Signal Transduction by the Polymeric Immunoglobulin Receptor Suggests a Role in Regulation of Receptor Transcytosis

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Abstract. Many membrane traffic events that were previously thought to be constitutive recently have been found to be regulated by a variety of intracellular signaling pathways. The polymeric immunoglobulin receptor (plgR) transcytoses dimeric IgA (dlgA) from the basolateral to the apical surface of polarized epithelial cells. Transcytosis is stimulated by binding of dlgA to the plgR, indicating that the plgR can transduce a signal to the cytoplasmic machinery responsible for membrane traffic. We report that dlgA binding to the plgR causes activation of protein kinase C (PKC) and release of inositol 1,4,5-trisphosphate (IP3). The IP3 causes an elevation of intracellular Ca. Artificially activating PKC with phorbol myristate acetate or poisoning the calcium pump with thapsigargin stimulates transcytosis of plgR, while the intracellular Ca chelator BAPTA-AM inhibits transcytosis. Our data suggest that ligand-induced signaling by the plgR may regulate membrane traffic via well-known second messenger pathways involving PKC, IP3, and Ca. This may be a model of a general means by which membrane traffic is regulated by receptor–ligand interaction and signaling pathways.

It has been known for decades that certain steps in membrane traffic, such as exocytosis of synaptic vesicles and dense core secretory granules, are highly regulated. However, in recent years it has become apparent that almost every "constitutive" step in membrane traffic is subject to regulation by intracellular signaling mechanisms (for review see Mostov and Cardone, 1995). In many cases this regulation has been uncovered by pharmacological manipulations. For example, treatment with agents that specifically act on heterotrimeric G proteins, such as cholera or pertussis toxins, has been shown to affect traffic through the Golgi (Stow et al., 1991). In some instances genetic methods have been used, e.g., a phosphatidylinositol 3-kinase (PI3K) has been demonstrated to play a role in delivery of proteins to the yeast vacuole (Schu et al., 1993). However, there is a paucity of data to tie specific receptors and signaling pathways to the physiologic regulation of individual steps in membrane traffic.

As a model system to study regulation of traffic, we have been using the polymeric immunoglobulin receptor (plgR), which transcytoses dimeric IgA (dlgA) from the basolateral to the apical surface of polarized epithelial cells (Mostov, 1994; Mostov and Cardone, 1995). The cytoplasmic domain of the plgR contains a basolateral targeting signal, which serves to direct the plgR to the basolateral surface from either the TGN or the endocytotic pathway (Aroeti et al., 1993; Casanova et al., 1991). Phosphorylation of Ser664 in this signal has been shown to affect traffic through the Golgi (Stow et al., 1991). In some instances genetic methods have been used, e.g., a phosphatidylinositol 3-kinase (PI3K) has been demonstrated to play a role in delivery of proteins to the yeast vacuole (Schu et al., 1993). However, there is a paucity of data to tie specific receptors and signaling pathways to the physiologic regulation of individual steps in membrane traffic.

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Abbriviations used in this paper: BAPTA-AM, 1,2-bis(O'-aminophenoxy)-ethane-N,N,N',N'-tetraacetic acid, tetraacetoxymethyl ester; Ca, intracellular free calcium; DAG, diacylglyceride; dlgA, dimeric IgA; IP3, inositol 1,4,5-trisphosphate; PI-PLC, phosphatidylinositol-specific phospholipase C; PKC, protein kinase C.
tation of the heterotrimeric Gs protein stimulates transcytosis (Bomsel and Mostov, 1992, 1993). At least a portion of this stimulation is due to the production of cAMP and activation of protein kinase A (Hansen and Casanova, 1994), although indirect data suggest that Gsα and Gβγ may play an additional, cAMP-independent role (Bomsel and Mostov, 1993). Second, treatment of MDCK cells with PMA activates the α and ε isozymes of protein kinase C (PKC), and these in turn stimulate transcytosis (Cardone et al., 1994). Both the Gs and PKC pathways seem to stimulate not only pIgR transcytosis, but more generally apical delivery of a variety of molecules in the transcytotic, recycling, and biosynthetic pathways (Cardone et al., 1994; Eker et al., 1994; Hansen and Casanova, 1994; Pimplikar et al., 1994; Pimplikar and Simons, 1994).

What are the signaling pathways involved in the stimulation of pIgR transcytosis by dlgA binding? Given the ability of the PKC and Gs pathways to stimulate transcytosis, it seemed reasonable to hypothesize that dlgA binding to pIgR might lead to activation of one of these pathways, and thereby cause stimulation of transcytosis. We now report that dlgA binding to pIgR gave a rapid activation of PKCε, production of inositol 1,4,5-trisphosphate (IP3) and elevation of intracellular free Ca (Ca2+). We further show that artificially raising Ca2+ with the drug thapsigargin stimulates transcytosis, while chelating intracellular Ca2+ with 1,2-bis(O-aminophenoxy)-ethane-N,N,N′,N′-tetraacetic acid (BAPTA-AM) inhibits transcytosis.

Materials and Methods

Cell Growth

MDCK type II cells and MDCK cells that have been stably transfected with the cDNA for rabbit pIgR were maintained on plastic 10-cm dishes, using MEM (UCSF Cell Culture Facility), 5% FBS, penicillin, and streptomycin, as previously described (Cardone et al., 1994). Cells were plated at confluent density onto Transwells (Corning-Costar Corp., Cambridge, MA), 0.4 μm pore size, of various diameters.

Activation of PKC in Response to dlgA Binding to the pIgR

We used a very similar approach to our previous study of the activation of PKC by PMA. Cells were grown on 75-mm Transwell filters for 5 d. Dimeric human myeloma IgA (300 μg/ml, kindly provided by Prof. J.-P. Vaerman, Catholic University of Louvain, Brussels, Belgium) was added to the basolateral medium at 37°C for the times indicated. The zero time control did not receive dlgA. Mouse IgG at 300 μg/ml was used as a control. The filters were then transferred to 4°C and the medium removed. Cells were scraped from the filters in 0.7 ml ice-cold homogenization buffer (10 mM Tris-HCl, pH 7.5, 1 mM EDTA, 1 mM EGTA, 17 μg/ml PMSF, 5 μg/ml each aprotinin, soybean trypsin inhibitor, and leupeptin) and homogenized. Homogenates were centrifuged at 10,000 g for 30 min and the cytosolic supernatant was collected. The pellets were resuspended in 0.7 ml homogenization buffer containing 0.1% Triton X-100. Equal amounts of protein were run on 10% gels, followed by blotting and probing with an insulin-specific polyclonal antibody to α PKC ( Gibco BRL, Gaithersburg, MD) and iodinated protein A. The distribution of the insulin in the soluble and pellet fractions was quantitated using a PhosphorImager (Molecular Dynamics, Inc., Sunnyvale, CA).

Production of IP3 in Response to dlgA Binding to the pIgR

MDCK cells expressing pIgR were grown on 24-mm Transwells for 4 d in MEM containing 5% FBS. The cells were then transferred into MEM containing 6 mg/ml BSA in place of the FBS (MEM-BSA) for 24 h. Cells were treated with 10 mM LiCl in MEM-BSA for 10 min before the assay and then their basolateral surface was exposed to dlgA at 300 μg/ml in MEM-BSA and 10 mM LiCl for the indicated times at 37°C. In certain experiments the dlgA was added to the apical medium, instead of the basolateral medium. Filters were removed and tumbled for 5 min in 20% TCA at 4°C. The TCA extract was then centrifuged at 15,000 g. The TCA extract was then precipitated at 4°C in TCA and washed four times with diethyl ether. The IP3 concentration was determined with a competitive binding assay kit (Dupont-NEN, Boston, MA). Measurements were adjusted to protein (dye binding assay, Bio-Rad Laboratories, Richmond, CA) in the TCA precipitate from each sample. Where indicated, cells were pretreated with 33 μM nocodazole (Sigma Chemical Co., St. Louis, MO) for 1 h at 4°C, or with 50 μM leupeptin (Chemicon International Inc., Temecula, CA) for 1 h at 37°C.

Effect of Thapsigargin or BAPTA-AM on dlgA Transcytosis

The assay to follow the fate of a cohort of preinternalized dlgA was performed as previously described (Cardone et al., 1994). Briefly, cells grown on 12-mm Transwells were allowed to internalize [125I]dlgA from the basolateral surface for 10 min. This and subsequent steps were at 37°C, using MEM-BSA in Hanks’ salts and 25 mM Hepes, pH 7.4. Cells were then washed for 5 min, so that >95% of the [125I]dlgA associated with the cells is intracellular. The release of [125I]dlgA into the apical and basolateral medium over a 2-h time course was then measured. [125I]dlgA released apically is transcytosed dlgA, while [35S]dlgA released into the basal medium is recycled dlgA. Where indicated, 5 μM thapsigargin (BIOMOL Research Laboratories, Inc., Plymouth Meeting, PA) was included in the apical and basolateral media during the 2-h chase. Alternatively, cells were pretreated with 50 μM BAPTA-AM (BIOMOL Research Laboratories, Inc.) for 1 h before the internalization of dlgA and the BAPTA-AM was present throughout subsequent steps. The pretreatment is necessary to give time for the BAPTA-AM to permeate into the cells and be cleaved to the active BAPTA. The total amount of ligand endocytosed was not changed by this treatment.

Fluorescence Techniques

Equipment. The basic components of the experimental apparatus consist of the following: an inverted epifluorescence microscope (Diaphot, Nikon Inc. Instrument Group, Melville, NY) equipped with a 75 W Xenon lamp, Nikon CF Fluor × 100/1.3 NA oil immersion objective, fluorescence excitation filter wheel (Metal Tek) coupled to an additional filter wheel (Metal Tek, Morrisville, NC) holding a variety of neutral density filters, computer controllable excitation light shutter, and a cooled CCD camera (Princeton Scientific Instruments Inc., Monmouth Junction, NJ) with a frame transfer chip (EE-37) and 12-bit readout. In addition, for some experiments a CCD camera (CCD 200; Video Scope International Ltd., Washington, DC) attached to an image intensifier (VS2525, Video Scope International Ltd.) was included in the fluorescence detection system. The emitted fluorescence signal is relayed as real time continuous output to an IBM PC/AT compatible clone and the image pairs were collected on a Sierra Pinnacle Micro optical disk drive (1.3 GByte) where data can be stored for future analysis on a pixel-by-pixel basis using the Metafluor software package (Universal Imaging Corp., Chester, PA). Quantitative image pairs at 340 and 380 nm excitation with emission at 510 nm, were obtained every 15 s over a period of ~15 min. Neutral density filters coupled to the excitation filters minimized the transmitted excitation light to between 1 and 10% depending on the experiment, to minimize photobleaching and photodynamic damage to the cells. The individual wavelength intensities were stable over the experimental time course. The fluorescence excitation was shuttered off, except during the brief periods required to record an image. To correct for intrinsic autofluorescence and background, background images were obtained on a new shard of filter (see below) containing a confluent monolayer of cells that was not loaded with the dye, using the exact acquisition configuration used for the experimental protocol. These background images were subtracted from the corresponding images of cell fluorescence and background corrected ratios were generated for data analysis.

Fluorescence Loading and Cell Preparation for Imaging. MDCK cells were grown to confluence (2–3 d after plating) on Nunc aluminum oxide inserts (25 mm diameter) and maintained in culture medium (DMEM) containing 5% FBS and 2% penicillin-streptomycin. Cells maintained at room temperature in Hepes buffered saline solution (137 mM NaCl, 4 mM KCl, 10 mM Hepes, 11 mM glucose, 1.5 mM CaCl2, 0.5 mM MgCl2, pH 7.4) were loaded with the membrane-permeant form of the intracellular Ca indicator...
tor fura-2 acetoxy methyl ester (5 μM) and the organic anion transport inhibitor, probenecid (3 mM) for 30 min at room temperature. The presence of probenecid was necessary to inhibit substantial leakage of dye out of the cells. Others have also observed significant leakage of fura-2 out of cells of probenicid was necessary to inhibit substantial leakage of dye out of the inhibitor, proberticid (3 mM) for 30 min at room temperature. The presence of probenecid containing salt solution before the start of the chamber. The cells were maintained at a temperature of 37.0°C for the experiments. Cells were first visualized under transmitted light with a Nikon CF Fluor ×100/1.3 NA oil immersion objective before starting the fluorescence measurements. Dimeric IgA or canine IgG (Sigma Chemical Co.) were added to the perfusion reservoir for a final concentration of 0.1 mg/ml.

Calibration of Signal. To correlate a change in the 340/380 ratio with relative changes in the intracellular Ca values (Ca,) an in situ calibration of the fura-2 signal was performed in some experiments as previously described (Nigam et al., 1992; Silver et al., 1993). Briefly calibration of the fura-2 signal was carried out in the presence of the Ca ionophore ionomycin (10 μM) in the presence of the Hepes buffered salt solution containing either 1.5 mM Ca (experimental superfusate) or 2 mM EGTA titrated to pH 7.4. Intracellular Ca levels were calculated as described by Grynkiewicz et al. (1985). Each cell in the field was calibrated on a pixel-by-pixel basis with its own corresponding R min and R max value according to this technique.

Results are presented as means ± SEM where n equals the number of cells. The means represent the average of individual cells. Comparisons were made by a paired t test.

Results
dlgA Binding to the plgR Causes Activation of PKC-ε
We have found previously that treatment of MDCK cells with PMA causes activation of PKC-ε and -α (Cardone et al., 1994). Activation can be measured by the translocation of PKC from the cytosol to particulate anchoring receptors for activated C kinase (RACKs) (Mochly-Rosen, 1995). We found that addition of dlgA to MDCK cells that had been transfected with the plgR caused a rapid translocation of PKC-ε from the soluble to the particulate fraction (Fig. 1). Translocation peaked at 3.5 min. Whereas PMA causes a permanent activation of PKC and eventually its down-regulation, physiological activation with diacylglyceride (DAG) is generally short-lived, consistent with our observed results. We did not observe any translocation if control IgG was used in place of dlgA.

In some experiments translocation of PKC-α was also observed. However, for unknown reasons this result was quite variable between experiments (unlike the reproducible results with PKC-ε), and so we cannot be sure of the involvement of PKC-α.

dlgA Binding Causes Production of IP3
PKC-ε is classically activated by DAG, and there is preliminary data that PKC-ε is also activated by phosphatidyl inositol 3,4,5-trisphosphate (PI3K). DAG is commonly produced by two pathways. One path is hydrolysis of phosphatidyl inositol 4,5-bis-phosphate (PIP2) by phosphatidyl inositol-specific phospholipase C (PI-PLC) to DAG and IP3, as described above. The other is hydrolysis of phosphatidylinositol by phospholipase D to phosphatic acid, which is then hydrolyzed to DAG. If the PI-PLC pathway is involved, we should also find that IP3 is produced. As shown in Fig. 2, addition of dlgA to the plgR-expressing MDCK cells resulted in production of IP3. Production peaked at 5 min, and soon declined almost to baseline. As controls for specificity, IgG (not shown) or

![Figure 1. Translocation of PKC-ε from the cytosol to a pellet fraction in response to dlgA binding. MDCK cells were treated with dlgA basolaterally for 0, 0.5, 1, 3.5, 5, or 15 min, or with control IgG for 3.5 or 15 min and then fractionated into cytosol and pellet. Equal amounts of protein from each fraction were subjected to SDS-10% PAGE and blotted using a polyclonal antibody against PKC-ε. Data are mean ± SE of four separate experiments.](https://www.jcb.org/cgi/doi/10.1083/jcb.9999999)

![Figure 2. Production of IP3 in response to dlgA binding. Intracellular concentration of IP3 was measured in MDCK cells expressing the plgR and MDCK control cells exposed basolaterally to dlgA for the indicated times. Data are mean ± SE of quadruplicate filters and are representative of four separate experiments.](https://www.jcb.org/cgi/doi/10.1083/jcb.9999999)
cells not transfected with the plgR (Fig. 3) gave no response above background.

Although the plgR is cleaved to secretory component at the apical surface, this cleavage is relatively slow, so there is a pool of uncleaved receptor at the apical surface. We have found previously that ligand can be bound to this apical plgR and can be internalized into an apical recycling compartment (Breitfeld et al., 1989). Moreover, we reported that the size of this pool can be increased by treatment of the cells with leupeptin, which inhibits the protease that produces secretory component. We found that addition of dlgA to only the apical surface of plgR expressing MDCK cells also led to the production of IP3 (Fig. 3). Treatment of the cells with leupeptin increased the signal obtained with apically applied plgR, which is consistent with the accumulation of apical plgR caused by leupeptin. These data indicate that the plgR signaling pathway also extends to the plgR that is at the apical surface or has been endocytosed from that surface. The signal produced by apically applied dlgA was weaker than that resulting from basolaterally applied dlgA, which is in keeping with the smaller amount of plgR at the apical surface. It seems likely that apical dlgA might also produce a translocation of PKC and an elevation of Ca$_i$ (see below). However, these assays were generally less sensitive and more cumbersome than the IP3 production assay (and in the case of Ca$_i$ measurement, our superfusion apparatus only allowed simultaneous addition of dlgA to both surfaces of the filter-grown cells and did not permit selective addition of dlgA to only the apical surface), so we did not pursue using them to detect the weak signal from apical dlgA.

**Intact Microtubules Are Required for plgR Signaling**

Microtubules are required for transcytosis of dlgA and plgR, and for the organization of the endosomal system in polarized epithelial cells (Breitfeld et al., 1990; Hunziker et al., 1990; Apodaca et al., 1994b). Experimentally, transcytosis can be divided into at least three steps (Apodaca et al., 1994a, b; Song et al., 1994a): (1) internalization from the basolateral surface into basolateral early endosomes; (2) transport from basolateral early endosomes to an apical recycling compartment; (3) delivery from the apical recycling compartment to the apical plasma membrane. Step 2 is strongly inhibited by the microtubule depolymerization agent, nocodazole, indicating a requirement for microtubules for this step (Hunziker et al., 1990; Apodaca et al., 1994b). Furthermore, the apical recycling compartment is normally clustered around the centriole underneath the center of the apical plasma membrane (Hughson and Hopkins, 1990). Nocodazole treatment causes the apical recycling compartment to disperse throughout the apical cytoplasm (Apodaca et al., 1994b). This indicates that

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**Figure 4.** Increase in Ca$_i$ in response to dlgA. (A) Effect of dlgA on the 340/380 ratio. The ordinate represents the 340/380 ratio and the x-axis is time (s). This figure depicts the 340/380 responses of seven individual cells in a field of view exposed at 170 s to dlgA (0.1 mg/ml). Within 90 s an increase in the 340/380 signal was evident in almost all of the cells. By 400 s all of the cells had an increase in the 340/380 ratio with addition of dlgA. (B) Effect of control IgG on the 340/380 ratio. The y-axis is the 340/380 ratio and the abscissa is time in seconds. Canine IgG (0.1 mg/ml; Sigma Chemical Co.) was added at 115 s as shown by the arrow. Over the time course for this experiment there was no effect on the 340/380 ratio in response to IgG. (D) Percent change in the 340/380 ratio with dlgA and IgG. Ratio values were normalized as the percent change from the initial baseline value. Addition of dlgA resulted in an overall increase of 18% ± 2% (n = 180) in the ratio signal above the baseline 340/380 value. In contrast there was no change in the initial 340/380 ratio with addition of IgG (-0.2% ± 0.6% n = 175). (E) Pseudocolor ratio images of MDCK cells grown on inserts and loaded with the intracellular Ca indicator, fura-2 visualized at ×100. The pseudocolor corresponds to the ratio values as follows: blue-green = low ratio = low Ca$_i$, to orange-red = high ratio = high Ca$_i$. (Left) initial basal ratio values in this field of cells. Addition of IgG to the superfusate (center) did not result in an increase in the 340/380 ratio on a cell-per-cell basis as evidenced by the pseudocolor image, rather it suggests a small decrease in the ratio (decreased Ca$_i$) by the preponderance of green compared with the left panel. Addition of dlgA (right) results in an increase in the ratio (increased Ca$_i$) as indicated by the switch to orange-red pseudocolor.
the normal functional organization of the apical recycling compartment requires intact microtubules. To examine the importance of microtubules in plgR signaling, we treated cells with nocodazole and then exposed to dlgA at either the basolateral or apical surface. The production of IP3 in response to the dlgA was assessed. As shown in Fig. 3, nocodazole treatment abrogated signaling by the plgR. A control of nocodazole treatment without dlgA exposure had no significant effect on the IP3 level in the cell.

dlgA Binding to plgR Causes an Increase in Ca

IP3 is a second messenger that causes the release of Ca from intracellular stores, and thus a rise in Ca. We used the Ca-sensitive fluorescent dye, fura-2 to measure changes in Ca in response to binding of dlgA. Fig. 4 A represents a typical recording of the experimentally determined 340/380 ratio as a function of time. In this particular experiment seven cells were individually tracked. The ordinate is the 340/380 ratio as a function of time. The chemistry of fura-2 binding to free Ca dictates that increases in the 340/380 ratio correspond to increases in Ca, and decreases in the 340/380 ratio correspond to decreases in Ca. In the example shown in Figure 4 A, dlgA (0.1 mg/ml) was added at the arrow (≈170 s). The mean steady-state ratio value before addition of dlgA in this group of cells averaged 0.68 ± 0.01. Upon addition of dlgA the 340/380 ratio began to increase ~90 s after addition of the ligand and then within another 2 min reached a steady-state value which was greater than that measured before addition of dlgA (0.97 ± 0.03 vs. 0.68 ± 0.01). In all experiments the response to dlgA (or, as a negative control, IgG) was followed for 10 min.

As shown in Fig. 4 A, the increase in the 340/380 signal was very similar for these seven cells. For a total of 180 cells studied, 141 responded to addition of dlgA; however, the magnitude of the response and rate of increase of the 340/380 ratio were quite variable. We found that cells which were going to show a dlgA-mediated increase in the 340/380 ratio responded within the first 2 min of adding the ligand to the superfusate and generally reached a peak by 200–400 s, after which the Ca was often regulated back toward the pre-dlgA level within 10 min. Therefore for each cell studied the 340/380 ratios were compared 60 s before addition of ligand and 200–400 s after addition of dlgA (IgG).

To be sure that the change in the 340/380 ratio observed with addition of dlgA was due to changes in Ca, we performed in situ calibrations at the end of several experiments. As shown in Fig. 4 B, for a total of 50 cells, addition of dlgA caused Ca to increase significantly from 100 nM ± 8 to 145 nM ± 25 (P < 0.02). These data demonstrate that increases in the 340/380 ratio with addition of dlgA correspond to increases in Ca.

To be certain that the increases in the 340/380 ratio were due to a dlgA-mediated response, experiments were performed where canine IgG was substituted for dlgA. Fig. 4 C is a time course of the 340/380 ratio for 10 cells exposed to IgG. The baseline ratio values averaged 0.70 ± 0.001. Addition of IgG (115 s) did not appear to have any effect on the 340/380 signal. As shown in the figure, the mean ratio calculated 265 s after addition of IgG (0.69 ± 0.005) was no different than the initial pre-IgG ratio value.

The quantitative differential responses to dlgA and IgG are summarized in Fig. 4 D. Addition of dlgA resulted in an 18% ± 2% (n = 180) increase in the 340/380 ratio above the initial baseline value, while exposure to IgG had no effect on the 340/380 ratio (~0.2% ± 0.6% n = 175).

Finally, Fig. 4 E presents an actual image of a group of cells, using pseudocolor to represent Ca. The left panel shows the baseline of untreated cells, while the center is of negative control cells treated with IgG. The right panel is of cells treated with dlgA. The shift from blue-green indicating low Ca in the left and center panels to yellow-red in the right panel is indicative of an increase in Ca in each of the cells in this field. These data strongly support the hypothesis that dlgA-induced transcytosis involves an IP3-sensitive Ca signaling pathway. However, the prolonged elevation of Ca after stimulation withdlgA raises the possibility that an additional mechanism(s) may be involved in elevation of Ca.

Role of Ca in Transcytosis

We next asked if the increase in Ca produced by dlgA binding could stimulate transcytosis. We used thapsigargin, which poisons the pump that normally sequesters Ca into intracellular stores. Short-term treatment with thapsigargin is widely used to raise Ca (Suzuki et al., 1991). As shown in Fig. 5 A, treatment with thapsigargin accelerated transcytosis of plgR. The effect was greatest, about two-fold, at early time points. Neither the ultimate extent of transcytosis nor the recycling of dlgA to the basolateral medium were significantly affected by thapsigargin. These results with thapsigargin are strikingly similar in magnitude and kinetics to those obtained previously with PMA (Cardone et al., 1994). However, down regulation of the Ca-sensitive isozymes of PKC by chronic exposure to PMA did not alter the response to thapsigargin (not shown), indicating that the effect of thapsigargin is not due to a secondary stimulation of PKC.

We further investigated the possible role of intracellular Ca with the drug BAPTA-AM. This compound is membrane permeable. After reaching the cytoplasm, the aetoxyethyl ester groups are cleaved off by intracellular esterases, releasing free BAPTA, a calcium chelator. As shown in Fig. 5 B, BAPTA-AM treatment inhibits transcytosis by ≈50%, but has little effect on recycling. This suggests that Ca probably plays an essential role(s) in transcytosis of dlgA by plgR.

Discussion

Our previous finding that dlgA binding to the plgR-stimulated plgR transcytosis suggested that the plgR is capable of ligand-induced signal transduction. Here we show that dlgA binding to the plgR activates several well-known signaling pathways, including PKC-¢, production of IP3, and elevation of Ca. We had shown previously that activation of PKC by phorbol ester can stimulate transcytosis, and now we present data that treatment with thapsigargin can cause a very similar stimulation of transcytosis, while BAPTA-AM inhibits transcytosis.

The plgR could be coupled to these signaling pathways by several possible mechanisms, although as of yet we have no strong evidence to distinguish among these possi-
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A

![Graph A](image)

Figure 5. Role of Ca in transcytosis. (A) Thapsigargin stimulates transcytosis of dlgA. (B) BAPTA-AM inhibits transcytosis. Cells grown on 12-mm Transwells were allowed to internalize 

125I
dlgA from the basolateral surface for 10 min at 37°C. Transcytosis and recycling of preinternalized 
dlgA was then examined over a 2-h chase, as described in Materials and Methods. Where indicated, 5 

μM thapsigargin (BIOMOL Research Laboratories Inc.) was included in the apical and basolateral media during the 2-h chase. Alternatively, cells were pretreated with 50 

μM BAPTA-AM for 1 h, and BAPTA-AM was included in all subsequent steps. Error bars are SE of triplicate filters.

B

![Graph B](image)

The plgR might activate a PI-PLC, which would hydrolyze PIP2 to DAG and IP3, thereby accounting for our results with PKC, IP3, and Ca++. There are two well-known mechanisms for activation of PI-PLC. Most single membrane spanning receptors (like the plgR) activate PI-PLCγ via a pathway involving tyrosine phosphorylation (Cohen et al., 1995). The cytoplasmic domain plgR does not have any homology to any known tyrosine kinases, and it lacks the “immune receptor tyrosine activation motif” found in many receptors that are coupled to tyrosine kinases (Weiss and Littman, 1994). Furthermore, the plgR itself is not detectably phosphorylated on Tyr (Hirt et al., 1993; Cardone, M.H., and K.E. Mostov, unpublished data) and has no obvious homologies to consensus recognition sites for SH2, SH3, PTB, or pleckstrin homology domains (Cohen et al., 1995; Kavanaugh and Williams, 1994). It is possible that the plgR is coupled to a nonreceptor tyrosine kinase(s), either directly or via a second subunit, which in turn recruits the kinase. Many other receptors in the immune system signal in this manner. Another possibility is that the plgR is coupled to a heterotrimeric G protein, which in turn activates a PI-PLCβ. Although most receptors that activate heterotrimeric G proteins span the membrane seven times, there are examples of receptors that span the membrane once and activate heterotrimeric G proteins (for review see Bomsel and Mostov, 1992).

A nonmutually exclusive possibility is that the plgR activates a PI3K; this might be via a tyrosine kinase and/or heterotrimeric G protein. The resultant phosphatidylinositol 3,4,5-trisphosphate could activate PKC-ε (Kapeller and Cantly, 1994). PI3K has been shown to be involved in a number of membrane traffic events, such as delivery of hydrolases to yeast vacuoles, or the homologous delivery to lysosomes in mammalian cells (Brown et al., 1995; Davidson, 1995). It has recently been shown shown that the PI3K inhibitor, wortmannin, inhibits transcytosis of plgR (Cardone and Mostov, 1995; Hansen et al., 1995). A caveat is that wortmannin can inhibit other enzymes in addition to PI3K.

When endocytosed from the apical plasma membrane, dlgA and plgR reach the apical recycling compartment. Here they meet dlgA and plgR that have been endocytosed from the basolateral surface and are en route to the apical surface. We can imagine that the signaling initiated by the plgR might take place largely in the apical recycling compartment. Delivery from the apical recycling compartment to the apical plasma membrane (step 3 of transcytosis) is the principal event that is regulated by dlgA binding, PKC, and cAMP (Song et al., 1994a; Mostov and Cardone, 1995). Perhaps the plgR at either cell surface associates with an initial element of the signaling pathway (e.g., a kinase or heterotrimeric G protein) and travels with it to the apical recycling compartment, where downstream signaling events occur. Our experiments with apically bound dlgA and with nocodazole support a role for the apical recycling compartment in signaling. When dlgA is bound to the plgR at the apical surface and internalized into the apical recycling compartment, plgR-mediated IP3 response can also occur. Depolymerization of microtubules with nocodazole blocks the delivery of basolaterally added dlgA to the apical recycling compartment, and also causes this compartment to disperse from its normal localization clustered around the centriole underneath the apical plasma membrane (Apodaca et al., 1994b). Nocodazole also blocks IP3 signaling by dlgA added at either the apical or basolateral plasma membrane. The relatively slow onset and prolonged duration of the Ca signal are also consistent with signaling taking place in the apical recycling compartment, rather than at the basolateral plasma membrane. Taken together, these data suggest that signaling by the plgR may be immediately connected with microtubule-dependent delivery of plgR to the apical recycling compartment, and/or the microtubule-dependent organization of this compartment (Rodriguez-Boulan and Powell, 1992).
The stimulatory effects of thapsigargin on the kinetics and extent of transcytosis are strikingly similar to those of PMA, which was shown to stimulate delivery of dIgA to the apical surface from the apical recycling compartment (Cardone et al., 1994) making it likely that increasing free Ca^2+ also acts at this step of transcytosis. In pancreatic acinar cells, acetylcholine activates the PI-PLC pathway mobilizing second messenger IP3 and subsequently regionally increasing intracellular Ca^2+ (Kasai et al., 1993; Thorn et al., 1993; Berridge and Dupont, 1994). Stimulated exocytosis of granules ensues in a manner which coincides spatially and temporally with release of Ca^2+ (Kasai et al., 1993). The Ca^2+ signal in MDCK cells may be similarly localized to the apical region of the cell and thereby act on the apical recycling compartment and the last step in transcytosis.

Our results with thapsigargin and BAPTA-AM suggest that Ca^2+ plays an important role(s) in transcytosis. The imaging experiments demonstrate that addition of IgA to the superfusate induces an increase in Ca^2+ in the majority of cells studied. There was considerable heterogeneity in the magnitude and kinetics of this response, which may have been due to a variety of factors such as different stages of cell growth and development that could affect the intracellular Ca^2+ stores, and differential amounts of plgR expressed on the basolateral and apical membranes. Our experimental design did not allow us to differentiate between extracellular influx and intracellular release of Ca^2+ that led to the observed increase in Ca^2+. The plasma membrane of the MDCK cells is thought to contain both a Ca-ATPase and a Na/Ca exchanger, but there are no known Ca channels thought to exist there. Our results with thapsigargin and BAPTA-AM suggest that the source of the increase in Ca^2+ is from intracellular stores.

Ca^2+ regulates the exocytosis of synaptic vesicles and dense core secretory granules (Kelly, 1990). Ca^2+ is also important in a variety of constitutive membrane traffic processes, such as ER to Golgi transport (Beckers and Balch, 1989) and fusion of nuclear envelope vesicles (Sullivan, 1993). Synaptotagmin may be a sensor for Ca that controls fusion events in synapses and other cell types (Li et al., 1995; Sudhof, 1995).

Moreover, cellular events other than transcytosis may be regulated by dlgA binding. For instance, transcription of the plgR is stimulated by interferon γ, interleukin 4, and tumor necrosis factor α, which indicates that the transport of dlgA is coordinated with other aspects of the immune response (for review see Mostov, 1994). Binding of dlgA might lead to a stimulation of transcription of plgR, so the production of plgR could be raised in situations (e.g., inflammation or infection) where the production of dlgA is increased.

The results presented here illustrate how ligand binding to a receptor can regulate membrane traffic through well-known signaling pathways. There are other receptors whose movement is regulated by ligand binding (e.g., EGF, PDGF, and Fc receptors), although unlike the plgR, the trafficking of these receptors is considered largely secondary to their signaling function (for review see Fantl et al., 1993). We suggest that the plgR is a model for other membrane traffic processes, which may be regulated by unidentified receptors. These receptors might respond to extracellular ligands, to the lipid composition of the membrane, or to cargo moving through specific compartments.

Regulation of traffic by cargo is an attractive homeostatic mechanism, as it enables the cell to adjust to varying amounts of cargo, while maintaining the composition and size of organelles. For example, movement from the ER to the Golgi is highly regulated by several intracellular signaling pathways (Schwaninger et al., 1992). One proposal is that the cargo of newly synthesized (or recycling) secretory or membrane proteins might bind to a receptor in the transitional elements of the ER and trigger the formation of a vesicle that moves to the next station in the secretory pathway. The ligand and receptor involved are so far unknown. Similarly, in delivery from the yeast TGN to the endosome and vacuole, a P13K is involved (Schu et al., 1993). Perhaps the ligand and receptor there are a newly made vacuolar enzyme and the receptor that carries it to the vacuole. This receptor might somehow activate the P13K, leading to vesicle formation. We speculate that these systems might be broadly analogous to the one reported here, with the primary differences being that dlgA is provided to the cell externally, rather than being synthesized by the cell, and that we have presented evidence supporting a role for PKC and Ca^2+ in stimulating transcytosis.

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