Inhibitors of Tryptase as Mast Cell-Stabilizing Agents in the Human Airways: Effects of Tryptase and Other Agonists of Proteinase-Activated Receptor 2 on Histamine Release

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ABSTRACT

Tryptase, the major secretory product of human mast cells, is emerging as a new target for therapeutic intervention in allergic airways disease. We have investigated the ability of tryptase and inhibitors of tryptase to modulate histamine release from human lung mast cells and have examined the potential contribution of proteinase-activated receptor 2 (PAR2). The tryptase inhibitor APC366 \([N-(1\text{-hydroxy-2-naphthoyl})-L-\text{arginyl}-L-\text{prolinamide hydrochloride}]\) was highly effective at inhibiting histamine release stimulated by anti-IgE antibody or calcium ionophore from enzymatically dispersed human lung cells. A concentration of APC366 as low as \(10^{-7}\)M was able to inhibit anti-IgE-dependent histamine release by some 50%. Addition of leupeptin or the tryptic substrate \(\text{N}\text{-benzoyl-D,L-arginine-}\text{p-nitroanilide} \) also inhibited IgE-dependent histamine release. Purified tryptase in the presence of heparin stimulated a small but significant release of histamine from lung cells, suggesting that tryptase may provide an amplification signal from activated cells that may be susceptible to proteinase inhibitors. Trypsin was also able to induce histamine release apparently by a catalytic mechanism. Moreover, pretreatment of cells with metabolic inhibitors or with pertussis toxin reduced responses, indicating a noncytotoxic pertussis toxin-sensitive G protein-mediated signaling process. Addition to cells of the PAR2 agonists SLIGKV-NH$_2$ or tc-LIGRLO-NH$_2$ or appropriate control peptides were without effect on histamine release, and PAR2 was not detected by immunohistochemistry in tissue mast cells. The potent actions of tryptase inhibitors as mast cell-stabilizing agents could be of value in the treatment of allergic inflammation of the respiratory tract, possibly by targeting the non-PAR2-mediated actions of tryptase.

Mast cell activation is prominent in allergic airways disease. The mast cell has been implicated as an initial effector cell and also as a key cellular participant in later processes of acute inflammation and in tissue remodeling (Church et al., 1997). Several drugs used to treat allergic inflammation of the lower airways (such as salmeterol and salbutamol) or upper airways (terfenadine and cetirizine) possess mast cell-stabilizing activity (Naclerio et al., 1990; Butchers et al., 1991; Okayama and Church, 1992, 1994), and more recently the potential for mast cells to play a critical role in allergic inflammation has been highlighted by reports that omalizumab, a humanized antibody specific for IgE, may be efficacious in the treatment of asthma and other allergic conditions (D’Amato, 2003). The major secretory product of human mast cells is the serine proteinase tryptase (Walls, 2000). This enzyme is emerging as a major mediator of allergic disease and as a promising target for therapeutic intervention. Tryptase inhibitors have been reported to be particularly potent as mast cell-stabilizing compounds, though their effects on mast cells of the lung have not been examined. The ability of tryptase to stimulate mast cell degranulation first became apparent in studies involving transfer of this proteinase to laboratory animals. Microvascular leakage provoked by injection of human tryptase into guinea pig skin was found to be blocked by antihistamine pretreatment of the

Abbreviations: APC366, \(N-(1\text{-hydroxy-2-naphthoyl})-L-\text{arginyl}-L-\text{prolinamide hydrochloride} \); PAR2, proteinase-activated receptor 2; BAPNA, \(\text{N}-\text{benzoyl-D,L-arginine-p-nitroanilide} \); HBSS, HEPES-balanced salt solution; NA, nitroanilide; MES, 2-(\text{N-morpholino})ethane-sulfonic acid; MEM, minimum Eagle’s medium; FCS, fetal calf serum.
animals, and addition of human tryptase to guinea pig lung and skin fragments elicited histamine release (He and Walls 1997). Subsequently, it has been established that tryptase can stimulate histamine release from enzymatically dispersed human tonsil and synovial mast cells but not from human skin, and inhibitors of tryptase have been found to inhibit IgE- and non-IgE-dependent histamine release from all three of these sources of mast cells (He et al., 1998, 2001).

Administration of inhibitors of tryptase to sheep and guinea pig models of allergic airways disease has been reported to reduce allergen-induced early increases in specific lung resistance (Clark et al., 1995; Wright et al., 1999) consistent with inhibition of mast cell activation. Also reduced in these animal models were the late phase increases in lung resistance and airways hyper-responsiveness. In a clinical trial with the tryptase inhibitor APC366, significant reductions in allergen-induced late phase responses were observed in subjects with mild to moderate asthma (Krishna et al., 2001). In that study there was a trend for the early phase reaction to be reduced, though it did not reach significance.

Tryptase can interact with various cell types in addition to mast cells and induce profound alterations in cell behavior. Thus, tryptase can stimulate the accumulation and activation of eosinophils and neutrophils in vivo and in vitro (Walls et al., 1996, 1997, 1999; Compton et al., 1998), act as a growth factor for epithelial cells (Cairns and Walls, 1996, 1997), fibroblasts (Cairns and Walls, 1997), and airway smooth muscle cells (Berger et al., 2001), and provoke the release of collagen and collagenase from fibroblasts (Cairns and Walls, 1997). The precise mechanisms remain unclear, but the finding that tryptase may activate proteinase-activated receptor 2 (PAR2) (Molino et al., 1997; Schechter et al., 1998) has raised the possibility that at least some of the actions of tryptase on cellular targets may be mediated through this receptor. PAR2 has been identified on various cell types present in the human lung, and the activation of this G protein-coupled receptor has been associated with increases in microvascular permeability, cell accumulation, and cytokine release in various experimental models (Lan et al., 2002). Functional PAR2 has been demonstrated on human endothelial cells (Mirza et al., 1996), epithelial cells (Böhm et al., 1996), airway (Berger et al., 2001) and vascular smooth muscle cells (Molino et al., 1998), neutrophils (Howells et al., 1997), and eosinophils (Temkin et al., 2002). The immunohistochemical detection of PAR2 in mast cells has been reported in some human tissues (D’Andrea et al., 2000), but a subsequent study failed to find evidence of functional PAR2 in rat peritoneal mast cells (Stenton et al., 2002). The potential of human mast cells to respond to agonists of PAR2 remains to be determined.

In the present studies, we have investigated the ability of tryptase and inhibitors of tryptase to modulate histamine release from human lung mast cells. We have also examined the potential role of PAR2 in mast cell activation.

Materials and Methods

Materials. The following compounds were purchased from Sigma Chemical (Poole, Dorset, UK): leupeptin, benzamidine, N-benzoyle-D,L-arginine-p-nitroanilide (BAPNA), N-succinyl-L-Ala-L-Ala-L-Pro-L-Phe-p-NA, porcine heparin glycosaminoglycan, histamine dihydrochloride, collagenase (type I), hyaluronidase (type I), bovine serum albumin (fraction V), penicillin, streptomycin, MEM containing 25 mM HEPES, heparin agarose, calcium ionophore A23187, Tris-base, MES, antimycin A, 2-deoxy-D-glucose, Extravidin staining kits, 3-amino-9-ethylcarbazole, and Mayer’s hematoxylin. Goat anti-human IgE (inactivated) was obtained from Serotec (Kidlington, Oxford, UK), HEPES and all other chemicals were of analytical grade and were purchased from BDH (Poole, Dorset, UK), CNBr-activated Sepharose 4B from Pharmacia (Milton Keynes, UK), FCS from Invitrogen (Carlsbad, CA), phthalaldehyde from Fluka (Gillingham, Dorset, UK), Coomassie protein assay reagents from Pierce (Rockford, IL), the silver staining kit from Bio-Rad (Hemel Hempstead, UK), glycol methacrylate (JB4 resin) from Park Scientific (Northampton, UK), and 3,3-diaminobenzidine from Biogenex (San Ramon, CA). APC366 was a kind gift from Celera Corporation (San South Francisco, CA), Peptides SLIGKV-NH₂, VKGILS-NH₂, LIGKVN-NH₂, TNRSKGRSLIGKVC-NH₂, GPNRSKGRSLIGRLDTP-YGOC-NH₂, trans-cinnamoyl-OLRGLO-NH₂ (tc-OLRGLO-NH₂), and t(OLRGLO-NH₂) were synthesized as carbamoyl products by solid-phase methods at the Peptide Synthesis Facility, University of Calgary, Canada.

Preparation of Tryptase. Tryptase was purified from human lung tissue by high salt extraction, heparin agarose, and immunofinity chromatography procedures with monoclonal antibody AA5 against tryptase as described previously (He et al., 1997). The purified tryptase was then concentrated in C-30 Centriprep centrifugal concentrators (Millipore Corporation, Bedford, MA) and stored at −80 °C until use. Tryptic activity was determined with the chromogenic substrate BAPNA and protein concentration by the Coomassie protein assay with bovine serum albumin as standard, as described previously (He et al., 1997). Tryptase concentration was expressed in terms of micromolar quantities of tetrameric enzyme as determined by protein concentration. On SDS-polyacrylamide gel electrophoresis with silver staining and Western blotting with specific monoclonal antibody AA5 (Walls et al., 1990), tryptase appeared as a single diffuse band with a molecular weight of approximately 32 kDa (corresponding to the disassociated subunits of tetramer). The specific activity of the tryptase used in these studies was 1.84 U/mg, where 1 U of enzyme was taken as the amount that catalyzed the cleavage of 1 μmol of BAPNA per minute at 25°C. The preparation had no detectable chymotryptic or elastolytic activity (as determined using the substrates N-succinyl-L-Ala-L-Ala-L-Ala-p-NA or N-succinyl-L-Ala-L-Ala-L-Pro-L-Phe-p-NA, respectively; He et al., 1997), and endotoxin levels were very low, being less than 49 pg/mg tryptase (38 pg/ml).

Preparation of Compounds. Because tryptase is enzymatically unstable in physiological solutions, considerable care was taken in its preparation. Purified tryptase stored in high salt buffer in the presence or absence of heparin was diluted immediately before challenging the cells, first with sterile distilled water, adjusting the NaCl concentration to 0.15 M and then with HEPES balanced salt solution (HBSS) to obtain the required tryptase concentration.

Mast Cell Challenge and Analysis of Histamine Release. Macroscopically normal lung tissue was collected at bronchial resection from patients with lung cancer. The procedure for mast cell dispersion was similar to that described previously with human tonsil tissues (He et al., 1998). Briefly, tissue was chopped finely with scissors into fragments of 0.5 to 2.0 mm³ and incubated with 1.5 mg/ml collagenase and 0.75 mg/ml hyaluronidase in MEM containing 2% FCS (1 g of lung/10 ml of buffer) for 70 min at 37°C. Dispersed cells were separated from undigested tissue by filtration through nylon gauze (pore size 100-μm diameter) and were maintained in MEM (containing 10% FCS, 200 U/ml penicillin, and 200 μg/ml streptomycin) on a roller overnight at room temperature. Mast cell numbers were determined by light microscopy after staining with
Kimura staining solution and represented 2.3 to 4.5% of nucleated cells in suspensions.

Before the challenge with stimulus the cells were washed with HBSS (pH 7.4) without added calcium or magnesium (500g, 10 min, 25°C; Okayama et al., 1994) and then resuspended in HBSS with 1.8 mM CaCl₂ and 0.5 mM MgCl₂. Aliquots of 100 µl containing 4 to 6 × 10⁶ mast cells were added to a 50-µl aliquot of purified tryptase, PAR2 agonist, control secretagogue, or inhibitor in complete HBSS, and incubated for 15 to 60 min at 37°C. The reaction was terminated by the addition of 150 µl of ice-cold HBSS, and the tubes were centrifuged immediately (500g, 10 min, 4°C). All experiments were performed in duplicate. For the measurement of total histamine concentration, the suspension in some tubes was boiled for 6 min. Supernatants were stored at −20°C until histamine concentrations were determined.

A glass fiber-based fluorometric assay was employed to determine histamine levels in supernatants, as previously described (He et al., 1998). Histamine bound to a glass fiber matrix (Lundbeck Diagnostics, Copenhagen, Denmark) was detected by addition of α-phthalaldehyde, and the color change was measured using a spectrophotofluorimeter (LS-2; PerkinElmer Life and Analytical Sciences, Hvidovre, Denmark). Histamine release was expressed as a percentage of total cellular histamine levels and corrected for the spontaneous release measured in tubes in which cells had been incubated with the HBSS diluent alone.

In preliminary experiments, dispersed mast cell preparations were incubated with a range of concentrations of anti-IgE or calcium ionophore A23187, and net histamine release was calculated. Maximal noncytotoxic release of histamine was observed with 1% anti-IgE or with 1 µM calcium ionophore A23187 where cytotoxic mechanisms were assessed by comparing responses with cells preincubated with antixinycin A and 2-deoxy-o-glucose (data not shown). Both 1% anti-IgE and 1 µM calcium ionophore were selected as positive controls in all experiments involving mast cell challenge.

**Immunohistochemistry.** Bronchial biopsy tissue was collected from six subjects with mild asthma and embedded in glycol methacrylate resin. The subjects (aged 35 to 57) had normal lung function and were receiving no treatment apart from β-adrenoceptor agonists. In addition, human lung tissue (containing large airway and tissue parenchyma) was obtained at surgical resection from two subjects and tonsillar tissue (obtained at tonsillectomy) from five subjects. The study was approved by the Southampton and Southwest Hampshire and tonsil tissue (obtained at tonsillectomy) from five subjects. The study was approved by the Southampton and Southwest Hampshire

Results

**Inhibition of Histamine Release by Inhibitors of Tryptase.** A concentration-dependent inhibition of anti-IgE or calcium ionophore-induced histamine release was observed when dispersed lung cells were incubated with the tryptase inhibitor APC366 (from 10 to 300 µM) at 37°C for a period of 30 min (Fig. 1). With a 30-min preincubation period, significant inhibition of histamine release was achieved with as little as 10 µM APC366, and up to 60% inhibition of IgE-dependent histamine release was achieved with 300 µM APC366. Significant concentration-dependence inhibition was observed also when APC366 was added 5 min before the challenge or at the same time as the anti-IgE or calcium ionophore stimulus (data not shown). There was a trend for the degree of inhibition of IgE-dependent histamine release to be related to the period the compound was incubated with cells (Fig. 2), but this pattern was not observed with calcium ionophore-induced histamine release (data not shown). APC366 by itself at concentrations of up to 300 µM did not stimulate significant histamine release from mast cells.

Leupeptin, a broad-spectrum serine proteinase inhibitor, inhibited IgE-dependent histamine release by 35 ± 9.0% (mean ± S.E., n = 6, P = 0.0218) at a concentration of 10 µg/ml following a 30-min preincubation with cells. With a shorter preincubation period of 5 min, however, this leupeptin concentration did not have consistent effects on anti-IgE-induced histamine release from lung cells (data not shown). Benzamidine, a less potent inhibitor of trypsin, failed to inhibit IgE-dependent lung mast cell activation at concentrations of 10 and 100 µg/ml, whereas at higher concentrations it induced histamine release when added alone to cells (data not shown).

**Fig. 1.** Inhibitory actions of APC366 on histamine release induced from dispersed lung cells by anti-IgE (○) or calcium ionophore A23187 (■). Cells were preincubated with APC366 for 30 min at 37°C before challenge. Data are presented as mean ± S.E. for six to eight separate experiments. *, P < 0.05 compared with the responses with uninhibited controls. A mean net histamine release (±S.E.) of 17 ± 2.5% was elicited with anti-IgE and 45 ± 6.1% with calcium ionophore.
**Tryptase and Trypsin As Stimuli of Mast Cell Activation.** Trypsin in the presence of heparin (added to stabilize enzymatic activity) stimulated a small but significant release of histamine from dispersed lung cells over the concentration range of 1.0 to 100 μM (Fig. 4A). In the absence of heparin, however, there was negligible histamine release (data not shown). Greater histamine release was elicited with anti-IgE or calcium ionophore at the optimal nontoxic doses employed (Fig. 4B). Histamine release provoked by 100 μM trypsin represented about 25% of that elicited by 1% anti-IgE (a concentration provoking maximal release). Addition of trypsin to cells also stimulated a concentration-dependent release of histamine from lung mast cells at concentrations from 1.0 to 100 μM (Fig. 4A) with maximal release of histamine representing about 40% of that provoked by 1% anti-IgE (Fig. 4B).

Histamine release induced by trypsin (100 μM) was inhibited by leupeptin (10 μg/ml) by 68 ± 8.0% (n = 6, P = 0.046), whereas histamine release provoked by trypsin (10 μM) was inhibited by soybean trypsin inhibitor (10 μg/ml) by 61 ± 6.8% (n = 8, P = 0.018), suggesting that an intact catalytic site was required for the actions of these two proteases on mast cells. Preincubation of cells with the metabolic inhibitors 2-deoxy-D-glucose (10 mM) and antimycin A (1.0 μM) for 40 min at 37°C abolished histamine release in response to trypsin completely (data not shown) indicating that the action of this protease on cells involved a nontoxic process. Treatment with pertussis toxin (0.1 or 1 μg/ml) for 4 h at 37°C before the challenge with trypsin also resulted in a complete inhibition of histamine release, suggesting signaling via a pertussis toxin-sensitive G protein.

**Effects of Tryptase and Heparin on IgE-Dependent Mast Cell Activation.** Preincubation of dispersed lung mast cells with either 3.0 or 30 μM trypsin (concentrations that are capable of activating mast cells) in the presence of heparin for 5 or 30 min lead to significant inhibition of the subsequent anti-IgE-induced histamine release (Fig. 5). This was not observed in the absence of heparin. With 0.3 μM trypsin, there was no significant inhibition of IgE-dependent histamine release. Adding trypsin at concentrations from 0.3 to 30 μM (either in the presence or absence of heparin) at the same time that anti-IgE was added to cells did not alter the extent of histamine release induced by anti-IgE (data not shown).

When various concentrations of heparin (0.3–30 μg/ml) were added simultaneously with anti-IgE to cells, IgE-dependent histamine release was inhibited by some 30 to 50% (Fig. 6). However, when cells were preincubated with heparin for 5 or 30 min before addition of anti-IgE, heparin had less influence on anti-IgE-induced histamine release (data not shown). Under the same conditions, neither heparin (up to 30 μg/ml) nor trypsin (up to 100 μM) had any significant effect on calcium ionophore-induced histamine release from dispersed lung mast cells. Heparin by itself (at 30 μg/ml) had no effect on histamine release from dispersed lung cells (Fig. 4B).

**Effects of Peptide Agonists of PAR2 on Histamine Release.** The PAR2 agonist peptides SLIGKV-NH₂ and tc-LIGRLO-NH₂ failed to stimulate histamine release from dispersed lung cells following incubation with cells for 20 min (Table 1) or 60 min (data not shown). Similarly, non-PAR2-activating peptides of similar amino acid composition (VKGILS-NH₂, LSIGKV-NH₂, and tc-OLRGIL-NH₂) did not
provoke histamine release when added for the same periods.

We considered the possibility that the peptide agonists could be degraded by proteinases released from the cells and included the proteinase inhibitor amastatin at concentrations of 0.1, 1.0, and 10.0 μM (added either simultaneously with the peptides or added to cells 30 min before the addition of the peptides). However, addition of amastatin was without effect at any of the concentrations employed (n = 4 separate experiments, data not shown).

Immunohistochemical Identification of PAR2. In bronchial biopsy tissues, PAR2 immunostaining as detected with monoclonal antibody P2A was found to be present predominantly on the epithelium with little or no staining of cells in the underlying tissue layer. Mast cells identified with tryptase-specific antibody AA1 were present throughout the subepithelial tissue but absent from the epithelium, and numbers ranged from 10 to 45 (median 30) per tissue [corresponding to 6.5 to 16.7 (median 14.8) mast cells/mm² subepithelial tissue]. No PAR2 staining was detected on a total of 162 mast cells examined in the bronchial biopsy tissue (Fig. 7, A and B). Similarly, no PAR2 immunostaining was found using antiserum B5 on a total of 39 mast cells identified in resected lung tissue (8 and 31 in each of the two tissues, representing 8.4 and 16.3 mast cells/mm²; Fig. 7, C and D) or in 879 mast cells in tonsil tissue [90 to 259 mast cells (median 178) per tissue, with 84 to 136 (median 93.7) cells/mm²].
Discussion

These studies indicate that inhibitors of mast cell tryptase may have potent actions as stabilizing agents for human lung mast cells. Because tryptase was found to be able to modulate the release of histamine from lung mast cells, the mechanism may depend, at least in part, on inhibition of this protease following release from the mast cells; however, the lack of responsiveness of lung mast cells to certain other agonists of PAR2 and the failure to detect this receptor on mast cells by immunohistochemistry must call into question a role for PAR2 in mediating the actions of tryptase on mast cells in the human airways.

The tryptase inhibitor APC366 inhibited IgE-dependent histamine release by some 50% at a concentration as low as 10 μM and by about 60% at 300 μM. This degree of inhibition has been noted when this tryptase inhibitor has been studied with mast cells of certain other human tissues (He et al., 1998, 2001), but it is high when compared with that for other antiallergic drugs with mast cell-stabilizing properties. Thus, in similar models of lung mast cell activation with dispersed cells, sodium cromoglycate has been reported to inhibit IgE-dependent histamine release by 20% (at 1000 μM), lodoxamide by 20% (100 μM), salbutamol by 40% (10 μM), ketotifen by 11% (10 μM), terfenadine by 15% (10 μM), and ceterizine by 25% (100 μM) (Church and Hiroi, 1987; Okayama and Church, 1992; Okayama et al., 1994).

Inhibition of IgE-dependent histamine release from lung cells, similar to that with APC366, was observed when cells were incubated with the substrate BAPNA. This further supports the idea that APC366 acts by inhibiting trypsin activity. The possibility of effects on proteases other than tryptase cannot be excluded, but some degree of inhibition was seen also with the proteinase inhibitor leupeptin. The apparent absence of an effect of BAPNA or leupeptin on calcium ionophore-induced histamine release could be related to these compounds being less effective, to the calcium

TABLE 1
Effect of peptide agonists of PAR2 and control peptides on histamine release from human lung mast cells

<table>
<thead>
<tr>
<th>Compounds</th>
<th>Concentration</th>
<th>Net Histamine Release (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0 μM</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SLIGKV-NH₂</td>
<td>1.0</td>
<td>1.0 ± 0.5</td>
</tr>
<tr>
<td>10 μM</td>
<td>0.3 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>100 μM</td>
<td>0 ± 0.5</td>
<td></td>
</tr>
<tr>
<td>VKGILS-NH₂</td>
<td>10</td>
<td>0.4 ± 0.6</td>
</tr>
<tr>
<td>100 μM</td>
<td>2.2 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>LSIGKV-NH₂</td>
<td>10</td>
<td>2.7 ± 1.6</td>
</tr>
<tr>
<td>100 μM</td>
<td>3.0 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>300 μM</td>
<td>1.1 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>tc-LIGRLO-NH₂</td>
<td>10</td>
<td>2.7 ± 1.8</td>
</tr>
<tr>
<td>100 μM</td>
<td>3.0 ± 1.5</td>
<td></td>
</tr>
<tr>
<td>300 μM</td>
<td>1.1 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>tc-OLRGIL-NH₂</td>
<td>1.0</td>
<td>1.2 ± 1.5</td>
</tr>
<tr>
<td>10 μM</td>
<td>0.7 ± 1.0</td>
<td></td>
</tr>
<tr>
<td>100 μM</td>
<td>2.2 ± 0.9</td>
<td></td>
</tr>
<tr>
<td>300 μM</td>
<td>1.5 ± 1.2</td>
<td></td>
</tr>
<tr>
<td>Anti-IgE 1%</td>
<td>18 ± 3.8</td>
<td></td>
</tr>
<tr>
<td>Calcium ionophore</td>
<td>60 ± 8.5</td>
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</tr>
</tbody>
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*P < 0.05 compared with buffer alone (Student’s t test).

Fig. 7. Mast cells (arrow) identified in resected human lung (A) and bronchial biopsy tissue (C), with monoclonal antibody AA1, and adjacent sections immunostained for PAR-2 with monoclonal antibody P2A (B) and antiserum B5 (D).
ionophore providing a supramaximal signal, or perhaps to differences in underlying cell signaling processes with each of these stimuli. Benzamidine, which was the least effective as an inhibitor of trypsin, did not significantly alter cell responsiveness to either IgE- or non-IgE-dependent stimulation, and the potential for cytotoxic actions precluded the use of higher concentrations in the present study.

Because trypsin was able to elicit significant histamine release from lung cells, it is possible that the proteinase inhibitors may act in part by inhibiting the ability of trypsin released from mast cells to stimulate further mast cell degranulation. Such a mechanism could underlie the ability of APC366 to inhibit histamine release triggered by anti-IgE and the calcium ionophore. Relatively high concentrations of trypsin were required to stimulate histamine release, but with quantities of some 10 to 35 pg of trypsin present in a human mast cell (Schwartz et al., 1987), the levels in the vicinity of a degranulating mast cell are also likely to be very high. The degree of histamine release stimulated by trypsin was quite small, and maximal histamine release stimulated by trypsin represented just some 25% of that induced by optimal concentrations of anti-IgE antibody. This proportion is lower than that found previously with tponsil (approximately 70%) or synovial mast cells (50%), though in studies with skin tissues no significant release of histamine was stimulated by addition of exogenous trypsin (He et al., 1998, 2001).

The stabilization of trypsin activity by heparin appeared to be necessary for trypsin to stimulate histamine release from lung mast cells. However, heparin was itself able to inhibit the activation of lung mast cells, at least with anti-IgE as the stimulus. This is consistent with a previous report by Ahmed et al. (1993) who found that addition of heparin to human uterine and rat peritoneal mast cells reduced the degree of IgE-dependent histamine release. Heparin may have mutually antagonistic roles in inhibiting histamine release and in allowing trypsin to act as a stimulus, and this makes it more difficult to assess the contribution of trypsin as an amplification signal. Moreover, addition of trypsin at concentrations capable of eliciting histamine release was found to reduce histamine release in response to subsequent addition of anti-IgE. It is not clear whether this is a consequence of mast cell unresponsiveness being induced by the initial stimulus, as has been reported with other secretagogues (Rubinchik et al., 1998), or to the actions of heparin added with trypsin. The mast cell-stabilizing properties of inhibitors of trypsin could be related in part to the inhibition of trypsin secreted following degranulation, but other mechanisms could be important.

There was a trend for APC366 to be more effective in stabilizing lung mast cells when the cells were preincubated with this inhibitor before challenge rather than added at the same time as the stimulus. The time dependence of this inhibitor has been noted previously with substrate cleavage (McEuen et al., 1996) and in studies with skin, tponsil, and synovial cells in vitro (He et al., 1998, 2001), as well as when administered in a sheep model of allergic airways disease (Clark et al., 1995). Leupeptin and even BAPNA also appeared to be more effective at inhibiting histamine release when cells were preincubated with these compounds. The extent to which APC366 and the other inhibitors may actually enter mast cells remains to be determined, though there would be parallels with previous observations that human mast cells may take up lactoferrin (a destabilizer of the trypsin-heparin complex; He et al., 2003), and rat peritoneal mast cells can ingest soybean trypsin inhibitor and Fab’3 fragments of a chymase-specific antibody (Kido et al., 1988). If the substrate whose cleavage is inhibited is in an intracellular or a pericellular location, then one might expect that uptake of the inhibitor by the cells could increase its effectiveness.

Trypsin, like trypsin, was able to stimulate histamine release from human lung mast cells, and the actions of both proteinases were reduced by addition of proteinase inhibitors. Trypsin and trypsin are potentially able to activate PAR2, and support for involvement of a G protein-coupled receptor was provided by observation of an inhibitory action for pertussis toxin on trypsin-induced histamine release. On the other hand, the PAR2 peptide agonists SLIGKV-NH2 and tc-LIGRLO-NH2 failed to stimulate histamine release even in the presence of amastatin. Moreover, although human mast cells have been reported to express immunoreactive PAR2 (D’Andrea at al., 2000), we were unable to find evidence for this in the present studies. Using either a specific monoclonal antibody or rabbit antiserum against PAR2 in immunohistochemistry, this receptor was not detected on any of the several hundred mast cells examined, including those from asthmatic subjects.

The presence of functional PAR2 on human mast cells has not previously been examined, though it has been reported that the peptide agonist SLIGRL-NH2 (based on the sequence of the tethered ligand of rat PAR2) fails to stimulate the release of histamine (Nishikawa et al., 2000) or β-hexosaminidase (Stenton et al., 2002) from rat peritoneal mast cells. Stenton and colleagues did observe β-hexosaminidase release from rat peritoneal mast cells in response to tc-LIGRLO-NH2, but the absence of responsiveness of those cells to trypsin or trypsin as well as to SLIGRL-NH2 would argue against involvement of a PAR2-mediated process. Mast cells from different sources and different species exhibit a considerable degree of functional heterogeneity (Church et al., 1997), and a role for PAR2 in mast cell degranulation cannot be excluded; however, the present studies suggest that trypsin-induced histamine release from human lung mast cells is not a consequence of PAR2 activation.

The potential of trypsin inhibitors to act as potent mast cell-stabilizing agents would make them particularly suitable as a novel treatment for bronchial asthma and other inflammatory conditions of the airways. The underlying mechanism may be related in part to the actions of trypsin on mast cells, but there is little evidence for the involvement of PAR2-mediated processes.

References


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