Phospholipase C in Dictyostelium discoideum
Identification of stimulatory and inhibitory surface receptors and G-proteins
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A combined biochemical and genetic approach was used to show that phospholipase C in the cellular slime mould Dictyostelium is under dual regulation by the chemotactic cyclic AMP (cAMP). This dual regulation involves stimulatory and inhibitory surface receptors and G-proteins. In wild-type cells both cAMP and guanosine 5'-[γ-thio]triphosphate (GTP[S]) stimulated phospholipase C. In contrast, mutant fgd A, lacking the G-protein α-subunit Ga2, showed no stimulation by either cAMP or GTP[S], indicating that Ga2 is the stimulatory G-protein. In mutant fgd C cAMP did not stimulate phospholipase C, but stimulation by GTP[S] was normal, suggesting that the defect in this mutant is upstream of the stimulatory Ga2. Inhibition of phospholipase C was achieved in wild-type cells by the partial antagonist 3'-deoxo-3'-aminoadenosine 3',5'-phosphate (3'NH-cAMP). This inhibition was no longer observed in transformed cell lines lacking either the surface cAMP receptor cAR1 or the G-protein α-subunit Ga1; in these cells the agonist cAMP still activated phospholipase C. These results indicate that Dictyostelium phospholipase C is regulated via a stimulatory and an inhibitory pathway. The inhibitory pathway is composed of the surface receptor cAR1 and the G-protein G1. The stimulatory pathway consists of an unknown cAMP receptor (possibly the fgd C gene product) and the G-protein G2.

INTRODUCTION

In many organisms, signal transduction via Ins(1,4,5)P₂ plays a crucial role in Ca²⁺ homoeostasis and related cellular responses ranging from chemotaxis to cell proliferation (for reviews see [1,2]). In the cellular slime mould Dictyostelium discoideum the transition from the unicellular vegetative stage to the developmental multicellular stage is mediated by chemotaxis towards extracellular cyclic AMP (cAMP) [3]. After starvation, cells develop a cAMP-signal-transducing system [4,5]. In response to cAMP, multiple second-messenger systems are activated, including adenylate and guanylate cyclase [5-9]. Apart from these two enzymes generating cAMP and cyclic GMP, Dictyostelium also shows an increase in cellular levels of Ins(1,4,5)P₃ in response to the chemotactic cAMP [10-13].

Mutants of the frigid class (fgd) are defective in cAMP-induced development [14]. Previous work showed that Ins(1,4,5)P₃ signalling is impaired in mutants fgd A and fgd C [15-17]. In the mutant fgd A nearly all signal transduction is blocked, due to a deletion in one of the α-subunits of G-proteins, Ga2 [15,18]. The primary defect in the mutant fgd C is still unknown. This mutant shows relatively normal cAMP and cyclic GMP responses but no increase in Ins(1,4,5)P₃ levels after stimulation of cells with cAMP. At the same time this mutant needs 100-fold higher concentrations of cAMP for a chemotactic response as compared with wild-type cells [16].

By using analogues of cAMP, it was shown not only that Ins(1,4,5)P₃ levels may increase upon stimulation, but that a decrease of Ins(1,4,5)P₃ levels is also possible [19]. Analogues which were shown previously to act as partial antagonists [20] induced inhibition of Ins(1,4,5)P₃ production in vivo. This inhibition of Ins(1,4,5)P₃ production correlates well with the observed antagonism for chemotaxis. The data described above indicate that, apart from a stimulatory pathway, phospholipase C activity in Dictyostelium is regulated by an inhibitory pathway as well. Recently several reports suggest such a dual regulation of phospholipase C in other organisms [21-27].

To date, four different genes coding for cAMP surface receptors and eight different genes coding for G-protein α-subunits have been cloned in Dictyostelium [28-32]. By using homologous recombination, cell lines were made lacking the surface receptor cAR1 or the G-protein α-subunits Ga1, Ga2 or G33 [33,34]; M. Pupillo and P. N. Devreotes, unpublished work). These transformed cells, together with signal-transduction mutants and cAMP antagonists, provide a powerful tool for investigating the function of receptors and G-proteins in specific parts of the transmembrane signal-transduction pathways. In the preceding paper [35] a receptor- and G-protein-sensitive phospholipase C activity in Dictyostelium discoideum was characterized. Here we used a combined approach of mutants, transformants and cAMP analogues to identify the receptors and G-proteins involved in the dual regulation of phospholipase C activity in Dictyostelium.

MATERIALS AND METHODS

Chemicals

[3H]Ins(1,4,5)P₃ (20–60 μCi/mmoll was obtained from Amerham International. Guanosine 5'-[α-thio]triphosphate (GTP[S]) was obtained from Boehringer Mannheim. cAMP, EGTA and Hepes were from Sigma. 3'-Deoxy-3'-aminoadenosine 3',5'-monophosphate (3'-NH-cAMP) was kindly given by Dr. B. Jastorff (University of Bremen, Germany); all other chemicals used were of at least analytical grade.

Cells and cell culture

Cell strains AX3, JH130, JH131, HPS400, G3T2, 1A3 and c280 were grown in axenic medium HG-5, which is an adapted form of the HL-5 medium [36] containing 10 g/l instead of 16 g/l

Abbreviations used: cAMP, cyclic AMP; GTP[S], guanosine 5'-[γ-thio]triphosphate; 3'NH-cAMP, 3'-deoxy-3'-aminoadenosine 3',5'-monophosphate.

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glucose. Cell strains NC-4, HC-85, HC-317, XP-55 and HC-6 were grown in co-culture with *Klebsiella aerogenes* on solid medium containing 3.3 g/l glucose, 3.3 g/l peptone and 10 mM Na/K phosphate buffer, pH 6.5. Axenically grown strains were harvested in the late-exponential phase, and bacterial-grown strains just before clearing of the bacterial lawn. Cells were starved for 4 h by shaking in Na/K phosphate buffer, pH 6.5, to acquire aggregation competence.

**Ins(1,4,5)P_3** production in vivo
Aggregation-competent cells were harvested, washed once in 40 mM Hepes/NaOH, pH 6.5, and resuspended in this buffer at 5 x 10^7 cells/ml. Before starting the experiment, cells were aerated for 10 min, and aeration was continued during the experiment. Stimulation of cells was performed by adding 270 μl of cell suspension to 30 μl of 10-times-concentrated stimulus. Subsequently 50 μl samples were withdrawn at the indicated times and quenched by addition of an equal volume of 3.5 % HClO_4. The zero-time points were obtained by taking 45 μl of cell suspension and adding this to 50 μl of 3.5 % HClO_4 plus 5 μl of stimulus just before the stimulation of the other cells.

**Phospholipase C activity in vitro**
Phospholipase C activity was determined as described in the preceding paper [35]. In short, cells were harvested and resuspended as described above. Portions of cells were stimulated with cAMP and lysed in the presence of 5.9 mM EDTA; 10 s after lysis, part of the sample was quenched with an equal volume of 3.5 % HClO_4 and the other part was adjusted to 10 μM free Ca_2+ by addition of 5.9 mM CaCl_2 and incubated for another 20 s before being quenched. Ins(1,4,5)P_3 levels were determined in samples neutralized with KHCO_3 by using an isotope-dilution assay as described previously [13,37]. Phospholipase C activity is defined as the amount of Ins(1,4,5)P_3 produced during the 20 s incubation with Ca_2+.

Ins(1,4,5)P_3 phosphatase activity was measured as described in the preceding manuscript [35].

**RESULTS**

**Mutants fgd A and fgd C defective in phospholipase C stimulation**
Stimulation of fgd C and fgd A cells with the chemoattractant cAMP in vivo does not elicit an increase in Ins(1,4,5)P_3 levels; in fact, cAMP induces a small decrease in both strains (Figure 1a). To investigate the nature of the defect in these mutants, the activation of phospholipase C by cAMP and GTP[S] was investigated in vitro. Mutant cells were stimulated with cAMP and phospholipase C activity was determined. Basal phospholipase C activity in these mutants is not significantly different from the activity of wild-type cells. Whereas cAMP stimulates phospholipase C activity about 2-fold in wild-type cells, addition of cAMP to these mutants leads to the inhibition of basal phospholipase C activity (Figure 1b); activities relative to unstimulated activity are: wild-type 216 ± 63 %, fgd A 71 ± 37 %, fgd C 42 ± 20 %.

The non-hydrolysable GTP analogue GTP[S] was used to activate G-proteins. In wild-type cells GTP[S] stimulates phospholipase C about 2-fold [35]. Figure 1(b) demonstrates that GTP[S] does not stimulate phospholipase C in fgd A cells, suggesting that the Ga2 protein, which is impaired in fgd A, is responsible for activation of phospholipase C. In contrast, fgd C shows a wild-type response towards GTP[S] in vitro, indicating that G-protein/phospholipase C coupling is intact in this mutant (Figure 1b). Since receptor-stimulated activity is lost, this suggests that the defect in fgd C is upstream from the G-protein. All current models for G-protein-based signal transduction have only one component upstream of the G-protein, i.e. the receptor; fgd C may be a stimulatory receptor mutant.

Several observations, including the inhibition of phospholipase C by cAMP in fgd A and fgd C (Figure 1), suggest the presence of another receptor- and G-protein-based mechanism involved in the decrease of phospholipase C activity.

**Inhibition of phospholipase C by the cAMP analogue 3'NH-cAMP**
The hypothesis for a G-protein-coupled inhibitory pathway of phospholipase C is supported by the finding that certain cAMP...
Analogs such as 3'NH-cAMP induce a decrease in Ins(1,4,5)P$_3$ levels in vivo. In Figure 2 the effect of 3'NH-cAMP both on Ins(1,4,5)P$_3$ levels in vivo as well as on phospholipase C activity in vitro is shown. In vivo the analogue induces a rapid decrease in Ins(1,4,5)P$_3$ levels, with hardly any Ins(1,4,5)P$_3$ remaining at 30 s after stimulation (Figure 2a). In vitro a strong inhibition of phospholipase C activity is observed after stimulation with the analogue. Basal phospholipase C activity is decreased to 30% of that in untreated cells (Figure 2b).

Apparently 3'NH-cAMP activates an inhibitory pathway of phospholipase C. Although no reports are available to date on G-protein-coupled stimulation of Ins(1,4,5)P$_3$ phosphatases, this possibility could not be excluded as a partial source for the observed decrease in Ins(1,4,5)P$_3$ in vivo. Therefore Ins(1,4,5)P$_3$ phosphatase activity after stimulation of cells with 3'NH-cAMP was measured. No difference in Ins(1,4,5)P$_3$ phosphatase activity in lysates of untreated cells compared with 3'NH-cAMP-treated cells was observed (results not shown).

**Identification of the receptors and G-proteins involved in phospholipase C inhibition**

Since 3'NH-cAMP was recognized as a selective activator of the inhibitory pathway, it was used to identify the receptor and G-protein that mediate inhibition of phospholipase C activity. Cell lines with a gene disruption of one of the possible components were tested for activation and inhibition of phospholipase C in response to cAMP or the analogue 3'NH-cAMP. To date, eight different Gz subunits have been cloned, and four different cAMP receptors [28-32]. By using homologous recombination, cell lines have been created carrying three different Gz-gene disruptions, i.e. Gz1, Gz2 (=fgdA) and Gz3, and a receptor-gene disruption for cAR1 [32,33]; M. Pupillo and P. N. Devreotes, unpublished work.

Cells with a disruption of the Gz3 gene show a normal decrease in Ins(1,4,5)P$_3$ levels in response to 3'NH-cAMP (results not shown), indicating that Gz3 does not mediate inhibition of phospholipase C. The Gz2-null cell line was not tested with 3'-NH-cAMP, since this cell line is comparable with the fgd A strain HC-85, which revealed that Gz2 is the stimulatory G-protein. Figure 3 shows the effect of 3'NH-cAMP on the Ins(1,4,5)P$_3$ levels in the Gz1-null strain and its isogenic control cell line, JH131 and JH130 respectively. Whereas 3'NH-cAMP induces a decrease in Ins(1,4,5)P$_3$ levels in control cells, the Gz1-null cells show neither a decrease in the cellular Ins(1,4,5)P$_3$ level in vivo nor a decrease in phospholipase C activity in vitro in response to 3'NH-cAMP (Figure 3). Thus in the Gz1-null cells the inhibitory pathway to phospholipase C has been disrupted, which identifies...
Gz1 as the G-protein coupling the receptor for 3'NH-cAMP to inhibition of phospholipase C.

In order to find the function of the surface cAMP receptor cAR1 in the regulation of phospholipase C, cAR1-null cells were stimulated with 3'NH-cAMP and cAMP. The results show that disruption of cAR1 leads to the absence of 3'NH-cAMP-induced inhibition of phospholipase C (Figure 4), whereas cAMP still stimulates the enzyme (results not shown). Thus the receptor coupling the inhibitory action of 3'NH-cAMP to phospholipase C is coded for by cAR1. Since cAMP stimulation of phospholipase C is unimpaired in these cells, cAR1 appears not to be essential in the stimulatory pathway.

**DISCUSSION**

Regulation of phospholipase C has been studied extensively in many organisms and cell types, and several reports on the inhibition of phospholipase C are known. Basically two mechanisms are proposed for this inhibition: on the one hand, phosphorylation of activating compounds through the action of either protein kinase C, providing a negative-feedback mechanism, or protein kinase A, allowing cross-talk between cAMP and Ins(1,4,5)P_3 signalling [21-24]; on the other hand, a direct inhibitory action of G-proteins. The evidence for this latter possibility is based on indirect observations, e.g. the effect of guanine nucleotides and NaF on the activation of phospholipase C [25-27]. In the present paper we provide further genetic evidence for the presence of a receptor/G-protein-mediated inhibitory pathway for phospholipase C and identify the receptor and G-protein involved.

Using a combined approach of pharmacological and molecular-genetic techniques to elucidate the regulatory components involved in the modulation of phospholipase C activity in Dictyostelium discoideum, two regulatory pathways can be discerned, a stimulatory pathway activated by cAMP and an inhibitory one which is specifically activated by the analogue 3'NH-cAMP. This feature of 3'NH-cAMP allows pharmacological separation of the two different pathways. It is likely that cAMP activates both the stimulatory and the inhibitory pathway, since the cAMP-dose–response curve of phospholipase C stimulation is bell-shaped, with stimulation at low cAMP concentrations and inhibition at high concentrations [35]. Using cell lines with deletions of either specific G-protein α-subunits or cAR1, the components involved in phospholipase C regulation were identified; the results are summarized in Table 1. cAR1 was identified as the inhibitory receptor and Gz1 as the inhibitory G-protein α-subunit, since removal of either of these two proteins through homologous recombination resulted in the loss of 3'NH-cAMP-mediated inhibition of phospholipase C. The stimulatory pathway is composed of an unknown receptor and Gz2 as the α-subunit of the stimulatory G-protein. The latter was shown by the lack of phospholipase C activation in mutant fgd A by either cAMP or GTP[S]. The identity of the stimulatory receptor remained to be established. To date, four different cAMP receptors have been identified genetically in Dictyostelium, designated cAR1-4. As shown above, cAR1 is the inhibitory receptor, and cAR2 and cAR4 are not expressed in aggregation-competent cells, which would leave only cAR3 as a possible candidate. However, the binding specificity of cAR1-3 for various cAMP analogues is very similar, including the binding specificity for 3'NH-cAMP [38]. This implies that cAR3 would bind 3'NH-cAMP as efficiently as cAR1. Since the stimulatory receptor is not effected by 3'NH-cAMP, involvement of cAR3 is unlikely, which would mean that the stimulatory receptor is an unknown cAR. It is possible that the stimulatory receptor is the product of the fgd C gene, which is suggested by the observation that the defect in fgd C is upstream of Gz2. Final proof of this hypothesis can only be obtained by cloning the fgd C gene. Restoration of stimulation of phospholipase C could be used in complementation assays.

Thus a model for the regulation of phospholipase C in Dictyostelium emerges. Figure 5 is a schematic representation of this model, in which all components, with the exception of the stimulatory receptor, have been characterized and their respective genes cloned, including phospholipase C [39]. During development of wild-type cells phospholipase C is inhibited by GTP[S] during growth and stimulated during cell aggregation [35]. This differential regulation coincides with the expression of the regulatory G-proteins. The inhibitory Gz1 is expressed throughout development, whereas the stimulatory Gz2 only during cell aggregation. The interaction of two different G-proteins with phospholipase C, the simple and fast assay for phospholipase C and the possibility to create cell lines lacking either of these G-proteins provides a powerful tool to study the interaction between G-proteins and phospholipase C. Using chimeras of G1 and G2, the functional domains of G-proteins interacting with phospholipase C can be determined.

In most eukaryotic cells one hormone activates multiple effector enzymes. Specificity of signal transduction is generally provided by the effector enzyme being activated by a specific G-protein and sometimes by a specific receptor. The current model for signal transduction in Dictyostelium is largely based on the observations made with fgd A. This mutant lacks one G-protein and is defective in nearly all sensory transduction in vivo, including the activation of adenylyl cyclase, guanylate cyclase and phospholipase C [14,15,17]. Since GTP[S] stimulation of adenylyl and guanylate cyclases in vitro are essentially normal, and GTP[S] stimulation of phospholipase C is absent, a hierarchy of signal transduction was proposed, with G2 and its effector (possibly phospholipase C) at the heart and adenylyl and guanylate cyclases downstream. The present results are probably not in accordance with such a model. The defect of mutant fgd C for the activation of phospholipase C is upstream of G2. Whereas the fgd A gene product Ga2 is essential for nearly all signal transduction, the fgd C gene product is not required for the activation of adenylyl and guanylate cyclases [14,16]. These considerations suggest several parallel signal-transduction routes in Dictyostelium, in which G2 is essential for the coupling of the stimulatory receptors to the different effectors. Specificity of signal transduction may be provided by three non-exclusive mechanisms: (i) different receptors, (ii) other G-proteins, and (iii) other intracellular proteins. Arguments for each of these models are available. Receptor: if the fgd C gene product is a receptor, as tentatively suggested in the present paper, then this

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**Table 1 Summary of the regulation of phospholipase C in Dictyostelium**

<table>
<thead>
<tr>
<th>Cells</th>
<th>Defective protein</th>
<th>Phospholipase C after stimulation with</th>
<th>cAMP</th>
<th>3'NH-cAMP</th>
<th>GTP[S]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wild-type</td>
<td>none</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>fgd A</td>
<td>Gz2</td>
<td>0/–</td>
<td></td>
<td></td>
<td>0/–</td>
</tr>
<tr>
<td>fgd C</td>
<td>?</td>
<td>0/–</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>JH131</td>
<td>Gz1</td>
<td>+</td>
<td></td>
<td></td>
<td>+</td>
</tr>
<tr>
<td>G3T2</td>
<td>Gz3</td>
<td>+</td>
<td></td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>C280</td>
<td>cAR1</td>
<td>0/–</td>
<td></td>
<td></td>
<td>ND</td>
</tr>
</tbody>
</table>

Key: +, stimulation; −, inhibition; 0, no effect; 0/−, slight inhibition; ND, not determined.
The identities of the stimulatory receptor $R_s$ and $fgo C$ are unknown. The $fgo C$ gene product functions upstream of the $G_2$-protein $G_2$. Abbreviations used: $R_p$, stimulatory receptor; $R_s$, inhibitory receptor; $G_{sp}$, stimulatory $G$-protein; $G_{ip}$, inhibitory $G$-protein.

A receptor is not involved in the activation of adenylate and guanylate cyclases [16]. G-protein: cAMP-mediated stimulation of adenylate cyclase is absent in G2-null cells; however, GTP[S]-mediated stimulation of this enzyme is normal in membranes, indicating that, besides G2, another G-protein is required for stimulation of adenylate cyclase [15]. Other proteins: different cytosolic proteins are essential for the optimal activity of adenylate cyclase [7,40] and guanylate cyclase [41]; these associated proteins could be involved in the routing of the cAMP signal from one receptor or G-protein to the different effector enzymes.

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