Abstract. Human neutrophil peptides (HNPs) are antimicrobial peptides produced predominantly by neutrophils. We have previously reported that HNP 1-3 levels are increased in the sera and plasma of patients with active ulcerative colitis. The increased expression of interleukin-8 (IL-8) has also been demonstrated in the colonic mucosa of patients with active ulcerative colitis. HNPs induce IL-8 in lung epithelial cells and monocytes through the P2Y<sub>6</sub> signaling pathway. However, the association between HNPs and IL-8 in the intestinal mucosa has not yet been investigated. In the present study, we investigated the effects of HNP-1 on the production of IL-8 by human intestinal epithelial cells and the underlying signaling mechanisms. We observed a significant increase in IL-8 expression in the human colon carcinoma cell line, Caco-2, following treatment with HNP-1. The non-selective P2 receptor antagonists, suramin and pyridoxal phosphate-6-azo (benzene-2,4-disulfonic acid) tetrasodium salt hydrate (PPADS), significantly blocked the HNP-1-induced expression of IL-8 in the Caco-2 cells. The P2Y<sub>6</sub>-specific antagonist, MRS2578, led to a significant but partial decrease in IL-8 expression, suggesting that P2 receptors in addition to P2Y<sub>6</sub> are involved in the HNP-1-induced production of IL-8 by Caco-2 cells. In agreement with this finding, HNP-1 also significantly increased IL-8 production in the P2Y<sub>6</sub>-negative human colon cancer cell line, HT-29, and this increase was blocked by treatment with suramin and PPADS. HNP-1 significantly increased the phosphorylation of extracellular signal-regulated kinase 1/2 (ERK1/2) and p38 mitogen-activated protein kinase (MAPK) in the HT-29 cells. However, the HNP-1-induced production of IL-8 was suppressed by the ERK1/2 inhibitor, U0126, but not by the p38 MAPK inhibitor, SB203580. In conclusion, our data demonstrate that HNP-1 induces IL-8 production not only through P2Y<sub>6</sub>, but also through additional P2 receptors via an ERK1/2-dependent mechanism in intestinal epithelial cells.

Introduction

Inflammatory bowel disease (IBD), including ulcerative colitis (UC) and Crohn's disease (CD), is a group of chronic inflammatory disorders of the gastrointestinal tract. The incidence of IBD is more frequent in Western countries, but it is rapidly increasing in Asian populations (1). Although the pathogenesis of IBD remains unknown, genetic and environmental factors resulting in an aberrant immune response to commensal bacteria seem to play a pivotal role in the development of IBD (2). One of the key histological characteristics of IBD, particularly in UC, is the accumulation of neutrophils in crypt lumens. Neutrophils provide the first line of cellular immune defense against foreign microbes. However, uncontrolled neutrophil trafficking has been implicated in the pathogenesis of IBD (3).

Human neutrophils generate four α-defensins, human neutrophil peptides (HNPs) 1 to 4. We have previously reported that the plasma concentrations of HNP 1-3 in patients with active UC are higher than in healthy subjects or in those with inactive UC, CD or infectious enterocolitis (4). Thus, HNP 1-3 are considered to be useful biomarkers that may be used to diagnose and predict treatment outcomes in patients with UC. Moreover, we demonstrated that high concentrations of HNP-1 aggravated dextran sodium sulfate (DSS)-induced colitis by elevating the levels of inflammatory cytokines, suggesting a potential proinflammatory role for HNP-1 in colitis (5). In addition to their direct antimicrobial abilities, HNPs have a broad range of immune activation functions. HNPs are chemotactic in vitro for human monocytes, T-cells and immature dendritic cells (6-8). HNPs induce the production of interleukin-8 (IL-8, also known as CXCL8) by epithelial cells of the lungs and bronchus (9-14),
monocytes (13), lung fibroblasts (14), conjunctival epithelial cells (15) and rheumatoid fibroblast-like synoviocytes (16). IL-8 primarily mediates the activation and migration of neutrophils into tissue from peripheral blood. In addition to this pro-inflammatory function, IL-8 is also known to be a potent promoter of angiogenesis (17). The increased expression of IL-8 in the colonic tissues of patients with UC has been demonstrated and may contribute to the pathogenesis of UC (18,19). The serum concentrations of IL-8 have also been shown to be related to the endoscopic and histological severity of UC (20). In lung epithelial cells and monocytes, the HNP-induced production of IL-8 is regulated by the P2Y\(_{12}\) receptor (10,13). P2 receptors are activated by extracellular nucleotides. These receptors are divided into two subfamilies: ligand-gated ion channels (P2X) and G-protein-coupled receptors (P2Y). Both P2X and P2Y are expressed widely throughout the intestinal tract and participate in the regulation of a variety of physiological functions (21). However, the association among HNPs, IL-8 and P2 receptors in the intestinal mucosa has not yet been investigated. In the present study, we sought to determine whether HNP-1 induces IL-8 in intestinal epithelial cells, and if so, to elucidate the mechanisms that underlie this activity.

Materials and methods

Chemicals. The synthetic products of HNP-1 were purchased from Peptide Institute, Inc. (Osaka, Japan). MEM and McCoy's 5A medium, fetal bovine serum, penicillin-streptomycin, L-glutamine and the IL-8 ELISA kit were obtained from Life Technologies Corp. (Carlsbad, CA, USA). Suramin sodium (non-selective P2 receptor antagonist) was obtained from Wako Pure Chemical Industries (Osaka, Japan). Pyridoxal phosphate-6-azo (benzene-2,4-disulfonic acid) tetrasodium salt hydrate (PPADS, another non-selective P2 receptor antagonist) was obtained from Sigma-Aldrich Japan (Tokyo, Japan). U0126 [extracellular signal-regulated kinase 1/2 (ERK1/2) inhibitor] and SB203580 [p38 mitogen-activated protein kinase (MAPK) inhibitor] were obtained from Calbiochem (Darmstadt, Germany). MRS2578 (P2Y\(_{4}\)-specific antagonist) was obtained from Tocris Bioscience (Ellisville, MO, USA).

Cell culture. The human colon carcinoma cell line, Caco-2, was obtained from RIKEN BioResource Center (Ibaraki, Japan). The Caco-2 cells were grown in minimal essential medium (MEM) containing 20% heat-inactivated fetal bovine serum, 100 µg/ml streptomycin, 100 µg/ml penicillin and 2 mM L-glutamine. The Caco-2 cells were incubated with 50 µg/ml HNP-1 with or without 100 µM suramin, 100 µM PPADS or 10 µM MRS2578 for 24 h. The human colon cancer cell line, HT-29, was obtained from Dr. Otto G. Pantuck (RIKEN BioResource Center, Tokyo, Japan). The HT-29 cells were run on 10% sodium dodecylsulfate polyacrylamide gels and electroblotted onto polyvinylidene fluoride membranes. After blocking overnight at 4°C with 5% non-fat milk, the blots were probed with primary antibodies for 1 h at room temperature. Polyclonal rabbit antibodies against phosphorylated ERK1/2 (p-ERK1/2; 9101) and phosphorylated c-Jun N-terminal kinase (p-JNK; 9251), as well as monoclonal rabbit antibody against phosphorylated p38 MAPK (p-p38 MAPK; 4511) were purchased from Cell Signaling Technology (Danvers, MA, USA). Monoclonal mouse antibody against β-actin (A5441) was purchased from Sigma-Aldrich (St. Louis, MO, USA). After incubating the membrane with the appropriate peroxidase-conjugated secondary antibodies (MP Biomedicals, Santa Ana, CA, USA) for 1 h at room temperature, the reactivity was visualized using an electro-generated chemiluminescence detection kit (GE Healthcare Biosciences, Tokyo, Japan).

Statistical analysis. All experiments were repeated three times with cells at different passage numbers. Statistical analysis was performed using Tukey's honest significant difference method with SPSS 15.0J software (SPSS, Inc., Chicago, IL, USA). A value of P<0.05 was considered to indicate a statistically significant difference.

Results

HNP-1 upregulates IL-8 expression partly through P2Y\(_{4}\) receptors in Caco-2 cells. We first investigated whether HNP-1 increases IL-8 expression in intestinal epithelial cells by using Caco-2 cells that possess mRNA for several P2 receptor subtypes, including P2Y\(_{4}\) (22,23). Incubation of the Caco-2 cells with...
50 µg/ml HNP-1 significantly increased the mRNA expression of IL-8 (Fig. 1A). To determine the involvement of P2 receptors in the HNP-1-induced expression of IL-8, the Caco-2 cells were treated with two non-selective P2 receptor antagonists, suramin and PPADS. Both antagonists significantly blocked the HNP-1-induced expression of IL-8 (Fig. 1A). In addition, treatment with the P2Y₆-specific antagonist, MRS2578, significantly decreased the expression of IL-8 (Fig. 1B). These data suggest that HNP-1 induces IL-8 expression through the P2Y₆ signaling pathway in intestinal epithelial cells. However, MRS2578 only caused a partial reduction (37%) in IL-8 expression (Fig. 1B), suggesting that P2 receptors other than P2Y₆ are involved in the HNP-1-induced IL-8 expression.

HNP-1 significantly increases IL-8 production through P2 receptors in P2Y₆-negative HT-29 cells. To determine the non-P2Y₆-mediated mechanisms underlying the HNP-1 induction of IL-8, we used HT-29 cells in the subsequent experiments, since HT-29 cells have no, or very low levels of P2Y₆ mRNA expression (24). Exposure of the HT-29 cells to HNP-1 significantly increased IL-8 mRNA expression in a dose-dependent manner (Fig. 2A). Consistent with the induction of IL-8 expression, the release of IL-8 protein by the HT-29 cells was significantly enhanced by HNP-1 (Fig. 2B). This increase was effectively blocked by suramin and slightly, although significantly by PPADS (Fig. 3A), indicating the involvement of P2 receptors in the HNP-1-induced production of IL-8.

Figure 1. Involvement of P2 receptors in human neutrophil peptide-1 (HNP-1)-induced interleukin-8 (IL-8) expression in Caco-2 cells. (A) Caco-2 cells were incubated with 50 µg/ml HNP-1 with or without suramin (100 µM) or pyridoxal phosphate-6-azo(benzene-2,4-disulphonic acid) (PPADS) (100 µM) for 24 h. (B) Caco-2 cells were incubated with 50 µg/ml HNP-1 with or without 10 µM MRS2578 for 24 h. The mRNA expression of IL-8 was measured by RT-qPCR. The expression levels in the untreated cells were set to 1. Data are the means ± SE from three experiments. Significant differences relative to the HNP-1-treated cells with no antagonist are indicated as follows: *P<0.05; **P<0.01; ***P<0.001.

Figure 2. Human neutrophil peptide-1 (HNP-1) induces interleukin-8 (IL-8) production in a dose-dependent manner in P2Y₆-negative HT-29 cells. (A) HT-29 cells were incubated with varying concentrations of HNP-1 for 24 h and the mRNA expression of IL-8 was measured by RT-qPCR. The expression levels in the untreated cells were set to 1. (B) The IL-8 levels in culture supernatants from (A) were measured using ELISA. Data are the means ± SE from three experiments. Significant differences relative to untreated cells are indicated as follows: *P<0.05; **P<0.01; ***P<0.001.
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of IL-8 by HT-29 cells, despite the absence of P2Y6. Treatment of the HT-29 cells with MRS2578 had no effect on the expression of IL-8, as was expected (Fig. 3B).

P2 receptors, other than P2Y2 and P2Y6 subtypes are involved in the HNP-1-induced production of IL-8 by HT-29 cells. In addition to P2Y6 receptors, the P2Y2 and P2X7 receptors are involved in the production of IL-8 by epithelial cells. The activation of P2Y2 and P2X7 induces the release of IL-8 in renal epithelial cells and bronchial epithelial cells, respectively (25,26). HT-29 cells express the receptor for P2Y2 (24,27) but not the one for P2X7 (28). Although P2Y2 was not antagonized by PPADS, the involvement of P2Y2 in the HNP-1-induced production of IL-8 could not be excluded, as the inhibitory effects of PPADS on IL-8 production were much weaker than those of suramin. Therefore, we investigated the possibility that P2Y2 is the receptor primarily responsible for the HNP-1-induced production of IL-8 in HT-29 cells. As definitive antagonists of P2Y2 are not currently available, we applied P2Y2 siRNA and analyzed IL-8 expression following treatment with HNP-1. The silencing of P2Y2 decreased the mRNA expression level of P2Y2 by 40%, which was a significant decrease (Fig. 4A); however, the expression of IL-8 following treatment with HNP-1 was not altered (Fig. 4B). These results indicate that P2 receptors, other than the P2Y2 and P2Y6 subtypes are involved in the HNP-1-induced production of IL-8 by HT-29 cells.
HNP-1-induced production of IL-8 by HT-29 cells is dependent on ERK1/2 activation. In the Caco-2/15 cells, the increased production of IL-8 downstream of P2Y6 activation is dependent on the ERK1/2 signaling pathway (29). ERK1/2 activation is involved in the HNP-induced production of IL-8 in lung epithelial cells and monocytes, whereas p38 MAPK activation is required for IL-8 production only in monocytes (13). Moreover, it was recently reported that the HNP-1-induced production of IL-8 in rheumatoid fibroblast-like synovocytes is regulated by the JNK and ERK signaling pathways (16). Thus, we sought to determine which MAPK signaling pathways are involved in the HNP-1-induced production of IL-8 by HT-29 cells. Using western blot analysis, we found that HNP-1 induced the phosphorylation of ERK1/2 and p38 MAPK, while no significant changes were observed in JNK activity in the HT-29 cells (Fig. 5A). To identify the relevant signaling pathway involved in the HNP-1-induced production of IL-8, we treated the HT-29 cells with specific inhibitors of ERK1/2 (U0126) and p38 MAPK (SB203580). Treatment with U0126 significantly reduced the HNP-1-induced production of IL-8; however, the addition of SB203580 did not have any significant inhibitory effects on IL-8 production (Fig. 5B). These results suggest that the HNP-1-induced production of IL-8 is dependent on ERK1/2 activation in intestinal epithelial cells.

Discussion

In the present study, to the best of our knowledge, we demonstrate for the first time the induction of IL-8 by HNP-1 in intestinal epithelial cells. Our results suggest that HNP-1 released from infiltrated neutrophils induces IL-8 production by the intestinal mucosa. As a result of the increase in IL-8 expression, neutrophils are recruited to the site of inflammation, where they contribute to the extended tissue damage observed in patients with IBD.

HNP-1 induced IL-8 expression partly through P2Y6 in Caco-2 cells. The involvement of P2Y6 in IBD has previously been suggested. P2Y6 is highly expressed in T-cells infiltrating active IBD (30). The mRNA expression levels of the P2Y6 and P2Y2 receptors have been shown to be upregulated in the colonic epithelium of patients with IBD and DSS-treated mice (29). The activation of P2Y6 by its natural ligand, UDP, stimulates the sustained NaCl secretion in rat colonic enterocytes (31). In addition to P2Y6, we considered the involvement of other P2 receptors in HNP-1-induced IL-8 expression. Thus, we used HT-29 cells, which do not express P2Y6, in order to investigate non-P2Y6-mediated mechanisms. As was the case with the Caco-2 cells, HNP-1 significantly induced IL-8 production in the HT-29 cells, and this production was suppressed by suramin and PPADS. We hypothesized that P2Y2 is responsible for the HNP-1-induced production of IL-8 in HT-29 cells, as the P2Y2-mediated release of IL-8 by other epithelial cell lines has been previously reported (25), and the inhibitory effects on IL-8 production by PPADS were much weaker than those exerted by suramin. However, the silencing of P2Y2 had no effect on the induction of IL-8. It has been reported that P2 receptors expressed by HT-29 cells are those for P2Y1, P2Y2, P2Y4 and P2Y11 (24,27,32). The selective P2Y1 antagonist, MRS2179, did not exert any significant inhibitory effects on the HNP-1-induced production of IL-8 by HT-29 cells (data not shown). The involvement of P2Y12 is unlikely as its receptor is insensitive to suramin. Since PPADS is completely inactive at the human P2Y11 receptor (33), this also does not appear to be a dominant pathway involved in the HNP-1-induced production of IL-8.
Further studies on the identification of P2 receptors involved in the HNP-induced production of IL-8 are required in order to better understand the role of HNPs in intestinal epithelial cells. Three MAPK pathways, the ERK1/2, JNK and p38 MAPK cascades, contribute to the downstream activation of transcription factors, including nuclear factor-κB (NF-κB) and activator protein-1 (AP-1), both of which upregulate IL-8 transcription. The involvement of particular MAPK signaling pathways in the induction of IL-8 is dependent on the cell type and the stimulus (34). A previous study demonstrated that the ERK1/2 and p38 MAPK pathways contribute to the secretion of IL-8 by HT-29 cells in response to tumor necrosis factor (TNF)-α (35). Our results revealed that HNP-1 activated ERK1/2 and p38 MAPK in HT-29 cells. On the other hand, the HNP-1-induced production of IL-8 was inhibited by the blockade of ERK1/2 activation, but not by that of p38 MAPK, indicating that ERK1/2 plays a pivotal role in IL-8 production. Notably, P2Y₁ receptor activation by UDP has been shown to increase IL-8 production by Caco-2/15 cells through a mechanism that is ERK1/2-dependent, but p38 MAPK-independent (29). Therefore, the HNP-1-induced production of IL-8 appears to occur through the ERK1/2-dependent signaling pathway in intestinal epithelial cells regardless of the expression of P2Y₁.

It has been shown that ERK1/2, p38 MAPK and JNK are activated in the inflamed colonic mucosa of patients with IBD (36). Mesalamine, a drug effective in the treatment of IBD, has been shown to inhibit the TNF-α-induced activation of ERK1/2 (37). A recent study using gene expression profiling confirmed that the ERK/MAPK pathway is regulated by mesalamine (38). Another study demonstrated that the release of IL-8 triggered by mucosal E. Coli isolated from IBD is mediated by the ERK1/2 and p38 MAPK pathways and inhibited by mesalamine, but not by hydrocortisone (39). Hence, the reduction in the HNP-induced production of IL-8 by the inhibition of ERK1/2 may be part of the mechanism of action of mesalamine in the treatment of IBD.

In conclusion, in the present study, we demonstrate that the HNP-1-induced production of IL-8 in intestinal epithelial cells is dependent, not only on P2Y₁, but also on P2 receptors other than P2Y₁. Moreover, we reveal that the activation of the ERK1/2 pathway is required for the HNP-1-induced production of IL-8 by intestinal epithelial cells. HNPs released by infiltrating neutrophils in the UC intestine may stimulate additional neutrophil accumulation by inducing IL-8. The findings of the present study may lead to the development of novel therapeutic strategies to reduce HNP-induced intestinal inflammation.

References