Clarithromycin Inhibits Type A Seasonal Influenza Virus Infection in Human Airway Epithelial Cells

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ABSTRACT

Human influenza viruses attach to sialic acid with an α2,6 linkage (SAα2,6Gal) on the airway epithelial cells, and the entry of the viruses into the cells and uncoating of the viruses require low pH of endosomes. Bafilomycin A₁, a macrolide antibiotic and a specific inhibitor of vacuolar H⁺-ATPase, inhibits growth of type A and type B human influenza viruses in Madin-Darby canine kidney cells. However, the inhibitory effects of clinically used macrolide antibiotics on influenza virus infection in human airways have not been studied. To examine the effects of clarithromycin on seasonal human influenza virus infection, cultured human tracheal epithelial cells were infected with type A influenza virus (H1, N1). Influenza virus infection increased viral titers and the content of cytokines, including interleukin (IL)-1β and IL-6, in supernatant fluids, and viral RNA in the cells. Clarithromycin reduced viral titers and the content of cytokines in supernatant fluids, viral RNA in the cells, and the susceptibility to virus infection. Clarithromycin reduced the expression of SAα2,6Gal, a receptor for human influenza virus, on the mucosal surface of human tracheae, and the number and fluorescence intensity of acidic endosomes in the cells from which viral ribonucleoproteins enter into the cytoplasm. Furthermore, clarithromycin reduced nuclear factor-κB (NF-κB) proteins, including p50 and p65, in the nuclear extracts. These results suggest that clarithromycin may inhibit seasonal human influenza virus infection by reducing SAα2,6Gal partly through the inhibition of NF-κB, and increasing pH in endosomes in airway epithelial cells. Clarithromycin may modulate airway inflammation in influenza virus infection.

Human influenza virus infection causes rapid onset constitutional symptoms, including fever and lower respiratory tract symptoms, and also induces exacerbations of bronchial asthma and chronic obstructive pulmonary disease (COPD) in the winter (Hayden and Gwaltney, 1988; Johnston et al., 1995). To prevent exacerbations of bronchial asthma and COPD by influenza virus infection, the use of vaccination against influenza is recommended. Influenza vaccination reduces the mortality rate in elderly people with COPD (Nicholl et al., 1994). Clinically used anti-influenza drugs, which include neuraminidase inhibitors such as oseltamivir and zanamivir, are beneficial for uncomplicated human influenza infection (Beigel and Bray, 2008). Conversely, oseltamivir-resistant influenza A (H1N1) virus infection has been reported previously (Gooskens et al., 2009), and inhalation of zanamivir may be difficult for patients with a severe condition and for small children. Therefore, further development of anti-influenza virus drugs is needed.

Human influenza viruses attach to sialic acid with an α2,6 linkage (SAα2,6Gal) on the airway epithelial cells (Rogers and Paulson, 1983). The viruses are then delivered into the cytoplasm, and ribonucleoproteins (RNP)s of viruses, which include viral RNA, are released from acidic endosomes into the cytoplasm of the cells (Palese and Shaw, 2006). Bafilomycin A₁, a macrolide antibiotic and a specific inhibitor

ABBREVIATIONS: COPD, chronic obstructive pulmonary disease; SAα2,6Gal, sialic acid with an α2,6 linkage; RNP, ribonucleoprotein; MDCK, Madin-Darby canine kidney; IL, interleukin; FluA, type A seasonal human influenza; USG, Ulitroser G; PBS, phosphate-buffered saline; MEM, minimal essential medium; DF-12, DMEM-Ham’s F-12 medium; TCID, tissue culture infective dose; CPE, cytopathic effects; RT-PCR, reverse transcription-polymerase chain reaction; FITC, fluorescein isothiocyanate; NF-κB, nuclear factor κB; LDH, lactate dehydrogenase.
of vacular H^+ -ATPase, inhibits growth of type A and type B human influenza viruses in Madin-Darby Canine Kidney (MDCK) cells (Ochiai et al., 1995). Furthermore, the macrolide antibiotic erythromycin reduces the number of low pH endosomes and reduces intercellular adhesion molecule-1, the receptor for rhinovirus, a major virus of common colds, and it inhibits rhinovirus infection in human airway epithelial cells (Suzuki et al., 2002). However, the inhibitory effects of clinically used macrolide antibiotics on the influenza virus infection in human airway cells have not been studied.

Increases in proinflammatory cytokines and monokines, including interleukin (IL)-1, IL-6, and IL-8, are observed in the serum in patients and in the lung of mice infected with influenza virus (Konstantinos and Sheridan, 2001; Deng et al., 2008). These factors are suggested to be associated with the pathogenesis and severity of influenza virus infection (Deng et al., 2008). Macroolides reduce the production of proinflammatory cytokines in human airways (Suzuki et al., 2002), and the reduction of these factors are suggested to relate to the clinical benefits of macrolides in diffuse panbronchiolitis and cystic fibrosis (Kudoh et al., 1998; Equi et al., 2002). Furthermore, macrolides, including bafilomycin A1, erythromycin, and clarithromycin reduce the secretion of proinflammatory cytokines in supernatants of human airway epithelial cells after rhinovirus infection (Suzuki et al., 2001a, 2002; Jang et al., 2006). However, the effects of clarithromycin on the secretion of proinflammatory cytokines by human airway epithelial cells after influenza infection have not been studied.

In the present study, we examined the effects of clarithromycin on type A seasonal human influenza (FluA) virus (H1N1) infection in human airway epithelium. We also studied the effects of clarithromycin on the receptor expression and acidic endosomes to clarify the mechanisms.

Materials and Methods

Media Components. Reagents for cell culture media were obtained as follows: Dulbecco’s modified Eagle’s medium, Ham’s F-12 medium, and fetal calf serum were from Invitrogen (Carlsbad, CA); Ultroser G (USG) was from BioSera (Cergy-Saint-Christophe, France); and phosphate-buffered saline (PBS), Eagle’s minimum essential medium (MEM), and trypsin were from Sigma-Aldrich (St. Louis, MO).

Human Tracheal Epithelial Cell Culture. Isolation and culture of the human tracheal surface epithelial cells were performed as described previously (Suzuki et al., 2001a, 2002), with some modification (Yamaya et al., 2007). The human tracheal surface epithelial cells were plated at 5 x 10^5 viable cells/ml in plastic tubes with round bottoms (16 mm in diameter and 125 mm in length; BD Biosciences, San Jose, CA) coated with human placental collagen, because attachment of the cells in plastic tubes was much better than that in glass tubes (data not shown; Yamaya et al., 2007). Cells were cultured in 1 ml of a mixture of Dulbecco’s modified Eagle’s medium/Ham’s F-12 medium [DF-12; 50/50 (v/v)] containing 2% USG and antibiotics (Suzuki et al., 2001a, 2002; Yamaya et al., 2007). The position of plastic tubes, where cells were cultured, was fixed in an inclined stainless-steel tube rack (30 cm in width, 10 cm in height, and 10 cm in depth, TE-HER TUBE RACK INCLINABLE RF-6; Hirasawa Works Co. Ltd., Tokyo, Japan), and this tube rack was placed in a humid incubator. The positioning of plastic tubes in the tube rack made an ~5° angle between the long axis of the tubes and the flat-bottomed plate of the incubator where the tube rack was placed (Suzuki et al., 2001a, 2002; Yamaya et al., 2007). The tubes were kept stationary, and cells were immersed in 1 ml of medium and cultured at 37°C in 5% CO_2, 95% air in the incubator. Because of this laid position of the plastic tubes, the cells attached and proliferated on the inner surface of the lateral wall of the tubes and the round shape of the bottom of the tubes.

The surface area of culture vessels of the plastic tubes covered by the cells became 11.6 ± 0.2 cm^2 (n = 3). The opening of the tubes was loosely covered with a screw cap to make air that contained CO_2 move through the slit. We confirmed the presence of a dome formation when the cells made confluent cell sheets on days 5 to 7 of culture by using an inverted microscope (MIT-2; Olympus, Tokyo, Japan; Suzuki et al., 2002) as described by Widdicombe et al. (1987).

Tracheas for cell cultures were obtained after death from 40 patients (age, 68 ± 3 years; 11 female, 29 male) without complications with bronchial asthma or COPD. The causes of death included malignant tumor other than lung cancer (n = 20), acute myocardial infarction (n = 4), rupture of an aortic aneurysm (n = 3), sepsis (n = 3), ileus (n = 3), malignant lymphoma (n = 2), cerebral infarction (n = 2), amyotrophic lateral sclerosis (n = 1), congestive heart failure (n = 1), and cerebral bleeding (n = 1). Of 40 patients, 15 were ex-smokers and 25 had never smoked. This study was approved by the Tohoku University Ethics Committee.

Culture of Madin-Darby Canine Kidney Cells. MDCK cells were also cultured in 25-cm^2 flasks (BD Biosciences) in MEM containing 10% fetal calf serum supplemented with 5 x 10^-4 IU penicillin and 50 mg/ml streptomycin (Numazaki et al., 1987). The cells were then plated in plastic dishes (96-well plate; BD Biosciences) or plastic tubes with round bottoms (16 mm in diameter and 125 mm in length; BD Biosciences). The opening of the tubes was loosely covered with a screw cap to make air that contained CO_2 move through the slit. Cells in the plastic dishes or tubes were cultured at 37°C in 5% CO_2, 95% air.

Viral Stocks. FluA virus (H1N1) was prepared in our laboratory from a patient with a common cold (Numazaki et al., 1987). FluA virus was identified by the hemadsorption inhibition test using an antiserum (New York/55/2004), as described previously (Numazaki et al., 1987). MDCK cells were cultured in plastic tubes with round bottoms and cultured for 7 days at 37°C in 5% CO_2, 95% air to make confluent cell sheets. Then, to generate stocks of FluA virus, MDCK cells in plastic tubes were rinsed with PBS and cultured in the medium (1.1 ml) containing 100 µl of FluA virus stock solution [10^4 tissue culture infective dose (TCID)_{50} units in 100 µl] and 1 ml of the MEM supplemented with 5 x 10^-4 IU penicillin, 50 mg/ml streptomycin, and 3.5 µg/ml trypsin. The opening of the tubes was loosely covered with a screw cap to make air that contained CO_2 move through the slit. Cells in the tubes were cultured at 33°C in 5% CO_2, 95% air after infection with FluA virus (Numazaki et al., 1987), because it has been shown that respiratory viruses such as human influenza virus and rhinovirus are well replicated and produced at 33°C in the cells (Storch, 2006). To obtain the FluA virus solution, 7 days after infection with FluA virus, MDCK cells and culture medium in the tubes were frozen in a short time in ethanol at ~80°C, thawed, and sonicated. The virus containing fluid was frozen in aliquots at ~80°C.

Detection and Titration of Viruses. Detection and titration of influenza viruses in supernatant fluids was performed with the endpoint methods (Condit, 2006), by infecting replicate confluent MDCK cells in plastic 96-well dishes (BD Biosciences) with serial 10-fold dilutions of virus-containing supernatant fluids as described previously (Numazaki et al., 1987; Yamaya et al., 2007). In brief, virus-containing supernatant fluids were 10-fold diluted in MEM supplemented with 5 x 10^-4 IU penicillin, 50 mg/ml streptomycin, and 3.5 µg/ml trypsin, and then they were added into the replicate MDCK cells in the wells (200 µl/well) of 96-well dishes. MDCK cells in the wells were then cultured at 33°C in 5% CO_2, 95% air for 7 days, and the presence of the typical cytopathic effects (CPE) of influenza virus was examined in all replicate cells as described previously (Numazaki et al., 1987; Condit, 2006). The number of wells that...
showed CPE of influenza virus was counted in each dilution of supernatant fluids. Then, the dilution of virus-containing supernatant fluids that showed CPE in more than 50% of replicate wells, and the dilution of the fluids that showed CPE in less than 50% of the replicate wells, were estimated. Based on these data, the TCID_{50} value was calculated with methods as described previously (Condit, 2006). Because the human tracheal epithelial cells were cultured in 1 ml of DF-12 containing 2% USG in the tubes, viral titers in supernatant fluids are expressed as TCID_{50} units/ml (Numazaki et al., 1987; Condit, 2006; Yamaya et al., 2007). Furthermore, the rates obtained by dividing the value of influenza viral titer (TCID_{50} units/ml) in supernatant fluids by incubation time and are expressed as TCID_{50} units/ml/24 h (Yamaya et al., 2007).

**Viral Infection of the Cells.** Infection of FluA virus to the human tracheal epithelial cells was performed with methods described previously (Suzuki et al., 2001a, 2002; Yamaya et al., 2007). A stock solution of FluA virus (H1N1, New York/55/2004) was added to the human tracheal epithelial cells in the tubes (100 μl in each tube; 1.0 × 10^{3} TCID_{50} units/100 μl). Because the number of the epithelial cells in the tubes was 2.0 ± 0.3 × 10^{6} cells/tube (n = 7), the multiplicity of infection was 0.5 × 10^{−3} TCID_{50} units/cell. Because, in preliminary experiments, we found that the human tracheal epithelial cells were detached from culture vessels of the tubes when the cells were infected with 0.5 × 10^{−3} TCID_{50} units/cell or more of influenza virus, the cells were therefore infected with 0.5 × 10^{−3} TCID_{50} units/cell of viruses. After a 1-h incubation at 33°C in 5% CO_{2}, 95% air, the viral solution was removed, and the epithelial cells were rinsed once with 1 ml of PBS. The cells were then fed with 1 ml of fresh DF-12 containing 2% USG supplemented with antibiotics. The opening of the tubes was loosely covered with a screw cap, the tubes were laid with a slant of approximately 5° and kept stationary in a humid incubator, and cells were cultured at 33°C in 5% CO_{2}, 95% air as described previously (Numazaki et al., 1987). The supernatant fluids were stored at −80°C for the determination of viral titers.

**Treatment of the Cells with Clarithromycin.** To examine the effects of clarithromycin on fluA virus infection, the cells were treated with clarithromycin (10 μM) (Jang et al., 2006), unless we describe other concentrations. Cells were treated with clarithromycin from 3 days before FluA virus infection until the end of the experiments after FluA virus infection (Suzuki et al., 2002). A concentration of 10 μM clarithromycin was chosen, because a concentration of 15 μM clarithromycin is the maximal serum concentration of macrolides in clinical use (500 mg of oral clarithromycin administered; Honeybourne et al., 1994). We also studied the relationship between the concentration of clarithromycin and the potency of inhibitory effects. To examine the concentration-dependent effects of clarithromycin on FluA virus infection, the cells were treated with clarithromycin at concentrations ranging from 10 nM to 100 μM.

**Collection of Supernatant Fluids for Measurements.** We measured the time course of FluA viral release with methods as described previously (Suzuki et al., 2002; Yamaya et al., 2007). In brief, to measure viral release during the first 24 h, we used two separate cultures from the same tranche. We collected the supernatant fluids at either 1 or 24 h after influenza virus infection. Furthermore, to measure the viral titer during 1 to 3 days after virus infection, we used one culture from each tranche after collecting supernatant fluids at 1 day (24 h) after virus infection. After collecting supernatant fluids at 1 day after infection, the cells were rinsed with PBS and 1 ml of DF-12 containing 2% USG was replaced. Supernatant fluids were also collected at 3 days after infection. Likewise, to measure the viral titer during 3 to 5 days after FluA virus infection, after collecting supernatant fluids at 3 days after infection, the cells were rinsed with PBS and 1 ml of the fresh medium was replaced. Supernatant fluids were also collected at 5 days after virus infection. The cells were then rinsed with PBS and 1 ml of the fresh medium was replaced. Supernatant fluids were also collected at 7 days after FluA virus infection to measure the viral titer during 5 to 7 days after virus infection.

**Effects of Clarithromycin on Susceptibility to Influenza Virus Infection.** The effects of clarithromycin on the susceptibility to FluA virus infection were evaluated as described previously (Sub-auste et al., 1995; Suzuki et al., 2002; Yamaya et al., 2007) using epithelial cells pretreated with clarithromycin (10 μM) or vehicle (0.1% ethanol) from 3 days before infection with FluA virus until just finishing the FluA virus infection. The epithelial cells were then exposed to serial 10-fold dilutions of FluA virus (H1N1) or vehicle of influenza virus (MEM) for 1 h at 33°C in 5% CO_{2}, 95% air. Because we found in the preliminary experiments that the maximal viral titers were observed in the supernatant fluids collected for 3 to 5 days, the presence of FluA virus was determined in the supernatant fluids collected for 3 to 5 days after infection with methods described above to assess whether infection occurred at each dose of FluA virus used.

**Quantification of Influenza Virus RNA.** To quantify the FluA virus RNA and rRNA expression in the human tracheal epithelial cells before and after FluA virus infection, real-time quantitative RT-PCR using the TaqMan technique (Roche Molecular Systems, Inc., Alameda, CA) was performed as described previously (Yamaya et al., 2007), with some modification. Each RNA sample (100 ng/10 μl of water) was mixed in 40 μl of buffer containing 100 nM forward primer (5′-AGATGAGCTTCTCACCGAGTCCG-3′), 100 nM reverse primer (5′-TGCAAAAACATCTTAAAGTCGGAGCG-3′), and other agents as described previously (Spackman et al., 2002). TaqMan probe influenza virus [5′-(carboxytetramethylrhodamine)-3′,6-diamino-2-phenylindole, dihydrochloride], and the emission signal of these probes was measured by the ABI PRISM 7700 sequence detection system (Applied Biosystems, Japan) equipped with a 7-color detection system. The cDNAs for influenza virus were amplified by real-time quantitative RT-PCR (TaqMan) with the forward primer (5′-GCAAATCCCTTCTAGGGCCCAACAGCAAGCCGA (5-carboxytetramethylrhodamine)-3′), 100 nM reverse primer (5′-AGATGAGCTTCTCACCGAGTCCG-3′), and other agents as described previously (Spackman et al., 2002). TaqMan probe influenza virus [5′-(carboxytetramethylrhodamine)-3′,6-diamino-2-phenylindole, dihydrochloride], and the emission signal of these probes was measured by the ABI PRISM 7700 sequence detection system (Applied Biosystems, Japan) equipped with a 7-color detection system.

**Detection of SAα2,6Gal in Human Trachea.** SAα2,6Gal in human trachea was detected using lectins as described previously (Shinya et al., 2006). In brief, human tracheae were cut into small pieces (10 × 10 mm) and incubated in the DF-12 containing 2% USG, antibiotics, and either clarithromycin (10 μM) or vehicle of clarithromycin (0.1% ethanol) for 24 h at 37°C in 5% CO_{2}, 95% air. Paraffin-embedded tissues were cut into 5-μm-thick sections with a microtome and mounted on a 3-aminopropyltriethoxy-silane-coated slides (Matsunami Glass Ind., Ltd., Tokyo, Japan). Sections were incubated with 250 μl of fluorescein isothiocyanate (FITC)-labeled Staphylococcus nigro lectin (1:100; Vector Laboratories, Burlingame, CA) overnight at 4°C. Sections were incubated with Alexa Fluor 594-conjugated streptavidin (1:250; Invitrogen) for 2 h at room temperature and counterstained with 4’,6-diamino-2-phenylindole, dihydrochloride (Dojindo Molecular Technologies, Inc., Kumamoto, Japan). The coverglasses were mounted on the sections and observed with a fluorescence microscope (BZ-8000; Keyence Co. Ltd., Osaka, Japan). The excitation wave lengths were 470 (FITC), 560 (Alexa Fluor 594), and 360 nm (4’,6-diamino-2-phenylindole, dihydrochloride), and the emitted light from the cells was detected through 495-, 595-, and 635-nm filters, respectively. The fluorescence intensity was calculated using a fluorescence image analyzer system (Lumina Vision, Mitani Co. Ltd., Pukui, Japan) equipped with a fluorescence microscope.
Measurement of Changes in Acidic Endosomes. The distribution and the fluorescence intensity of acidic endosomes in the cells was measured with the dye LysoSensor DND-189 (Invitrogen), as described previously (Suzuki et al., 2002; Yamaya et al., 2007). The cells on coverslips in Petri dishes were observed with a fluorescence microscope (IX70; Olympus, Tokyo, Japan). The excitation wavelength was 443 nm, and the emitted light from the cells was detected through a 505-nm filter. The fluorescence intensity was calculated using a fluorescence image analyzer system (Lumina Vision; Mitani Co. Ltd.) equipped with a fluorescence microscope. The effects of clarithromycin on acidic endosomes were examined from 100 s before to 300 s after the treatment with clarithromycin (10 μM) or vehicle (0.1% ethanol). Furthermore, we studied the effects of a long period of treatment with clarithromycin (10 μM; 3 days) on the distribution and the fluorescence intensity of acidic endosomes. Fluorescence intensity of acidic endosomes was measured in 100 human tracheal epithelial cells, and the mean value of fluorescence intensity is expressed as percentage of control value compared with the fluorescence intensity of the cells treated with vehicle of clarithromycin (0.1% ethanol).

Measurement of Cytokines Production. We measured IL-1β, IL-6, and IL-8 of supernatant fluids by specific enzyme-linked immunosorbent assays (Suzuki et al., 2002; Yamaya et al., 2007). To demonstrate the time course of cytokines release, we expressed the rates of change in cytokine concentrations in the supernatant fluids. The rates were obtained by dividing the value of cytokines concentration in supernatant fluids by incubation time and are expressed as picograms per milliliter per 24 h.

NF-κB Assay. Nuclear extracts from human tracheal epithelial cells were prepared by using a TransFactor extraction kit (BD Biosciences/Clontech, Mountain View, CA) according to manufacturer’s instructions. After centrifugation at 20,000g for 5 min at 4°C, nuclear extracts were assayed for p50, p65, and c-Rel content. An equal amount of nuclear lysate was added to incubation wells that were precoated with the DNA-binding consensus sequence. The presence of translocated p50, p65, and c-Rel subunit was assayed by using a TransFactor family colorimetric kit-NFκB (BD Biosciences/Clontech) according to manufacturer’s instructions (Fiorucci et al., 2002). Plates were read at 655 nm, and results are expressed as optical density.

Statistical Analysis. Results are expressed as means ± S.E. Statistical analysis was performed using two-way repeated measures of analysis of variance. Subsequent post hoc analysis was made using Bonferroni’s method. For all analyses, values of p < 0.05 were assumed to be significant. In the experiments using culture of human tracheal epithelial cells, n refers to the number of donors (tracheae) from which cultured epithelial cells were used.

Results

Effects of Clarithromycin on Influenza Virus Infection of Human Tracheal Epithelial Cells. Exposing confluent human tracheal epithelial cell monolayers to FluA virus (H1N1; 0.5 × 10^−3 TCID50 units/cell) consistently led to infection. No detectable virus was revealed at 1 h after infection, whereas FluA virus was detected in culture supernatant fluids at 24 h, and the viral content progressively increased between 1 and 24 h after infection (Fig. 1). Evidence of continuous viral production was obtained by demonstrating that each of supernatant fluids collected during 1 to 3 days, 3 to 5 days, and 5 to 7 days after infection contained significant levels of FluA virus (Fig. 1). The viral titer levels in supernatant fluids increased significantly with time for the 5 days of observation (p < 0.05 in each case by analysis of variance).

Treatment of the cells with clarithromycin (10 μM) significantly decreased the viral titers of FluA virus in supernatant fluids from 1 day (24 h) after infection (Fig. 1). Furthermore, clarithromycin decreased the viral titers of FluA virus in supernatant fluids concentration-dependently, and the maximal inhibitory effect was obtained at 100 μM (Fig. 2).

Treatment with clarithromycin (10 μM) did not change the concentrations of lactate dehydrogenase (LDH) in supernatant fluids throughout the experiments. The concentrations of LDH were 35 ± 3 IU/l/24 h before treatment with clarithromycin and 33 ± 3 IU/l/24 h 24 h after treatment (p > 0.20, compared with the concentrations before treatment; n = 5), 34 ± 3 IU/l/24 h 72 h after treatment (p > 0.20; n = 5), 34 ± 3 IU/l/24 h 120 h after treatment (p > 0.20; n = 5), and 33 ± 3 IU/l/24 h 144 h after treatment (p > 0.20; n = 5).

Effects of Clarithromycin on Viral RNA by PCR. Further evidence of the inhibitory effects of clarithromycin on FluA viral RNA replication in human tracheal epithelial cells was provided by real-time quantitative RT-PCR analysis. FluA viral RNA in the cells was consistently observed from 1 day (24 h) after infection, and increased with time (Fig. 3), whereas FluA viral RNA in the cells was not observed before infection (data not shown). Maximal FluA viral RNA in the cells was observed at 5 days (120 h) after infection (Fig. 3; data at 144 h not shown). Clarithromycin (10 μM) decreased the FluA viral RNA from 1 day after infection (Fig. 3).

Effects of Clarithromycin on Susceptibility to FluA Virus Infection. Treatment of the cells with clarithromycin (10 μM) decreased the susceptibility of the cells to infection by FluA virus. The minimal dose of FluA virus necessary to cause infection in the cells treated with clarithromycin (10 μM; 3 days) was significantly higher than that in the cells treated with vehicle (0.1% ethanol; Fig. 4).

Effects of Clarithromycin on SAα2,6Gal Expression. Sαα2,6Gal, a receptor for human influenza, was observed as a green line or spots of green staining on the mucosal surface
of human tracheal epithelium (Fig. 5A). Clarithromycin (10 μM; 24 h) reduced the number of green spots on the human tracheal epithelium (Fig. 5B), and the fluorescence intensity from the receptor (by 62 ± 7% compared with that in vehicle of clarithromycin; p < 0.001, Student’s t test; n = 8; Fig. 5C).

Effects of Clarithromycin on the Acidification of Endosomes. Acidic endosomes in human tracheal epithelial cells were stained green with LysoSensor DND-189 (Fig. 6, A and B). Clarithromycin (10 μM; 300 s) significantly reduced the fluorescence intensity from acidic endosomes in the epithelial cells (by 32 ± 2%; p < 0.01; n = 5; Fig. 6, C and D). Clarithromycin also reduced the number of acidic endosomes with green fluorescence in the cells with time (data not shown).

Likewise, a long period of treatment with clarithromycin (10 μM; 3 days) significantly reduced the number of acidic endosomes with green fluorescence in the cells (Fig. 6B), and the fluorescence intensity from acidic endosomes in the epithelial cells compared with that in the cells treated with vehicle (0.1% ethanol; by 69 ± 4%; p < 0.01; n = 5; Fig. 6D). The inhibitory effects of a long period of treatment with clarithromycin (3 days) on the fluorescence intensity were concentration-dependent (Table 1).

Effects of Clarithromycin on Cytokines. To examine the effects of clarithromycin on proinflammatory cytokines, supernatant fluids were collected just before infection, and 1 day (24 h), 3 days (72 h), 5 days (120 h), and 7 days (144 h) after FluA virus infection. The secretion of IL-1β, IL-6, and IL-8 all increased after FluA virus infection (Fig. 7), and maximal secretion was observed at 5 days after the infection (data not shown). Treatment with clarithromycin (10 μM) reduced the concentrations of IL-1β, IL-6, and IL-8 5 days after FluA virus infection as well as baseline concentrations of these cytokines before FluA virus infection (Fig. 7). In contrast, ultraviolet-irradiated FluA virus did not increase the secretion of IL-1β, IL-6, and IL-8 (data not shown). Treatment with clarithromycin (10 μM; 3 days) significantly reduced the amount of p50, p65, and c-Rel of NF-κB in the nuclear extracts in the cells before FluA virus infection (Fig. 8). In contrast, the amount of p50, p65, and c-Rel of NF-κB in the nuclear extracts increased 5 days after FluA virus infection (Fig. 8), and clarithromycin (10 μM) also significantly reduced the amount of p50, p65, and c-Rel of NF-κB induced by FluA virus infection (Fig. 8).
Discussion

In the present study, we have shown that viral titers in supernatant fluids and RNA of FluA virus in human tracheal epithelial cells increased with time, and clarithromycin reduced viral titers in supernatant fluids concentration-dependently, RNA replication of FluA virus in the cells, and the susceptibility to FluA virus infection. The surface epithelium of human tracheae expressed sialic acid with SA\(^{2,6}\)Gal, a receptor for human influenza virus (Rogers and Paulson, 1983), stained with FITC-labeled S. nigra lectin as shown by Shinya et al. (2006). Treatment of human tracheae with clarithromycin reduced the expression of the receptor on the epithelium. These findings suggest that clarithromycin might inhibit FluA virus infection, partly through the reduced expression of the receptor for human influenza virus in the human tracheal epithelium. Clarithromycin also reduced the number of acidic endosomes from which viral RNPs containing RNA of FluA virus enter into the cytoplasm, and it reduced the fluorescence intensity from acidic endosomes. These findings suggest that the reduction of acidic endosomes might also relate to the inhibition of FluA virus infection by clarithromycin. Furthermore, clarithromycin reduced concentrations of cytokines, including IL-1\( \beta\), IL-6, and IL-8 in supernatant fluids. Clarithromycin may also modulate airway inflammation induced by FluA virus infection.

Human seasonal influenza viruses and classical H1N1 swine influenza viruses bind to SA\(^{2,6}\)Gal, and most avian and equine viruses bind to SA\(^{2,3}\)Gal (Rogers and Paulson, 1983). An expression of SA\(^{2,6}\)Gal was observed in epithelial cells in the nasal mucosa, pharynx, tracheae, and bronchi (Couceiro et al., 1993; Shinya et al., 2006). In contrast, SA\(^{2,3}\)Gal was reported not to express on the tracheal epithelial cells (Couceiro et al., 1993), whereas recent reports demonstrated its expression on ciliated cells in the human trachea (Matrosovich et al., 2004). SA\(^{2,3}\)Gal is also expressed in nonciliated cuboidal bronchiolar cells and type II cells lining the alveolar wall (Shinya et al., 2006). In this study, human tracheal epithelial cells expressed SA\(^{2,6}\)Gal, but they did not express SA\(^{2,3}\)Gal (data not shown). These findings are consistent with those in previous reports (Couceiro et al., 1993; Shinya et al., 2006). In the present study, immunohistochemistry demonstrated the reduced expression of SA\(^{2,6}\)Gal in human tracheal epithelial cells after treatment with clarithromycin. Furthermore, the minimal dose of FluA virus necessary to cause infection in the cells treated with clarithromycin was significantly higher than that in the cells treated with vehicle of clarithromycin, showing the reduced susceptibility to FluA virus infection. These effects are similar to those of erythromycin on the reduced expression of intercellular adhesion molecule-1, a receptor for rhinovirus, and on inhibition of the rhinovirus infection (Suzuki et al., 2002). These effects are also similar to those of clarithromycin on the reduced expression of activated isoform A of the Ras-homologous, one of receptors for respiratory syncytial virus, and on inhibition of respiratory syncytial virus infection (Asada et al., 2009). Clarithromycin might reduce the amount of FluA virus virions attached to the epithelial cells through the reduced expression of SA\(^{2,6}\)Gal in the cells.

The mechanisms for the reduction of SA\(^{2,6}\)Gal expression by clarithromycin are uncertain. However, tumor necrosis factor-\( \alpha\), one of inflammatory mediators in airways, increases the expression glycosyltransferase and sulfotransferase responsible for biosynthesis of sialylated epitopes in the bronchial mucosa (Delmotte et al., 2002), through the activation of NF-\( \kappa\)B (Chen et al., 2008). \( \alpha\)2,6-Sialic acid in glycoproteins also increases in inflamed mouse serum in response to turpentine oil (Yasukawa et al., 2005). In contrast, erythromycin, one of macrolides, reduces the increased activation of NF-\( \kappa\)B by rhinovirus infection as well as the baseline NF-\( \kappa\)B activity before rhinovirus infection (Suzuki et al., 2002). In the present study, clarithromycin reduced NF-\( \kappa\)B proteins including p50, p65, and c-Rel in the cells and reduced the expression of SA\(^{2,6}\)Gal, a receptor for human influenza virus, on the mucosal surface of human tracheae before in-
fluorescence from acidic endosomes in human tracheal epithelial cells 3 days after treatment with clarithromycin (CAM; 10 μM) or vehicle of clarithromycin (0.1% ethanol, control). Data are representative of five different experiments (magnification, 400×). C, time course changes in the intensity of green fluorescence from acidic endosomes in human tracheal epithelial cells after treatment with either clarithromycin (10 μM; open circles) or vehicle (0.1% ethanol; closed circles). Inhibitors were administrated at time 0. D, fluorescence intensity of acidic endosomes 300 s and 3 days (72 h) after the addition of CAM (10 μM) or vehicle of clarithromycin (0.1% ethanol, control). Results are expressed as relative fluorescence intensity (percentage) compared with those treated with vehicle for each period and are reported as means ± S.E. from five samples. Significant differences from control values are indicated by **, p < 0.01.

<table>
<thead>
<tr>
<th>Condition</th>
<th>Fluorescence Intensity</th>
<th>P Value</th>
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</thead>
<tbody>
<tr>
<td>% pretreatment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>100 ± 2</td>
<td>&gt;0.50</td>
</tr>
<tr>
<td>CAM (0.01 μM)</td>
<td>99 ± 2</td>
<td>&gt;0.20</td>
</tr>
<tr>
<td>CAM (0.1 μM)</td>
<td>82 ± 9</td>
<td>&lt;0.05</td>
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<tr>
<td>CAM (1.0 μM)</td>
<td>54 ± 5</td>
<td>&lt;0.01</td>
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<tr>
<td>CAM (10 μM)</td>
<td>31 ± 4</td>
<td></td>
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</table>

Macrolide and Seasonal Influenza

Treatment of the cells with clarithromycin did not change the concentrations of LDH in supernatant fluids throughout the experiments. These findings suggest that clarithromycin did not have toxic effects on the epithelial cells, and toxic effects of clarithromycin were not responsible for the effects described for clarithromycin in the present study.

After attachment of influenza virus to the receptor, viruses enter the airway epithelial cells and are internalized by endocytic compartments via four internalization mechanisms, including clathrin-coated pits, caveola, nonclathrin, noncaveolae pathway, and macropinocytosis (Palese and Shaw, 2006). Of these mechanisms, a nonclathrin, noncaveolae-mediated internalization pathway depends on low pH (Siezmkarski and Whittaker, 2003). Furthermore, after binding on the cell surface, the virus is internalized by receptor-mediated endocytosis, and the low pH in the endosome triggers fusion of the viral and endosomal membranes. The viruses then release their RNPs containing viral RNA into the cytoplasm, resulting in the next processes of viral replication (White et al., 1983; Palese and Shaw, 2006). As shown
previously (Suzuki et al., 2002) and in this study, macrolide antibiotics including erythromycin and clarithromycin reduced the number of acidic endosomes and the fluorescence intensity from acidic endosomes. Furthermore, clarithromycin reduced FluA viral RNA in human tracheal epithelial cells and viral titers of FluA in supernatant fluids. These findings are consistent with the reports that bafilomycin A1 reduces the number of acidic endosomes (Ochiai et al., 1995; Suzuki et al., 2001a) in the epithelial cells and reduces the growth of influenza virus in MDCK cells (Ochiai et al., 1995). Increased pH in acidic endosomes might relate to the inhibition of entry of the viral RNPs into the cytoplasm and might inhibit FluA virus infection in this study.

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Various inflammatory factors are suggested be associated with not only the pathogenesis and severity of influenza virus infection (Deng et al., 2008) but also exacerbations of bronchial asthma and COPD in the influenza virus infection (Seemungal et al., 2001). Increases in proinflammatory cytokines and monokines, including interleukin IL-1, IL-6, and IL-8, are observed in the serum in patients and in the lung of mice infected with influenza virus (Konstantinos and Sheridan, 2001; Deng et al., 2008). Macrolide antibiotics reduce the production of proinflammatory cytokines in human airways (Takizawa et al., 1995), after infection of rhinovirus and respiratory syncytial virus (Suzuki et al., 2002; Jang et al., 2006; Asada et al., 2009). Erythromycin and clarithromycin reduce the frequencies of exacerbations and hospitalization in COPD patients (Suzuki et al., 2001b; Seemungal et al., 2008; Yamaya et al., 2008) and the frequencies of common colds in COPD patients (Suzuki et al., 2001b). Erythromycin reduces the mortality rate by pneumonia in mice after influenza virus infection (Sato et al., 1998). Although the clinical benefits of macrolides in influenza virus infection are still uncertain, reduction of proinflammatory cytokines by clarithromycin may modulate influenza virus infection-induced inflammation and severity of the disease, and may modulate COPD exacerbations.

In this study, we examined the inhibitory effects of clarithromycin on the expression of FluA virus receptor and on acidic endosomes in the airway epithelial cells. However, there are many other interactions between epithelial cells and influenza virus components such as neuraminidase that have important roles in virus infection (Palese and Shaw, 2006). Further studies are needed to clarify the mechanisms of clarithromycin.

In summary, we demonstrated that clarithromycin, a clinically used macrolide, reduces FluA virus titers and cytokines secretion in supernatant fluids, FluA virus RNA replication in the cells, and susceptibility of the cells to infection by the virus. Clarithromycin also reduced the expression of SAα2,6Gal, a receptor for human influenza, on the mucosal surface of human trachea, and reduced the number of acidic endosomes from which viral RNPs enter into the cytoplasm. These findings suggest that a clinically used macrolide antibiotic clarithromycin may inhibit type A seasonal human influenza virus infection via reducing its receptor on the airway epithelial cells and via reducing entry of viral RNPs, which contain viral RNA, into the cytoplasm. Clarithromycin may also inhibit airway inflammation induced by influenza virus infection. Macrolide antibiotics may modulate the severity of influenza infection.
Fig. 8. Amount of p50 (A), p65 (B), and c-Rel (C) in nuclear extracts in human tracheal epithelial cells treated with clarithromycin (CAM; 10 μM) or vehicle (C; 0.1% ethanol) for 3 days before FluA virus infection, and the amount of p50, p65, and c-Rel in the cells 5 days (120 h) after infection with either FluA virus or vehicle of FluA virus (minimal essential medium) in the presence of clarithromycin (0.1% ethanol) from 3 days before FluA virus infection until the end of the experiments after FluA virus infection. Results are expressed as optical density (OD) and are means ± S.E. from five different tracheae. Significant differences from control values (C) before FluA virus infection are indicated by *, p < 0.05 and **, p < 0.01. Significant differences from FluA virus infection alone (FluA) are indicated by +, p < 0.05 and +, p < 0.01.

Acknowledgments

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References


Honeybourne D, Kees F, Andrews JM, Baldwin D, and Wise R (1994) The levels of influenza viral infection are indicated by +, p < 0.05 and **, p < 0.01. Significant differences from FluA virus infection alone (FluA) are indicated by +, p < 0.05 and +, p < 0.01.


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