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# Gastrin and the neuropeptide PACAP evoke secretion from rat stomach histamine-containing (ECL) cells by stimulating influx of $\text{Ca}^{2+}$ through different $\text{Ca}^{2+}$ channels

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1. Gastrin and PACAP stimulate secretion of histamine and pancreastatin from isolated rat stomach ECL cells. We have examined whether or not secretion depends on the free cytosolic  $\text{Ca}^{2+}$  concentration ( $[\text{Ca}^{2+}]_i$ ) and the pathways by which gastrin and PACAP elevate  $[\text{Ca}^{2+}]_i$ . Secretion was monitored by radioimmunoassay of pancreastatin and changes in  $[\text{Ca}^{2+}]_i$  by video imaging. The patch clamp technique was used to record whole-cell currents and membrane capacitance (reflecting exocytosis).
2. In the presence of 2 mM extracellular  $\text{Ca}^{2+}$ , gastrin and PACAP induced secretion and raised  $[\text{Ca}^{2+}]_i$ . Without extracellular  $\text{Ca}^{2+}$  (or in the presence of  $\text{La}^{3+}$ ) no secretion occurred. The extracellular  $\text{Ca}^{2+}$  concentration required to stimulate secretion was 10 times higher for gastrin than for PACAP. Depletion of intracellular  $\text{Ca}^{2+}$  pools by thapsigargin had no effect on the capacity of gastrin and PACAP to stimulate secretion.
3. Gastrin-evoked secretion was inhibited 60–80% by L-type channel blockers and 40% by the N-type channel blocker  $\omega$ -conotoxin GVIA. Combining L-type and N-type channel blockers did not result in greater inhibition than L-type channel blockers alone. Whole-cell patch clamp measurements confirmed that the ECL cells are equipped with voltage-dependent inward  $\text{Ca}^{2+}$  currents. A 500 ms depolarising pulse from  $-60$  mV to  $+10$  mV which maximally opened these channels resulted in an increase in membrane capacitance of 100 fF reflecting exocytosis of secretory vesicles.
4. PACAP-evoked secretion was reduced 40% by L-type channel blockers but was not influenced by inhibition of N-type channels. SKF 96365, a blocker of both L-type and receptor-operated  $\text{Ca}^{2+}$  channels, inhibited PACAP-evoked secretion by 85%. Combining L-type channel blockade with SKF 96365 abolished PACAP-evoked secretion.
5. The results indicate that gastrin- and PACAP-evoked secretion depends on  $\text{Ca}^{2+}$  entry and not on mobilisation of intracellular  $\text{Ca}^{2+}$ . While gastrin stimulates secretion via voltage-dependent L-type and N-type  $\text{Ca}^{2+}$  channels, PACAP acts via L-type and receptor-operated  $\text{Ca}^{2+}$  channels.

ECL cells are histamine-containing endocrine/paracrine cells in the oxyntic mucosa of the stomach. They play a key role in the control of acid secretion because of their ability to secrete histamine, which stimulates adjacent acid-producing cells (for reviews see Håkanson *et al.* 1994, 1998). Like most peptide hormone-producing cells, ECL cells contain chromogranin A (CGA) and/or CGA-derived peptides. One of these peptides is pancreastatin, which is co-secreted with histamine (Chen *et al.* 1994, 1996; Lindström *et al.* 1997). The two products are stored together in the same secretory organelles (Zhao *et al.* 1999). Unlike histamine, which is synthesised in the cytosol prior to accumulation in secretory organelles, pancreastatin is located in secretory organelles only (Zhao *et al.* 1999). Thus,

pancreastatin may be considered a better marker for ECL cell exocytosis than histamine.

From studies of isolated ECL cells, it has become clear that secretion of histamine and pancreastatin can be stimulated by the peptide hormone gastrin (Prinz *et al.* 1993; Lindström *et al.* 1997). The neuropeptide pituitary adenylate cyclase-activating peptide (PACAP) and its chemical relatives vasoactive intestinal peptide (VIP) and peptide histidine isoleucine (PHI) likewise are powerful activators of ECL cell secretion *in vitro* (Lindström *et al.* 1997; Zeng *et al.* 1998, 1999a; Lindström & Håkanson, 2001).

Gastrin stimulates secretion from the ECL cells by binding to cholecystokinin ( $\text{CCK}_2$ ) receptors (Sandvik &

Waldum, 1991; Prinz *et al.* 1993; Lindström *et al.* 1997, 1999). Binding of gastrin to its receptor causes phosphatidylinositol biphosphate breakdown by phospholipase C (Seva *et al.* 1994; Kinoshita *et al.* 1998). This leads to the production of inositol trisphosphate ( $\text{IP}_3$ ), which can be expected to mobilise  $\text{Ca}^{2+}$  from intracellular stores. Indeed, it has been demonstrated that gastrin elicits  $\text{IP}_3$  formation (Kinoshita *et al.* 1998) and induces an initial transient peak followed by sustained elevation in free cytosolic  $\text{Ca}^{2+}$  concentrations ( $[\text{Ca}^{2+}]_i$ ) in ECL cells (Prinz *et al.* 1993, 1994). The transient peak was thought to reflect mobilisation of  $\text{Ca}^{2+}$  from intracellular stores while the subsequent plateau phase depended on the influx of extracellular  $\text{Ca}^{2+}$ . PACAP was likewise found to induce biphasic  $[\text{Ca}^{2+}]_i$  responses in isolated ECL cells (Zeng *et al.* 1999a). Although  $\text{Ca}^{2+}$ -induced histamine secretion has been demonstrated in permeabilised ECL cells (Höhne-Zell *et al.* 1997) and the  $\text{Ca}^{2+}$  ionophore A23187 has been shown to stimulate histamine secretion from isolated ECL cells (Sakai *et al.* 1995), it is not yet clear to which extent different sources of  $\text{Ca}^{2+}$  contribute to exocytosis.  $\text{Ca}^{2+}$  channels are of three major types: voltage-operated, receptor-operated and store-operated channels (or capacitative; for a review see Berridge, 1997). Electrophysiological characterisation of ECL cells has suggested the involvement of voltage-operated  $\text{Ca}^{2+}$  channels of both L-type and N-type (Bufler *et al.* 1998; reviewed by Prinz *et al.* 1999).

The aim of the work is to evaluate the  $\text{Ca}^{2+}$  dependence of exocytosis in ECL cells and to explore the differential regulation of secretion by gastrin and PACAP.

## METHODS

### Chemicals

Rat gastrin-17 was obtained from Research Plus (Bayonne, NJ, USA). Rat PACAP-27 was from Peninsula Europe (St Helens, Merseyside, UK). Thapsigargin and all the voltage-operated  $\text{Ca}^{2+}$  channel blockers were supplied by Alomone Labs (Jerusalem, Israel). The receptor- and voltage-operated  $\text{Ca}^{2+}$  channel blocker SKF 96365, the L-type channel activator Bay K 8644 and the neurotoxic  $\text{Na}^+$  channel inhibitor tetrodotoxin (TTX) were purchased from Calbiochem (La Jolla, CA, USA). Fura-2 AM was purchased from Molecular Probes (Eugene, OR, USA). Matrigel was from Collaborative Biomedical Products (Bedford, MA, USA). Cadmium-, barium- and lanthanum chloride, fetal calf serum and DMEM–Ham's F12 medium were from Sigma (St Louis, MO, USA). Bovine serum albumin (BSA, fraction V) was from ICN (Aurora, OH, USA). Pronase was from Boehringer Mannheim (Mannheim, Germany). Iodixanol (Optiprep) was from Nycomed Pharma (Oslo, Norway).

### Isolation of ECL cells

The stomachs from four male Sprague-Dawley rats (300–400 g) were used for each cell preparation. The rats were killed by a blow to the head followed by decapitation. All experiments were carried out according to the guidelines of our institution's animal welfare committee. Anaesthesia was avoided due to its suppressive effects on ECL cell function (Norlén *et al.* 2000). ECL cells were purified as described earlier (Lindström *et al.* 1997) with a few modifications. Briefly, oxyntic mucosal cells were dispersed using pronase digestion ( $0.9 \text{ mg ml}^{-1}$ ) and  $\text{Ca}^{2+}$  chelation (1 mM EDTA). The ECL cells were

enriched by repeated counterflow elutriation using first a standard chamber and then a Sanderson chamber (Beckman, Palo Alto, CA, USA). The enriched cells from the standard chamber were collected at  $25 \text{ ml min}^{-1}$  and at a speed of 2000 r.p.m. (380–560 g). They were purified further in a Sanderson chamber and collected at  $18 \text{ ml min}^{-1}$  and 2000 r.p.m. This cell preparation consisted of approximately 2 million cells, about 80% being ECL cells (verified by histamine immunocytochemistry, see below).

The ECL cell preparation was then subjected to density gradient centrifugation. A stock solution of 60% iodixanol was enriched with Hepes (final concentration 15 mM, pH 7.4) and  $10 \text{ mg ml}^{-1}$  BSA. This solution was diluted to 10.8% iodixanol with a medium (medium C) consisting of (mM): 140 NaCl, 1.2  $\text{MgSO}_4$ , 1  $\text{CaCl}_2$ , 15 Hepes at pH 7.4, 11 glucose, 0.5 dithiothreitol and  $10 \text{ mg ml}^{-1}$  BSA. In a 15 ml centrifuge tube, 10 ml of the 10.8% iodixanol solution was overlaid with the enriched ECL cells ( $2 \times 10^6$  in 1 ml medium C) and centrifuged (Spinchron R centrifuge, Beckman). A slow acceleration period (400 r.p.m.) was followed by 5 min centrifugation at 1000 r.p.m. Deceleration lasted 5 min. The cells in the light density fraction (above the 10.8% cushion) were collected. This fraction consisted of 90–95% ECL cells determined by immunocytochemistry using an anti-histamine antiserum (1:1000) (Håkanson *et al.* 1986) with 4% 1-ethyl-3(3-dimethylaminopropyl)-carbodiimide as fixative (Panula *et al.* 1988).

### Primary cell culture

For secretion experiments, purified ECL cells were cultured in 96-well plates pre-coated with Matrigel (diluted 1:10 in DMEM–Ham's F12 medium, 10 000 cells per well,  $100 \mu\text{l vol}$ ). The cells were cultured on cover slips (diameter: 25 mm) or in Petri dishes (diameter: 40 mm) pre-coated with diluted Matrigel for video-image analysis experiments or for patch-clamp studies, respectively. All cell cultures were incubated in a humid atmosphere with 5%  $\text{CO}_2$ –95% air at  $37^\circ\text{C}$  for 24–48 h until the start of the experiments. The culture medium consisted of DMEM–Ham's F12 medium (1:1) supplemented with 2% fetal calf serum, 2 mM glutamine,  $100 \text{ IU ml}^{-1}$  penicillin,  $100 \mu\text{g ml}^{-1}$  streptomycin,  $250 \text{ ng ml}^{-1}$  amphotericin B,  $10 \mu\text{g ml}^{-1}$  insulin,  $5.5 \mu\text{g ml}^{-1}$  transferrin,  $5 \text{ ng ml}^{-1}$  selenious acid,  $0.5 \mu\text{g ml}^{-1}$  BSA, 15 mM Hepes,  $10 \mu\text{M}$  pyridoxal-5-phosphate, 10 nM hydrocortisone and 100 pM gastrin-17.

### Secretion experiments

After 48 h, the cells were washed with serum-free and gastrin-free culture medium. After equilibration for about 2 h, the medium was again aspirated and replaced with secretion medium consisting of (mM): 150 NaCl, 5 KCl, 2  $\text{CaCl}_2$  (unless otherwise stated), 10 Hepes at pH 7.0, containing the various stimulatory or inhibitory compounds. Maximally effective concentrations (10 nM) of gastrin and PACAP were used to challenge the cells (Lindström *et al.* 1997). To analyse the effects of  $\text{Ca}^{2+}$  channel blockade, the cells were pretreated with the respective blocker for 30 min, while control cells were pretreated with secretion medium only. Voltage-operated  $\text{Ca}^{2+}$  channels can be classified based on their pharmacological and/or electrophysiological properties (for recent reviews see Jones, 1998; Davila, 1999). High voltage-activated (HVA)  $\text{Ca}^{2+}$  channels are of the L, N, P, Q or R type. L-type  $\text{Ca}^{2+}$  channels mediate dihydropyridine (e.g. nifedipine)-sensitive currents, while N-type  $\text{Ca}^{2+}$  channels are blocked irreversibly by  $\omega$ -conotoxin GVIA. P-type  $\text{Ca}^{2+}$  channels are resistant to dihydropyridine and  $\omega$ -conotoxin GVIA but sensitive to  $\omega$ -agatoxin IVA and funnel spider venom toxin. This is also the case for Q-type  $\text{Ca}^{2+}$  channels, but they can also be effectively blocked by  $\omega$ -agatoxin MVIIC. R-type currents are HVA  $\text{Ca}^{2+}$  currents resistant to the all-above mentioned blockers. T-type  $\text{Ca}^{2+}$  channels on the other hand mediate a low-threshold  $\text{Ca}^{2+}$  current with fast inactivation. The  $\text{Ca}^{2+}$  channel blockers tested and the concentrations used are listed in Table 2. The concentrations were chosen from the literature references

in the table. To explore the consequences of depletion of intracellular Ca<sup>2+</sup>, the cells were pretreated for 4 h with various concentrations of thapsigargin, which is an irreversible inhibitor of the Ca<sup>2+</sup> pumps operating in the sarcoplasmic and endoplasmic reticulum (for a review see Treiman *et al.* 1998). Secretion studies lasted for 30 min at 37 °C and were interrupted by centrifuging the plates at 220 *g* for 1 min. The supernatants were collected and stored at −20 °C until measurement of pancreastatin.

### Video image analysis of free cytosolic Ca<sup>2+</sup>

After 24–48 h, ECL cells cultured on Matrigel-coated glass cover slips were loaded with 0.5 μM of the Ca<sup>2+</sup> fluorophore fura-2 AM for 30 min at 37 °C in 2 ml of medium consisting of (mM): 125 NaCl, 5.9 KCl, 1.28 CaCl<sub>2</sub>, 1.2 MgCl<sub>2</sub>, 25 Hepes, 3 glucose (pH 7.4). This solution was used as the standard medium throughout the experiment. Following 30 min incubation, extracellular fluorophore was removed by washing the cells with 2 ml of the medium. The cover slip was mounted in a perfusion chamber (37 °C) placed over the objective of an inverted microscope (Nikon Diaphot 200, Tokyo, Japan). The light was generated by a xenon arc lamp and filtered through two narrow band-pass filters (340 and 380 nm). The filters alternated by the use of a computer-controlled filter wheel. The light reached the cells via a dichroic reflector. Fluorescence emission (at 510 nm) from individual cells was monitored using an intensified videocamera (PTI 100) and the fluorescence intensity ratio (340/380 nm) was calculated using PTI software (Imagemaster, South Brunswick, NJ, USA). The 340/380 nm ratios were used to obtain estimates of the free Ca<sup>2+</sup> concentrations (Gryniewicz *et al.* 1985) using fura-2 after calibration with known Ca<sup>2+</sup> concentrations (Calcium Imaging Calibration Kit; Molecular Probes). The peak cytosolic Ca<sup>2+</sup> level attained for each cell is referred to as peak [Ca<sup>2+</sup>]<sub>i</sub>. The sustained response was calculated by integrating the curve during the 3 min (180 s) stimulation period ( $\int \Delta[\text{Ca}^{2+}]_i$ ) and expressed in micromolar seconds (μM s).

### Electrophysiological measurements

Patch pipettes were pulled from borosilicate glass capillaries, coated with Sylgard (Sekema, Stockholm, Sweden) and fire polished before use. The pipette resistance ranged between 3–6 MΩ when filled with pipette-filling solution specified below. Whole-cell currents were recorded using an EPC-9 patch clamp amplifier and the software Pulse (Heka Elektronik, Lambrecht/Pfalz, Germany). Exocytosis was detected as changes in the cell membrane capacitance (Neher & Marty, 1982) by using the 'lock-in' (which adds a 500 Hz sinus wave to the holding potential) or the 'captrack' functions of the EPC-9 amplifier. The zero-current potential was adjusted with the pipette in the bath before establishing the seal and the holding potential was −60 mV. All recordings were performed using the standard whole-cell configuration, in which the pipette solution is washed into the cell replacing the cytosol. Exocytosis was elicited either by voltage clamp depolarisation (from −60 to +10 mV) or by infusion of Ca<sup>2+</sup>–EGTA buffers.

The standard extracellular (bath) solution used for the electrophysiological measurements consisted of (mM): 138 NaCl, 5.6 KCl, 2.6 CaCl<sub>2</sub>, 1.2 MgCl<sub>2</sub>, 5 Hepes and 3 glucose. When exocytosis and/or Ca<sup>2+</sup> currents were elicited with voltage-clamp depolarisation, 20 mM NaCl were equimolarly replaced by tetraethylammonium (TEA) chloride which blocks voltage-gated K<sup>+</sup> currents. To study the pharmacology of the Ca<sup>2+</sup> currents, Ba<sup>2+</sup> was used as a charge carrier with the concentration of the divalent ion increased to 10 mM. This increases the Ca<sup>2+</sup> current amplitude 3-fold above that seen at physiological Ca<sup>2+</sup>. The pH of the extracellular solutions was adjusted to 7.4 with addition of NaOH.

For the infusion experiments, the intracellular solution contained (mM): 125 potassium glutamate, 10 NaCl, 10 KCl, 1 MgCl<sub>2</sub>, 5 Hepes

(pH 7.15 with KOH), 5 EGTA and 0, 2.5, 3.5 or 4.5 CaCl<sub>2</sub>, yielding a free Ca<sup>2+</sup> concentration of either < 0.0001, 0.16, 0.36 or 1.5 μM. The free Ca<sup>2+</sup> concentration was calculated using the constants of Martell & Smith (1971). When exocytosis was initiated by voltage-clamp depolarisation the intracellular medium contained (mM): 125 caesium glutamate, 10 CsCl, 10 NaCl, 1 MgCl<sub>2</sub>, 3 Mg-ATP, 0.05 EGTA and 5 Hepes. Measurements of Ca<sup>2+</sup> currents were performed with (mM): 125 CsCl, 1 MgCl<sub>2</sub>, 10 EGTA, 3 Mg-ATP, 10 Hepes (pH 7.15 with CsOH) and 0.1 cAMP in the pipette solution. Adjustment of the pH of the pipette solution was made by adding either KOH or CsOH.

All electrophysiological measurements were performed at a temperature of 31–34 °C. In the infusion experiments, the rate of capacitance increase ( $\Delta C_m/\Delta t$ ) was measured during the linear phase, usually during the first 2 min.

### Determination of pancreastatin

The pancreastatin-like immunoreactivity was measured by radioimmunoassay using rat pancreastatin as standard (Håkanson *et al.* 1995). The amount of pancreastatin released during the 30 min incubation period was expressed as femtomolar equivalents of rat pancreastatin per well.

### Data analysis

Statistical analysis was performed using Student's unpaired *t* test or one-way analysis of variance (ANOVA) followed by Dunnett's test for multiple comparisons. *P* values of < 0.05 were considered to be statistically significant.

## RESULTS

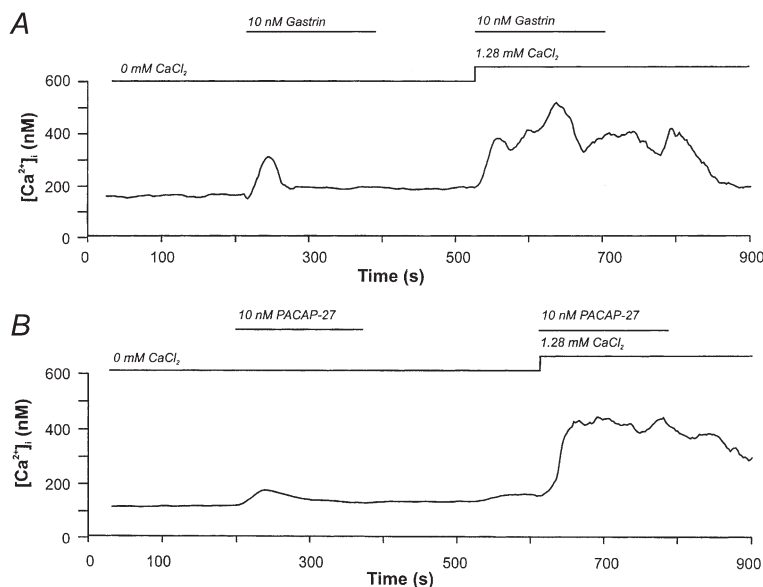
### Effects of gastrin and PACAP on cytosolic Ca<sup>2+</sup>

Cytosolic Ca<sup>2+</sup> levels were  $171 \pm 3$  nM (*n* = 98 cells) in resting ECL cells. In a Ca<sup>2+</sup>-free medium (0 Ca<sup>2+</sup> + 1 mM EGTA), gastrin and PACAP (10 nM) produced a transient increase in [Ca<sup>2+</sup>]<sub>i</sub> peaking at  $286 \pm 25$  nM and  $249 \pm 19$  nM, respectively (Fig. 1*A* and *B*). Presumably, this increase reflects mobilisation of Ca<sup>2+</sup> from intracellular stores. With Ca<sup>2+</sup> present in the extracellular medium (1.28 mM) the peak [Ca<sup>2+</sup>]<sub>i</sub> increased to  $441 \pm 21$  nM (*n* = 63) in response to gastrin and  $492 \pm 20$  nM (*n* = 43) in response to PACAP. Also, under these circumstances, the increases in [Ca<sup>2+</sup>]<sub>i</sub> measured over 3 min were sustained rather than transient (Fig. 1*A* and *B*). The integrated Ca<sup>2+</sup> responses (3 min), illustrating the magnitude and duration of the increase in [Ca<sup>2+</sup>]<sub>i</sub>, were  $29.4 \pm 2.0$  μM after stimulation by gastrin and  $35.5 \pm 2.5$  μM after PACAP. Without Ca<sup>2+</sup> in the medium the corresponding values were  $7.0 \pm 1.3$  μM and  $7.0 \pm 0.9$  μM, respectively. The results are in agreement with previous reports (Prinz *et al.* 1994, 1999; Zeng *et al.* 1999*a*).

### Effects of intracellular Ca<sup>2+</sup>–EGTA buffers on exocytosis

Secretion from many endocrine cells depends on increases in [Ca<sup>2+</sup>]<sub>i</sub> (Burgoyne, 1991). Since PACAP and gastrin increase [Ca<sup>2+</sup>]<sub>i</sub>, we were interested in investigating the correlation between [Ca<sup>2+</sup>]<sub>i</sub> and exocytosis in ECL cells. To this end we used the whole-cell configuration of the patch-clamp technique in combination with measurement of cell capacitance increase as a single-cell indicator of exocytosis (i.e. fusion of secretory vesicles with the





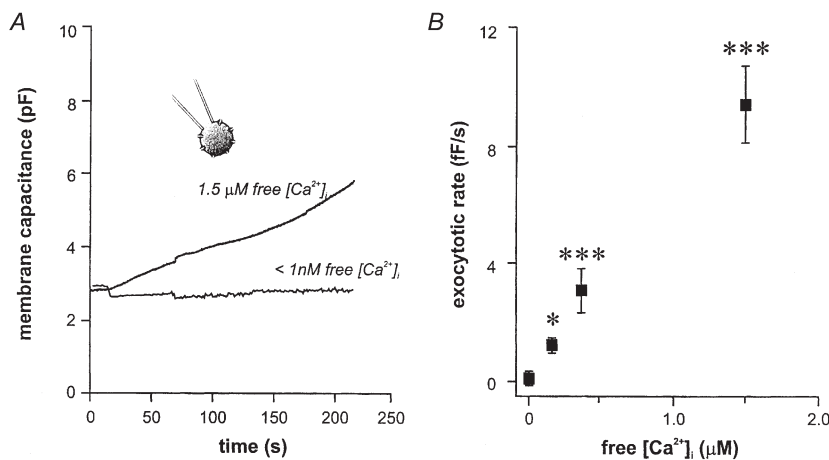
**Figure 1. Increased cytosolic  $\text{Ca}^{2+}$  in ECL cells upon PACAP and gastrin stimulation**

Stimulation with 10 nM gastrin (A) or PACAP (B) for 3 min in a  $\text{Ca}^{2+}$ -free medium resulted in a transient increase in  $[\text{Ca}^{2+}]_i$ . The peak rapidly returned back to basal levels. Stimulation with 10 nM gastrin (A) or PACAP (B) for 3 min in a  $\text{Ca}^{2+}$ -containing medium (1.28 mM  $\text{CaCl}_2$ ) resulted in sustained increases in  $[\text{Ca}^{2+}]_i$ .

plasma membrane; Neher & Marty, 1982). This has the additional advantage that it is possible to control the intracellular environment since the pipette solution replaces the cytosol when the cell is dialysed. The membrane potential was clamped at  $-60$  mV to avoid activation of voltage-dependent  $\text{Ca}^{2+}$  channels; the resting membrane potential in the ECL cells has been measured to be between  $-60$  and  $-70$  mV (Loo *et al.* 1995; Bufler *et al.* 1998). Figure 2A shows two representative curves demonstrating the increase in cell capacitance (exocytosis) upon infusion of a solution containing a high concentration ( $1.5 \mu\text{M}$ ) of  $\text{Ca}^{2+}$  or a medium devoid of the cation ( $< 1$  nM). In both traces, step changes of 100–200 fF were observed suggesting compound exocytosis and endocytosis as in other endocrine cells (Eliasson *et al.* 1996). In the absence of  $[\text{Ca}^{2+}]_i$ , exocytosis did not occur. The rate of exocytosis increased in response to increasing intracellular  $\text{Ca}^{2+}$  levels in a linear fashion up to  $1.5 \mu\text{M}$   $[\text{Ca}^{2+}]_i$  (Fig. 2B).

### Effect of extracellular $\text{Ca}^{2+}$ on secretion

To investigate the source of  $\text{Ca}^{2+}$  initiating exocytosis in response to gastrin and PACAP, we first studied the effect of varying the extracellular  $\text{Ca}^{2+}$  concentration. In previous studies of ECL cell secretion, we used a medium containing 2 mM  $\text{CaCl}_2$  (Lindström *et al.* 1999). Here we studied the influence of extracellular  $\text{Ca}^{2+}$  on pancreastatin secretion by varying the extracellular  $\text{Ca}^{2+}$  concentration between 0 and 30 mM  $\text{Ca}^{2+}$ . In the absence of gastrin or PACAP the ECL cells did not respond to variations of extracellular  $\text{Ca}^{2+}$  (Fig. 3A and B). In the absence of extracellular  $\text{Ca}^{2+}$  (0  $\text{Ca}^{2+}$  + 1 mM EGTA), the ECL cells failed to respond to either gastrin or PACAP (although there was a clear but transient rise in  $[\text{Ca}^{2+}]_i$ , see Fig. 1). Gastrin was likewise without stimulatory effect in a medium containing 0.3 mM  $\text{Ca}^{2+}$  (Fig. 3A); in fact, a response was not obtained until  $\text{Ca}^{2+}$  was increased to 1 mM. In contrast, PACAP induced secretion at external  $\text{Ca}^{2+}$  concentrations as low as 0.1 mM, but the efficacy was



**Figure 2. Increase in membrane capacitance upon infusion of  $\text{Ca}^{2+}$ -EGTA buffers**

A, infusion of a  $\text{Ca}^{2+}$ -EGTA buffer containing  $1.5 \mu\text{M}$  free  $\text{Ca}^{2+}$  or zero ( $< 1$  nM)  $\text{Ca}^{2+}$  into single ECL cells caused an increase in membrane capacitance of 12 fF and  $0.1 \text{ fF s}^{-1}$ , respectively. B, the exocytotic rate as a function of  $[\text{Ca}^{2+}]_i$ . The data points are means of 7, 3, 3 and 12 experiments, respectively, performed with  $< 1$  nM, 160 nM, 365 nM and  $1.5 \mu\text{M}$  free  $\text{Ca}^{2+}$  in the pipette solution.

only 45% of that obtained at 2 mM (Fig. 3*B*). Increasing external Ca<sup>2+</sup> to 10 mM resulted in similar gastrin-evoked pancreastatin secretion as with 2 mM Ca<sup>2+</sup>, while it reduced PACAP-evoked secretion (Fig. 3*C* and *D*). Increasing external Ca<sup>2+</sup> to 30 mM reduced both gastrin- and PACAP-stimulated secretion compared to that observed at 2 mM Ca<sup>2+</sup>. This is probably due to a shift in the activation of the voltage-dependent Ca<sup>2+</sup> channels towards a more positive membrane potential due to surface screening effects (Hille, 1991).

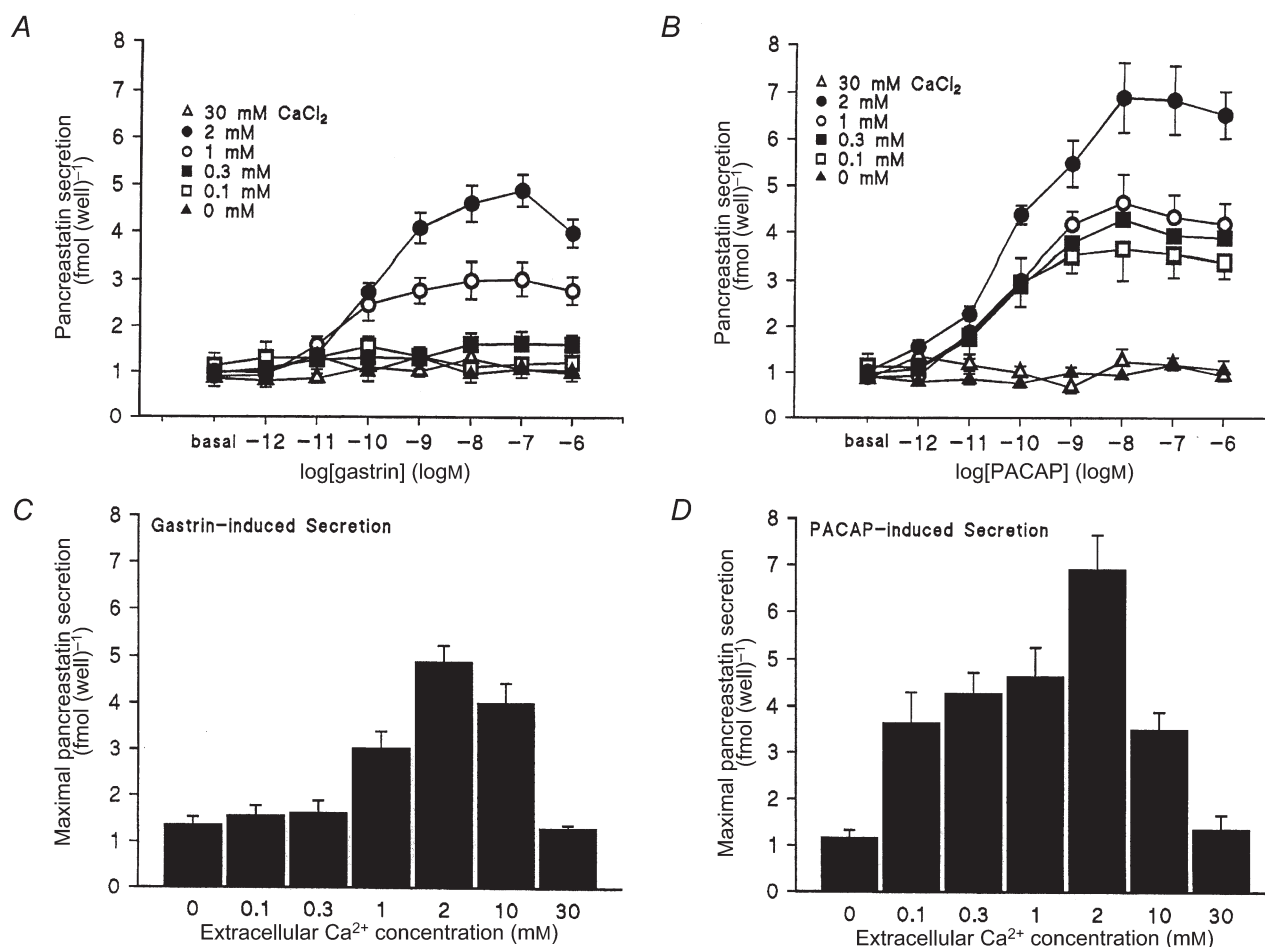
### Effect of intracellular Ca<sup>2+</sup> depletion

The contribution of intracellularly stored Ca<sup>2+</sup> was studied using thapsigargin. Pretreatment with thapsigargin (0.1 nM for 4 h) depleted intracellular stores of Ca<sup>2+</sup>, as indicated by the fact that PACAP and gastrin failed to produce the expected transient [Ca<sup>2+</sup>]<sub>i</sub> response in a Ca<sup>2+</sup>-free medium (see Fig. 4*A*). In a medium containing 1.28 mM Ca<sup>2+</sup>, neither PACAP- nor gastrin-stimulated secretion of pancreastatin

was affected by pretreatment with thapsigargin (Fig. 4*B*). Higher concentrations of thapsigargin than 0.1 μM were not tested because of the risk of inducing Ca<sup>2+</sup> entry blockade (see review by Taylor & Broad, 1998). Thapsigargin *per se* (30 min incubation) did not increase [Ca<sup>2+</sup>]<sub>i</sub> (data not shown) or pancreastatin secretion (Fig. 4*C*).

### Effect of Ca<sup>2+</sup> entry blockers on secretion and cytosolic Ca<sup>2+</sup> response

Since extracellular Ca<sup>2+</sup> proved crucial for secretion, we used a variety of Ca<sup>2+</sup> entry blockers to determine which entry pathways were involved. Lanthanum (La<sup>3+</sup>), a non-selective Ca<sup>2+</sup> channel blocker, completely blocked gastrin- and PACAP-evoked secretion (Fig. 5*A*), confirming the importance of Ca<sup>2+</sup> entry. Nifedipine (10 μM) and nimodipine (10 μM), blockers of voltage-operated L-type Ca<sup>2+</sup> channels, inhibited gastrin-evoked secretion by 75–80% and PACAP-evoked secretion by 40–45% (Fig. 5*B* and *C*). Nifedipine also reduced the peak (35–40% decrease)



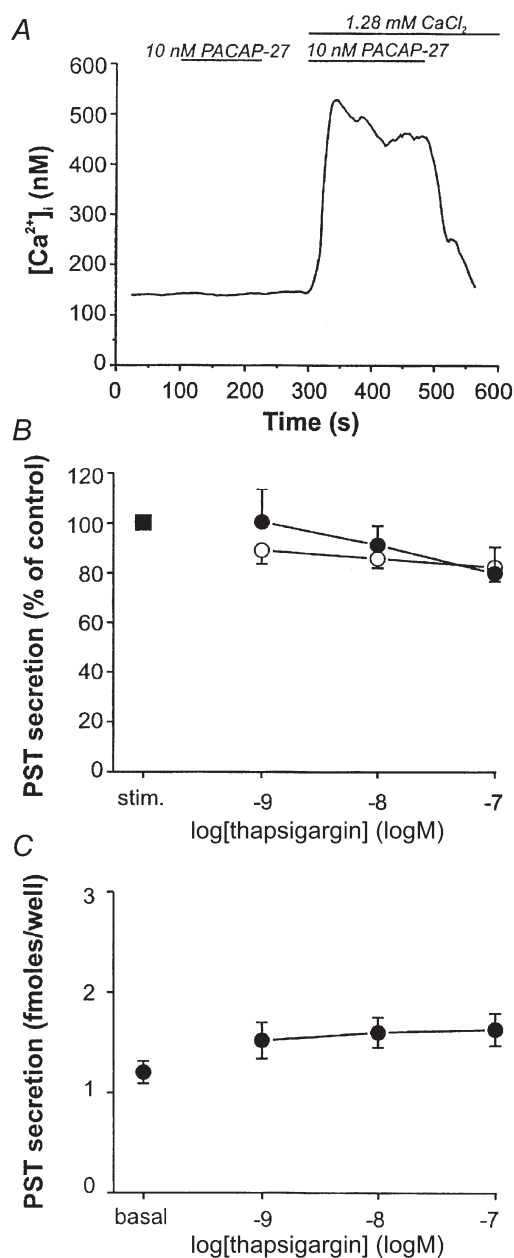
**Figure 3. Effect of the extracellular Ca<sup>2+</sup> concentration on PACAP- and gastrin-induced pancreastatin secretion**

Concentration–response curves for gastrin (*A*) and PACAP (*B*) in the presence of different extracellular Ca<sup>2+</sup> concentrations on pancreastatin secretion. Histograms demonstrating the effect of the extracellular Ca<sup>2+</sup> concentration on the maximal pancreastatin secretion induced by 10 nM gastrin (*C*) or 10 nM PACAP (*D*). Means ± S.E.M.; *n* = 8–10.

Table 1. Effect of nifedipine or SKF 96365 on gastrin- and PACAP-evoked rise in  $[Ca^{2+}]_i$ 

	Peak response (nM $[Ca^{2+}]_i$ )	Sustained response ( $\mu$ M s)	<i>n</i>
PACAP	482 $\pm$ 25	37.0 $\pm$ 2.5	18
PACAP + 10 $\mu$ M Nifedipine	372 $\pm$ 20**	18.9 $\pm$ 2.6***	18
Gastrin	378 $\pm$ 25	26.6 $\pm$ 2.7	27
Gastrin + 10 $\mu$ M Nifedipine	308 $\pm$ 16*	11.8 $\pm$ 1.3***	27
PACAP	414 $\pm$ 16	31.8 $\pm$ 1.5	6
PACAP + 30 $\mu$ M SKF 96365	337 $\pm$ 37	17.4 $\pm$ 3.4*	6
Gastrin	446 $\pm$ 22	34.7 $\pm$ 2.4	6
Gastrin + 30 $\mu$ M SKF 96365	342 $\pm$ 14**	12.1 $\pm$ 3.0***	6

The response to each agonist is given with or without added channel blocker (\*  $P < 0.05$ , \*\*  $P < 0.01$ , \*\*\*  $P < 0.001$ , Student's unpaired *t* test). The  $Ca^{2+}$  response is monitored during 3 min.



as well as the sustained  $[Ca^{2+}]_i$  response (50–55% decrease) to both gastrin and PACAP (see Table 1). The L-type channel blockers calcicludine and verapamil also inhibited secretion, but to a lesser degree than nifedipine and nimodipine (Table 2).  $\omega$ -Conotoxin GVIA (1  $\mu$ M), an effective blocker of voltage-operated N-type channels, reduced the gastrin-evoked secretion by 40% without affecting PACAP-evoked secretion (Fig. 5D). The P/Q-type and T-type channel blockers had little or no effect on stimulated secretion (Table 2). SKF96365 (30  $\mu$ M), an effective blocker of both receptor- and voltage-operated  $Ca^{2+}$  entry (Merritt *et al.* 1990), inhibited both gastrin- and PACAP-evoked secretion by 80% (Fig. 5E) and reduced peak and sustained  $[Ca^{2+}]_i$  responses to both peptides by 30–65% (see Table 1).

Complete inhibition of secretion was not found with any individual blocker. We therefore examined possible additive effects by combining different types of blockers. Combining maximal concentrations of nifedipine and  $\omega$ -conotoxin GVIA did not cause additive inhibition of either gastrin- or PACAP-stimulated secretion (Fig. 6A).

Figure 4. Effect of thapsigargin on pancreastatin secretion from the ECL cells

A, ECL cells were pretreated with 100 nM thapsigargin for 4 h. Stimulation with 10 nM PACAP in a  $Ca^{2+}$ -free extracellular media did not evoke an increase in  $[Ca^{2+}]_i$ ; however, an increase was evident in  $Ca^{2+}$ -containing media. B, concentration–response curve illustrating the lack of effect of pretreatment (4 h) with increasing concentrations of thapsigargin on stimulated pancreastatin (PST) secretion.

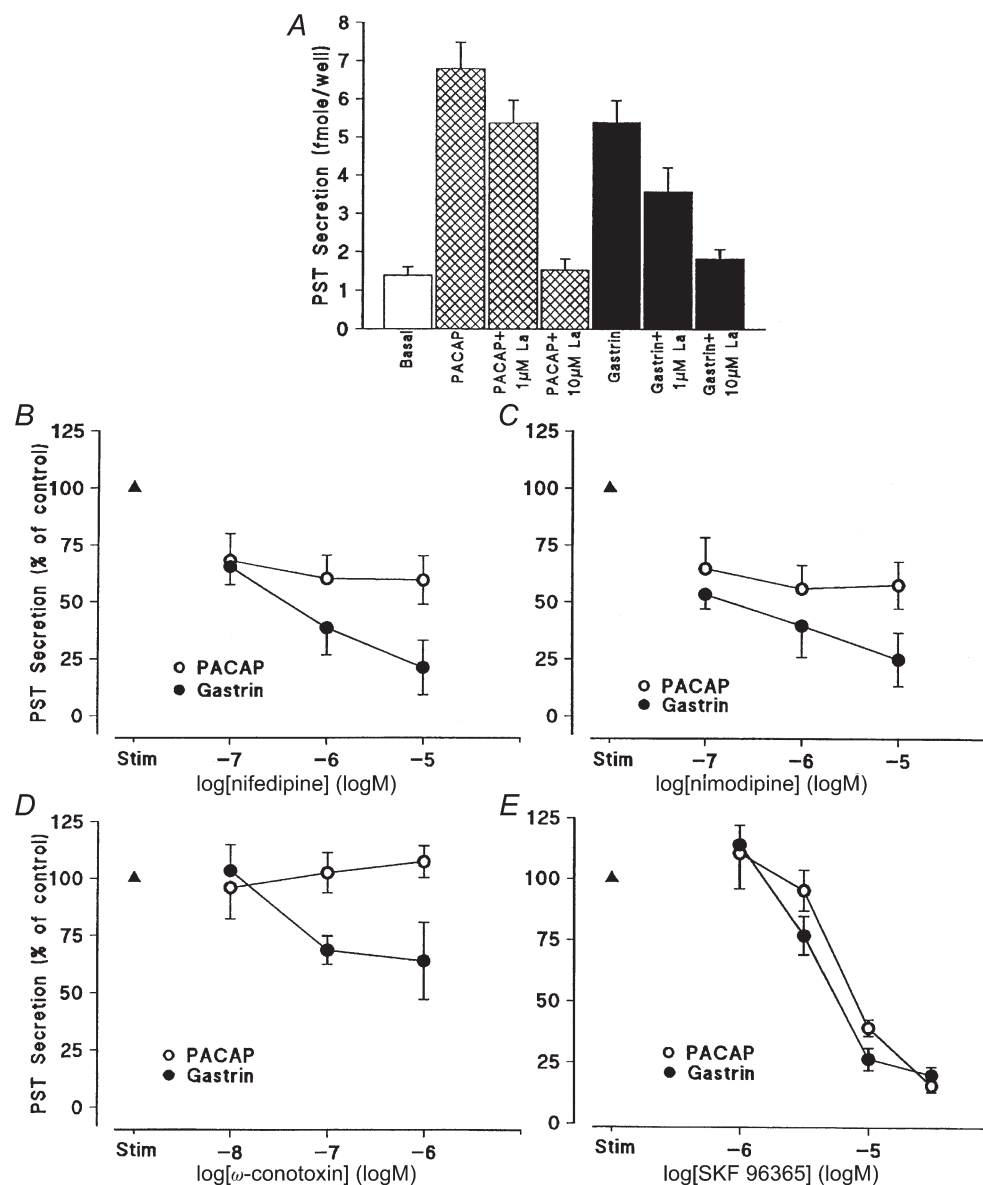
●, gastrin-induced secretion, ○, PACAP-induced secretion. ■, PACAP- and gastrin-evoked PST secretion (stim) from controls (set to 100%).

Means  $\pm$  S.E.M.; *n* = 6–7. C, effect of thapsigargin *per se* on pancreastatin secretion from ECL cells. Basal, indicates basal secretion. Means  $\pm$  S.E.M.; *n* = 10.

Interestingly, the combination of nifedipine and SKF 96365 abolished PACAP-evoked secretion but failed to cause additive inhibition of gastrin-stimulated secretion (Fig. 6*B*).

Further evidence for the involvement of L-type Ca<sup>2+</sup>-channels in the secretion of pancreastatin was obtained using the L-type Ca<sup>2+</sup>-channel activator Bay K 8644 (Triggle & Rampe, 1989). Bay K 8644 *per se* stimulated

pancreastatin secretion in a concentration-dependent manner (Fig. 7), inducing a 2.6-fold increase at 3  $\mu$ M. However, the same concentration of Bay K 8644 did not influence the secretion evoked by 10 nM PACAP or gastrin (data not shown). Also, at 3  $\mu$ M, Bay K 8644 raised [Ca<sup>2+</sup>]<sub>i</sub> (peak response:  $332 \pm 25$  nM; integrated 3 min response:  $15.9 \pm 2.8$   $\mu$ M s,  $n = 8$ ) compared to basal levels. These effects were prevented by 10  $\mu$ M nifedipine (Fig. 7).



**Figure 5.** Effect of Ca<sup>2+</sup> entry blockers on stimulated pancreastatin secretion from ECL cells

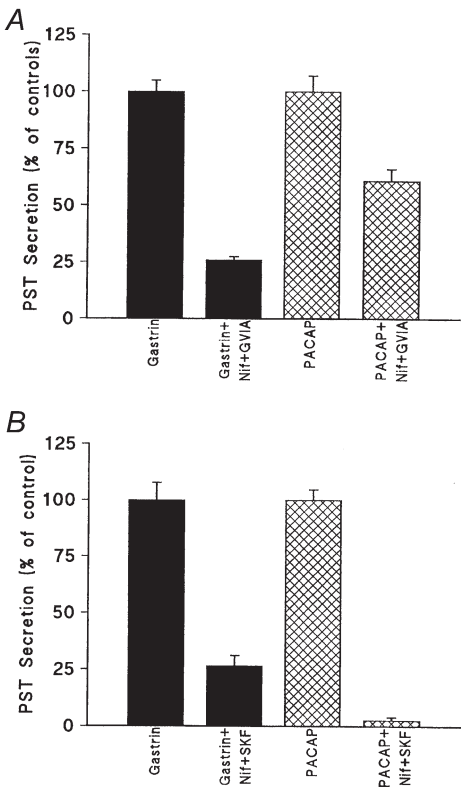
*A*, histogram illustrating the effect of LaCl<sub>3</sub> (La) on both gastrin- and PACAP-induced pancreastatin (PST) secretion. Concentration-response curves demonstrating the effect of the L-type Ca<sup>2+</sup> channel blockers nifedipine (*B*) and nimodipine (*C*) and the N-type Ca<sup>2+</sup> channel blocker  $\omega$ -conotoxin GVIA (*D*) on gastrin-induced (●) and PACAP-induced (○) pancreastatin (PST) secretion. ▲, PACAP- and gastrin-evoked secretion (Stim) from controls (secretion set at 100%). *E*, concentration-response curve demonstrating the effect of the receptor-operated and L-type channel blocker SKF 96365 on gastrin-induced (●) and PACAP-induced (○) pancreastatin (PST) secretion. ▲, PACAP- and gastrin-evoked secretion (Stim) from controls (secretion set at 100%). Means  $\pm$  S.E.M.;  $n = 6-10$ .



**Table 2.** Effects of various Ca<sup>2+</sup> channel blockers on gastrin- and PACAP-evoked secretion of pancreastatin from isolated ECL cells

Blocker	Channel selectivity	Maximally effective concentration (Reference)	Gastrin-stimulated secretion (% remaining)	PACAP-stimulated secretion (% remaining)
<i>ω</i> -Agatoxin	P-/Q-types	1 μM (Teramoto <i>et al.</i> 1995)	91.3 ± 17.5	113.4 ± 13.0
sFTX-3.3	P-/Q-/T-types	100 nM (Scott <i>et al.</i> 1992)	74.4 ± 14.0	111.5 ± 10.3
Calcicludein	Neuronal L-type	10 nM (Schweitz <i>et al.</i> 1994)	28.2 ± 8.9**	65.9 ± 19.5
Nifedipine	L-type	10 μM (Triggle & Janis, 1987)	20.9 ± 2.5**	59.3 ± 6.3*
Nimodipine	L-type	10 μM (Triggle & Janis, 1987)	24.7 ± 2.9**	55.7 ± 5.8*
Verapamil	L-type	50 μM (Triggle & Janis, 1987)	39.6 ± 12.2**	54.9 ± 15.3*
<i>ω</i> -Conotoxin MVIIA	N-type	1 μM (Olivera <i>et al.</i> 1987)	58.9 ± 8.5*	76.4 ± 7.2
<i>ω</i> -Conotoxin GVIA	N-type	1 μM (Olivera <i>et al.</i> 1985)	63.8 ± 6.8*	95.7 ± 16.9
SKF 96365	L-type and ROC	30 μM (Merritt <i>et al.</i> 1990)	20.2 ± 3.2**	15.9 ± 2.7**

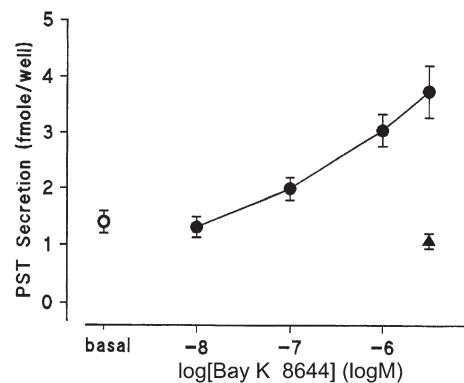
The effect of each blocker is expressed as the percentage of the response to gastrin or PACAP that remains (\*  $P < 0.05$ , \*\*  $P < 0.01$ ; ANOVA followed by Dunnett's test for multiple comparisons). Means ± S.E.M.;  $n = 6$ –10. Secretion is measured after 30 min incubation with gastrin or PACAP. ROC, receptor-operated channels.



**Figure 6.** Effect of combining Ca<sup>2+</sup> entry blockers on stimulated pancreastatin secretion from ECL cells. *A*, effect of combining 10 μM nifedipine (Nif) and 1 μM *ω*-conotoxin GVIA (GVIA) on gastrin- and PACAP-stimulated pancreastatin (PST) secretion. *B*, effect of combining 10 μM nifedipine and 30 μM SKF 96365 (SKF) on gastrin- and PACAP-stimulated pancreastatin (PST) secretion. Means ± S.E.M.;  $n = 6$ –8.

**Figure 7.** Effect of the L-type Ca<sup>2+</sup> channel activator Bay K 8644 on pancreastatin secretion from ECL cells

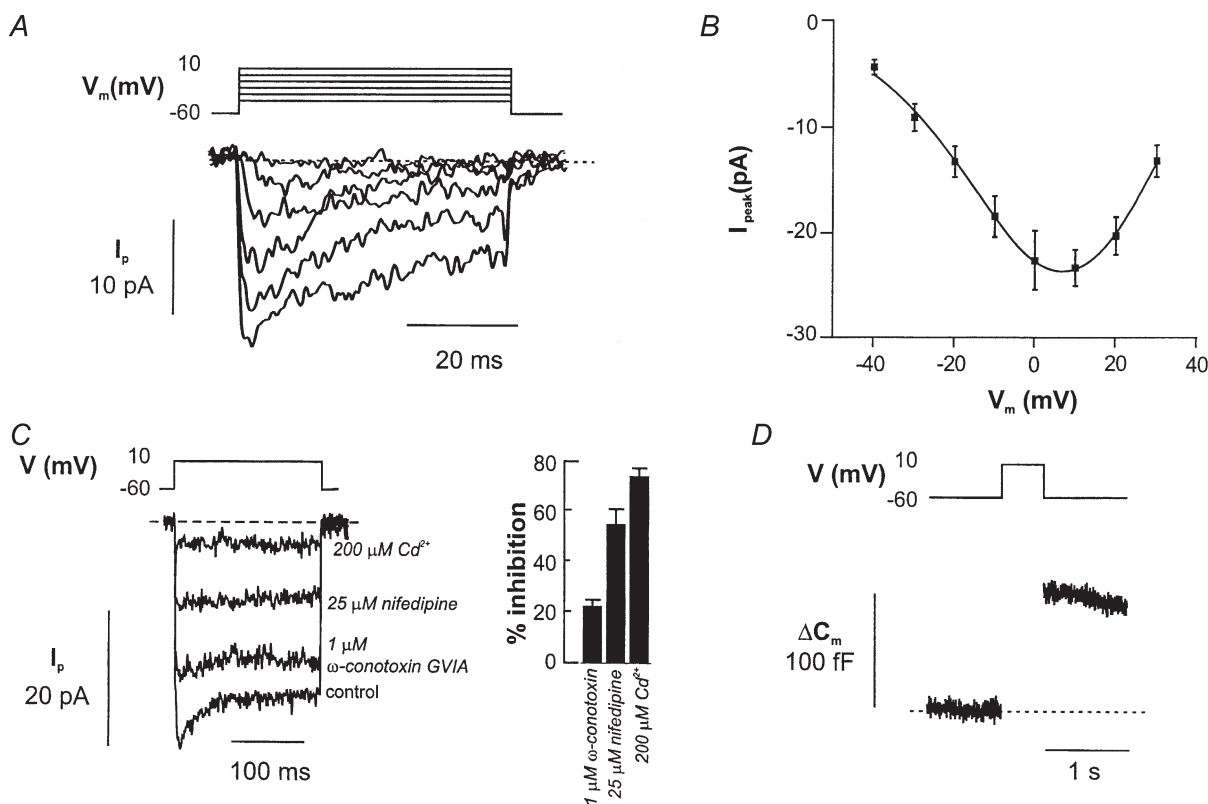
Concentration–response curve demonstrating the stimulatory effect of the L-type Ca<sup>2+</sup> channel activator Bay K 8644 on pancreastatin (PST) secretion. O, basal secretion. ▲, effect of combining 3  $\mu$ M Bay K 8644 with 10  $\mu$ M nifedipine. Means  $\pm$  S.E.M.;  $n = 6$ .



### Exocytosis elicited by voltage-clamp depolarisation: demonstration of L-type and N-type Ca<sup>2+</sup> channels

Since pancreastatin secretion was reduced by L-type channel blockers (Fig. 5*B* and *C*), we characterised voltage-gated Ca<sup>2+</sup> channels in single ECL cells using the patch-clamp technique. First we measured the current(*I*)–

voltage(*V*) relationship of the Ca<sup>2+</sup> current using the whole-cell configuration in the presence of 2.6 mM extracellular CaCl<sub>2</sub> (Fig. 8*A* and *B*). Depolarising pulses from –60 mV to various membrane potentials ranging between –40 to +30 mV with 10 mV increments were applied. The summed responses from 10 cells are shown in Fig. 8*B*. The



**Figure 8.** Electrophysiological measurements of Ca<sup>2+</sup> currents in single ECL cells

*A*, ECL cells were depolarised from –60 mV to voltages between –40 and +30 mV in 10 mV increments. For clarity only the responses up to +10 mV are shown. The experiments were performed with 2.6 mM extracellular Ca<sup>2+</sup> and in the presence of 0.1  $\mu$ g ml<sup>–1</sup> TTX. *B*, peak current (*I*)–voltage (*V*) relationship for the Ca<sup>2+</sup> current. The curve is drawn according to eqn (1). *C* (left panel), to investigate the presence of L-type and N-type voltage-dependent Ca<sup>2+</sup> channels on single ECL cells, inward currents were elicited by 200 ms voltage-clamp depolarisations from –60 to +10 mV and the Ca<sup>2+</sup> channel blockers  $\omega$ -conotoxin GVIA, nifedipine and Cd<sup>2+</sup> were added after each other at concentrations of 1  $\mu$ M, 25  $\mu$ M and 200  $\mu$ M, respectively. *C* (right panel), histogram demonstrating the effect of Ca<sup>2+</sup> channel blockers on the peak current. Means  $\pm$  S.E.M. of 3–8 experiments. *D*, increase in membrane capacitance upon a 500 ms depolarisation from –60 to 0 mV measured on a single ECL cell in the presence of NaCl.

activation properties of the  $\text{Ca}^{2+}$  current can be described by approximating the data points to a modified Boltzmann equation:

$$I = G \frac{V - V_r}{1 + \exp(-(V - V_h)/k)}, \quad (1)$$

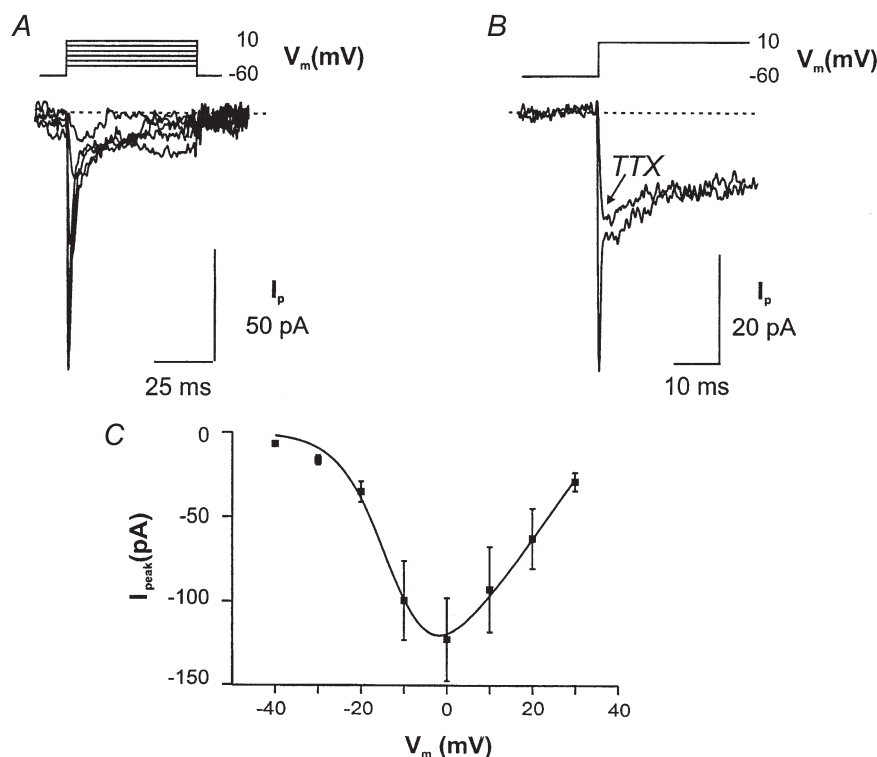
where  $I$  is the measured current,  $G$  is the whole-cell conductance of the calcium current (estimated to be  $0.9 \pm 0.2$  nS,  $n = 10$ ),  $V$  is the measured membrane potential,  $V_r$  is the reversal potential (determined to be  $53 \pm 5$  mV),  $V_h$  is the membrane potential at which the current is half-maximally activated ( $-3 \pm 4$  mV) and  $k$  is the slope coefficient ( $13 \pm 1$  mV). The maximal current was achieved when the cell was depolarised to +10 mV and amounted to  $-23 \pm 2$  pA. The results are comparable to those of previous studies on ECL cells using  $\text{Ba}^{2+}$  as charge carrier (Bufler *et al.* 1998).

The pharmacology of the  $\text{Ca}^{2+}$  current, induced by depolarising single ECL cells, was investigated using  $\text{Ba}^{2+}$  as charge carrier instead of  $\text{Ca}^{2+}$ . This generates currents larger in magnitude, which makes it easier to detect possible inhibition caused by the blockers. Fig. 8C (left panel) demonstrates that voltage-dependent  $\text{Ca}^{2+}$  channels are activated by depolarising a single ECL cell from  $-60$  to +10 mV during 200 ms. The N-type channel

blocker  $\omega$ -conotoxin GVIA suppressed the  $\text{Ca}^{2+}$  current and adding nifedipine ( $25 \mu\text{M}$ ) caused a further inhibition. Combining  $\omega$ -conotoxin GVIA and nifedipine did not result in total suppression of the current as indicated in Fig. 8C, suggesting that besides voltage-dependent L- and N-type  $\text{Ca}^{2+}$  channels, the ECL cells employ additional  $\text{Ca}^{2+}$  channels. Alternatively, the blockers were used at submaximal concentrations. Finally, the current was virtually abolished ( $\sim 90\%$  inhibition) by the non-selective calcium channel blocker  $\text{Cd}^{2+}$ . The mean effect of each individual blocker is shown in Fig. 8C (right panel). We also studied exocytosis evoked by influx of  $\text{Ca}^{2+}$  through voltage-dependent  $\text{Ca}^{2+}$  channels as shown in Fig. 8D. A 500 ms depolarisation from  $-60$  to +10 mV evoked an increase in capacitance of 106 fF in this particular cell and the mean membrane capacitance increase amounted to  $75 \pm 19$  fF ( $n = 8$ ).

### $\text{Na}^+$ channels are not involved in exocytosis

TTX-sensitive and voltage-dependent  $\text{Na}^+$  currents could be detected in ECL cells as shown in Fig. 9A and B. The voltage dependence was investigated by application of 50 ms depolarising pulses from  $-60$  mV to potentials ranging between  $-40$  to +10 mV. The mean peak currents (Fig. 9C) were approximated with eqn (1) to yield the activation properties. The calculated value for



**Figure 9.** Electrophysiological measurements of  $\text{Na}^+$  currents in single ECL cells

A, inward currents from a single ECL cell were elicited by depolarisation from  $-60$  mV to varying voltages between  $-40$  and +10 mV. B, the  $\text{Na}^+$  peak (the fast transient part of the current) was blocked by application of  $0.1 \mu\text{g ml}^{-1}$  TTX. C, peak  $I-V$  relationship for the  $\text{Na}^+$  current. The curve was drawn according to eqn (1). Means  $\pm$  S.E.M. of 6–8 experiments.

conductance ( $G$ ), the reversal potential ( $V_r$ ), the membrane potential at which the current is half-maximally activated ( $V_h$ ) and the slope coefficient ( $k$ ) was  $3.9 \pm 1.4$  nS,  $41 \pm 3$  mV,  $-12 \pm 3$  mV and  $5.7 \pm 1.4$  mV, respectively. The maximal current was achieved when a depolarising pulse from  $-60$  to  $0$  mV was applied and amounted to  $-122 \pm 25$  pA ( $n = 6$ ).

To investigate if the Na<sup>+</sup> current was important for exocytosis, NaCl was replaced with choline chloride (Fig. 10A). The Na<sup>+</sup> current did not seem to be coupled to exocytosis since the increase in membrane capacitance in the presence of choline chloride did not differ from that in the presence of NaCl (Fig. 10B). In accordance with the patch-clamp findings we found that pretreatment with  $0.1 \mu\text{g ml}^{-1}$  TTX or replacement of extracellular Na<sup>+</sup> with choline failed to affect either gastrin- or PACAP-stimulated pancreastatin secretion (Fig. 10C and D).

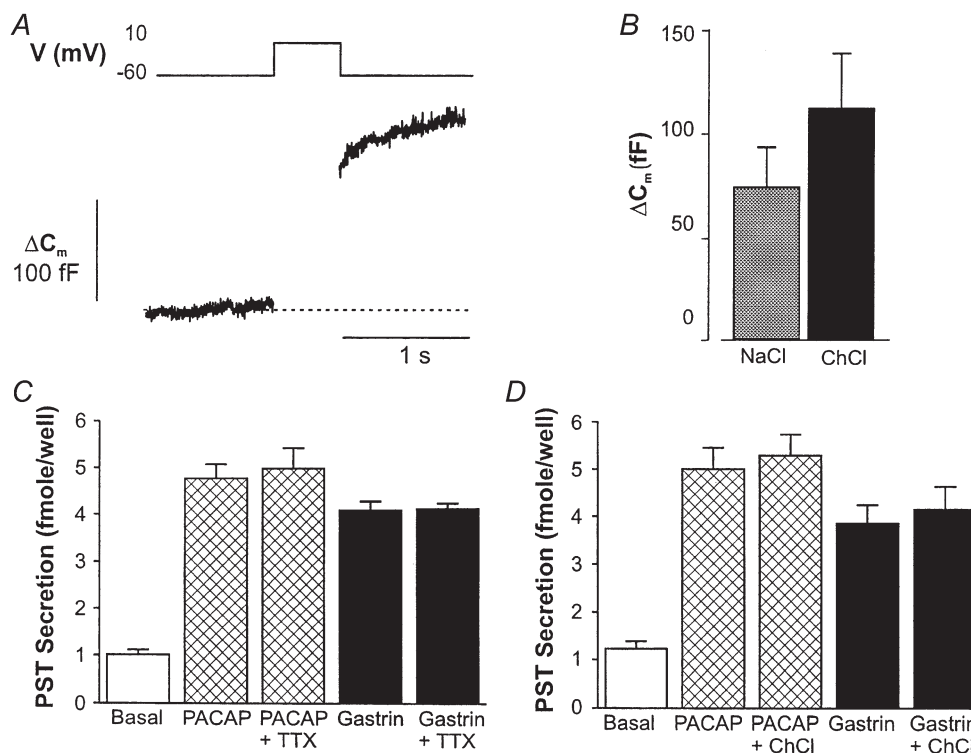
## DISCUSSION

Rat stomach ECL cells operate under the control of circulating gastrin. Local messengers/neurotransmitters also control ECL cell function but their physiological significance remains to be explored. Isolated ECL cells respond not only to gastrin (via an action on CCK<sub>2</sub>

receptors) but also to the neuropeptides PACAP-27, -38 and VIP (Lindström *et al.* 1997; Zeng *et al.* 1998, 1999a; Löffler *et al.* 1999). In fact, PACAP stimulates secretion with a greater efficacy than gastrin (Lindström *et al.* 1997; Löffler *et al.* 1999; Lindström & Håkanson, 2001). However, the pathways behind the stimulus–secretion coupling evoked by either gastrin or PACAP have so far not been examined in detail.

### Gastrin and PACAP evoke increases in cytosolic Ca<sup>2+</sup>

Isolated ECL cells, incubated in a medium containing  $1.28$  mM Ca<sup>2+</sup>, responded to both gastrin and PACAP with increases in [Ca<sup>2+</sup>]<sub>i</sub> in agreement with previous reports (Prinz *et al.* 1993, 1994; Zeng *et al.* 1996, 1999a). The initial rapid response is most likely due to the formation of IP<sub>3</sub>, which in turn acts on intracellular IP<sub>3</sub> receptors to mobilise Ca<sup>2+</sup> from stores in the endoplasmic reticulum (Berridge & Irvine, 1984). On the other hand, the sustained response probably depends on Ca<sup>2+</sup> influx as it is abolished in the absence of extracellular Ca<sup>2+</sup> (Prinz *et al.* 1993, 1994; Zeng *et al.* 1996). Infusion of Ca<sup>2+</sup> up to a free concentration of  $1.5 \mu\text{M}$  into the cytosol stimulated exocytosis in a linear fashion. The concentrations of [Ca<sup>2+</sup>]<sub>i</sub> required for exocytosis to occur in ECL cells (Fig. 2) were similar to those recorded after stimulating with



**Figure 10.** Effects of extracellular Na<sup>+</sup> on secretion from ECL cells

A, increase in membrane capacitance upon a 500 ms depolarisation from  $-60$  to  $0$  mV measured on a single ECL cell in the presence of choline chloride (ChCl). B, the mean increase in membrane capacitance in the presence of NaCl or ChCl, respectively. C, histogram showing that 30 min pretreatment with  $0.1 \mu\text{g ml}^{-1}$  TTX did not affect PACAP- or gastrin-evoked pancreastatin secretion. D, replacing extracellular NaCl with ChCl had no effect on PACAP- or gastrin-evoked pancreastatin secretion. Means  $\pm$  S.E.M. of 6–8 experiments.

maximally effective concentrations of gastrin and PACAP (Fig. 1). It is therefore likely that gastrin- and PACAP-evoked secretion is dependent upon increases in  $[Ca^{2+}]_i$ . This conclusion reinforces earlier observations using permeabilised ECL cells, where elevations of  $[Ca^{2+}]_i$  led to stimulated histamine secretion (Höhne-Zell *et al.* 1997).

### Is $Ca^{2+}$ entry or mobilisation of intracellular $Ca^{2+}$ responsible for secretion in ECL cells?

PACAP- and gastrin-induced secretion did not occur in the absence of extracellular  $Ca^{2+}$  despite a transient increase in  $[Ca^{2+}]_i$  (Figs 1 and 3). Stimulated secretion was also abolished in the presence of the non-selective  $Ca^{2+}$ -channel blocker  $LaCl_3$  (Fig. 5A). These results illustrate the importance of  $Ca^{2+}$  influx. Interestingly, basal pancreastatin release in  $Ca^{2+}$ -free medium was the same as in 2 mM  $Ca^{2+}$ , suggesting that whereas extracellular  $Ca^{2+}$  is important for stimulated secretion, it is not required for basal, unstimulated (constitutive?) release.

The importance of intracellular stores of  $Ca^{2+}$  for secretion was examined by pretreatment with thapsigargin, which is known to deplete intracellular  $Ca^{2+}$  stores by irreversibly inhibiting the  $Ca^{2+}$  pumps of the sarco- and endoplasmic reticulae (for a review see Treiman *et al.* 1998). Pretreatment with 100 nM thapsigargin for 4 h failed to impair either gastrin- or PACAP-evoked secretion. The thapsigargin concentrations used (1–100 nM) are known to deplete  $Ca^{2+}$  from other cells (Mason *et al.* 1991; Cavallini *et al.* 1995). Hence, although both gastrin and PACAP are capable of mobilising  $Ca^{2+}$  from intracellular stores, this does not seem to be critical for secretion, and we therefore suggest that  $Ca^{2+}$  entry rather than  $IP_3$ -triggered mobilisation of intracellular  $Ca^{2+}$  is responsible for exocytosis in ECL cells.

Thapsigargin is sometimes used to open store-operated (capacitative)  $Ca^{2+}$  channels, an effect which is thought to be secondary to the thapsigargin-evoked depletion of intracellular  $Ca^{2+}$  stores (Jan *et al.* 1999). An acute thapsigargin challenge (30 min) failed to induce pancreastatin secretion, which suggests that  $Ca^{2+}$  entry through store-operated channels either does not occur, is sub-threshold or does not occur in the vicinity of those secretory vesicles that are docked to the plasma membrane in preparation for exocytosis (Zhao *et al.* 1999).

### Gastrin- and PACAP-evoked secretion involve different $Ca^{2+}$ entry pathways

The results described above strongly suggest that  $Ca^{2+}$  entry, rather than mobilisation of intracellular  $Ca^{2+}$ , is critical for secretion from the ECL cells. However, the level of extracellular  $Ca^{2+}$  seemed to be more critical for gastrin-evoked than for PACAP-evoked secretion. At low extracellular  $Ca^{2+}$  concentrations (< 1 mM), gastrin failed to stimulate secretion, while PACAP maintained its ability to stimulate secretion at  $Ca^{2+}$  levels as low as 0.1 mM. The PACAP-induced response at this  $Ca^{2+}$

concentration was 45% of that observed at 2 mM  $Ca^{2+}$ . Conceivably, PACAP-stimulated secretion also at low extracellular  $Ca^{2+}$  is due to activation of an additional second messenger pathway besides  $Ca^{2+}$  influx. Alternatively, PACAP and gastrin stimulate different (or differently located)  $Ca^{2+}$  entry pathways.

The importance of the various  $Ca^{2+}$  channels was studied by using selective blockers of the different channel types (see Table 2). No significant reduction in gastrin- or PACAP-evoked secretion was seen when blockers of T-, P- and Q-type  $Ca^{2+}$  channels were used. Hence, such channels do not appear to be involved in ECL cell exocytosis. On the other hand, various L-type channel blockers and the N-type blocker  $\omega$ -conotoxin GVIA inhibited gastrin-evoked secretion (Fig. 5), L-type channel blockers being more effective (~75 vs. 40% for N-type). The presence of L-type and N-type  $Ca^{2+}$  channels in ECL cells was further confirmed by measurements of depolarisation-evoked whole-cell currents in single cells. The inward  $Ca^{2+}$  current was reduced to the same degree as secretion by nifedipine and  $\omega$ -conotoxin GVIA. Indeed, in earlier studies the ECL cells have been shown to be equipped with L-type channels and the existence of N-type channels was also suggested (Bufler *et al.* 1998). The L-type channel blocker nifedipine also reduced the increase in  $[Ca^{2+}]_i$  in response to gastrin (Table 1). These results are in contrast to the recent results of Zeng *et al.* (1999b) which indicated that L-type channels are not involved in gastrin-evoked increases in  $[Ca^{2+}]_i$  or histamine secretion. The L-type  $Ca^{2+}$  channel activator Bay K 8644 raised cytosolic  $Ca^{2+}$  and induced pancreastatin secretion, thus providing further evidence for the involvement of L-type channels in exocytosis. Indeed, Bay K 8644 has been shown to stimulate secretion from other cell types as well (Yamada *et al.* 1996; Jordinson *et al.* 1998; Negishi *et al.* 1999). Surprisingly, Bay K 8644 did not enhance gastrin- or PACAP-evoked secretion, possibly because gastrin and PACAP at the concentrations used already induce sufficient activation of the L-type channels. Influx of  $Ca^{2+}$  through  $Ca^{2+}$  channels have been shown to be of importance in mediating secretion from several types of endocrine cells (Henkel & Almers, 1996) including cholecystokinin-secreting I cells (Chang *et al.* 2000) and insulin secreting  $\beta$  cells (Rorsman *et al.* 2000).

Although the results of the present study indicate that gastrin-induced secretion involves the opening of both L-type and N-type channels, the combination did not produce an additive inhibitory effect (Fig. 6A). SKF 96365, which is an inhibitor of both receptor-operated and L-type  $Ca^{2+}$  channels (Merritt *et al.* 1990), blocked gastrin-induced secretion to the same extent as nifedipine (Table 1). Combining nifedipine and SKF 96365 did not result in further inhibition of gastrin-evoked secretion, suggesting that gastrin opens L-type and N-type channels but not receptor-operated channels.



However, 25% of the secretory response to gastrin remained after treatment with L-type and N-type Ca<sup>2+</sup> channel blockers. This might suggest that additional Ca<sup>2+</sup> entry pathways exist or that L-type and N-type channels are not completely blocked by the inhibitors at the concentrations used.

At variance with gastrin-evoked secretion, PACAP-evoked secretion was reduced only by ~40% by nifedipine and not at all by  $\omega$ -conotoxin GVIA, which agrees with the report by Zeng *et al.* (1999b). This suggests that PACAP-stimulated secretion is not as dependent on influx of Ca<sup>2+</sup> through voltage-sensitive channels as gastrin-induced secretion. Instead, it is likely that a voltage-independent Ca<sup>2+</sup> entry pathway is involved. SKF 96365 was by far the most potent blocker of PACAP-evoked secretion (~85% inhibition). This inhibitory effect is probably not due to L-type channel blockade, since the effect of SKF 96365 was more pronounced compared to the more selective L-type channel blocker nifedipine. Also, combining SKF 96365 with nifedipine resulted in total blockade of PACAP-evoked secretion suggesting that PACAP induces Ca<sup>2+</sup> entry through both L-type and receptor-operated Ca<sup>2+</sup> channels. PACAP is known to stimulate intracellular levels of cAMP and indeed this appears to be the case in ECL cells (Zeng *et al.* 1999a). The opening of receptor-operated channels has been suggested to be regulated by second messengers such as cAMP (Lenz & Kleineke, 1997; Barritt, 1999). Hence, this might explain why PACAP-induced secretion and not gastrin-stimulated secretion involves receptor-operated channels. The involvement of different Ca<sup>2+</sup> channels might generate different types (and different locations) of intracellular Ca<sup>2+</sup> signals.

#### Dynamics of exocytosis: quantitative, morphological considerations

When the membrane potential was depolarised to generate a maximal inward Ca<sup>2+</sup> current the cells responded with an increase in membrane capacitance, reflecting exocytosis, of 100 fF. This gives further evidence for voltage-dependent exocytosis in ECL cells. Depolarisation was found to open TTX-sensitive Na<sup>+</sup> channels in addition to Ca<sup>2+</sup> channels (Fig. 9). This is in contrast with Bufler *et al.* (1998) who failed to identify Na<sup>+</sup> channels in ECL cells. However, Na<sup>+</sup> influx through these channels does not seem to be necessary for exocytosis since addition of TTX and replacement of extracellular Na<sup>+</sup> with choline did not significantly affect depolarisation-induced exocytosis or gastrin- and PACAP-evoked pancreastatin secretion (Fig. 9).

Ultrastructural studies have indicated that the mean profile diameter of secretory vesicles close to the plasma membrane in ECL cells is around 200 nm (Zhao *et al.* 1999). This means that the surface area of the average secretory vesicle is approximately 0.125  $\mu\text{m}^2$ . The specific capacitance for biological membranes is 10 fF  $\mu\text{m}^{-2}$  (Hille, 1991), hence upon fusion with the plasma membrane each

vesicle adds about 1.25 fF of capacitance. Each cell contains a total of about 10 fmol histamine (Prinz *et al.* 1993; Sakai *et al.* 1995; E. Lindström *et al.* unpublished observations) and 5 amol pancreastatin (E. Lindström *et al.* unpublished observations) in approximately 10 000 secretory vesicles (calculated from Zhao *et al.* 1999). Depolarisation of the ECL cells resulted in an 100 fF increase in cell capacitance, and we can thus estimate the number of vesicles released from a single cell during 500 ms to be about 80. This readily releasable pool, which probably represents primed vesicles docked to the plasma membrane (Zhao *et al.* 1999), thus constitutes close to 1% of the secretory vesicle compartment (100 amol histamine per cell). Similar estimations have been made in other endocrine cells (see for example Eliasson *et al.* 1997).

Intracellular infusion of Ca<sup>2+</sup> resulted in a sustained capacitance increase. Infusion of 1.5  $\mu\text{M}$  Ca<sup>2+</sup> resulted in a rate of capacitance increase of 9.4 fF s<sup>-1</sup> which corresponds to an increase of 1.7 pF over a 3 min period. Using the above conversion factor (1.25 fF) we can thus estimate that approximately 1000 vesicles are being released during the 3 min time frame. This vesicle population possibly represents a less readily releasable pool, which needs to be translocated and chemically modified (primed) prior to release. This pool represents about 10% of the secretory vesicle compartment (1 fmol histamine per cell).

#### Concluding remarks

Gastrin controls the ECL cells via the circulation while the neuropeptide PACAP acts locally, being released from nerve fibres in the vicinity of the oxyntic glands. Thus, ECL cells are under hormonal as well as nervous control in turn controlling HCl secretion from parietal cells as part of the gastrin–ECL cell–parietal cell pathway. The results of the present study indicate that gastrin- and PACAP-induced secretion from ECL cells depends on the influx of extracellular Ca<sup>2+</sup> rather than on the mobilisation of intracellular Ca<sup>2+</sup>. The Ca<sup>2+</sup> influx responsible for exocytosis upon gastrin stimulation appears to involve voltage-gated L-type and N-type Ca<sup>2+</sup> channels. PACAP-induced secretion, on the other hand, involves L-type and receptor-operated Ca<sup>2+</sup> channels. However, the mechanisms behind the opening of these Ca<sup>2+</sup> channels in the ECL cells are unknown and will be the subject of further investigation.

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