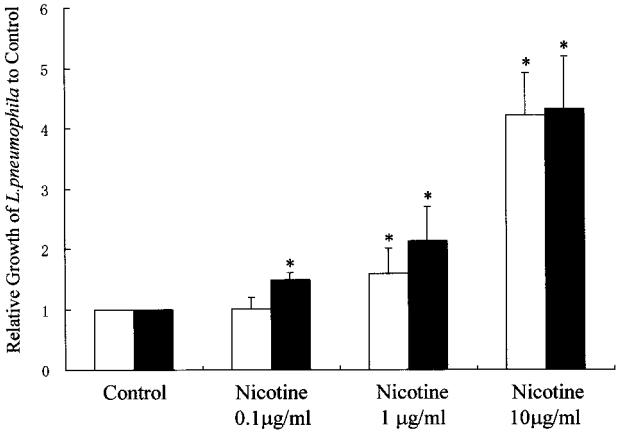

FIGURE 1. Effect of nicotine on *L. pneumophila* growth in alveolar macrophages. Macrophages infected with *L. pneumophila* were treated with the indicated concentrations of nicotine. The number of viable bacteria (CFU) in macrophages was determined by the standard plate count method. □, 24 h after infection; ■, 48 h after infection. Data represent the means + SD of relative bacterial growth to control for triplicate macrophage cultures. Data are representative of three experiments. *, $p < 0.05$, significantly different from the nicotine-untreated control group at the same time point. The numbers of viable bacteria (CFU) of the control group 24 and 48 h after infection were $2.6 \pm 1.4 \times 10^5$ and $1.2 \pm 0.4 \times 10^6$, respectively.

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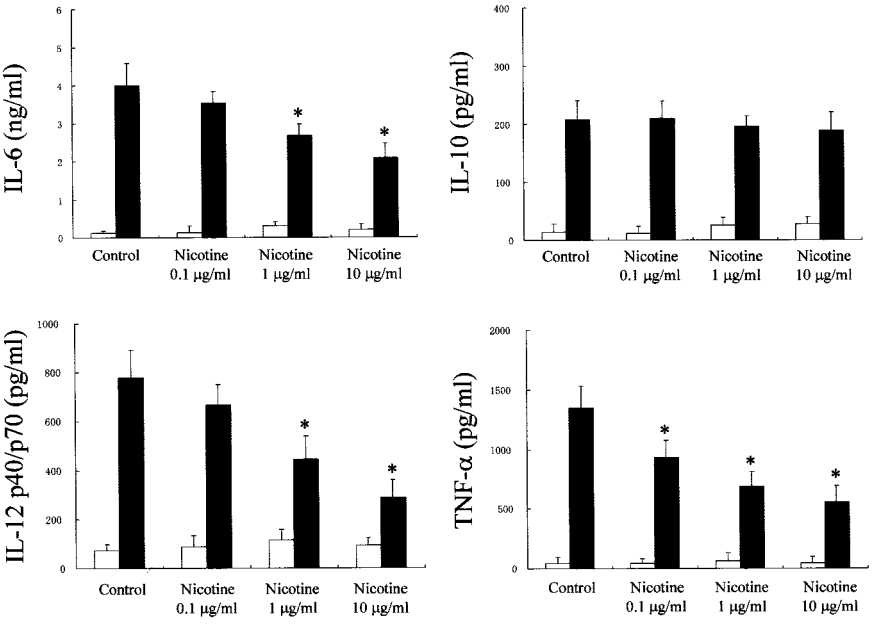

FIGURE 2. Effect of nicotine on macrophage cytokine production. The production of IL-6, Il-10, IL-12 p40/p70, and TNF-α protein in the supernatants obtained from the macrophage cultures 24 h after *L. pneumophila* infection was measured by ELISA. □, Non-*L. pneumophila* infection group; ■, *L. pneumophila* infection group. Results are expressed as means + SD for three independent experiments. *, $p < 0.05$, significantly different from the nicotine-untreated control group.

by trypan blue dye exclusion and tetrazolium colorimetric assay. Nicotine did not show any cytotoxicity for the macrophages up to 10 μg/ml. However, 100 μg/ml nicotine treatment significantly reduced the macrophage viability (~70% reduction of viability compared with nontreated control group). In contrast, all concentrations of DMPP, α-BGTX, and d-TC tested did not affect the cell viability. These results were consistent in the two assay methods (data not shown).

Effect of nicotine on L. pneumophila *growth*

Because the growth of *L. pneumophila* in macrophages is dependent on the host's macrophage activity, treatment of macrophages with nicotine may alter the growth of *L. pneumophila* in cells if nicotine has any immunomodulatory activity on macrophages. From the previous results, we used the concentration range of 0.1–10 μg nicotine/ml to evaluate the effect of nicotine on *L. pneumophila* growth in macrophages. As shown in Fig. 1, the treatment of macrophages with nicotine after infection with bacteria induced an enhancement of the growth of *L. pneumophila* in the cells in a dose-dependent manner at both 24 and 48 h after infection. A significant enhancement of *L. pneumophila* growth by nicotine occurred even with a concentration as low as 0.1 μg/ml at 48 h after infection. In contrast, it has been reported that nicotine has a direct antimicrobial activity against some bacterial and fungal pathogens (28). Therefore, to determine whether nicotine has a direct modulatory activity on *L. pneumophila* growth, the growth of *L. pneumophila* in liquid bacterial medium without host cells in the presence or absence of nicotine (0.1–100 μg/ml) was examined. However, nicotine did not alter the *L. pneumophila* growth in the bacterial medium regardless of the concentrations tested (data not shown). These results indicate that nicotine does not have a direct modulatory activity on *L. pneumophila* growth at the concentrations tested.

Effect of nicotine on macrophage cytokine production

Because nicotine enhanced the growth of *L. pneumophila* in macrophages without a direct effect on bacteria, it seemed likely that host cell modulation may be involved in the enhancement of *L. pneumophila* growth by nicotine. To examine such a possibility, the effect of nicotine on the production of macrophage cytokines, which are known to be involved in the regulation of bacterial growth in cells (29), was examined. As evident in Fig. 2, the treatment of macrophages with nicotine alone slightly induced macrophage IL-6, IL-10, IL-12, and TNF-α protein production, but this was minimal when compared with *L. pneumophila*-infected macrophages. In contrast, nicotine treatment markedly down-regulated the production of IL-6, IL-12, and TNF-α induced by *L. pneumophila* infection in a dose-dependent manner, even with a concentration as low as 0.1 μg/ml in the case of TNF-α. In contrast, the production of IL-10 induced by *L. pneumophila* infection was not affected by nicotine, even with a concentration as high as 10 μg/ml. These results indicate that nicotine may selectively alter the cytokine responses of macrophages against *L. pneumophila* infection and lead to an enhancement of bacteria growth in macrophages.

nAChRs mRNA expression in alveolar macrophages

It is widely accepted that nAChRs form a family of receptors and that they are differentially expressed in many tissues (30). Although the most frequent way to acquire nicotine is via tobacco smoking, the existence of nAChRs on lung tissues and cells has not yet been well investigated. If nAChRs exists on alveolar macrophages, the nicotine-induced immunomodulation of macrophages may be possibly mediated by nAChRs. To determine such a possibility, steady state levels of nAChR mRNA (α4, α7, and β2

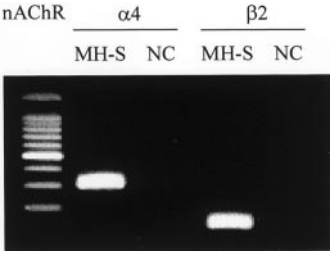

FIGURE 3. nAChR mRNA expression levels in alveolar macrophages. The expression levels of nAChR mRNAs (α4 and β2 subunits) in MH-S alveolar macrophages were analyzed by RT-PCR. NC, PCR products of MH-S cells without RT.

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Table I. *Effect of nAChR antagonists on* L. pneumophila *growth in nicotine-treated or untreated macrophages*[a]

Treatment	% Control of *L. pneumophila* Growth (mean ± SD) at Following Times After Infection			
	24 h		48 h	
Control	100		100	
d-TC (10 μM)	89 ± 15	$p < 0.01$	95 ± 19	$p < 0.01$
α-BGTX (100 nM)	113 ± 8		97 ± 11	
Nicotine (10 μg/ml)	421 ± 91	$p < 0.01$	432 ± 97	$p < 0.01$
Nicotine + d-TC	113 ± 28		114 ± 24	
Nicotine + α-BGTX	293 ± 67		322 ± 69	

[a] Macrophage cultures infected with bacteria and treated with or without d-TC or α-BGTX were incubated with or without nicotine. The number of viable bacteria in macrophages was determined by the standard plate count method. Data are representative of three experiments. The numbers of viable bacteria (CFU) at 24 and 48 h after infection were $2.8 \pm 0.6 \times 10^5$ and $1.4 \pm 0.4 \times 10^6$, respectively.

subunits) in MH-S alveolar macrophages were analyzed by RT-PCR. The PCR products of MH-S cells without RT were examined as a negative control. As seen in Fig. 3, mRNAs for the nAChR α4 and β2 subunits were detected in MH-S alveolar macrophages. However, it is not clear whether MH-S cells possibly may not express nAChR α7 because the RT-PCR specific for α7 did not successfully demonstrate the message (data not shown). The oligonucleotide sequencing analysis of PCR products confirmed the specificity of both α4 and β2 (data not shown).

Involvement of nAChRs in the nicotine-induced suppression of antimicrobial activity

Because nicotine exerts its effects by both receptor-mediated and non-receptor-mediated mechanisms (6), a possible involvement of nAChRs in nicotine-induced suppression of antimicrobial activity was examined using nAChR-specific antagonists. Macrophage monolayers infected with bacteria were pretreated with either α-BGTX (selective antagonists for α7-nAChR) or d-TC (nonselective antagonists for nAChRs), and then the cells were incubated with nicotine for up to 48 h. As shown in Table I, pretreatment of macrophages with d-TC markedly abolished the nicotine-induced enhancement of bacterial growth at both 24 and 48 h after infection. In contrast, α-BGTX pretreatment did not significantly alter the growth of *L. pneumophila* enhanced by nicotine. The treatment of nAChR antagonists alone did not show any alteration of the bacterial growth in the macrophages.

Involvement of nAChRs in nicotine-induced immunomodulation

When macrophages infected with bacteria were pretreated with d-TC, nicotine-induced suppression of IL-6, IL-12, and TNF-α production was readily restored to the control levels without the modulation of IL-10 production (Fig. 4). In contrast, pretreatment of macrophages with α-BGTX did not result in recovery of the nicotine-suppressed cytokine production. The treatment of nAChR antagonists alone did not alter the production of cytokines tested. Thus, the results with the nAChR antagonist treatment clearly indicate that the nicotine-induced suppression of alveolar macrophage activity, which is involved not only in antimicrobial activity but also cytokine responses against bacteria, is mediated, at least, by α4β2-nAChRs. The failure of blocking with the α7-nAChR antagonist α-BGTX on nicotine-induced modulation of macrophage cytokine production as well as antimicrobial activity was consistent with the results of no α7-nAChR message expression determined by RT-PCR.

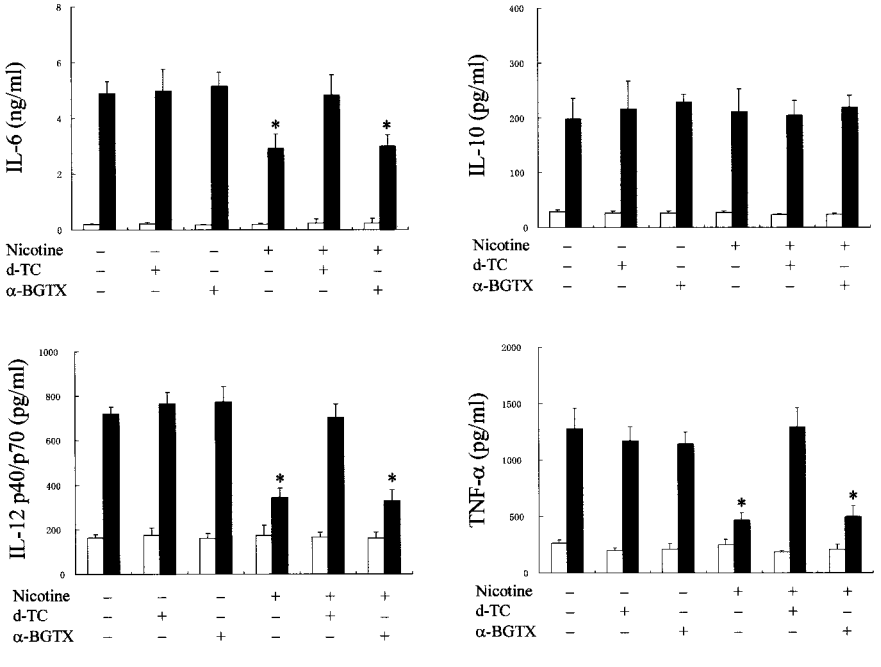

FIGURE 4. Effect of nAChR antagonists on cytokine production of nicotine-treated or untreated macrophages in response to *L. pneumophila* infection. See the legend to Fig. 2. Macrophage cultures infected with bacteria and pretreated with or without 10 μM d-TC or 100 nM α-BGTX were incubated with or without 10 μg/ml nicotine. □, Non-*L. pneumophila* infection group; ■, *L. pneumophila* infection group. Results are expressed as means + SD for three independent experiments. *, $p < 0.05$, significantly different from the control group.

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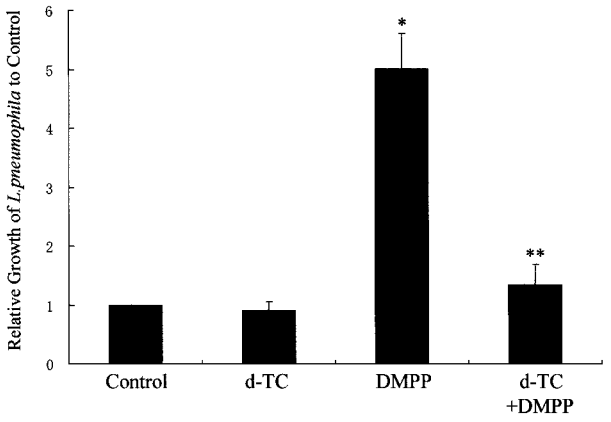

FIGURE 5. Effect of nAChR agonist on *L. pneumophila* growth in macrophages. See the legend to Fig. 1. Macrophages infected with bacteria and pretreated with or without 10 μM d-TC were incubated with or without 100 μM DMPP. Data represent the means + SD of relative bacterial growth to control for triplicate macrophage cultures. Data are representative of three experiments. *, $p < 0.05$ significantly different from the *L. pneumophila* infection control group. **, $p < 0.05$, significantly different from the DMPP-treated *L. pneumophila* infection group at the same time point. The number of viable bacteria (CFU) of control group at 24 h after infection was $2.7 \pm 0.3 \times 10^5$.

nAChR agonist-induced modulation of macrophage function

To determine whether stimulation of nAChRs with other agonists causes modulation of macrophage function, the effect of another nAChR agonist on antimicrobial activity and immune responses of alveolar macrophages was examined. The nonselective nAChR agonist DMPP was used for this purpose. When macrophages infected with the bacteria were treated with DMPP, a marked enhancement of bacterial growth in the cells was observed at 24 h after infection (Fig. 5), similar to the case with nicotine. Pretreatment of macrophages with antagonist d-TC completely abolished the effect of DMPP. A similar effect of DMPP and blocking with d-TC on cytokine production of the macrophages in response to bacterial infection was also evident (Fig. 6); i.e, the DMPP-treatment significantly down-regulated the production of IL-6, IL-12, and TNF-α induced by *L. pneumophila* infection. This selective inhibition on cytokine production by DMPP was completely blocked by d-TC treatment.

Discussion

Cigarette smoking is a significant risk factor in respiratory diseases including chronic obstructive lung disease and pneumonia. The bronchial alveolar lavage fluids obtained from cigarette smokers have increased numbers of alveolar macrophages and neutrophils (31, 32). Moreover, compared with nonsmokers, alveolar macrophages from smokers appear to be in an active state, exhibiting increased microsomal and lysosomal enzymes, elevated resting rates of glucose use, increased production of oxygen radicals and myeloperoxidase activity, and increased migration and chemotactic responsiveness (33). However, despite this increased activity, alveolar macrophages from smokers appear to be deficient in phagocytosis and bactericidal activity (34). Thus, it has been conjectured that cigarette smoking may cause a disruption of normal lung immune function against respiratory infections. However, little is known about the effect of cigarette components on antimicrobial activity and immune responses of alveolar macrophages. In this regard, the present study concerning the effect of nicotine on the susceptibility of alveolar macrophages to *L. pneumophila* infection revealed that nicotine suppresses cytokine responses of macrophages to infection by the bacteria and leads to an enhancement of bacterial replication in macrophages. The nicotine concentrations used in this study were higher than the level of nicotine reported in the plasma of heavy smokers (35). However, the concentrations of nicotine at the site of alveoli after smoking cigarettes, the nicotine yield of which is ~0.91 mg/cigarette (36), may be higher than the plasma level. Nevertheless, the findings constitute the first in vitro demonstration of how cigarette smoke components may contribute to risk factors for respiratory infections in smokers. In particular, the findings of the selective inhibition of cytokine productions, such as IL-6, IL-12, and TNF-α, by nicotine indicates how such immunomodulation may contribute to the susceptibility of cells to infections. TNF-α is required for the prompt resolution of pneumonic legionellosis and points to a direct role for TNF-α in the activation of phagocytes (19). The precise mechanism of nicotine-induced suppression of antimicrobial activity of macrophages is still unclear. However, our recent studies have

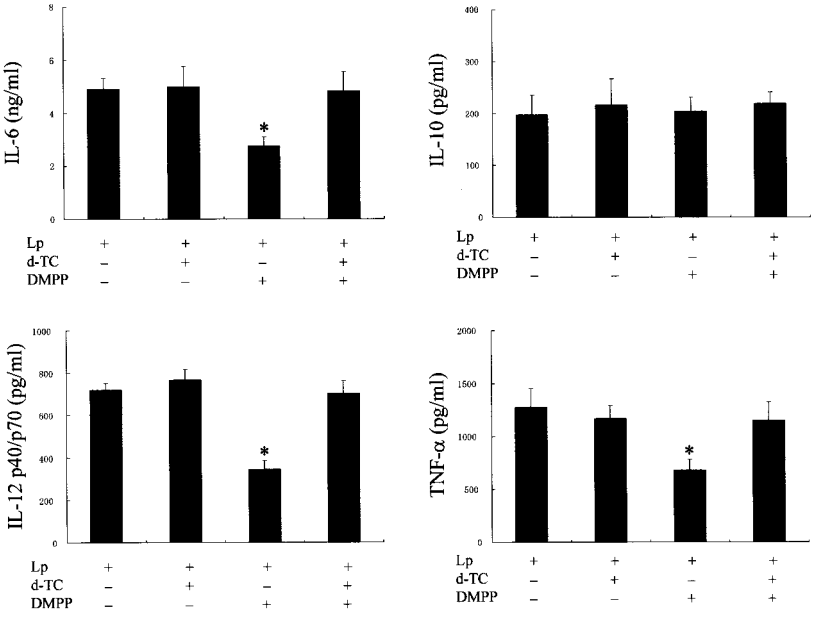

FIGURE 6. Effect of nAChR agonist DMPP on macrophage cytokine production in response to *L. pneumophila* infection. See the legend to Fig. 2. Macrophages infected with bacteria and pretreated with or without 10 μM d-TC were incubated with or without 100 μM DMPP. Results are expressed as means + SD for three independent experiments. *, $p < 0.05$, significantly different from the *L. pneumophila* infection control group.

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shown that epigallocatechin gallate, the major form of tea catechins, restores nicotine-suppressed TNF-α production as well as antimicrobial activity of macrophages (our unpublished data). Therefore, it seems likely that the impaired TNF-α production may be one of the major mechanisms responsible for the nicotine-induced impairment of antimicrobial activity against *L. pneumophila* infection. This hypothesis can be supported by previous reports that TNF-α is a strong activator for macrophages to induce anti-*L. pneumophila* activity (19, 37). In contrast, the role of the reduced IL-6 production in the nicotine-induced impaired antimicrobial activity is not clear. However, this may not have a direct role because of the absence of IL-6 modulatory effects on macrophages regarding anti-*L. pneumophila* activity (38).

IL-10 and IL-12 are key cytokines in the regulation of development of Th1/Th2 responses (18, 39, 40). Therefore, the participation of these two cytokines in the defense against *L. pneumophila* infection is critical (13, 17). The direct involvement of these cytokines in the regulation of bacterial growth in cells is less likely. Nevertheless, the suppression of IL-12 production, but not IL-10, by nicotine may cause an alteration of Th1 development by nicotine during infection, if this occurs in vivo. In this regard, it has been reported that the nicotine-derived *N*-nitrosamine directly modulates cytokine production, including inhibition of IL-2, IL-6, IL-10, GM-CSF, and monocyte chemoattractant protein-1 production in the U937 human macrophage cell line (41). It is also known that nicotine itself suppresses in vitro production of IL-2, TNF-α, and IFN-γ from human PBMC (10). Therefore, the present results are consistent with these previous reports regarding the inhibitory activity of nicotine and its derivative on cytokine production.

nAChRs form a family of receptors that are differentially expressed mainly in the central and peripheral nervous system, as well as on many other tissue cells. For instance, nAChRs are found in cochlea (8), ganglionic tissue (42), developing muscles (43), and lymphocytes and polymorphonuclear cells in the peripheral blood (7, 44). Although the function of peripheral nAChRs has not been well investigated, such localization suggests that peripheral nAChRs have nonsynaptic roles. The results of this study clearly support a possible nonsynaptic role of nAChRs in alveolar macrophages. Whether in muscle or neurons, nAChRs are allosteric membrane proteins that are assembled from five subunits according to defined combination rules. In mammals, nine homologous subunits (α2–α7 and β2–β4) have been identified thus far in the nervous system whereas the α9 subunit is present in sensory end organs (30). Equilibrium binding studies have distinguished two main categories of nAChR pentamers on the basis of their high affinity for either nicotine or α-BGTX. The former are considered to be formed by α4 and β2 subunits containing nAChRs, and the latter are thought to be α7 subunit containing nAChRs (45, 46). Furthermore, α7-nAChRs exhibit low affinity for acetylcholine and nicotine and are rapidly desensitized, whereas α4β2-nAChRs are considered to form a high affinity receptor for acetylcholine and nicotine and are desensitized slowly (30). Although we attempted to determine the partial nAChR subunit mRNA expression in alveolar macrophages, the results of nAChR antagonist and agonist treatment and the determination of mRNA expression for nAChR α4 and β2 subunits in alveolar macrophages revealed the involvement of nAChR-mediated mechanism in the nicotine-induced suppression of antimicrobial activity and immune responses of macrophages. In addition, the results of this study indicated that nicotine-induced suppression of alveolar macrophage activity, which is involved in not only antimicrobial activity but also cytokine responses against bacteria, is mediated, at least, by α4β2-nAChRs.

Thus, the present study revealed that nicotine causes an alteration of immune responses of alveolar macrophages to bacterial infection by an nAChR-mediated mechanism.

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References

1. Hays, J. T., L. C. Dale, R. D. Hurt, and I. T. Croghan. 1998. Trends in smoking-related diseases: why smoking cessation is still the best medicine. *Postgrad. Med. 104:56.*
2. Ruiz, M., S. Ewing, M. A. Marcos, J. A. Martinez, F. Arancibia, J. Mensa, and A. Torres. 1999. Etiology of community-acquired pneumonia: impact of age, comorbidity, and severity. *Am. J. Respir. Crit. Care Med. 160:397.*
3. Straus, W. L., J. F. Plouffe, T. M. File, H. B. Lipman, B. H. Hackman, S. J. Salstrom, R. F. Benson, and R. F. Breiman. 1996. Risk factors for domestic acquisition of Legionnaires' disease: Ohio Legionnaires' disease group. *Arch. Intern. Med. 156:1685.*
4. Nuorti, J. .P., J. C. Butler, M. M. Farley, L. H. Harrison, A. McGeer, M. S. Kolczak, and R. F. Breiman. 2000. Cigarette smoking and invasive pneumococcal disease. *N. Engl. J. Med. 342:681.*
5. Alcaide, J., M. N. Altet, P. Plans, I. Parron, L. Folguera, E. Salto, A. Dominguez, H. Pardell, and L. Salleras. 1996. Cigarette smoking as a risk factor for tuberculosis in young adults: a case-control study. *Tuberc. Lung Dis. 30:27.*
6. Bhandari, N., S. L. Sylvester, and N. A. Rogotti. 1996. *Source Book of Substance Abuse and Addiction.* L. Friedman, N. F. Fleming, D. H. Roberts, and S. E. Hyman, eds. Williams & Wilkins, Baltimore, p. 140.
7. Hiemke, C., M. Stolp, S. Reuss, A. Wevers, S. Reinhardt, A. Maelicke, S. Schlegel, and H. Schroder. 1996. Expression of α subunit genes of nicotinic acetylcholine receptors in human lymphocytes. *Neurosci. Lett. 214:171.*
8. Drescher, D. G., K. M. Khan, G. E. Green, B. J. Morley, K. W. Beisel, H. Kaul, D. Gordon, A. K. Gupta, M. J. Drescher, and R. L. Barretto. 1995. Analysis of nicotinic acetylcholine receptor subunits in the cochlea of the mouse. *Comp. Biochem. Physiol. 112:267.*
9. Klapproth, H., K. Racke, and I. Wessler. 1998. Acetylcholine and nicotine stimulate the release of granulocyte-macrophage colony stimulating factor from cultured human bronchial epithelial cells. *Naunyn Schmiedebergs Arch. Pharmacol. 357:472.*
10. Ouyang, Y., N. Virasch, P. Hao, M. T. Aubrey, N. Mukerjee, B. E. Bierer, and B. M. Freed. 2000. Suppression of human IL-1β, IL-2, IFN-γ, and TNF-α production by cigarette smoke extracts. *J. Allergy Clin. Immunol. 106:280.*
11. Hakki, A., N. Hallquist, H. Friedman, and S. Pross. 2000. Differential impact of nicotine on cellular proliferation and cytokine production by LPS-stimulated murine splenocytes. *Int. J. Immunopharmacol. 22:403.*
12. Hallquist, N., A. Hakki, L. Wecker, H. Friedman, and S. Pross. 2000. Differential effects of nicotine and aging on splenocyte proliferation and the production of Th1- versus Th2-type cytokines. *Proc. Soc. Exp. Biol. Med. 224:141.*
13. Horwitz, M. A. 1980. Cell mediated immunity in Legionnaires' disease. *J. Clin. Invest. 66:441.*
14. Nash, T. W., D. M. Libby, and D. M. Horwitz. 1988. IFN-γ-activated human alveolar macrophages inhibit the intracellular multiplication of *Legionella pneumophila. J. Immunol. 140:3978.*
15. Bhardwaj, N., T. W. Nash, and D. M. Horwitz. 1986. IFN-γ-activated human monocytes inhibit the intracellular multiplication of *Legionella pneumophila. J. Immunol. 137:2662.*
16. Flesch, I. E., and S. H. Kaufmann. 1990. Stimulation of antibacterial macrophage activates by B-cell stimulatory factor 2 (interleukin-6). *Infect. Immun. 58:269.*
17. Park, D. R., and S. J. Skerrett. 1996. IL-10 enhances the growth of *Legionella pneumophila* in human mononuclear phagocytes and reverses the protective effect of IFN-γ. *J. Immunol. 157:2528.*
18. Hsieh, C.-S., S. E. Macatonia, C. S. Tripp, S. F. Wolf, A. O'Garra, and K. M. Murphy. 1993. Development of Th1 $CD4^+$ T cells through IL-12 produced by *Listeria*-induced macrophages. *Science 260:547.*
19. Skerrett, S. J., G. J. Bagby, R, A. Schmidt, and S. Nelson. 1997. Antibody-mediated depletion of tumor necrosis factor-α impairs pulmonary host defenses to *Legionella pneumophila. J. Infect. Dis. 176:1019.*
20. Matsunaga, K., T. W. Klein, H. Friedman, and Y. Yamamoto. 2001. The alveolar macrophage cell line MH-S is valuable as in vitro model for *Legionella pneumophila* infection. *Am. J. Respir. Cell Mol. Biol. 24:326.*
21. Friedman, H., R. Widen, T. W. Klein, L. Searls, and K. Cabrian. 1984. *Legionella pneumophila*-induced blastogenesis of murine lymphoid cells in vitro. *Infect. Immun. 43:314.*
22. Blanchard, S. G., U. Quast, K. Reed, T. Lee, M. I. Schimerlik, R. Vandlen, T. Claudio, C. D. Strader, H. P. Moore, and M. A. Raftery. 1979. Interaction of [^{125}I]-α-bungarotoxin with acetylcholine receptor from *Torpedo californica. Biochemistry 18:1875.*
23. Haggerty, J. G., and S. C. Froehner. 1981. Restoration of ^{125}I-α-bungarotoxin binding activity to the α subunit of *Torpedo* acetylcholine receptor isolated by gel electrophoresis in sodium dodecyl sulfate. *J. Biol. Chem. 256:8294.*
24. Luetje, C. W., and J. Patrick. 1991. Both α- and β-subunits contribute to the agonist sensitivity of neuronal nicotinic acetylcholine receptors. *J. Neurosci. 11: 837.*

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25. Beani, L., T. Antonelli, M. C. Tomasini, L. Marani, and C. Bianchi. 2000. The nicotinic modulation of [^{3}H]D-aspartate outflow in primary cultures of rat neocortical neurons: effect of acute and long term nicotine treatment. *Neuropharmacology 39:2646.*
26. Yamamoto, Y., T. W. Klein, C. A. Newton, R. Widen, and H. Friedman. 1988. Growth of *Legionella pneumophila* in thioglycollate-elicited peritoneal macrophages from A/J mice. *Infect. Immun. 56:370.*
27. Gebran, S. J., C. A. Newton, Y. Yamamoto, T. W. Klein, and H. Friedman. 1994. A rapid colorimetric assay for evaluating *Legionella pneumophila* growth in macrophages in vitro. *J. Clin. Microbiol. 32:127.*
28. Pavia, C. S., A. Pierre, and J. Nowakowski. 2000. Antimicrobial activity of nicotine against a spectrum of bacterial and fungal pathogens. *J. Med. Microbiol. 49:675.*
29. Matsunaga, K., T. W. Klein, H. Friedman, and Y. Yamamoto. 2001. *Legionella pneumophila* replication in macrophages inhibited by selective immunomodulatory effects on cytokine formation by epigallocatechin gallate, a major form of tea catechins. *Infect. Immun. 69:3947.*
30. Cordero-Erausquin, M., L. M. Marubio, R. Klink, and J. P. Changeux. 2000. Nicotinic receptor function: new perspectives from knockout mice. *Trends Pharmacol. Sci. 21:211.*
31. Adesina, A. M., V. Vallyathan, E. N. McQuillen, S. O. Weaver, and J. E. Craighead. 1991. Bronchiolar inflammation and fibrosis associated with smoking: a morphologic cross-sectional population analysis. *Am. Rev. Respir. Dis. 143:144.*
32. Bosken, C. H., J. Hards, K. Gatter, and J. C. Hogg. 1992. Characterization of the inflammatory reaction in the peripheral airways of cigarette smokers using immunocytochemistry. *Am. Rev. Respir. Dis. 145:911.*
33. Sopori, M. L., N. S. Goud, and A. M. Kaplan. 1994. Effects of tobacco smoke on the immune system. In *Immunotoxicology and Immunopharmacology*, J. H. Dean, M. I. Luster, A. E. Munson, and I. Kimber, eds. Raven Press, New York, p. 413.
34. Plowman, P. N. 1982. The pulmonary macrophage population of human smokers. *Ann. Occup. Hyg. 25:393.*
35. Ebert, R. V., M. E. McNabb, K. T. McCusker, and S. L. Snow. 1983. Amount of nicotine and carbon monoxide inhaled by smokers of low-tar, low-nicotine cigarettes. *JAMA 250:2840.*
36. Jarvis, M. J., R. Boreham, P. Primatesta, C. Feyerabend, and A. Bryant. 2001. Nicotine yield from machine-smoked cigarettes and nicotine intakes in smoker: evidence from a representative population survey. *J. Natl. Cancer Inst. 93:134.*
37. McHugh, S. L., C. A. Newton, Y. Yamamoto, T. W. Klein, and H. Friedman. 2000. Tumor necrosis factor induces resistance of macrophages to *Legionella pneumophila* infection. *Proc. Soc. Exp. Biol. Med. 224:191.*
38. McHugh, S., Y. Yamamoto, T. W. Klein, and H. Friedman. 2000. Differential expression of IL-1 and TNF receptors in murine macrophages infected with virulent vs. avirulent *Legionella pneumophila. Can. J. Microbiol. 46:885.*
39. Fenton, M. J., M. W. Vermeulen, S. Kim, M. Burdick, R. M. Strieter, and H. Kornfeld. 1997. Induction of γ interferon production in human alveolar macrophages by *Mycobacterium tuberculosis. Infect. Immun. 65:5149.*
40. Puddu, P., L. Fantuzzi, P. Borghi, B. Varano, G. Rainaldi, E. Guillemard, W. Malorni, P. Nicaise, S. F. Wolf, F. Belardelli, and S. Gessani. 1997. IL-12 induces IFN-γ expression and secretion in mouse peritoneal macrophages. *J. Immunol. 159:3490.*
41. Rioux, N., and A. Castonguay. 2001. 4-(Methylnitrosamino)-1-(3-pyridyl)-1-butanone modulation of cytokine release in U937 human macrophages. *Cancer Immunol. Immunother. 49:663.*
42. Joy, A. M., H. N. Siegel, and R. J. Lukas. 1993. Photoaffinity labeling of muscle-type nicotinic acetylcholine receptors and neuronal/nicotinic α-bungarotoxin binding sites with a derivative of α-bungarotoxin. *Brain Res. Mol. Brain Res. 17:95.*
43. Romano, C., and A. Goldstein. 1980. Stereospecific nicotine receptors on rat brain membranes. *Science 210:647.*
44. Lebargy, F., K. Benhammou, D. Morin, R. Zini, S. Urien, F. Bree, J. Bignon, A. Branellec, and G. Lagrue. Tobacco smoking induces expression of very-high-affinity nicotine binding sites on blood polymorphonuclear cells. *Am. J. Respir. Crit. Care Med. 153:1056.*
45. Lukas, R. J., J. P. Changeux, N. Le Novere, E. X. Albuquerque, D. J. Balfour, D. K. Berg, D. Bertrand, V. A. Chiappinelli, P. B. Clarke, A. C. Collins, et al. 1999. Current status of the nomenclature for nicotinic acetylcholine receptors and their subunits. *Pharmacol. Rev. 51:397.*
46. Alkondon, M., and E. X. Albuquerque. 1993. Diversity of nicotinic acetylcholine receptors in rat hippocampal neurons. I. Pharmacological and functional evidence for distinct structural subtypes. *J. Pharmacol. Exp. Ther. 265:1455.*

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