JPET #74922

Comparison study between the mechanisms of allergic asthma amelioration by a cysteinyl-leukotriene type 1 receptor antagonist, montelukast, and methylprednisolone

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RUNNING TITLE

Short running title ; Comparison of cysLT$_1$RA with steroid

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The number of text pages ; 25
The number of tables ; 2
The number of figures ; 8
The number of references ; 40
The number of words in the Abstruct ; 237
The number of words in the Introduction ; 545
The number of words in the Discussion ; 1221

Abbreviations list: cysLT$_1$RA, cysteinyl-leukotriene type 1 receptor antagonist; cysLT, cysteinyl-leukotriene; MK, montelukast; MP, metylprednisolone; OVA, ovalbumin; LAR, late airway response; IAR, immediate airway response; R_L, pulmonary resistance; A-LTE$_4$, N-acetyl-LTE$_4$; HE, Hematoxylin-Eosin; BALF, Bronchoalveolar lavage fluid; HPLC, high performance liquid chromatography; EIA, enzyme immunoassay; SAS, statistical analysis system.

A recommended section assignment to guide the listing in the table of contents.
Section options are: Inflammation & Immunopharmacology

ABSTRACT

We investigated the effects of cysteinyl-leukotriene type 1 receptor antagonist, montelukast (MK), and compared them with those of methylprednisolone (MP) in an allergic asthma model. Rats sensitized to ovalbumin (OVA) received repeated intratracheal exposure to OVA for up to three consecutive days. Pretreatment with MK or MP before OVA exposure inhibited late airway response (LAR) and reduced cellular infiltration into the bronchial submucosa after the triple OVA. The amount of N-acetyl-leukotriene E_4 in the bile was significantly reduced by pretreatment with MK or MP, suggesting that both drugs reduced the production of cysteinyl-leukotrienes (cysLTs) in the lungs. In the *in vitro* study, when the fragments of lungs that had been repeatedly pretreated with MK or MP and exposed to OVA were removed and incubated with OVA, the co-addition of either drug significantly reduced cysLT production. In contrast, the cysLT production following the addition of OVA to the lung fragments that had not received *in vivo* pretreatment with either drug was inhibited by MK, but not by MP. These results indicate that MK and MP inhibit LAR by suppressing the infiltration of inflammatory cells into the bronchial submucosa and thereby inhibiting the production of cysLTs in the lungs, and that MK, but not MP, may inhibit cysLT production directly. The different effects on cysLT production between the two drugs may provide a rationale for the use of combination therapy with $cysLT_1$RAs and steroids for treatment of asthma.

INTRODUCTION

Asthma, one of the most prevalent disorders among industrialized nations, is characterized by reversible bronchoconstriction, increased mucous secretion, and complex airway inflammation (Busse and Rosenwasser, 2003). Inhalation of a specific antigen in allergic subjects usually results in dual responses, an immediate airway response (IAR) and a late airway response (LAR) (Nagy et al., 1982). The mechanisms for LAR are considered to be causally related to infiltration of eosinophils and other inflammatory cells into the bronchial submucosa following the IAR (Bousquet et al., 1990). Recent basic and clinical studies indicate that cysteinyl-leukotrienes (cysLTs) play an important role in both the responses of bronchial asthma (Smith, 1996) via the following effects on the airway system: induction of profound bronchoconstriction (Dahlen et al., 1980), enhancement of vascular leakage (Dahlen et al., 1981), enhancement of mucous secretion in the bronchi (Coles et al., 1983), and induction of chemotactic activity of eosinophils (Laitinen et al., 1993; Henderson et al., 1996). The cellular origins of cysLTs in the lungs are considered to be mast cells, eosinophils, basophils, monocytes-macrophages, and cell-cell interactions, such as those between

neutrophils and platelets (Samuelsson et al., 1987; Maclouf and Murphy, 1988). Several new drugs known as “leukotriene modifiers” have been developed to modulate the actions of cysLTs (Busse, 1998; Drazen et al., 1999). Namely, cysLT type1 receptor antagonists ($cysLT_1RAs$) and 5-lipoxygenase inhibitors block the effects of cysLTs on airway tissue and decrease the generation of cysLTs, respectively. On the basis of clinical studies, $cysLT_1RAs$ have been shown to be as effective at reducing asthma symptoms (Reiss et al., 1997) and inflammatory cell infiltration into the bronchial submucosa as 5-lipoxygenase inhibitors (Nakamura et al., 1998). The $cysLT_1RA$ has been shown to inhibit airway eosinophilia, hyper-responsiveness and microvascular leakage in mice after allergen challenge (Blain and Sirois, 2000). It has been reported that montelukast (MK), a $cysLT_1RA$, additively or synergistically improves lung function and patients’ symptoms when administered in conjunction with β-adrenergic receptor agonists or steroids (Reiss et al., 1997; Price et al., 2003).

Although $cysLT_1RAs$ are effective in both acute and chronic bronchial asthma and are recommended for clinical use as maintenance therapy (Busse and Lemanske, 2001; Naureckas and Solway, 2001; Price et al., 2003), the precise mechanisms by which

these drugs achieve their effects remain unclear (Leff, 2001). Consequently, we investigated the effects of MK in an allergic asthma model after repeated antigen exposure by estimating pulmonary resistance (R_L), pathological findings, and biliary excretion of N-acetyl-LTE_4 (A-LTE_4) as indices of the production of cysLTs in the lungs (Powell et al., 1995; Kodani et al., 2000). In addition, to examine the direct effects of MK or methylprednisolone (MP) on cysLT production in allergic lungs, we performed *in vitro* experiments using chopped lung fragments. On the other hand, steroids still remain the first-line drug for the treatment of acute exacerbation of asthma (National Institutes of Health/World Health Organization, 2002). Although there have been numerous studies concerning the mechanisms of steroids on allergic reactions, the effects of steroids on the generation of leukotrienes remain controversial (Barnes, 1998; Colamorea et al., 1999; Vachier et al., 2001; Barnes and Adcock, 2003). We therefore compared the mechanisms of the effects of MK on cysLT production in the lungs with those of MP using an allergic asthma model with repeated antigen exposures.

MATERIALS AND METHODS

Materials

All experimental protocols were approved by the institutional animal care and use committee of the School of Medicine, Fukuoka University. The cysLT$_1$RA (montelukast sodium; MK) was donated by Merck & Co., Inc. (Rahway, NJ). Methylprednisolone sodium succinate (MP) and Bordetella pertussis vaccine were purchased from Pfizer Manufacturing (Puurs, Belgium) and Wako Chemicals (Osaka, Japan), respectively.

Sensitization of rats

Male Brown-Norway rats (Seakku-Yoshitomi, Fukuoka, Japan) that were 6 to 8 weeks old and weighed around 250 g were used for the study. Active sensitization against OVA was performed by subcutaneous injection of sterile normal saline (1 ml) containing 1 mg OVA (grade II; Sigma, St. Louis, MO) and 200 mg aluminum hydroxide (Sigma). Bordetella pertussis vaccine (50 μl) containing $6x10^9$ heat-killed bacilli was given intraperitoneally as an adjuvant. Three days later, sterile normal saline (1 ml) containing 1 mg OVA and 200 mg aluminum hydroxide was subcutaneously injected for a booster

effect. All animals selected for these studies were used from 14 to 28 days after the first injection.

Evaluation of the effects of MK and MP

Sensitized rats were divided into groups by the number of OVA exposures and the different schedules of drug administration, as shown in Fig.1. With respect to the number of OVA exposures, the sensitized rats were daily challenged by inhalation of OVA aerosol for two successive days (Days 1 and 2) in the triple OVA exposure experiment. For this purpose, the inhalation of 0.25% OVA aerosol was accomplished by placing the rats for 20 min on each occasion in a 10-liter Plexiglass chamber connected to an ultrasonic nebulizer known as the "Comfort-mini" (Model-10; Sin-Ei Industries, Inc., Ageo, Japan). The next day (Day 3), the final OVA challenge was performed by intratracheal (i.t.) administration of 0.1 ml of a 1.7% OVA solution, as shown in Fig.1A and B. Ovalbumin grade V (Sigma) was used for OVA exposure (Abe et al., 2001). In the double OVA exposure, the sensitized rats were challenged by inhalation of OVA aerosol only for one day, and the final OVA challenge was performed

by i.t. on the next day (OVA Day 2). In the single OVA exposure, the rats were challenged by i.t. administration without any previous inhalation of OVA aerosol (Fig.1C). The control indicates the OVA sensitized rats received triple administration of saline. Administration of MK or MP was performed according to two different regimens on OVA Day 3; in one schedule the drug was administered before every OVA exposure (triple pretreatment), whereas in the other the drug was administered only before the 3rd OVA exposure (single pretreatment), as shown in Fig.1A and B, respectively. MK was dissolved in sterile saline, and the rats received the drugs gastrically at a rate of 10 mg/kg 1 hour before the start of the i.t. OVA challenge. MP was dissolved in the dissolving solution supplied by the manufacturer (Pfizer Manufacturing) and injected into the rats intramuscularly at a rate of 10 mg/kg 1 hour before the start of the i.t. challenge.

Measurement of pulmonary resistance (R_L)

The rats were anesthetized by intraperitoneal (i.p.) injection with urethane (1 g/kg, 25 % wt/vol). The tip of the tracheal tube (a 5 cm length of polyethylene tubing (PE-240))

was inserted into the trachea through an open tracheostomy. The transpulmonary pressure was determined by monitoring the difference between the pressure in the external end of the tracheal cannula and the esophageal cannula using a Statham differential transducer (DP-45; Validyne Engineering Corp., Northridge, CA). The intrapleural pressure was measured through a water-filled cannula (PE-240) that was placed in the lower third of the esophagus and connected to one port of a differential pressure transducer (DP-45; Validyne). A Fleisch pneumotachograph and a differential transducer were used to monitor the respiratory flow rate (PULMOS-II system; M.I.P.S., Osaka, Japan). R_L was estimated under artificial ventilation with a Harvard Apparatus Rodent Respirator (Millis, Bedford, MA) at a respiration rate of 70 breaths/min and a tidal volume of 3.5 ml (Abe et al., 2001). The R_L was measured before the challenge (baseline value). After challenge with OVA, the R_L was measured at 1, 5, 10, 15, 30, 45, and 60 min, and thereafter R_L was examined every 30 min for 6 hours.

Histological and cytological examination

At 6 hours after the i.t. administration of OVA, the rats were exsanguinated by cutting

the abdominal aorta. The trachea was joined to a tube with a three-way stopcock connected to a reservoir containing the fixative. The lungs were fixed *in situ* by the i.t. administration of 8% formaldehyde solution given at a pressure of 15 cmH_2O. The lungs were then stained with Hematoxylin-Eosin (HE) to assess the degree of inflammation.

Bronchoalveolar lavage (BAL) was performed via the tracheal cannula using 2x10 ml of saline containing 1 mM EDTA. The BALF was centrifuged at 300 x g for 5 min at 4°C and the cell pellet resuspended in 1.0 ml sterile saline with 0.2% rat serum. The total cell count was determined by adding 50 µl of the cell suspension to 50 µl Trypan blue stain and counting cells under a light microscope. The differential cell count was carried out from the smear preparation stained with Diff-Quik (International Reagents Corp., Kobe, Japan) and counting 200 cells at random under x200 magnification. The cells were identified by standard morphology.

Measurement of A-LTE_4 in bile

The rats were anesthetized with urethane and then the common bile duct was exposed

and cannulated by a PE-20 polyethylene tube (15 cm in length) after the ligation of the duodenal end. The rats were allowed to stabilize for a period of 2 hours prior to i.t. challenge with OVA. The bile was collected every hour on ice in 1.5 ml Eppendorf tubes under a stream of argon before and after the i.t. challenge, and then was stored at –80°C until analyzed. A-LTE_4 was measured in bile using precolumn extraction/reversed-phase high performance liquid chromatography (RP-HPLC) according to the previously reported method (Powell et al., 1995; Kodani et al., 2000). Briefly, ethanol was added to the aliquots (including [^{3}H]-LTE_4 as an internal standard) to give a final concentration of 15%. After adjusting to pH 3.0-3.5, the samples were loaded onto a Sep-PAK cartridge (Waters Corporation, Milford, MA). Methanol-eluted fractions passed through the minicolumn were concentrated under reduced pressure by a Speed Vac Concentrator (Savant Instruments Inc., Hicksville, NY). After resuspension with 150 μl of HPLC solvent A, 75 μl of the concentrated fraction was injected onto a Novapak C18, 5 μm column (0.39 x 15 cm) (Waters Corporation). The A-LTE_4 and LTE_4 fractions were collected using a fraction collector (Model 201; Gilson S.A.S, Villiers le Bel, France), then evaporated under reduced pressure. The residue was

analyzed by enzyme immunoassay (EIA) using a Leukotriene $C_4/D_4/E_4$ EIA kit (Amersham, Buckinghamshire, UK) according to the manufacturer's instructions. The values of LTC_4, LTD_4, and LTE_4 were normalized based on the recovery rates of [^{3}H]-LTE_4 (31.6±1.0%, n=27).

In vitro experiments for estimation of cysLT production in lung fragments

The lungs were removed from the actively sensitized rats with or without previous OVA exposure, and then the large bronchi or blood vessels were dissected from the lung tissue. The tissues were chopped into small pieces (approximately 2x2x2 mm) by fine scissors. The chopped lung tissue (300 mg) was preincubated in Tyrodes' buffer with or without co-addition of MK or MP for 5 min at 37°C, and further incubated for 30 min at 37°C after the addition of OVA solution (100 μg/ml). For incubation in the controls, saline was added instead of OVA. After terminating the reaction by addition of cold ethanol, LTs were partially purified through a Sep-Pak cartridge (Waters Corporation). After evaporation of methanol eluates under reduced pressure and resuspension with HPLC solvent A, LTC_4, LTD_4, and LTE_4 were separated with the Novapak C18 column

and each fraction was collected. LTC_4 and LTD_4 fractions were assayed using a CysLT-EIA kit (Cayman Chemicals, Ann Arbor, MI), and the LTE_4 fraction was assayed using a LTE_4-EIA kit (Cayman Chemicals). The sum of the amounts of LTC_4, LTD_4, and LTE_4 was considered the cysLT amount.

High-performance liquid chromatography (HPLC)

The HPLC system consisted of a Model 600 controller, a 717 autosampler (Waters Corporation) and the Novapak C18 column. We used solvent A (acetonitrile/methanol/water/acetic acid, 30:12:58:0.03, vol/vol) containing 0.03% ethylenediamine-N,N,N',N'-tetraacetic acid (EDTA-free acid; Dojindo, Kumamoto, Japan), and solvent B consisting of acetonitrile/methanol/water/acetic acid (68:12:20:0.01, vol/vol) containing 0.001% EDTA. All solvents were adjusted to pH 5.6 with ammonia solution (Nacalai, Kyoto, Japan). The mobile phase began with solvent A and then was changed to solvent B at 20 min. The flow rate was 1 ml/min. The retention times for LTC_4, A-LTE_4, LTD_4, and LTE_4 were approximately 4.2, 9.1, 13.1, and 15.1 min, respectively.

Statistical Analysis

Data are reported as the means+SEM. The statistical analysis was performed using the General Linear Models Procedure in SAS (Statistical Analysis System). A p value of less than 0.05 was considered to be statistically significant.

RESULTS

Time course for changes of R_L

Figure 2 shows the time course for changes of R_L after the third OVA challenge. Although control rats given 0.1 ml saline i.t. did not show any significant changes in R_L up to 6 hours after the challenge, rats that received the triple OVA exposure showed prominent LAR. As shown in Fig. 2A, triple pretreatment with MK or MP significantly suppressed LAR, but the intervention with MP seemed to be more potent than that with MK. The control indicates the OVA sensitized rats received triple i.t. administration of saline. Single pretreatment with MK or MP only before the 3rd OVA exposure also significantly inhibited LAR, but the inhibition by either drug was less than that by the triple pretreatment (Fig. 2B).

Table 1 shows the peak height of IAR and LAR after the 3rd OVA exposure with or without pretreatment with MK or MP. Although triple pretreatment with MP significantly suppressed IAR, both single and triple pretreatment with MK tended to suppress IAR, but not significantly. On the other hand, both drugs with either

administration schedule significantly suppressed LAR.

Cytological studies in BALF

Cytological studies were performed to examine the changes of total leukocyte number and the recovery of cellular differentiation in BALF, and to evaluate the effects of MK and MP on the infiltration of inflammatory cells into airway space. The results are shown in Fig. 3. Alveolar macrophages made up more than 90% of recovered cells in BALF after the saline i.t. challenge (control). The triple OVA exposure resulted in significantly more leukocytes in BALF than in the controls, and showed a diathesis toward increase in leukocyte number compared with the double exposure (OVA Day 2). Concerning cellular differentiation, eosinophils and neutrophils were the predominant cells, and the lymphocyte number also increased significantly. As shown in Fig. 3A and 3B, repeated pretreatment before every OVA exposure with either drug suppressed the accumulation of all types of leukocytes in BALF, but the effect of the single pretreatment only before the 3rd exposure was weaker than that of the triple pretreatment. The single pretreatment with MK or MP did not significantly inhibit

infiltration of eosinophils in the airway space after the 3rd exposure.

Histological studies

When the rats received double or triple OVA exposures, histological findings in bronchial tissue were examined at 6 hours after the last exposure. As shown in Fig. 4A and B, an extremely high infiltration of inflammatory cells including eosinophils and neutrophils was recognized in the bronchial submucosa after the 3rd exposure, in comparison with the double exposure. While triple pretreatment with MK suppressed the infiltration of inflammatory cells into the bronchial submucosa, as shown in Fig. 4C, that with MP almost completely inhibited the cellular infiltration (Fig. 4D). On the other hand, when the other administration schedule, single pretreatment only before the 3rd OVA exposure, was used to evaluate the effects of both drugs, pretreatment with either MK or MP also moderately suppressed the infiltration of inflammatory cells into the bronchial submucosa, and these suppressions were less potent than those by triple pretreatment (Fig. 4E and F).

N-acetyl-LTE_4 level in bile

In order to examine the time course of the generation of cysLTs in the lungs, we measured A-LTE_4 excretion in biliary fluid after the 3rd exposure to OVA. Saline administration did not change the level of A-LTE_4 (control). The 3rd OVA challenge resulted in significantly greater biliary excretion of A-LTE_4 up to 6 hours after challenge. As shown in Fig. 5A, triple pretreatment with MK or MP significantly reduced A-LTE_4 excretion in biliary fluid, but pretreatment with MP seemed to be more potent than that with MK. On the other hand, the single pretreatment with either drug only before the 3rd challenge also significantly reduced A-LTE_4 excretion in bile (Fig. 5B), suggesting that these two drugs suppressed cysLT production in the lungs after antigen challenge.

Relationship between N-acetyl-LTE_4 level and leukocyte number in BALF

When the A-LTE_4 level in bile and leukocyte number in BALF from the individual rats were plotted, a significant correlation was observed between the two parameters, as shown in Fig. 6A and B. The correlation coefficient for this relationship (OVA Day 3 + saline) was 0.849 ($p=0.0051$). When rats were pretreated with MK or MP, the

relationship between the A-LTE_4 level in bile and the leukocyte number in BALF was well correlated under the single pretreatment regimen (Fig. 6B), but not under the triple pretreatment regimen (Fig. 6A). The correlation coefficients in the former treatment were 0.719 ($p=0.0266$) for the single pretreatment with MK and 0.862 ($p=0.0092$) for that with MP, respectively.

In vitro production of cysLTs from chopped lung fragments

In order to examine the influence of MK or MP on the production of cysLTs in lung tissue after stimulation with the antigen, the chopped sensitized lung fragments without previous OVA exposure were incubated with OVA in Tyrodes' buffer in the presence or absence of either drug at various concentrations for 30 min at 37°C. An approximately three-fold higher amount of cysLT was produced in the chopped lung fragments supplemented with OVA compared to those supplemented with saline (control), as shown in Fig. 7. When MK was added at various concentrations (1–100 μg/ml), the production of cysLTs was significantly suppressed at the highest concentration (100 μg/ml). In contrast, the addition of MP at 1–100 μg/ml seemed to increase the

production of cysLTs, but not to a significant extent in comparison with that by OVA alone. The cysLT amount in the presence of MK (100 μg/ml) was significantly lower than that in the presence of MP (100 μg/ml). Next, the influence of MK or MP on cysLT production was evaluated in the lungs that were removed after repeated exposures to the antigen (Fig. 8). The lungs were removed from rats that were sequentially exposed to OVA for the last 2 days without pretreatment of MK or MP (Fig. 8A). The lungs were chopped into small pieces and then incubated with OVA in the buffer with or without co-addition of either MK (100 μg/ml) or MP (100 μg/ml) for 30 min at 37°C. While the amount of cysLT from the chopped lung fragments was significantly greater by the addition of OVA than by the addition of saline (control), co-addition of MK, but not MP, significantly inhibited cysLT production. The cysLT amount in the presence of MK was significantly lower than that in the presence of MP (Fig. 8A). In another trial, rats were daily challenged by inhalation of OVA aerosol for two successive days with or without repeated pretreatment of MK (10 mg/kg) or MP (10 mg/kg) before every challenge. On the next day, the lungs were removed and chopped into small pieces. When the chopped lung fragments were incubated with the OVA solution for 30 min at 37°C, the

co-addition of either MK (100 μg/ml) or MP (100 μg/ml) significantly inhibited cysLT production (Fig. 8B).

Table 2 summarizes the percent ratios of LTC_4, LTD_4, and LTE_4 in cysLTs produced from each incubation mixture containing the chopped lung fragments. LTC_4 was a major metabolite and occupied 55-70% of cysLTs produced by incubation for up to 30 min.

DISCUSSION

This study indicates that either cysLT$_1$R antagonist or steroid suppresses LAR and infiltration of inflammatory cells into the bronchial submucosa following repeated antigen challenge. In a previous study, Henderson et al. (1996) reported that a 5-lipoxygenase inhibitor inhibited the infiltration of eosinophils into the bronchial wall following antigen challenge in a murine asthma model. Equivalent effects have been observed using cysLT$_1$R antagonists in similar models (Muñoz et al., 1997). It has already been reported that LTE$_4$ shows chemotactic activity toward eosinophils (Laitinen et al., 1993). In the present study, a cysLT$_1$R antagonist and a steroid each inhibited the accumulation of inflammatory cells in the bronchial submucosa and airway space in parallel with a decrease of A-LTE$_4$ excretion into bile. We speculate that the decrease in the number of cells accumulated in the lung, especially in the bronchial submucosal tissues, contributed to the decreased excretion of A- LTE$_4$ into the bile, suggesting a reduction in the generation of cysLTs in the lungs (Powell et al., 1995). In support of this idea, we observed a linear relationship between the number of leukocytes in BALF and the A-LTE$_4$ levels in bile. Pretreatment with either drug suppressed

bronchoconstriction while maintaining the linear relationship between these two parameters. The single pretreatment with MP or MK significantly suppressed A-LTE_4 in the bile, but did not inhibit number of eosinophils in BALF. These results suggest that the cellular origin of cysLTs may come from macrophages rather than from eosinophils during LAR, as previously reported (Yu et al., 1995). These results may suggest that the suppression in the infiltration of leukocytes into the airway tissues by MP or MK contributes to the reduced production of cysLTs in the lungs. However, whether or not MK and MP directly reduce cysLT production from the sensitized lungs after antigen challenge remained unclear in these *in vivo* experiments.

To further analyze the mechanisms by which the two drugs reduce the generation of cysLTs, the effects of either drug on cysLT production in the sensitized chopped lungs were evaluated *in vitro*. The two drugs had different effects on the production of cysLTs induced by incubation with the antigen (see Fig.7). While MK reduced cysLT production at the high dose, MP showed a diathesis to increase cysLT production from the chopped lungs after antigen challenge. This relationship between the two drugs was also similar in the experiment using chopped lung fragments after repeated antigen

exposure (see Fig.8A). Namely, co-addition of MK at the high dose reduced cysLT production from the lungs with or without previous OVA exposure following the addition of OVA, but this effect was not observed with MP. This result suggests that MK is able to directly suppress the generation of cysLTs in the lung tissue, but MP is not. On the other hand, when we performed a similar experiment using the lung fragments from rats subjected to repeated OVA exposure and repeated *in vivo* pretreatment with either drug (see Fig. 8B), both drugs suppressed the *in vitro* generation of cysLTs after the third OVA exposure, and the suppression of cysLTs by MP was similar to that by MK. Consequently, it is concluded that MP does not directly inhibit cysLT generation from the lung tissue following antigen challenge, but MP is able to suppress cysLT production in the case of repeated treatment through broad anti-inflammatory effects, including inhibition of cellular infiltration into the bronchial submucosa after repeated antigen exposure. We could not propose an explanation of how cysLT production from the chopped lungs was inhibited by MK. On the other hand, Ramires et al. (2003) reported that montelukast directly inhibited 5-lipoxygenase activity in mast cells at the lower micromolar ranges when stimulated by calcium

ionophore A23187. However, this inhibition required cellular integrity, because MK did not inhibit 5-lipoxygenase activity in the homogenates from the cells. The dose of MK (100 μg/ml) used in the *in vitro* study is much higher than the concentrations required to block $CysLT_1R$ in human lung preparations (Fregonese et al., 2002). However, in our *in vivo* experiments, MK was administered to rats at 10 mg/kg, which is approximately 50 times more than the usual clinical dosage. Concerning the *in vivo* dose of MK used in the present animal studies, other groups have used similar doses (10-25 mg/kg) (Wu et al., 2003; Leick-Maldonado et al., 2004). A blood concentration of 100 μg/ml may be hardly achievable after the administration of the in vivo dose at 10 mg/kg. However, this concentraion may be achievable if used at high doses of 25 mg/kg or more, because the dose at 25 mg/kg raised the blood concentration nearly up to 80 μg/ml as shown by Wu et al. (2003). The dose of MK needed to block LTC_4 is much higher than that needed to block LTD_4 (Jones et al., 1995). The ratios of production of LTC_4 to LTD_4 in the rat lungs in the present study suggests that conversion of LTC_4 to LTD_4 was slower in this species than in human beings (see Table 2). Concerning human chopped lung, Kumlin and Dahlen (1990) reported that LTC_4 was rapidly converted to LTD_4 and LTE_4,

and only 10% of LTC_4 remained intact after 30 min of incubation at 37°C. Consequently, the discrepancy in γ-glutamyl transpeptidase activity between the two species may be one reason that the dose of $cysLT_1RA$ required to ameliorate asthma in rats is higher than that in humans (Shi et al., 2001).

With respect to the two administration schedules used in this study, both were effective at inhibiting late bronchoconstriction, cellular infiltration into the bronchial submucosa, and cysLT production in the lungs, but the triple pretreatment regimen resulted in more complete suppression than the single pretreatment regimen. These results suggest that both drugs are also effective for treatment in the later advanced stages of the disease, when inflammation is already present. MP seemed to show similar but more potent effects than MK did. These results may be compatible with the previous clinical observation that severe asthma attack was not always ameliorated by $cysLT_1R$ antagonists alone, but required co-administration of steroids (Tomari et al., 2001). This result provides further evidence for the effectiveness of steroids and $cysLT_1RAs$ on allergic disorders as anti-inflammatory therapy. Concerning anti-inflammatory effects, Wu et al. (2003) reported that high doses of MK exerted anti-inflammatory effects in an

animal model of acute asthma by inhibiting cytokine production. Since steroids have various anti-inflammatory and immunosuppressive effects on allergic reactions, including inhibition of cytokine gene induction, inhibition of chemokine synthesis, repression of genes encoding cell surface receptors, and repression of adhesion molecules involved in leukocyte activation, migration, and recruitment (Karin, 1998), the present finding that the effects of the cysLT$_1$R antagonist were almost equal to those of the steroid suggests that cysLTs play a major role in allergic asthma through cysLT$_1$R, as supported by previous reports using receptor-disrupted mice (Maekawa et al., 2002).

In conclusion, this study revealed that MK may have the novel effect of directly inhibiting cysLT generation when administered at a high dose, in addition to the previously reported ameliorative effects of cysLT$_1$R antagonists on bronchoconstriction, recruitment of inflammatory cells into loci, and inflammation (Wu et al., 2003). The finding that MK and MP had different effects on cysLT production may provide a further rationale for the use of combination therapy with cysLT$_1$RAs and steroids for treatment of asthma.

REFERENCES

National Institutes of Health/World Health Organization (2002) Global strategy for asthma management and prevention. *NIH Publication* No. 02-3659. Department of Health, Education, and Welfare, Washington, DC.

Abe M, Shibata K, Akatsu H, Shimizu N, Sakata N, Katsuragi T and Okada H (2001) Contribution of anaphylatoxin C5a to late airway responses after repeated exposure of antigen to allergic rats. *J Immunol* **167:**4651-4660.

Barnes PJ (1998) Anti-inflammatory actions of glucocorticoids: molecular mechanisms. *Clin Sci (Lond)* **94:**557-572.

Barnes PJ and Adcock IM (2003) How do corticosteroids work in asthma? *Ann Intern Med* **139:**359-370.

Blain JF and Sirois P (2000) Involvement of LTD_4 in allergic pulmonary inflammation in mice: modulation by $cysLT_1$ antagonist MK-571. *Prostaglandins Leukotrienes Essent Fatty Acids* **62:**361-368.

Bousquet J, Chanez P, Lacoste JY, Barneon G, Ghavanian N, Enander I, Venge P, Ahlstedt S, Simony-Lafontaine J, Godard P and et al. (1990) Eosinophilic inflammation in asthma. *N Engl J Med* **323:**1033-1039.

Busse W (1998) The role and contribution of leukotrienes in asthma. *Ann Allergy Asthma Immunol* **81:**17-19.

Busse WW and Lemanske RF Jr (2001) Asthma. *N Engl J Med* **344:**350-362.

Busse WW and Rosenwasser LJ (2003) Mechanisms of asthma. *J Allergy Clin Immunol* **111:**S799-S804.

Colamorea T, Di Paola R, Macchia F, Guerrese MC, Tursi A, Butterfield JH, Caiaffa MF, Haeggstrom JZ and Macchia L (1999) 5-Lipoxygenase upregulation by dexamethasone in human mast cells. *Biochem Biophys Res Commun* **265:**617-624.

Coles SJ, Neill KH, Reid LM, Austen KF, Nii Y, Corey EJ and Lewis RA (1983) Effects of leukotrienes C_4 and D_4 on glycoprotein and lysozyme secretion by human bronchial mucosa. *Prostaglandins* **25:**155-170.

Dahlen SE, Hedqvist P, Hammarstrom S and Samuelsson B (1980) Leukotrienes are potent constrictors of human bronchi. *Nature* **288:**484-486.

Dahlen SE, Bjork J, Hedqvist P, Arfors KE, Hammarstrom S, Lindgren JA and Samuelsson B (1981) Leukotrienes promote plasma leakage and leukocyte adhesion in postcapillary venules: in vivo effects with relevance to the acute inflammatory response. *Proc Natl Acad Sci U S A* **78:**3887-3891.

Drazen JM, Israel E and O'Byrne PM (1999) Treatment of asthma with drugs modifying the leukotriene pathway. *N Engl J Med* **340:**197-206.

Fregonese L, Silvestri M, Sabatini F and Rossi GA (2002) Cysteinyl leukotrienes induce human eosinophil locomotion and adhesion molecule expression via a $CysLT_1$ receptor-mediated mechanism. *Clin Exp Allergy* **32:**745-750.

Henderson WR Jr, Lewis DB, Albert RK, Zhang Y, Lamm WJ, Chiang GK, Jones F, Eriksen P, Tien YT, Jonas M and Chi EY (1996) The importance of leukotrienes in airway inflammation in a mouse model of asthma. *J Exp Med* **184:**1483-1494.

Jones TR, Labelle M, Belley M, Champion E, Charette L, Evans J, Ford-Hutchinson AW, Gauthier JY, Lord A, Masson P and et al. (1995) Pharmacology of montelukast sodium (Singulair), a potent and selective leukotriene D_4 receptor antagonist. *Can J Physiol Pharmacol* **73:**191-201.

Karin M (1998) New twists in gene regulation by glucocorticoid receptor: is DNA binding dispensable? *Cell* **93:**487-490.

Kodani M, Sakata N, Takano Y, Kamiya H, Katsuragi T, Hugli TE and Abe M (2000) Intratracheal administration of anaphylatoxin C5a potentiates antigen-induced pulmonary reactions through the prolonged production of cysteinyl-leukotrienes. *Immunopharmacology* **49:**263-274.

Kumlin M and Dahlen SE (1990) Characteristics of formation and further metabolism of leukotrienes in the chopped human lung. *Biochim Biophys Acta* **1044:**201-210.

Laitinen LA, Laitinen A, Haahtela T, Vilkka V, Spur BW and Lee TH (1993) Leukotriene E_4 and granulocytic infiltration into asthmatic airways. *Lancet* **341:**989-990.

Leff AR (2001) Regulation of leukotrienes in the management of asthma: biology and clinical therapy. *Annu Rev Med* **52:**1-14.

Leick-Maldonado EA, Kay FU, Leonhardt MC, Kasahara DI, Prado CM, Fernandes FT, Martins MA and Tiberio IF (2004) Comparison of glucocorticoid and cysteinyl leukotriene receptor antagonist treatments in an experimental model of chronic airway inflammation in guinea-pigs. *Clin Exp Allergy* **34:**145-152.

Maclouf JA and Murphy RC (1988) Transcellular metabolism of neutrophil-derived leukotriene A_4 by human platelets. A potential cellular source of leukotriene C_4. *J Biol Chem* **263:**174-181.

Maekawa A, Austen KF and Kanaoka Y (2002) Targeted gene disruption reveals the role of cysteinyl leukotriene 1 receptor in the enhanced vascular permeability of mice undergoing acute inflammatory responses. *J Biol Chem* **277:**20820-20824.

Muñoz NM, Douglas I, Mayer D, Herrnreiter A, Zhu X and Leff AR (1997) Eosinophil chemotaxis inhibited by 5-lipoxygenase blockade and leukotriene receptor antagonism. *Am J Respir Crit Care Med* **155:**1398-1403.

Nagy L, Lee TH and Kay AB (1982) Neutrophil chemotactic activity in antigen-induced late asthmatic reactions. *N Engl J Med* **306:**497-501.

Nakamura Y, Hoshino M, Sim JJ, Ishii K, Hosaka K and Sakamoto T (1998) Effect of the leukotriene receptor antagonist pranlukast on cellular infiltration in the bronchial mucosa of patients with asthma. *Thorax* **53:**835-841.

Naureckas ET and Solway J (2001) Clinical practice. Mild asthma. *N Engl J Med* **345:**1257-1262.

Powell WS, Xu LJ and Martin JG (1995) Effects of dexamethasone on leukotriene synthesis and airway responses to antigen and leukotriene D_4 in rats. *Am J Respir Crit Care Med* **151:**1143-1150.

Price DB, Hernandez D, Magyar P, Fiterman J, Beeh KM, James IG, Konstantopoulos S, Rojas R, van Noord JA, Pons M, Gilles L and Leff JA (2003) Randomised controlled trial of montelukast plus inhaled budesonide versus double dose inhaled budesonide in adult patients with asthma. *Thorax* **58:**211-216.

Ramires R, Caiaffa MF, Tursi A, Haeggström JZ and Macchia L (2003) Inhibition of 5-lipoxygenase activity by montelukast. Requirement of cellular integrity. (Honn KV) 8th International conference of eicosanoids & other bioactive lipids in cancer, inflammation and related diseases. pp90 (Abstract).

Reiss TF, Sorkness CA, Stricker W, Botto A, Busse WW, Kundu S and Zhang J (1997) Effects of montelukast (MK-0476); a potent cysteinyl leukotriene receptor antagonist, on bronchodilation in asthmatic subjects treated with and without inhaled corticosteroids. *Thorax* **52:**45-48.

Samuelsson B, Dahlen SE, Lindgren JA, Rouzer CA and Serhan CN (1987) Leukotrienes and lipoxins: structures, biosynthesis, and biological effects. *Science* **237:**1171-1176.

Shi ZZ, Han B, Habib GM, Matzuk MM and Lieberman MW (2001) Disruption of gamma-glutamyl leukotrienase results in disruption of leukotriene D_4 synthesis in vivo and attenuation of the acute inflammatory response. *Mol Cell Biol* **21:**5389-5395.

Smith LJ (1996) Leukotrienes in asthma. The potential therapeutic role of antileukotriene agents. *Arch Intern Med* **156:**2181-2189.

Tomari S, Shimoda T, Kawano T, Mitsuta K, Obase Y, Fukushima C, Matsuse H and Kohno S (2001) Effects of pranlukast, a cysteinyl leukotriene receptor 1 antagonist, combined with inhaled beclomethasone in patients with moderate or severe asthma. *Ann Allergy Asthma Immunol* **87:**156-161.

Vachier I, Chavis C, Majori M, Farce M, Bousquet J, Godard P and Chanez P (2001) Effects of glucocorticoids on endogenous and transcellular metabolism of eicosanoids in asthma. *J Allergy Clin Immunol* **107:**824-831.

Wu AY, Chik SC, Chan AW, Li Z, Tsang KW and Li W (2003) Anti-inflammatory effects of high-dose montelukast in an animal model of acute asthma. *Clin Exp Allergy* **33:**359-366.

Yu W, Xu L, Martin JG and Powell WS (1995) Cellular infiltration and eicosanoid synthesis in Brown Norway rat lungs after allergen challenge. *Am J Respir Cell Mol Biol* **13**:477-486.

FOOTNOTES

a) Unnumbered footnote providing the source of financial support, thesis information, citation of meeting abstracts where the work was previously presented, etc.

Grants; Fukuoka University

Gift;

Equipment;

Drugs; The cysLT$_1$RA (montelukast; MK) was donated by Merck & Co., Inc. (Rahway, NJ).

b) The name and full address (with street address or P.O. box, and postal code) of person to receive reprint requests.

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c) Numbered footnotes, using superscript numbers, beginning with those (if any) to authors' names and listed in order of appearance.

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LEGENDS FOR FIGURES

Fig.1. Experimental schedules for the exposure of sensitized rats to OVA and pretreatment with MK, MP, or saline. Certain rats were exposed to the antigen by inhalation of OVA aerosol, and the final challenge was conducted by an i.t. administration of OVA solution. A) Triple OVA exposure with triple pretreatment before every exposure; B) triple OVA exposure with a single pretreatment only before the 3rd exposure; and C) single OVA exposure with pretreatment.

Fig. 2. A. Time course of changes in pulmonary resistance (R_L) after the 3rd OVA exposure to actively sensitized rats with or without pretreatment with MK (10 mg/kg, gastrically) or MP (10 mg/kg, intramuscularly) 1 hour before every OVA exposure. Control rats were given 0.1 ml saline i.t. instead of OVA solution namely, triple administration of saline. B. Time course of R_L changes after the 3rd OVA exposure in rats pretreated with MK (10 mg/kg) or MP (10 mg/kg) only before the final OVA exposure. The rats inhaled OVA aerosol for the last 2 consecutive days. The baseline value of saline was 0.217 ± 0.003 cm H_2O/(ml/s). The baseline value of each group differed from that of the saline group by less than 10%. Data are expressed as a

percentage of the baseline value (R_L value before challenge = 100%) and presented as the means±SEM. *p<0.05, **p<0.01 between the positive control group (OVA day 3 + saline) and the OVA day 3 + MK group; $^{+}$p<0.05, $^{++}$p<0.01 between the positive control group and OVA day 3 + MP group.

Fig. 3. Cytological studies for changes in leukocyte number and cellular differentiation in broncho-alveolar lavage fluid (BALF) and effects of MK and MP. A. Pretreatment with MK (10 mg/kg) or MP (10 mg/kg) was performed 1 hour before every OVA exposure. The number of total inflammatory cells in BALF was counted 6 hours after the 2nd or 3rd OVA challenge. Cellular differentiation of the infiltrating inflammatory cells showed that the levels of neutrophils (No), eosinophils (Eo), lymphocytes (Ly), and macrophages (Mo) were recovered in BALF 6 hours after the 2nd or 3rd OVA challenge. Control rats were given 0.1 ml saline i.t. instead of OVA solution. B. Pretreatment with MK (10 mg/kg) or MP (10 mg/kg) was performed only before the 3rd exposure. Values are presented as the means±SEM. *p<0.05, **p<0.01 between the positive control group (OVA day 3 + saline) and the OVA day 3 + MK group; $^{+}$p<0.05,

$^{++}p<0.01$ between the positive control group and OVA day 3 + MP group.

Fig. 4. Histological findings in bronchial tissues after the 3rd OVA exposure of actively sensitized rats and the effects of pretreatment with MK or MP. A, double OVA exposure (OVA Day 2 + saline); B, triple OVA exposure (OVA Day 3 + saline); C, triple OVA exposure with triple pretreatment with MK (10 mg/kg) before every exposure; D, triple OVA exposure with triple pretreatment with MP (10 mg/kg) before every exposure; E, triple OVA exposure with single pretreatment with MK (10 mg/kg) only before the 3rd exposure; F, triple OVA exposure with single pretreatment with MP (10 mg/kg) only before the 3rd exposure. The upper and lower panels show x40 and x400 magnification by light microscopy following H.E. staining, respectively.

Fig. 5. Estimation of N-acetyl-leukotriene E_4 excreted in the biliary fluid after the 3rd OVA exposure and effects of pretreatment with MK (10 mg/kg) and MP (10 mg/kg). A-LTE_4 was measured as described in the MATERIALS and METHODS and expressed as ng/ml bile per hour for consecutive periods commencing 1 hour before challenge up

to 6 hours after OVA challenge. A. Pretreatment with MK (10 mg/kg) or MP (10 mg/kg) was performed 1 hour before every OVA exposure. B. MK (10 mg/kg) or MP (10 mg/kg) was pretreated only before the 3rd exposure. Values are presented as the means±SEM. *$p<0.05$ between the positive control group (OVA Day 3 + saline) and OVA day 3 + MK group; $^{+}p<0.05$, $^{++}p< 0.01$ between the positive control group and OVA day 3 + MP group.

Fig. 6. Relationship between the amount of N-acetyl-LTE_4 in bile and total number of leukocytes in BALF at 6 hour after the 3rd OVA exposure with or without pretreatment of MK or MP. A. Pretreatment with MK (10 mg/kg) or MP (10 mg/kg) was performed 1 hour before every OVA exposure. B. Pretreatment with MK (10 mg/kg) or MP (10 mg/kg) was performed only before the 3rd exposure.

Fig. 7. Generation of cysLTs from the lung fragments without previous OVA exposure by stimulation with OVA and effects of co-addition with MK or MP. Various doses of MK or MP (1–100 μg/ml) were added to the incubation mixture, which contained 300

mg chopped sensitized lung fragments. Each mixture containing either drug was preincubated for 5 min at 37°C, and then further incubated for 30 min after the addition of OVA (final concentration = 100 μg/ml).Values are presented as the means±SEM (n=3-10). *$p<0.05$ and **$p<0.01$ compared to the controls.

Fig. 8. Generation of cysLTs from the lung fragments with previous OVA exposure by stimulation with the 3rd OVA challenge and effects of co-addition with MK or MP. (A) Sensitized rats were exposed to the antigen by inhalation of OVA aerosol for the last 2 consecutive days without pretreatment, and the next day the lungs were removed and cut in small pieces (chopped lung). Each incubation mixture containing 300 mg chopped lung fragments was preincubated for 5 min at 37°C in the presence or absence of MK (100 μg/ml) or MP (100 μg/ml), and then *in vitro* challenged with OVA (final concentration = 100 μg/ml) and incubated for 30 min at 37°C. Saline was used in place of OVA solution for the controls. (B) Sensitized rats were exposed to the antigen by inhalation of OVA aerosol for the last 2 consecutive days with or without pretreatment of MK (10 mg/kg) or MP (10 mg/kg) before every exposure. The next day, the lungs

were removed and cut in small pieces (chopped lung). Each incubation mixture containing 300 mg chopped lung fragments in the presence or absence of MK (100 μg/ml) or MP (100 μg/ml) was similarly incubated as in (A). Values are presented as the means±SEM (n=4-8). *$p<0.05$ and **$p<0.01$ compared to the controls.

TABLES

Table 1.

Table 1. Effects of pretreatment with montelukast (MK) or methylprednisolone (MP) on IAR and LAR following the 3rd OVA exposure.

The peak heights of immediate airway response (IAR) and late airway response (LAR) after the 3rd ovalbumin (OVA) exposure with or without pretreatment with MK (10 mg/kg, gastrically) or MP (10 mg/kg, intramuscularly) are given. The peak height of IAR was the highest value over the first 30 min after the challenge and that of LAR was the highest value at 240 to 360 min. OVA + MK or MP (triple) indicates that the rats were pretreated with MK 1 hour before every OVA exposure and OVA + MK or MP (single) indicates that the rats were pretreated with MK only before the last OVA exposure. Data are expressed as the percent baseline (pulmonary resistance value before challenge = 100%) and values are presented as the means±SEM. *$p < 0.05$, **$p < 0.01$ compared to the positive controls (OVA + saline). The number of rats used is given in parentheses.

	Peak height of IAR (% baseline)		Peak height of LAR (% baseline)	
Control	1.099 ± 0.026	(n=3)	0.960 ± 0.038	(n=3)
OVA + Saline	1.722 ± 0.130	(n=7)	1.733 ± 0.069	(n=5)
OVA + MK (triple)	1.467 ± 0.076	(n=10)	1.239 ± 0.080	(n=9)
OVA + MP (triple)	1.315 ± 0.104	(n=7)	1.190 ± 0.090	(n=7)
OVA + MK (single)	1.555 ± 0.074	(n=7)	1.303 ± 0.122	(n=6)
OVA + MP (single)	1.501 ± 0.087	(n=5)	1.204 ± 0.071	(n=5)

Table 2.

Table 2. Percent ratios of LTC_4, LTD_4, and LTE_4 in cysLTs produced from each incubation mixture.

The percent ratios of LTC_4, LTD_4, and LTE_4 in cysLTs produced from the chopped lung fragments are shown. The sensitized lung fragments (each 300 mg) without previous ovalbumin (OVA) inhalation were incubated with OVA at 100 μg/ml (OVA Day 1 + saline) or without (Control) for 30 min at 37°C. The sensitized rats were exposed to OVA by inhalation for the last 2 consecutive days, and on the next day the lungs were removed, cut in small pieces (chopped lung), and incubated with OVA (OVA Day 3 + saline). Values are expressed as the means±SEM. The number in parentheses indicates the number of experiments.

		LTC_4(%)	LTD_4(%)	LTE_4(%)
Control	(5)	68.0 ± 5.0	6.8 ± 3.7	25.1 ± 4.7
OVA Day1 + Saline	(5)	54.7 ± 9.7	5.5 ± 2.4	39.8 ± 9.9
OVA Day3 + Saline	(6)	70.8 ± 3.6	2.8 ± 1.3	26.4 ± 3.7

Fig.1

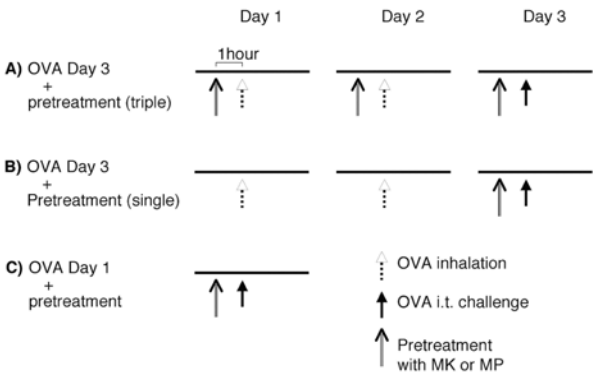
Day 1
Day 2
Day 3
1hour
A) OVA Day 3
+
pretreatment (triple)
B) OVA Day 3
+
Pretreatment (single)
C) OVA Day 1
+
pretreatment
OVA inhalation
OVA i.t. challenge
Pretreatment
with MK or MP

Fig.1

Fig.2

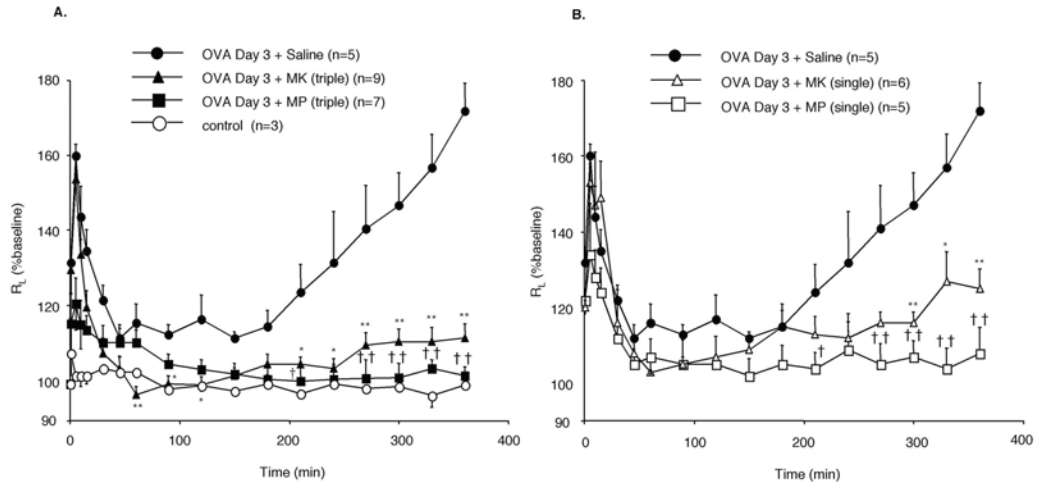
A.
OVA Day 3 + Saline (n=5)
OVA Day 3 + MK (triple) (n=9)
OVA Day 3 + MP (triple) (n=7)
control (n=3)
R_L (%baseline)
Time (min)
B.
OVA Day 3 + Saline (n=5)
OVA Day 3 + MK (single) (n=6)
OVA Day 3 + MP (single) (n=5)
R_L (%baseline)
Time (min)

Fig.2

Fig.3

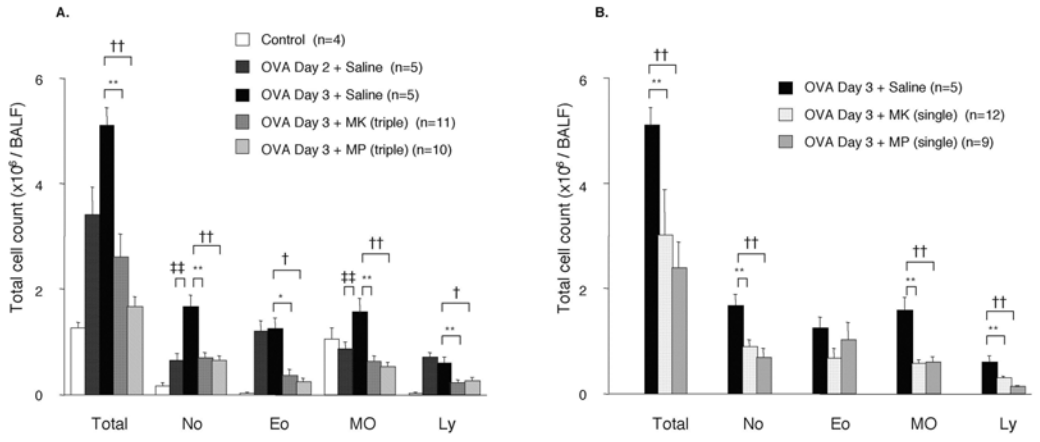
A.
Control (n=4)
OVA Day 2 + Saline (n=5)
OVA Day 3 + Saline (n=5)
OVA Day 3 + MK (triple) (n=11)
OVA Day 3 + MP (triple) (n=10)
Total cell count (x10⁶ / BALF)
0
2
4
6
Total
No
Eo
MO
Ly
B.
OVA Day 3 + Saline (n=5)
OVA Day 3 + MK (single) (n=12)
OVA Day 3 + MP (single) (n=9)
Total cell count (x10⁶ / BALF)
0
2
4
6
Total
No
Eo
MO
Ly

Fig.3

Fig.4

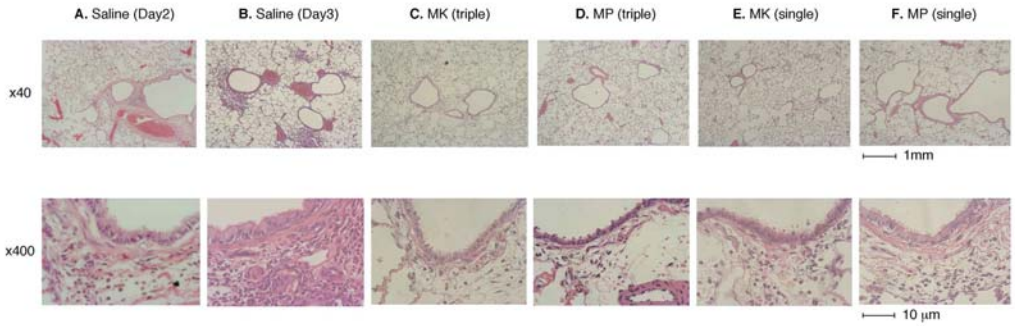
A. Saline (Day2)
B. Saline (Day3)
C. MK (triple)
D. MP (triple)
E. MK (single)
F. MP (single)
x40
1mm
x400
10 μm

Fig.4

Fig.5

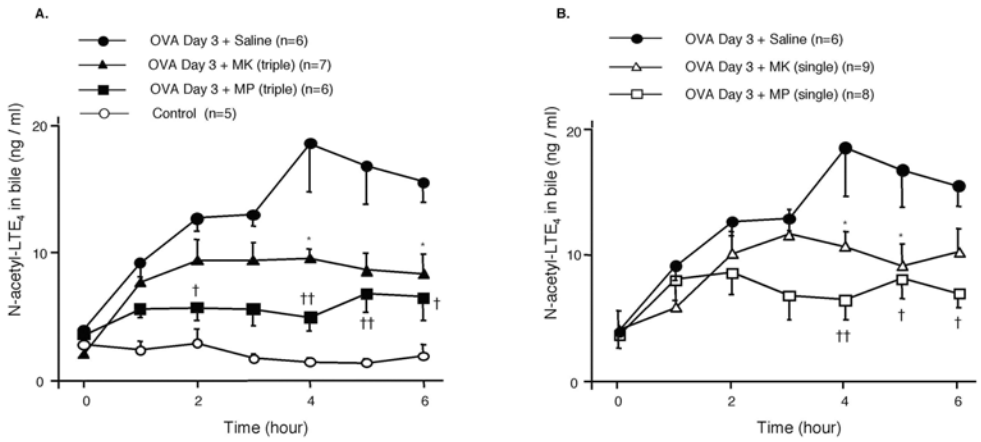
A.
OVA Day 3 + Saline (n=6)
OVA Day 3 + MK (triple) (n=7)
OVA Day 3 + MP (triple) (n=6)
Control (n=5)
N-acetyl-LTE4 in bile (ng / ml)
Time (hour)
B.
OVA Day 3 + Saline (n=6)
OVA Day 3 + MK (single) (n=9)
OVA Day 3 + MP (single) (n=8)
N-acetyl-LTE4 in bile (ng / ml)
Time (hour)

Fig.5

Fig.6

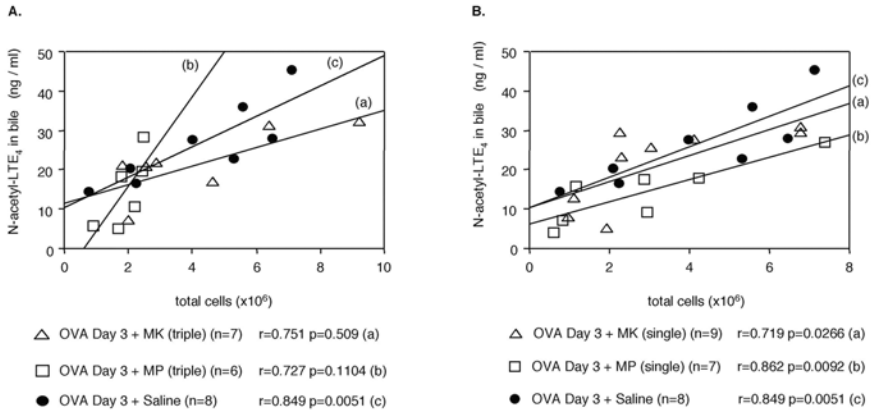
A.
N-acetyl-LTE4 in bile (ng / ml)
total cells (x10^6)
(a)
(b)
(c)
OVA Day 3 + MK (triple) (n=7) r=0.751 p=0.509 (a)
OVA Day 3 + MP (triple) (n=6) r=0.727 p=0.1104 (b)
OVA Day 3 + Saline (n=8) r=0.849 p=0.0051 (c)
B.
N-acetyl-LTE4 in bile (ng / ml)
total cells (x10^6)
(a)
(b)
(c)
OVA Day 3 + MK (single) (n=9) r=0.719 p=0.0266 (a)
OVA Day 3 + MP (single) (n=7) r=0.862 p=0.0092 (b)
OVA Day 3 + Saline (n=8) r=0.849 p=0.0051 (c)

Fig.6

Fig.7

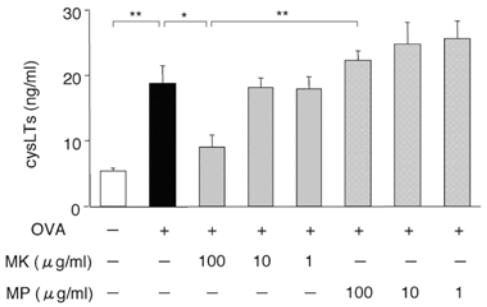

Fig.7

Fig.8

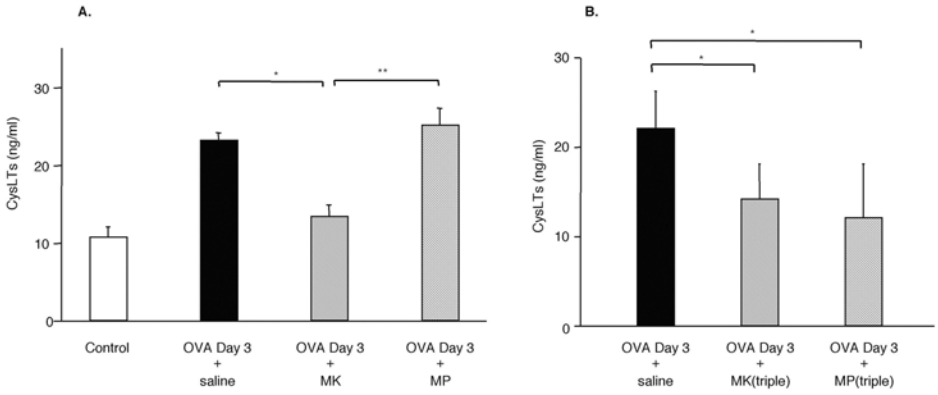
A.
CysLTs (ng/ml)
30
20
10
0
*
**
Control
OVA Day 3 + saline
OVA Day 3 + MK
OVA Day 3 + MP
B.
CysLTs (ng/ml)
30
20
10
0
*
*
OVA Day 3 + saline
OVA Day 3 + MK(triple)
OVA Day 3 + MP(triple)

Fig.8