Activation of βγ Subunits of G_{i2} and G_{i3} Proteins by Basic Secretagogues Induces Exocytosis Through Phospholipase Cβ and Arachidonate Release Through Phospholipase Cγ in Mast Cells

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Activation of βγ Subunits of G\textsubscript{i2} and G\textsubscript{i3} Proteins by Basic Secretagogues Induces Exocytosis Through Phospholipase Cβ and Arachidonate Release Through Phospholipase Cγ in Mast Cells

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Mast cells are activated by Ag-induced clustering of IgE bound to FceRI receptors or by basic secretagogues that stimulate pertussis toxin-sensitive heterotrimeric G proteins. The cell response includes the secretion of stored molecules, such as histamine, through exocytosis and of de novo synthesized mediators, such as arachidonate metabolites. The respective roles of G proteins α and βγ subunits as well as various types of phospholipase C (PLC) in the signaling pathways elicited by basic secretagogues remain unknown. We show that a specific Ab produced against the C-terminus of G\textsubscript{α3} and an anti-recombinant G\textsubscript{α3} Ab inhibited, with additive effects, both exocytosis and arachidonate release from permeabilized rat peritoneal mast cells elicited by the basic secretagogues mastoparan and spermine. A specific Ab directed against G\textsubscript{βγ} dimers prevented both secretions. Anti-PLCβ Abs selectively prevented exocytosis. The selective phosphatidylinositol 3-kinase inhibitor LY 294002 prevented arachidonate release without modifying exocytosis. G\textsubscript{βγ} coimmunoprecipitated with PLCβ and phosphatidylinositol 3-kinase. The anti-PLCγ1 and anti-phospholipase A\textsubscript{2}, Abs selectively blocked arachidonate release. Protein tyrosine phosphorylation was inhibited by anti-G\textsubscript{βγ} Abs, LY 294002, and anti PLCγ1 Abs. These data show that the early step of basic secretagogue transduction is common to both signaling pathways, involving βγ subunits of G\textsubscript{i2} and G\textsubscript{i3} proteins. Activated G\textsubscript{βγ} interacts, on one hand, with PLCβ to elicit exocytosis and, on the other hand, with phosphatidylinositol 3-kinase to initiate the sequential activation of PLCγ1, tyrosine kinases, and phospholipase A\textsubscript{2}, leading to arachidonate release. The Journal of Immunology, 2001, 167: 4805–4813.

A crucial characteristic of the effect of basic secretagogues on mast cells is its sensitivity to pertussis toxin (8, 12–14), which is known to ADP-riboseylate a cysteine residue in the carboxyl terminus of α subunits from G\textsubscript{αi1} and G\textsubscript{αi3} proteins (15). Two pertussis toxin substrates have been proposed in rat peritoneal mast cells (16) and were identified as the G\textsubscript{αi2} and G\textsubscript{αi3} proteins (17, 18). The G\textsubscript{αi3} protein has been proposed to be responsible for histamine secretion, since an Ab directed toward a decapeptide corresponding to the carboxy terminus of its α subunit (G\textsubscript{αi3}) inhibited mast cell exocytosis (17). The involvement of G\textsubscript{αi2} protein was unlikely, since an Ab directed against the decapetide of the carboxy terminus of G\textsubscript{αi2} considered an analog of G\textsubscript{αi2} with 90% identity between them, failed to inhibit exocytosis (see Fig. 1). The respective roles of α and βγ subunits of pertussis toxin-sensitive G proteins in the signaling pathways of basic secretagogues have not been investigated. G\textsubscript{βγ} subunits introduced into permeabilized mast cells amplified secretion induced by Ca\textsuperscript{2+} and GTPγS, whereas G\textsubscript{αi3} subunits had no effect (19).

The mechanism by which basic secretagogues activate exocytosis and release of stored mediators appears to be distinct from the IgE-dependent pathway. Unlike IgE-induced exocytosis, secretion elicited by basic secretagogues is faster (seconds vs minutes). Antigenic cross-linking of IgE/FceRI initiates the activation of Lyn and Syk tyrosine kinases followed by the Syk-mediated phosphorylation of phospholipase Cγ1 (PLCγ1) (2). PLCγ1, in turn, catalyzes the hydrolysis of phosphatidylinositol-4,5-bisphosphate (PIP2) to

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\section*{Abbreviations used in this paper: PLC, phospholipase C; cPLA\textsubscript{2}, cytosolic phospholipase A\textsubscript{2}; IP\textsubscript{γ}, inositol-1,4,5-trisphosphate; G protein, heterotrimeric GTP-binding protein; MAPK, mitogen-activated protein kinase; PK\textsubscript{J}, phosphatidylinositol 3-kinase; PK\textsubscript{II}, phosphatidylinositol-4,5-bisphosphate; PK\textsubscript{III}, phosphatidylinositol-3,4,5-trisphosphate; PKB, protein kinase B (Akt); PKC, protein kinase C; PTK, protein tyrosine kinase.}

\section*{References}

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The activation of cPLA2 was mediated by various protein kinases, including PKC and mitogen-activated protein kinase (MAPK) isozymes (24). FcγRI-dependent (21) or G protein-mediated triggers (22). The activation of cPLA2 was first considered to be a consequence of the increase in cytosolic calcium elicited by basic secretagogues and was proposed to be a prerequisite for histamine secretion (14, 23). However, alternative regulatory pathways can be considered to be a consequence of the increase in cytosolic calcium elicited by basic secretagogues and was proposed to be a prerequisite for histamine secretion. The activation of PLC is not preceded by protein tyrosine phosphorylation (20). The subtype of PLC involved in this process remains unknown.

Following cytosolic phospholipase A2 (cPLA2) activation, arachidonate release reaches a maximum after 20- to 30-min incubation with IgE/FcεRI-dependent (21) or G protein-mediated triggers (22). The activation of cPLA2 was first considered to be a consequence of the increase in cytosolic calcium elicited by basic secretagogues and was proposed to be a prerequisite for histamine secretion (14, 23). However, alternative regulatory pathways can be considered to be a prerequisite for histamine secretion. The activation of PLC is not preceded by protein tyrosine phosphorylation (20). The subtype of PLC involved in this process remains unknown.

The present study was undertaken to assess the roles of both pertussis toxin-sensitive substrates Gαi2 and Gαi3 heterotrimeric G proteins, and their respective α and βy subunits in the secretion of histamine (exocytosis) and arachidonate release induced by basic secretagogues in mast cells. Putative relationships between the pathways of stored and de novo-synthesized mediators were also considered through the involvement of phosphatidylinositol-3 kinase (PI3K), PLC, PLCγ1, and cPLA2, to define the bifurcation point of these pathways. Here, we show that both Gαi2 and Gαi3 proteins are activated by basic secretagogues, allowing Gβγ subunits to initiate exocytosis through the activation of PLCβ, on the one hand, and the release of arachidonate through the activation of PI3K leading to PLCγ1 activation, on the other.

Materials and Methods

Materials

Mastoparan and spermine were purchased from Sigma (St. Louis, MO). Pertussis toxin was obtained from List Biological Laboratory (Campbell, CA). [3H]Arachidonic acid was purchased from Amersham Pharmacia Biotech (Little Chalfont, U.K.). Protein A-Sepharose and protein G-Sepharose beads were obtained from Amersham Pharmacia (Uppsala, Sweden). Protease inhibitor tablet cocktails were purchased from Roche Diagnostics GmbH (Mannheim, Germany). Anti-Gαi2 (amino-terminal 10 aa residues) and anti-recombinant Gαi2 protein Abs were purchased from Chemicon International (Temecula, CA). Anti-Gαi3 and anti-Gαi2 (carboxy-terminal 10 residues) Abs were obtained from Upstate Biotechnology (Lake Placid, NY). Anti-Gβγ (carboxy-terminal 10 residues) Ab and mAbs against p-Tyr (PY20) were purchased from Transduction Laboratory (Lexington, KY). Anti-Gβγ (carboxy-terminal 20 aa of βγ of mouse origin, with broad specificity to mouse, rat and human Gβ1 to Gβ4), anti-cPLA2 (amino-terminal domain), anti-PLCβ (carboxy-terminal 10 aa), and anti-PLCγ1 (epitope corresponding to aa residues 530–850 mapping within SH2-SH3 domains) Abs were purchased from Santa Cruz Biotechnology (Santa Cruz, CA). Anti-phospho-Akt (Ser473) Abs was purchased from Cell Signaling Technology (Beverly, MA).

Isolation and purification of mast cells

Male Wistar rats (Iffa-Credo, L’Arbresle, France), weighing 300–500 g, were stunned and bled. Twelve milliliters of balanced salt solution (HEPES buffer) containing 137 mM NaCl, 2.7 mM KCl, 0.3 mM CaCl2, 1.0 mM MgCl2, 0.4 mM NaH2PO4, 5.6 mM glucose, and 10 mM HEPES, NaOH to pH 7.4, and supplemented with 0.1% BSA were injected into the peritoneal cavity. The peritoneal fluid was collected and centrifuged for 3 min at 180 × g. The pellet was suspended in the same buffer, and mast cells were purified on a discontinuous BSA gradient (30 and 40%, w/v) as previously described (8). The pellet was resuspended in HEPES buffer, and cells were examined under a light microscope for purity (>97%). The Trypan blue exclusion test indicated a viability >95%.

FIGURE 1. Sequence of carboxyl-terminus domain of Gαi2, Gαi3, and Gαi4 proteins. Bold amino acids indicate the difference of homology between Gαi2 and Gαi4 proteins. Isoleucine cysteine residues represent the sites ADP-ribosylated by pertussis toxin.

FIGURE 2. Effect of anti-Gαi2 (A), Gαi3 (B), or Gαi4 (C) carboxy-terminal Abs on histamine secretion induced by basic secretagogues. Cells were incubated with streptolysin-O (0.4 U/ml) for 1 min at 37°C before the addition of Ab. Mast cells were stimulated 2 min later by adding mastoparan (0.1 mM) or spermine (3 mM). One hundred percent of each stimulation stands for histamine secretion induced by each compound on permeabilized cells in the absence of Ab (A, mastoparan, 17.2 ± 0.6%; spermine, 32.5 ± 4.9%; B, mastoparan, 29.2 ± 1.7%; spermine, 21.5 ± 3.5%; C, mastoparan, 30.4 ± 6.4%; spermine, 21.1 ± 0.9% of total histamine content). Controls show the Ab effect on unstimulated permeabilized cells (A, 7.9 ± 1.8%; B, 7.9 ± 1.8%; C, 14.2 ± 8.0%). Values are the mean ± SEM of four independent experiments.
Permeabilization and determination of histamine release

Purified mast cells (3 × 10⁶ cells/assay) were preincubated for 5 min at 37°C before permeabilization by adding streptolysin-O (0.4 U/ml). After 1 min Abs were added for 2 min. Then cells were triggered by basic secretagogues. Reactions were terminated 2 min later by addition of ice-cold buffer. The passive histamine release, in the absence of secretagogue, was <10% of the total content. The amount of histamine secretion was determined fluorometrically according to the method of Shore et al. (28) but without the extraction step.

Determination of arachidonate release

Purified mast cells were suspended in HEPES buffer (5 × 10⁶ cells/ml) and incubated with 5 μCi/ml [1H]arachidonic acid for 2 h at 37°C. The cells were washed twice, resuspended in HEPES buffer (10³ cells/ml), preincubated for 10 min, and triggered for 10 min at 37°C. The reaction was terminated by adding ice-cold buffer and placing the tubes on ice. Supernatants following centrifugation (180 × g, 3 min, 4°C) were collected and used to determine by liquid scintillation the amount of arachidonate released.

Determination of PI3K activation through Akt phosphorylation

Purified mast cells (5 × 10⁶ cells/assay) were preincubated for 15 min at 37°C with vanadate (0.1 mM) in HEPES buffer and triggered with secretagogues. Reactions were terminated by adding ice-cold buffer and placing the tubes on ice. Cell pellets obtained after centrifugation (3 min, 180 × g, 4°C) were treated by adding lysis buffer (150 mM NaCl, 1 mM EDTA, 0.1% SDS, 1% Triton X-100, protease inhibitor cocktail, and 20 mM Tris-HCl) and centrifuged (20 min, 12,000 × g, 4°C). Supernatants were suspended in 5× Laemmli buffer and boiled for 5 min. Then supernatants were resolved by 10% SDS-PAGE under reducing conditions and transferred to nitrocellulose membranes (Hybond ECL, Amersham). Membranes were saturated by incubation overnight in a blocking solution containing 100 mM NaCl and 0.1% casein (w/v), washed twice, and incubated for 2 h with primary Ab raised against p-Tyr, or PI3K, or anti-PLCγ Abs and with protein A-Sepharose beads were incubated overnight at 4°C. Immunocomplexes were washed, treated, and resolved by SDS-PAGE as described above. Nitrocellulose membranes were incubated for 1 h with primary Abs (anti-β-PI3K, or anti-p-Tyr Abs). After incubation with secondary Ab (anti-rabbit or anti-mouse IgG conjugated to HRP) for 1 h, membranes were incubated for 2 min in ECL reagents, and bound Abs were visualized by contact for 2 min with Kodak X-OMAT films.

Immunoprecipitation of Gβ and PLCβ or PI3K

Cell pellets were prepared and lysed as described above. Supernatants, mixed with 15 μl anti-PLCβ, anti-GFγ, or anti-PLCγ Abs and with protein A-Sepharose beads were incubated overnight at 4°C. Immunocomplexes were washed, treated, and resolved by SDS-PAGE as described above. Nitrocellulose membranes were incubated for 1 h with primary Abs (anti-β-PI3K, or anti-p-Tyr Abs). After incubation with secondary Ab (anti-rabbit or anti-mouse IgG conjugated to HRP) for 1 h, membranes were incubated for 2 min in ECL reagents, and bound Abs were visualized.

FIGURE 3. Effects of anti-Ga12 recombinant protein and anti-Ga12 carboxyl-terminus Abs on histamine secretion induced by basic secretagogues. Experiments were performed as detailed in Fig. 2. A, One hundred percent of histamine secretion in the absence of Ab corresponded to 24.3 ± 5.8% (mastoparan) or 21.8 ± 1.8% (spermine) of the total histamine content; controls are the Ab effect on unstimulated permeabilized cells (7 ± 3%). B, Effects of anti-recombinant Ga12 and anti-Ga12 Abs (dilution, 1/1000) added alone or simultaneously. Histamine secretion induced by each compound in permeabilized cells without Ab was 40.8 ± 1.1% (mastoparan) or 28.3 ± 3.3% (spermine) of the total histamine content. C, One hundred percent histamine secretion in the absence of Ab corresponded to 24.3 ± 5.8% (mastoparan) or 21.8 ± 1.8% (spermine) of the total histamine content; controls are the Ab effect on unstimulated permeabilized cells calculated as a percentage of the total histamine content. D, Effect of pretreatment (2 h at 37°C) of mast cells with pertussis toxin (PTx; 50 ng/ml), and the effect of anti-Gβ Ab (40 μg/ml; see Fig. 4) on histamine secretion induced by the Ab of the carboxyl terminus of Ga12 (shown as control in C). Values are the mean ± SEM of four independent experiments.
Results

The in vitro activation of heterotrimeric G proteins by basic secretagogues involves their interaction with the carboxyl terminus of G protein α subunits (29, 30), explaining the interest in using selective Abs of corresponding peptide sequences. We chose the wasp venom peptide mastoparan (7, 8) as a member of cationic peptide and the natural polyamine spermine (9, 10) to represent other cationic secretagogues. Streptolysin-O creates pores through the cell membrane and allows entry of Abs into mast cells (31). Permeabilization was controlled in each experiment (results not shown) by monitoring secretion elicited by GTPγS, a nonhydrolyzable analog of GTP that triggers heterotrimeric and small G proteins in permeabilized mast cells (32).

Involvement of G\textsubscript{i2} and G\textsubscript{i3} proteins in mast cells exocytosis and arachidonate release

We studied the effects of Abs directed against the C-terminal decapeptides (sequences shown in Fig. 1) from \(\text{G}_{\alpha_2}\), \(\text{G}_{\alpha_3}\), and \(\text{G}_{\alpha_i}\) on permeabilized mast cells. Anti-\(\text{G}_{\alpha_2}\) Abs dose-dependently inhibited approximately 60% of histamine secretion elicited by mastoparan or spermine (Fig. 2A). Anti-\(\text{G}_{\alpha_3}\) Abs did not modify the exocytotic response of mast cells to mastoparan or spermine (Fig. 2B). Similarly, Aridor et al. (17) showed that anti-\(\text{G}_{\alpha_i}\) Abs inhibited exocytosis triggered by GTPγS, whereas anti-\(\text{G}_{\alpha_i}\) Abs were inefficient. The \(\text{G}_{\alpha_i}\) subtype of heterotrimeric G proteins may regulate mast cell exocytosis (33), but we observed no effect of anti-\(\text{G}_{\alpha_i}\) Ab on the response to basic secretagogues (Fig. 2C).

The above results confirmed the involvement of \(\text{G}_{\alpha_i}\) in the triggering effects of basic secretagogues. To determine whether \(\text{G}_{\alpha_i}\), the second pertussis toxin substrate characterized in rat peritoneal mast cells (17), was also involved, we used two different anti-\(\text{G}_{\alpha_2}\) Abs (Fig. 3, A and C). The anti-recombinant \(\text{G}_{\alpha_2}\) protein Ab (Fig. 3A) prevented histamine secretion induced by basic secretagogues without modifying controls in the absence of mastoparan or spermine. These results allowed us to propose both \(\text{G}_{\alpha_2}\) and \(\text{G}_{\alpha_i}\) as targets of basic secretagogues. Accordingly, the simultaneous inactivation of \(\text{G}_{\alpha_2}\) and \(\text{G}_{\alpha_i}\) proteins by anti-\(\text{G}_{\alpha}\) Abs provided additive inhibition of histamine secretion elicited by basic secretagogues (Fig. 3B).

The anti-\(\text{G}_{\alpha_2}\) C-terminus Ab (Fig. 3C) was apparently less efficient in preventing induced histamine secretion. However, this Ab led to histamine secretion in the absence of cationic secretagogues (control, Fig. 3C). This observation suggested that the anti-\(\text{G}_{\alpha_2}\) C-terminus Ab might stimulate heterotrimeric G proteins, mimicking the basic secretagogue effect. To study this hypothesis we pretreated mast cells with pertussis toxin, which is known to ADP-ribosylate a cysteine residue in the \(\text{G}_{\alpha_i}\) protein carboxyl terminus (see Fig. 1). Pertussis toxin pretreatment decreased the secretory response of mast cells (Fig. 3D). Thus, the anti-\(\text{G}_{\alpha_2}\) C-terminus Ab mimics the effect of basic secretagogues characterized by pertussis toxin sensitivity. Also, histamine secretion elicited by this Ab (Fig. 3D) was prevented by anti-\(\text{G}_{\beta}\) Abs. Similarly, an anti-\(\text{G}_{\alpha_i}\) C-terminus Ab has been reported to activate \(\text{G}_{\iota}\) protein (34).

**FIGURE 4.** Effect of anti-\(\text{G}_{\alpha_2}\) recombinant protein and anti-\(\text{G}_{\alpha_i}\) carboxyl-terminus protein on arachidonate release (A and B) and anti-\(\text{G}_{\beta}\) Abs on histamine secretion and arachidonate release (C and D) induced by basic secretagogues. A, One hundred percent induced arachidonate release from permeabilized cells in the absence of Ab was 1086 ± 52 dpm (mastoparan) or 1331 ± 63 dpm (spermine). B, One hundred percent induced arachidonate release from permeabilized cells in the absence of Ab was 1055 ± 26 dpm (mastoparan) or 1057 ± 20 dpm (spermine). C, One hundred percent induced histamine secretion in the absence of Ab was 39.7 ± 12.7% (mastoparan) or 38.6 ± 3.8% (spermine) of the total histamine content. D, One hundred percent of induced arachidonate release from permeabilized cells without Ab was 778 ± 21 dpm (mastoparan) or 813 ± 29 dpm (spermine). The inset in D shows the effects of pretreatment (2 h at 37°C) of mast cells with pertussis toxin (PTx; 50 ng/ml) and the effect of anti-\(\text{G}_{\beta}\) Ab (40 μg/ml) on arachidonate release. Controls stand for the Ab effect on unstimulated permeabilized cells (A, 486 ± 32 dpm; B, 487 ± 30 dpm; C, 7.0 ± 3.1%; D, 435 ± 14 dpm). Values are the mean ± SEM of four independent experiments.
The anti-recombinant Go12 protein Ab and the anti-Go13 C-terminus Ab both prevented arachidonate release induced by basic secretagogues (Fig. 4, A and B) with additive effects (inset in Fig. 4D). These data indicate that Go12 and Go13 are similarly involved in exocytosis and arachidonate release, indicating that Go12 and Go13 activation is a common step of the corresponding signaling pathways.

**Involvement of βγ subunits of G proteins in exocytosis and arachidonate release**

Both α and βγ subunits of heterotrimeric G proteins can stimulate effectors (see Ref. 35 for review). To address the question of whether Gβγ subunits were involved in signal transduction elicited by basic secretagogues, we studied the effect of an anti-Gβγ Ab with broad specificity to mouse, human, and rat Gβ1 to Gβ4 subunits. This Ab did not elicit mast cell secretory responses (controls, Fig. 4, C and D), but strongly inhibited histamine and arachidonic acid release (Fig. 4, C and D). These observations strongly suggest that βγ dimers of pertussis toxin-sensitive G proteins are involved in both exocytosis and arachidonic acid release induced by basic secretagogues in connective tissue mast cells.

**Role of PLCβ, PLCγ1, and cPLA2 in exocytosis and arachidonate release**

The involvement of PLC in the secretory responses of mast cells to cationic triggers has been proposed by Nakamura and Ui (14), but the subtype of PLC has not been characterized. Considering the role of βγ dimers of heterotrimeric G proteins suggested by the above data, we assessed the involvement of PLCβ subtypes, with anti-PLCβ1, -β2, and -β3 Abs. We obtained similar results with all three Abs, calling into question their subtype selectivity. Although

![FIGURE 5. Effects of anti-PLCβ3, anti-PLCγ1, and anti-cPLA2 Abs on exocytosis and arachidonate release induced by basic secretagogues. Cells were incubated with streptolysin-O (0.4 U/ml) for 1 min at 37°C, and Abs were added. Mast cells were stimulated by mastoparan (0.1 mM) or spermine (3 mM). Controls are the Ab effect on unstimulated permeabilized cells. One hundred percent values correspond to induced histamine secretion or induced arachidonate release from permeabilized cells in the absence of Ab: A, 6.8 ± 0.7% (control), 36.9 ± 4.2% (mastoparan), and 28.3 ± 4.9% (spermine) of total histamine content; B, 534.2 ± 23.4 dpm (control), 944.5 ± 28.5 dpm (mastoparan), and 1106.8 ± 34.1 dpm (spermine); C, 9.6 ± 0.5% (control), 31.0 ± 5.2% (mastoparan), and 33.2 ± 5.9% (spermine) of total histamine content; D, 476 ± 16 dpm (control), 1020 ± 33 dpm (mastoparan), and 1118 ± 16 dpm (spermine); E, 6.7 ± 0.7% (control), 25.9 ± 7.9% (mastoparan), and 29.5 ± 1.2% (spermine) of total histamine content; F, 667 ± 29 dpm (control), 1003 ± 32 dpm (mastoparan), and 1291 ± 26 dpm (spermine). Insets in A and B show the respective effects of anti-PLCβ1, -β2, and -β3 Abs (40 μg/ml) on secretions triggered by 0.1 mM mastoparan. Values are the mean ± SEM of four independent experiments.](http://www.jimmunol.org//)
all PLCβ Abs were seen to prevent basic secretagogue-induced histamine secretion (Fig. 5A), none of them was able to modify induced arachidonic acid release (Fig. 5B). On the contrary, anti-PLCγ1 Abs did not alter exocytosis (Fig. 5C), but prevented arachidonate release (Fig. 5D) triggered by mastoparan or spermine. The various PLC Abs studied had no effect on mast cells in the absence of cationic triggers (controls, Fig. 5).

The activity of cPLA2 generates arachidonate from membrane phospholipids. The activation of cPLA2 has been proposed to be a prerequisite for histamine secretion induced by basic compounds, suggesting its involvement in both secretion types (14, 23). However, we observed that anti-cPLA2 Abs selectively prevented arachidonate release without affecting exocytosis or cells in the absence of trigger (Fig. 5, E and F). These results show that the involvement of PLCβ is restricted to the exocytotic pathway, and that PLCγ1 and cPLA2 are selectively involved in the arachidonate release pathway.

Sequence of events leading to exocytosis and arachidonate release

The above results suggested that the early step of basic secretagogue transduction is common to both signaling pathways, involving βγ subunits of G12 and G13 proteins. Gβγ is known to be able to interact with PLCβ (35) and PI3K (36), increasing their activities. This suggests that PI3K might be one of the direct effectors of basic secretagogue-activated G proteins. Activation of PI3K results in local accumulation of PIP3 at the plasma membrane, allowing the recruitment of cytosolic proteins characterized by a pleckstrin domain (37). However, the involvement of PI3K in mast cell secretion is poorly documented.

The selective inhibitor of PI3K, LY294002 (38), inhibited arachidonate release, but did not modify histamine secretion (Fig. 6, A and B). The activation of PI3K by basic secretagogues is further demonstrated in Fig. 6C by the LY29402-sensitive phosphorylation of Akt (PKB), a common substrate for PI3K (39).

The interaction of Gβγ with PLCβ and PI3K is confirmed by the experiments represented in Fig. 7. We observed by Western blotting the communoprecipitation of Gβ and PLCβ with the PLCβ serum (Fig. 7A), and the communoprecipitation of PI3K and Gβ with the anti-Gβ serum (Fig. 7B). These observations allow us to propose Gβγ as the bifurcation point of the two secretory pathways, with PLCβ as the first following member of the exocytotic pathway and PI3K as the first following member of the pathway leading to de novo-synthesized mediators.

The activation of PLCγ1 can be achieved through its binding to membrane PIP3 generated by PI3K and/or through tyrosine phosphorylation (40–42). PLCγ1 immunoprecipitate is shown in Fig. 7C. We did not observe any binding of anti-phosphotyrosine Abs to PLCγ1, suggesting that tyrosine phosphorylation was not involved in its activation by spermine. This observation strongly suggested that protein tyrosine kinases (PTK) might be downstream of PLC.

The activation of mast cells by basic secretagogues in the presence of vanadate to inhibit protein tyrosine phosphatases leads to tyrosine phosphorylation of several cellular proteins with Mr of 26–100 kDa (20). These phosphoproteins included the p42/p44 MAPKs (22). Fig. 9 shows that tyrosine phosphorylation of proteins of 36–57 kDa was prevented by anti-Gβ Abs, LY294002, and anti-PLCγ1 Abs. These data demonstrate that G proteins, PI3K, and PLCγ are upstream of PTK.

Discussion

The sensitivity to pertussis toxin of the secretory responses of mast cells to the basic secretagogue compound 48/80 has been the first indication of the involvement of G proteins in this process (13, 14). This property has been extended to other basic triggers considered to stimulate mast cells in a receptor-independent manner by directly activating pertussis toxin-sensitive G proteins (4, 6–9, 11, 12, 16, 17, 29, 30, 43–45). The direct activation of G proteins involves the ability of basic peptides and drugs to translocate across the plasma membrane into mast cells to reach their targets. This has been demonstrated for the neuropeptide substance P (46), but experimental evidence is lacking for other basic secretagogues.
role of α subunits cannot be excluded. Such a role would not involve adenylyl cyclase inhibition, since pertussis toxin did not increase the cAMP level in mast cells (13).

The participation of PLA$_2$ in exocytosis was first proposed by Nakamura and Ui (14). This was based on the inhibitory effect of mepacrine and p-bromophenacyl bromide, which are considered to be selective inhibitors of this enzyme, on both histamine secretion and arachidonate release triggered by compound 48/80. However, higher drug concentrations were required to inhibit histamine secretion than arachidonate release (14). Alternatively, Churcher et al. (50) proposed that PLA$_2$ activation is not an essential precursor of histamine secretion, considering that under some circumstances exocytosis was observed without measurable release of arachidonic acid. The present results confirm the latter view; anti-cPLA$_2$ Ab prevented arachidonate release without affecting histamine secretion (Fig. 5). Thus, the bifurcation point of the two pathways is localized upstream of cPLA$_2$.

Basic secretagogues induce a rapid production of IP$_3$, indicating concomitant PLC activation and histamine secretion (6, 8, 9, 14, 16). The present results confirm the participation of the PLCβ

**FIGURE 7.** Western blotting of Gβ from PLCβ immunoprecipitate (A), of PI3K from Gβ immunoprecipitate (B), and of tyrosine-phosphorylated proteins from PLCγ1 immunoprecipitate (C). Cells were preincubated for 15 min at 37°C with vanadate (0.1 mM) and stimulated by spermine (3 mM) for the indicated times. Cell extracts were immunoprecipitated, as indicated in Materials and Methods, by anti-PLCβ (A), anti-Gβ (B), or anti-PLCγ1 (C) Abs and subjected to Western blotting with anti-Gβ (A), anti-PI3K (B), or anti-p-Tyr (C) Abs. Data are representative of three separate experiments.

Thus, a role for some undetermined membrane receptor with low ligand selectivity, cannot be formally excluded. However, the receptor-mediated or receptor-independent stimulation of pertussis toxin-sensitive G proteins is an early step in the response of mast cells to basic secretagogues.

The present results allow us to propose both G$_{i2}$ and G$_{i3}$ as targets for basic secretagogues. G$_{i2}$ had been previously excluded (17), since anti-G$_{i2}$ Abs were unable to inhibit exocytosis, considering that anti-G$_{i2}$ Abs might recognize G$_{i3}$ due to the structural analogy of G$_{i2}$ and G$_{i3}$ C-terminals (Fig. 1). G$_{i3}$ was considered to mediate PLC-independent exocytosis, thus acting downstream of PLC, fulfilling the properties of the putative G$_{i}$ protein proposed by Gomperts (47, 48). It would be tempting to propose G$_{i2}$ and G$_{i3}$ as the G$_{i}$ and G$_{o}$ proteins acting in series to control stimulus-secretion coupling in mast cells (47). However, several observations argue against this being the case. Firstly, small G proteins, Rac2 and cdc42, have recently been considered as candidates for G$_{o}$ (49). Secondly, the cumulative inhibitory effect of anti-G$_{i2}$ and -G$_{i3}$ Abs (Fig. 3) is not compatible with the two proteins acting in series. Thus, we believe that both G$_{i2}$ and G$_{i3}$ correspond to the putative G$_{i}$ protein, acting upstream of PLC and leading to exocytosis and arachidonate release.

Anti-Gβ Abs fully inhibited exocytosis and arachidonate release (Fig. 4). This observation strongly suggests that βγ subunits of G$_{i2}$ and G$_{i3}$ play a major role in the transduction pathway. A regulatory
family in this process, as could be predicted from its ability to be activated by heterotrimeric G proteins (35). The coimmunoprecipitation of PLCβ and Gβγ (Fig. 7A) confirms that PLCβ interacts with Gβ subunits of G proteins. However, we were unable to distinguish between the different subtypes of PLCβ due to the lack of selectivity of the available Abs. More interestingly, the anti-PLCβ Abs were unable to prevent arachidonic acid release elicited by mastoparan or spermine. In contrast, PLCγ1 appeared to be selective for the arachidonate release pathway initiated by basic triggers (Fig. 5). This constitutes a major difference from secretory processes elicited by Ags, where PLCγ1 controls both exocytosis and arachidonate release (2). The involvement of PLCβ or PLCγ1 in exocytosis triggered by basic secretagogues or Ags, respectively, might be responsible for the different kinetics of histamine secretion observed in each case. The direct coupling of PLCβ induces exocytosis within seconds, whereas the indirect coupling of PLCγ1 to FcεRI receptors leads to a delayed exocytosis. PLCγ2 does not have a major role in the IgE/FcεRI pathway (42). Experiments are in progress to determine its putative involvement in the basic secretagogue pathway.

At this point of our study PLCγ1 can be placed upstream of cPLA2 and PKC in the activation order. The activation of PLCγ1 can be achieved by tyrosine phosphorylation or by the interaction of its pleckstrin domain with membrane PIP3 generated by PI3K (35, 36). We did not detect any tyrosine phosphorylation of PLCγ1 following mast cell stimulation by basic secretagogues (Fig. 7C), suggesting that the major stimulation of PLCγ1 was achieved through its recruitment at the membrane to PI3P-rich domains. However, we cannot exclude a minor participation of tyrosine phosphorylation in the activation of PLCγ. We propose that PLCγ1 is localized downstream of PI3K, which generates PIP3. This is compatible with the recent observation that PI3K can be activated through its interaction with cationic- and diacylglycerol, leading to the increase in cytosolic Ca2+.

In summary, we propose a sequence of signaling events (Fig. 9) initiated by basic secretagogues in mast cells with the respective roles of PLCβ and PLCγ1 in the control of exocytosis and arachidonate release. These two pathways elicited by a common stimulus suggest a selective subcellular localization for each PLC compatible with their respective roles. PLCs are known to generate IP3 and diacylglycerol, leading to the increase in cytosolic Ca2+ and to PKC activation. As we show that PLCγ1 precedes PTK, the activation of PTK might require Ca2+ increase and/or PKC activation. These points need to be thoroughly studied.

References


