Published March 24, 1997

Sequential Actions of Rab5 and Rab7 Regulate Endocytosis in the *Xenopus* Oocyte

Amitabha Mukhopadhyay, Alejandro M. Barbieri, Kouichi Funato, Richard Roberts, and Philip D. Stahl

Department of Cell Biology and Physiology, Washington University School of Medicine, St. Louis, Missouri 63110

Abstract. To explore the role of GTPases in endocytosis, we developed an assay using *Xenopus* oocytes injected with recombinant proteins to follow the uptake of the fluid phase marker HRP. HRP uptake was inhibited in cells injected with GTPγS or incubated with aluminum fluoride, suggesting a general role for GTPases in endocytosis. Injection of Rab5 into oocytes, as well as Rab5:Q79L, a mutant with decreased GTPase activity, increased HRP uptake. Injection of Rab5:S34N, the dominant-negative mutant, inhibited HRP uptake. Injection of *N*-ethylmaleimide–sensitive factor (NSF) stimulated HRP uptake, and ATPase-defective NSF mutants inhibited HRP uptake when coinjected with Rab5:Q79L, confirming a requirement for NSF in endocytosis. Surprisingly, injection of Rab7:WT stimulated both uptake and degradation/activation of HRP. The latter appears to be due to enhanced transport to a late endosomal/prelysosomal degradative compartment that is monensin sensitive. Enhancement of uptake by Rab7 appears to function via an Rab5-sensitive pathway in oocytes since the stimulatory effect of Rab7 was blocked by coinjection of Rab5:S34N. Stimulation of uptake by Rab5 was blocked by Rab5:S34N but not by Rab7:T22N. Our results suggest that Rab7, while functioning downstream of Rab5, may be rate limiting for endocytosis in oocytes.

GTP binding proteins are versatile molecular switches (Bourne, 1988; Bourne et al., 1990), and during the past few years, there has been an explosion of interest in unraveling the role of these proteins, particularly low molecular weight GTPases, in membrane traffic (Balch, 1990; Barr et al., 1992). Evidence from a variety of sources, including the temperature-sensitive secretion mutants in yeast and in vitro reconstitution experiments in permeabilized and broken cell preparations, has established that at least two subfamilies of GTP binding proteins, namely the Rab and ADP ribosylation factor subfamilies, are required for membrane traffic (Pfeffer, 1994; Rothman, 1994). Heterotrimeric GTPases (Colombo et al., 1992) and ras (Barsagi and Feramisco, 1986) also appear to play significant roles.

Among the monomeric small GTPases, the Rab family is well characterized as regulators of intracellular trafficking during endocytosis and secretion (Zerial and Stenmark, 1993). Rab proteins are specifically localized to the cytoplasmic surface of the intracellular compartments that they subserve, such as ER (Rab1 and Rab2) (Chavrier et al., 1990; Tisdale et al., 1992), *cis*-Golgi (Rab1 and Rab2) (Chavrier et al., 1990; Tisdale et al., 1992), medial Golgi (Rab6) (Goud et al., 1990), *trans*-Golgi (Rab9) (Gravotta et al., 1990; Lombardi et al., 1993), early endosomes (Rab4 and Rab5) (Chavrier et al., 1990; van der Sluijs et al., 1991), late endosomes (Rab7 and Rab9) (Chavrier et al., 1990; Lombardi et al., 1993; Feng et al., 1995), and plasma membrane/endosomes (Rab5) (Chavrier et al., 1990).

In transient transfection experiments and in vitro fusion assays using enriched membrane preparations, Rab5 has been shown to play a role in the regulation of endocytosis (Grovel et al., 1991; Li and Stahl, 1993). Overexpression of Rab5 increases the rate of endocytosis and the recycling of the transferrin receptor. Moreover, Rab5-specific antiserum and Rab5 dominant-negative mutants specifically inhibit endosome fusion in vitro (Bucci et al., 1992; Li et al., 1994; Barbieri et al., 1994). While it has been shown that Rab5 regulates endocytosis at the level of early endosome fusion, the mechanism by which Rab5 exerts its function remains to be established. Moreover, transport of macromolecules along the endocytic pathway requires a series of highly coordinated and specific fusion events involving multiple cytosolic and membrane-bound factors including the *N*-ethylmaleimide–sensitive factor (NSF)[1] (Diaz et al., 1988; Rothman, 1994) and a membrane-bound trypsin-sensitive factor (Colombo et al., 1991). Protein phosphorylation has also been shown to regulate the fusion of endosomal

Address all correspondence to Philip D. Stahl, Department of Cell Biology and Physiology, Washington University School of Medicine, 660 S. Euclid Avenue, St. Louis, MO 63110. Tel.: (314) 362-6950. Fax: (314) 362-1490. e-mail: pstahl@cellbio.wustl.edu

1. *Abbreviations used in this paper*: GST, glutathione-*S*-transferase; MBS, modified Barth's saline; NSF, *N*-ethylmaleimide–sensitive factor; WT, wild type.

Published March 24, 1997

vesicles (Toumikoski et al., 1989). Certain lipids may also play a role in membrane docking and fusion. Both PLA_2 (Mayorga et al., 1993) and PI3 kinase (Li et al., 1995) are intimately involved in the regulation and/or action of Rab5. However, the exact relationship among all these factors in the overall mechanism of intracellular trafficking during endocytosis is largely unknown.

Both fluid phase and receptor-mediated endocytosis occur through vesicle fusion and transfer of endocytic materials from one compartment to another in a highly regulated fashion. Depending on the receptor system, ligands and receptors are internalized and sorted in the early endosomal compartment (Goldstein et al., 1985), often requiring acidic pH, and selected molecules are recycled back to the plasma membrane. Some are transported to the late endosomal compartment that may communicate with the *trans*-Golgi network or the lysosomal compartment (Yamashiro et al., 1984). The late endosome represents the convergence point of several pathways such as (*a*) the targeting of newly synthesized lysosomal enzymes and lysosomal membrane proteins to the lysosome (Griffiths et al., 1990; Riederer et al., 1994), (*b*) the killing of internalized microorganisms by phagocytes (Ludwig et al., 1991; Rabinowitz et al., 1992; Desjardins et al., 1994; Beron et al., 1995), and (*c*) the processing and presentation of antigens where major histocompatibility complex class II molecules are recycled to the plasma membrane after the formation of peptide–major histocompatibility complex class II complex in the late endosomal compartment (Cresswell, 1994; Germain, 1994; Qui et al., 1994). It is now clear that multiple Rab proteins, including Rab7, Rab9, and Rab24, and perhaps others to be identified, are associated with the late endosomal compartment (Chavrier et al., 1990; Lombardi et al., 1993; Olkkonen et al., 1993). Rab9 has been shown to regulate the traffic from the late endosome to the TGN (Lombardi et al., 1993; Riederer et al., 1994), and Rab7 has been shown to regulate the traffic from early to late endosomes (Wichmann et al., 1992; Feng et al., 1995) or from late endosomes to vacuoles (Schimmoller et al., 1993; Hass et al., 1995). Considerable progress has been made toward understanding the regulation of transport by specific Rabs, each with its own family of effector proteins. However, the relation of one Rab to another and the regulation of intracellular pathways made up of a series of relays is poorly understood. In the present investigation, we have exploited the *Xenopus* oocyte as a model system to study the regulation of endocytosis by multiple Rabs. Our data suggest that the action of one Rab may influence the function of a second Rab acting downstream.

Materials and Methods

mAbs used in this study include: 4F11, a mouse 1 g $G2a_K$ mAb that recognizes mouse Rab5, generously provided by A. Wandinger-Ness (Northwestern University, Evanston, IL), and A46, a mouse IgM mAb that recognizes native NSF, kindly provided by J.E. Rothman (Sloan-Kettering Memorial Hospital, New York). Irrelevant IgG and IgM mAbs were purchased from Sigma Chemical Co. (St. Louis, MO) and used as control. Recombinant NSF wild-type and mutant proteins were generously provided by S.W. Whiteheart (University of Kentucky, Lexington). HRP-conjugated antibodies and enhanced chemiluminescence detection reagents were from Amersham Corp. (ECL; Arlington Heights, IL). All other reagents were from Sigma Chemical Co.

Preparation of Oocytes

Ovaries were dissected from adult female *Xenopus laevis* (Nasco, Fort Atkinson, WI) anesthetized with 3-aminobenzoic acid ethyl ester (1 g/liter) in ice water. The ovaries were agitated gently for 2 h in modified Barth's saline (MBS) containing no calcium with 2 mg/ml type 1 collagenase at room temperature (Swick et al., 1992). After collagenase treatment, the oocytes were washed six times in MBS containing 5% BSA. Cells obtained in this manner were incubated overnight in MBS with BSA and gentamycin (50 μg/ml) at 4°C.

Expression and Purification of Recombinant Rabs and Mutants

The Rab5 fusion proteins used in this study including Rab5:Q79L, Rab5:S34N, and Rab5:ΔC4 were described previously (Li and Stahl, 1993; Li et al., 1994). Rab7 wild type (WT) and Rab7:T22N were expressed and purified as glutathione-*S*-transferase (GST) fusion protein as described for Rab5 (Li and Stahl, 1993; Li et al., 1994). To prepare fusion proteins, cDNAs were amplified by 25 cycles of PCR and subcloned into unique BamH1/EcoR1 restriction sites of the bacteria expression vector pGEX-3X (Pharmacia Biotech Inc., Piscataway, NJ). Recombinant proteins were expressed in large quantities as GST fusion proteins in *Escherichia coli* strain JM 101. GST fusion proteins were affinity purified with glutathione–Sepharose.

Microinjection of Test Proteins in Xenopus Oocytes and HRP Uptake

Before microinjection, healthy oocytes (stage V or VI) were visually selected. Oocytes were injected with the indicated concentrations of test molecules in 50 nl of buffer A (20 mM Hepes, pH 7.4, containing 20 mM NaCl, 1 mM $MgCl_2$, and 100 μM ATP), and then allowed to recover in MBS at 18°C for 2 h. Finally, healthy oocytes were selected for HRP uptake. The injected oocytes were incubated in the presence of HRP (2 mg/ml) for 1 h at 18°C. HRP uptake by the oocytes was stopped by washing the cells three times with MBS containing 5% BSA. Individual oocytes were then lysed in 200 μl PBS containing 0.1% Triton X-100 and centrifuged, and the lysate was assayed for HRP. The enzyme assay was conducted in a 96-well plate (Costar Corp., Cambridge, MA) using *o*-phenylenediamine as the chromogenic substrate (Wolters et al., 1976). Briefly, the reaction was initiated by adding 5 μl of the lysate to 100 μl of 0.05 N sodium acetate buffer, pH 5.0, containing *o*-phenylenediamine (0.75 mg/ml) and H_2O_2 (0.006%). After incubation (5 min at room temperature), the reaction was stopped with 0.1 N H_2SO_4. The products were quantified by measuring the OD 490 nm in a microplate reader (Bio Rad Laboratories, Hercules, CA). Results were expressed as ng of HRP uptake per oocyte.

Western Blot Analysis of Rab5 and Mutants

Oocytes were injected with Rab5:Q79L or Rab5:ΔC4 (100 ng in 50 nl of buffer A) and incubated for 2 h at 18°C. The cells were then lysed, and crude membrane and cytosolic fraction were prepared by centrifuging at 70,000 rpm for 15 min in a TL-100 ultracentrifuge (Beckman Instruments, Inc., Palo Alto, CA). Each fraction (5 μg) was separated by SDS-PAGE and transferred onto nitrocellulose membranes, and Western blot analysis was carried out using polyclonal anti-Rab5 antibody and developed by enhanced chemiluminescence.

Degradation Assay Using Preloaded HRP in Oocytes

To monitor the inactivation/degradation of the marker protein, oocytes were preloaded with HRP (2 mg/ml) in MBS for 1 h at 18°C. Subsequently, cells were washed three times with ice-cold MBS to remove unbound HRP. HRP-preloaded cells were injected with the test proteins and incubated for 2 h at 18°C. The amount of HRP activity present after the incubation was determined after lysis of the oocytes.

To follow degradation, oocytes were incubated with ^{125}I-HRP (500 μg/ml; 2×10^5 cpm/μg) for 1 h at 18°C. The cells were then washed to remove unbound radioactivity. The preloaded cells were injected either with control buffer or Rab proteins and incubated in MBS for 2 h at 18°C, the media were collected, and the cells were lysed. TCA-soluble and -precipitable radioactivity both in the cell lysates and in the medium was determined by addition of 10% TCA followed by centrifugation.

Published March 24, 1997

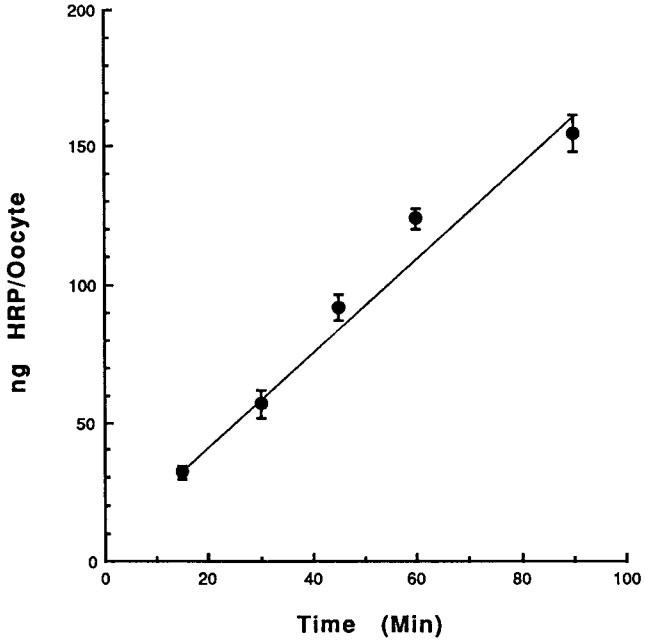

Figure 1. Time-dependent uptake of HRP by the oocytes. Oocytes were incubated with 2 mg/ml of HRP for different periods of times. The cells were washed three times with MBS and each oocyte was lysed in 200 μl of lysis buffer. Aliquots of the lysate were used to measure the amount of HRP present in each cell. The results, expressed as ng of HRP per oocyte, represent the average of eight independent observations.

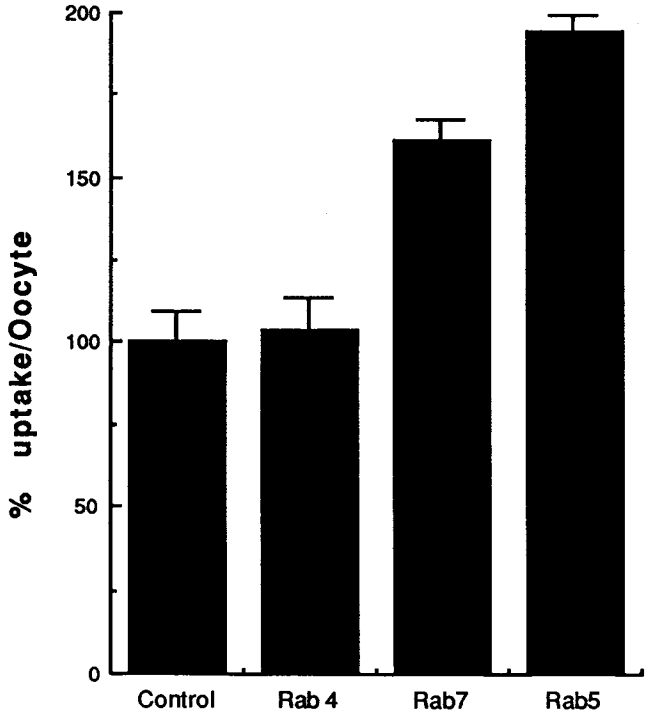

Figure 2. Effect of different Rab proteins on HRP uptake in oocytes. Oocytes were injected with 100 ng of the indicated Rabs in 50 nl of microinjection buffer and incubated for 2 h at 18°C. The cells were then incubated with HRP (2 mg/ml) for 1 h at 18°C to determine the uptake rate. Results were expressed as percentage of uptake per oocyte with respect to control (220 ng per oocyte) ± SD (average of eight experiments).

Confocal Microscopy

For confocal microscopy, oocytes were injected with Rab7 or mutant proteins and allowed to recover for 1 h at 18°C. The cells were then incubated with HRP-FITC for 1 h at room temperature under slow rotation in the dark. Subsequently, the cells were washed three times with MBS and incubated in the dark for one additional hour. The labeled oocytes were then observed with an MRC 600 laser confocal microscope (Bio Rad Microscience, Cambridge, MA) using a ×63 plan apochromat oil immersion objective (Carl Zeiss, Inc., Thornwood, NY).

Results

Role of GTPases in Endocytosis in Xenopus Ooocytes

To determine the function of GTPases in the endocytic pathway, we used HRP as a marker to follow endocytosis and transport from the cell surface to a lysosomal compartment. The results presented in Fig. 1 show that HRP uptake is linear with time when the cells are incubated with HRP at 2 mg/ml. All subsequent uptake experiments were carried out for 1 h with 2 mg/ml HRP. Many experiments were also carried out at a higher ligand concentration (5 mg/ml) with identical results.

To determine the role of GTPases in intracellular trafficking, we measured HRP uptake by oocytes after injection of GTPγS, a nonhydrolyzable analogue of GTP. About 80% inhibition of HRP uptake was obtained when GTPγS (20 μM; 50 nl per cell) was injected, suggesting that one or more GTPases are involved in endocytosis in oocytes (data not shown). HRP uptake was also inhibited by aluminum fluoride (data not shown) but was not significantly affected when the cells were microinjected with equivalent concentrations of aluminum sulfate or potassium fluoride. These results provide evidence for a role for heterotrimeric GTPases in endocytosis in oocytes (Mayorga et al., 1989; Chabre, 1990; Colombo et al., 1994).

Effect of Injected Rab GTPases on Oocyte Endocytosis

To explore the role of Rab GTPases in endocytosis in *Xenopus* oocytes, we microinjected different Rab proteins (100 ng) and followed HRP uptake. Both Rab5 and Rab7 significantly stimulated HRP uptake by oocytes by 1.5- to twofold (Fig. 2). This result is consistent with the finding that Rab5 stimulates endocytosis during transient expression in vivo and endosome–endosome fusion in vitro (Li and Stahl, 1993; Bucci et al., 1992; Li et al., 1994; Barbieri et al., 1994; Stenmark et al., 1994). The stimulation of HRP uptake by Rab7 was an unexpected but interesting observation. Injection of Rab4 had no effect on HRP endocytosis. We studied four different constructs of Rab5: Rab5:S34N, a dominant-negative mutant (Li and Stahl, 1993; Grovel et al., 1991; Burstein et al., 1992); Rab5:ΔC4 where the isoprenylation motif is deleted; Rab5:Q79L, a GTPase-defective mutant (Li et al., 1994; Burstein et al., 1992); and Rab5:wild type. All the proteins were prepared as GST fusion proteins and the purified proteins were injected directly into oocytes. As shown in Fig. 3 *a*, both Rab5:WT and Rab5:Q79L enhanced uptake of HRP. Rab5:S34N, on the other hand, markedly inhibited HRP uptake by the oocytes (Fig. 3 *a*). Rab5:ΔC4 failed to associate with mem-

Published March 24, 1997

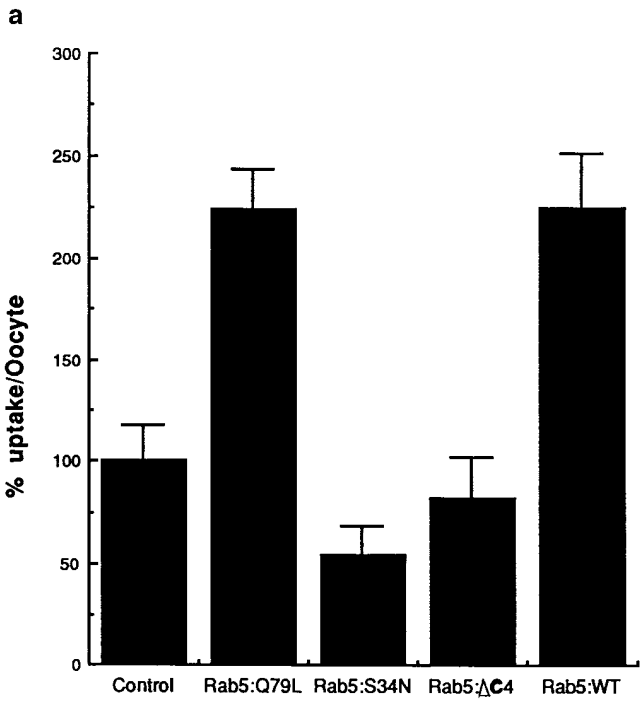

Figure 3. Effect of Rab5 and its mutants on endocytosis in oocytes. (*a*) Oocytes were injected with 100 ng each of the indicated proteins, and the uptake was carried out as described in Fig. 1. The results were expressed as percentage of control (200 ng/oocyte) ± SD. (*b*) Oocytes were injected with 100 ng of Rab5:Q79L or Rab5:ΔC4 in 50 nl of microinjection buffer and incubated for 2 h at 18°C. The cells were lysed, and crude membrane and cytosolic fractions were prepared by centrifuging at 70,000 rpm for 15 min. Each fraction (5 μg) was separated by SDS-PAGE and transferred onto nitrocellulose, and Rab5 protein was localized using polyclonal Rab5-specific antibodies (Alvarez-Dominguez et al., 1996).

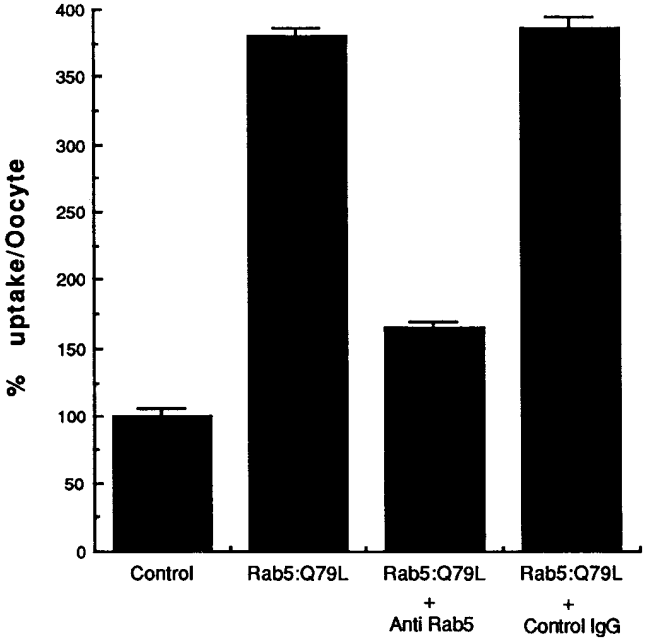

Figure 4. Inhibition of HRP uptake by anti-Rab5 antibody. The oocytes were injected with Rab5:Q79L (100 ng) alone or with anti-Rab5 antibody (200 ng). HRP uptake was followed as described in Fig. 1. Results are expressed as percentage of control uptake (150 ng per oocyte) from the average of eight experiments.

branes and did not significantly affect HRP uptake. Rab5:DC4 was present exclusively in the cytosolic fraction (Fig. 3 *b*). These results strongly suggest that frog oocytes have the ability to carry out the required posttranslational modification of Rab proteins, and that COOH-terminal isoprenylation is required for the binding of the Rab GTPase to the target membrane and for biological activity. Moreover, we have also found that Rab proteins are readily prenylated in vitro using oocyte cytosol in the presence of labeled substrate (data not shown). To confirm that the stimulatory effect of Rab5:Q79L was due to the injected Rab protein, coinjection experiments were carried out with the Rab fusion protein and an anti-Rab5 antibody. Coinjection of the fusion protein with anti-Rab5 antibody, but not with a control antibody, dramatically inhibited Rab5:Q79L-enhanced uptake of HRP (Fig. 4).

Role of NSF in Rab5-Stimulated Endocytosis of HRP

NSF is required for in vitro endosome fusion (Diaz et al., 1989). To delineate the role of NSF in endocytosis in oocytes, we injected anti-NSF antibody into the cells and measured HRP uptake. The results presented in Fig. 5 *a* demonstrate that anti-NSF antibody inhibits the stimulation of HRP uptake in cells injected with Rab5:Q79L when anti-NSF antibodies and Rab5:Q79L were coinjected. Injection of anti-NSF antibodies in control oocytes resulted in a modest reduction in uptake (data not shown). To confirm the participation of NSF in Rab5 function, we coinjected oocytes with Rab5:Q79L and His_6NSF wild-type protein. The results in Fig. 5 *b* show that Rab5:Q79L-stimulated HRP uptake is enhanced in the presence of NSF protein. NSF is a heterotrimer whose polypeptide subunits are made up of three distinct domains: an amino-terminal domain and two homologous ATP (D1 and D2) binding domains (Whiteheart et al., 1994). The ability of the D1 domain to hydrolyze ATP is required for NSF-mediated membrane fusion. The D2 domain is required for trimerization, but its ability to hydrolyze ATP is not absolutely required for NSF function. Two distinct mutations in the first ATP binding site (D1), i.e., D1-K266A and D1-E329Q, are known to affect ATP binding and hydrolysis, resulting in inactive forms of NSF (Whiteheart et al., 1994). To determine the role of the ATP binding domains of NSF in Rab5-mediated endocytosis, we coinjected Rab5:Q79L and different NSF mutant proteins into oocytes and followed HRP uptake. The results in Fig. 5 *b* demonstrate that His6 D1-E329Q and His6 D1-K266A significantly inhibit HRP uptake mediated by Rab5:Q79L, indicating that ATP hydrolysis and binding are required for NSF activity and Rab5-mediated endocytosis.

Published March 24, 1997

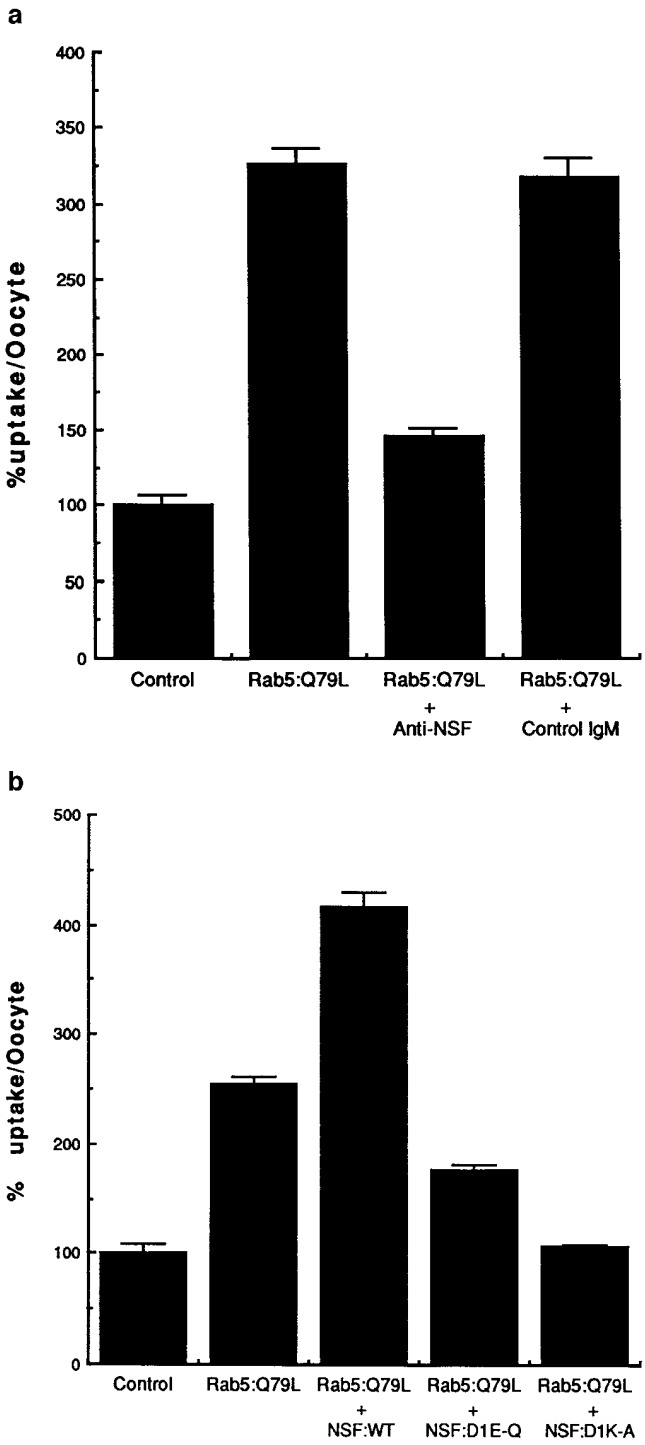

Figure 5. Effect of NSF on HRP uptake by oocytes. (*a*) Cells were injected with either 100 ng of Rab5:Q79L with or without anti-NSF (200 ng) antibody. Uptake was carried out as described in Materials and Methods. Results were expressed as percentage of control uptake (180 ng/oocyte) from the average of eight experiments. (*b*) Oocytes were injected with 75 ng of Rab5:Q79L alone or with 100 ng of NSF and its mutants as indicated. Uptake was determined as described, and the results are expressed as percentage of control (220 ng per oocyte) uptake.

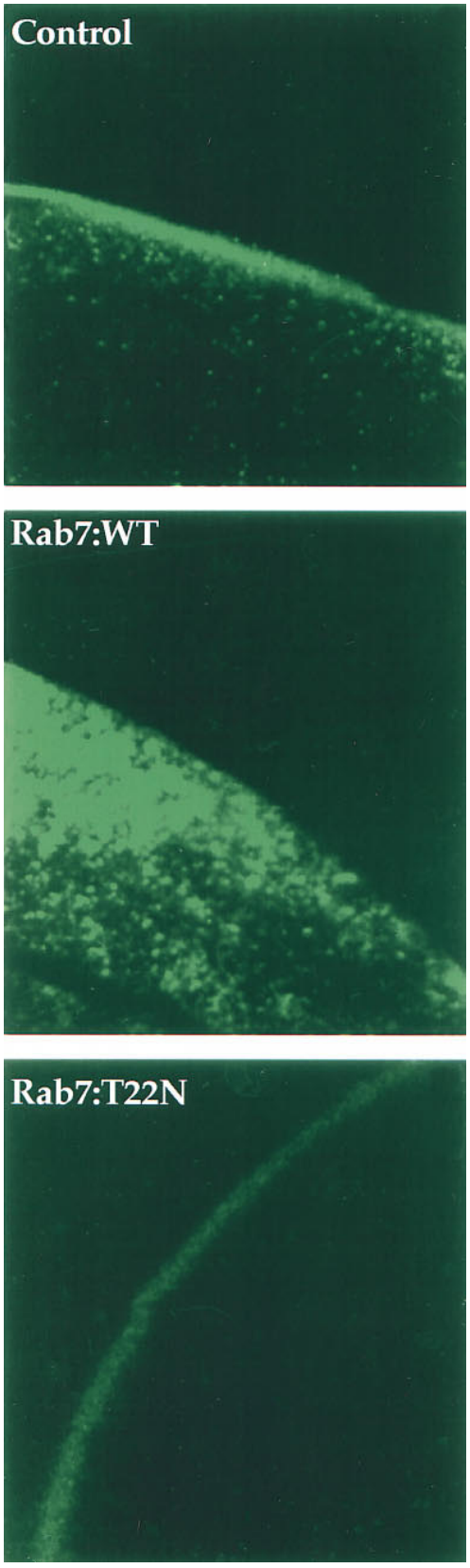

Figure 6. Rab7-mediated uptake of HRP by oocytes. Oocytes were injected with 100 ng of the indicated proteins and uptake was carried out with HRP-FITC for 1 h in the dark (1 mg/ml). Subsequently, the cells were washed three times with MBS, incubated in the dark for another 1 h, and then observed under the confocal microscope.

Published March 24, 1997

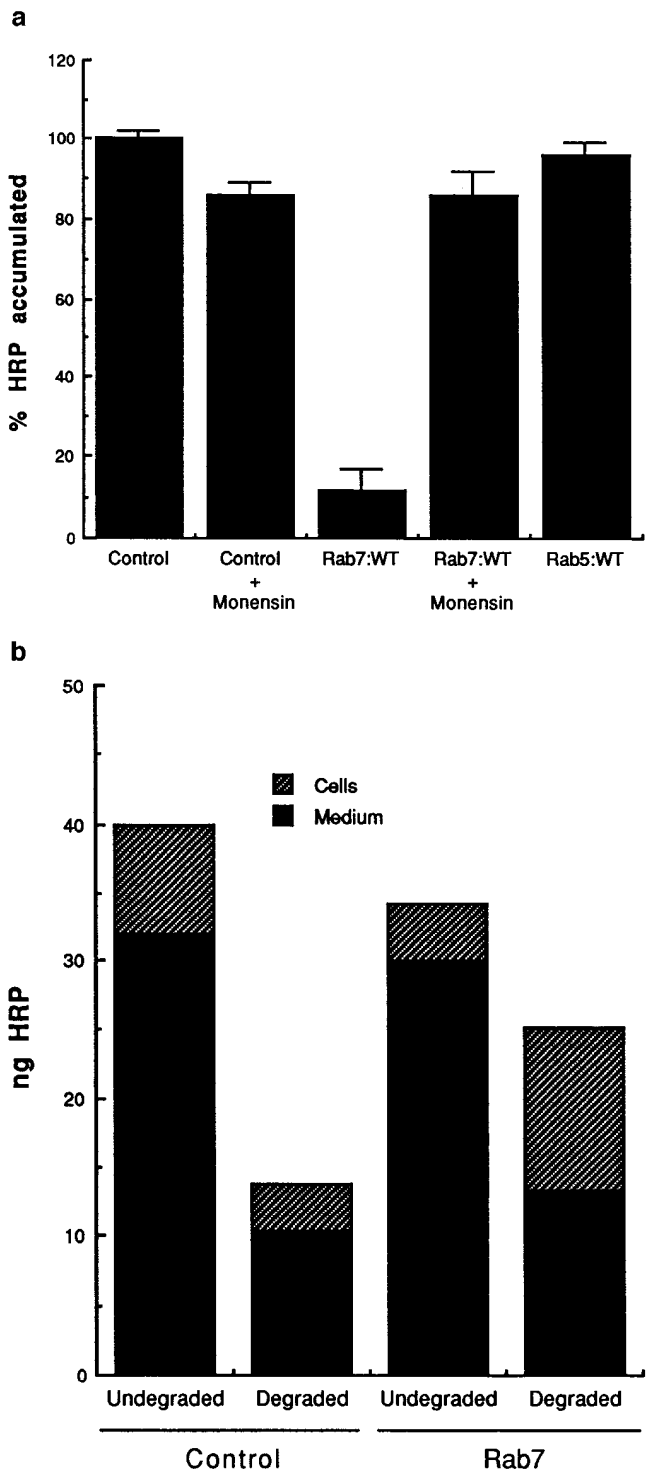

Figure 7. Rab7-mediated inactivation/degradation of HRP by oocytes. (*a*) Oocytes were preloaded with HRP by incubating with HRP (2 mg/ml) for 1 h at 18°C. Preloaded cells were washed and incubated with 100 μM monensin or control buffer as indicated for 1 h at 18°C. The cells were then injected with 100 ng of the respective fusion proteins. HRP activity present in the cells was measured after a 2-h incubation at 18°C. Results are expressed as percentage of control (110 ng HRP/oocyte) from the average of eight experiments. (*b*) Oocytes were incubated with ^{125}I-HRP (0.5 mg/ml; 2×10^5 cpm/μg) for 1 h at 18°C and washed three times to remove unbound radioactivity. Subsequently, the cells were injected with 100 ng of Rab7:WT protein or control buffer, and nine oocytes were incubated in 300 μl of MBS for 2 h at 18°C. Oocytes were washed and solublized in PBS containing 0.1% Triton X-100, and TCA-soluble and -precipitable radioactivity was determined in cell lysates and media. Results are expressed as ng of HRP associated with or degraded by the cells.

Effect of Rab7 and Its Mutants on HRP Uptake

As indicated above, injection of Rab7:WT (100 ng) into oocytes produced a marked stimulation in HRP uptake (Fig. 2). To characterize the effect of Rab7 on endocytosis, we examined the effect of Rab7 on the uptake HRP-FITC by confocal microscopy. The results presented in Fig. 6 show substantial increases in fluorescence when the cells were injected with Rab7:WT protein. Cells injected with Rab7:T22N appeared very similar to control cells. In fact, injection of Rab7:T22N showed significant inhibition of HRP-FITC uptake (data not shown). In control and Rab7:T22N injected cells, most of the staining was observed near the plasma membrane, presumably in early endosomal compartments. In Rab7:WT-injected cells, it is evident that HRP-FITC is localized to larger vesicles and much deeper into the cells, possibly reflecting the transport of the marker proteins into later compartments. To further confirm the effect of Rab5 and Rab7 on the endocytic pathway at the EM level, oocytes were injected with Rab5:WT and Rab7:WT, and then allowed to internalize WGA–gold particles for 60 min. The cells were then fixed and prepared for EM. Oocytes injected with Rab5 had substantially more early endosome–like vesicular structures, whereas a significant labeling of large multivesicular endosomes (1–1.5 μm) deeper inside the cells was observed when cells were injected with Rab7:WT. These data suggest that Rab7 induced the transport to a late endosome/prelysosome compartment. About 180–200 large multivesicular compartments were observed per square millimeter only in oocytes injected with Rab7:WT protein (data not shown).

Differential Kinetics of Rab5 and Rab7 on Endocytosis in Oocytes

Rab5 is an early endosomal Rab that regulates endosome fusion, whereas Rab7 is localized to the late endosomal compartment (Wichmann et al., 1992; Schimmoller et al., 1993; Feng et al., 1995). Our data indicate that both proteins stimulate HRP uptake in oocytes, suggesting an effect of both proteins on the early endocytic pathway. To check the effect of Rab5 and Rab7 on later events, we developed a more direct biochemical assay to measure the degradation of internalized HRP after injection of the test proteins, as a measure of transport to a degradative or late compartment. In this assay, oocytes were preloaded with HRP for 1 h at 18°C. HRP activity was then followed over time after injecting Rab5 or Rab7 proteins. The results presented in Fig. 7 *a* show that ~80% of the HRP activity is lost within 2 h when the cells were injected with Rab7:WT protein. In contrast, most of the HRP activity is retained when the cells were injected with Rab5:WT protein, much like control cells. Thus, Rab7 not only promotes the internalization of HRP but also mediates apparent rapid degradation possibly by transferring internalized mole-

Published March 24, 1997

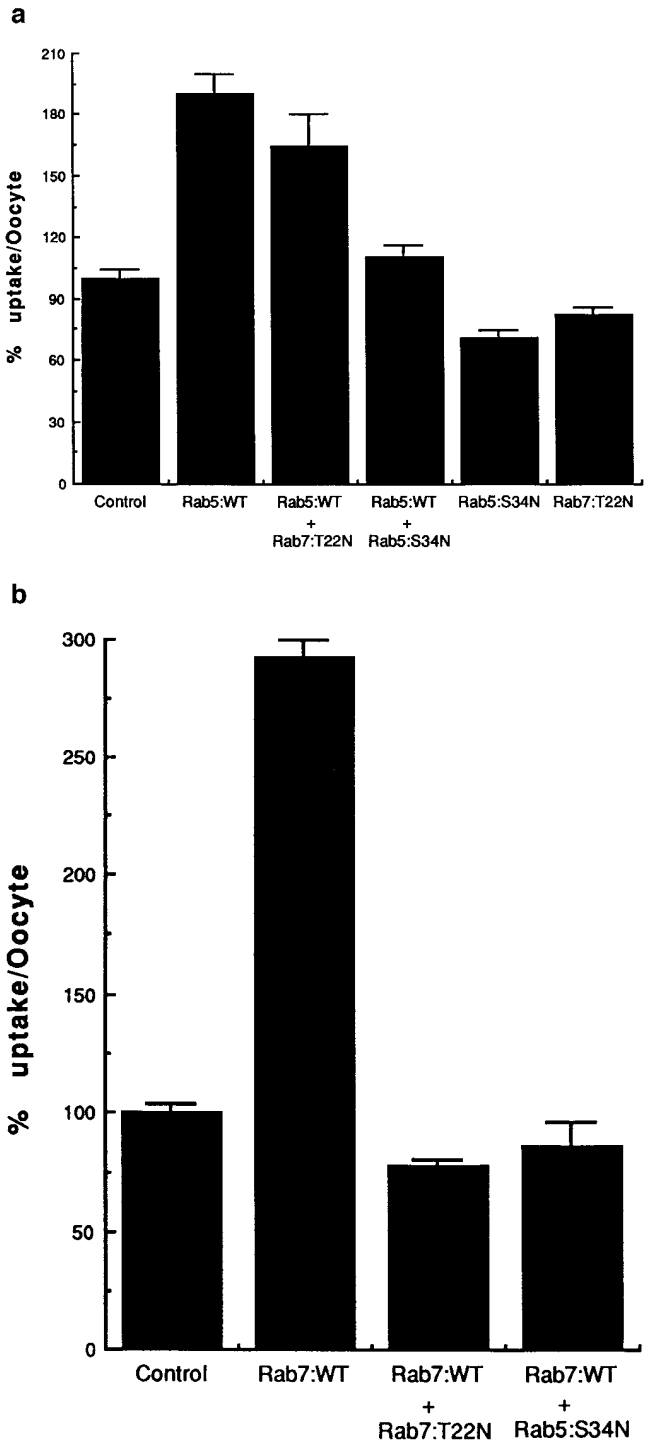

Figure 8. Rab5 regulation of endocytosis is upstream of Rab7. (*a*) Rab5 proteins were injected alone (50 ng) or in combination with both mutants (100 ng) of Rab5 and Rab7. (*b*) Rab7 proteins (50 ng) were injected alone or in combination with both mutants (100 ng) of Rab5 and Rab7. Results are expressed as percentage of control uptake by uninjected oocytes (average of eight experiments).

cules to a late compartment. Moreover, when the Rab7:WT-injected/HRP-preloaded cells were incubated in the presence of monensin (100 μM), ~80% of the HRP inactivation was prevented. We speculate that monensin prevents the inactivation and degradation of HRP either by blocking the transport to the later compartment or by increasing the pH of the lysosome-like compartment, which in turn inhibits the inactivation and/or degradation of HRP.

To examine the degradation of internalized HRP, oocytes were incubated with ^{125}I-HRP for 60 min, after which they were injected with control buffer or Rab7. The data presented in Fig. 7 *b* show the distribution of internalized ^{125}I-HRP in oocytes after injecting Rab7:WT protein into the cells. 43% of the HRP was degraded by the Rab7:WT protein–injected cells. In contrast, only 25% of the preloaded HRP was degraded when the cells were injected with control buffer. In both sets of cells, the same amount of the TCA-precipitable radioactivity (50%) was recovered in the medium, suggesting that a substantial amount of recycling occurs in this preparation. However, Rab7 did not induce or enhance recycling or regurgitation of the HRP to the medium.

Effects of Rab5- and Rab7-negative Mutants on Rab5-stimulated Endocytosis

We next examined the effects of the dominant-negative mutants of Rab5 and Rab7 to determine which acts first in the sequence. Injection of Rab5:WT into oocytes stimulated HRP uptake (Fig. 8 *a*) by about twofold. Coinjection of the Rab7 dominant-negative mutant (Rab7:T22N) with Rab5 had no effect on the Rab5-mediated stimulation of uptake. However, coinjection of the Rab5 dominant-negative mutant (Rab5:S34N) with Rab5:WT significantly at-

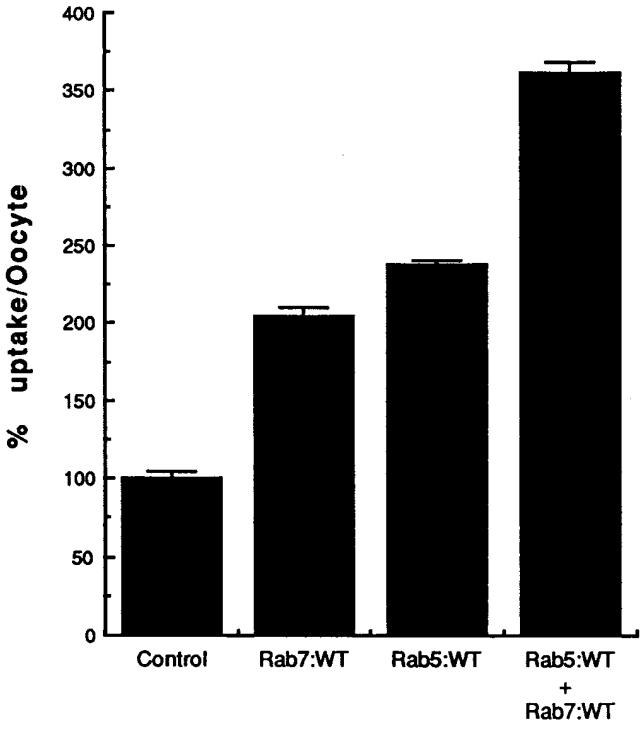

Figure 9. Rab5- and Rab7-coinjected cells produced additive effects. Oocytes were injected with 50 ng of Rab5 and Rab7 alone or in combination and incubated for 2 h at 18°C. The cells were incubated with 2 mg/ml of HRP for 1 h at 18°C to determine the rate of HRP uptake. Results are expressed as percentage of uptake per oocyte with respect to control (205 ng per oocyte) ±SD (average of eight experiments).

Published March 24, 1997

tenuated the Rab5:WT effect. On the other hand, injection of Rab7:WT produced a threefold increase in uptake, as shown in Fig. 8 *b*, and coinjection of the Rab7 dominant-negative mutant with Rab7:WT blocked the Rab7:WT effect. Interestingly, Rab5:S34N inhibited Rab7:WT-induced endocytosis. Moreover, Rab7:T22N and Rab5:S34N inhibited uptake when injected alone. Lastly, we examined the additive effects of Rab5 and Rab7 on endocytosis when coinjected. Injection of Rab5 and Rab7 separately increased endocytosis. Coinjection of Rab5 and Rab7 produced an additive effect on uptake of HRP (Fig. 9).

Discussion

The *Xenopus laevis* oocyte is an excellent cell model for investigating the mechanisms and the regulation of endocytosis (Opresko et al., 1980). Several characteristics of receptor-mediated endocytosis have been explored in the frog oocyte (Wall and Patel, 1987), and ultrastructural and biochemical studies have shown that intracellular transport of internalized ligands occurs via fusion between early endocytic vesicles and consecutively enlarged endosomes (Busson et al., 1989). In brief, these studies show that vitellogenin, the precursor to stored yolk protein, is taken up by receptor-mediated endocytosis. Internalized vitellogenin receptor–ligand complexes are selectively proteolyzed and sequestered from the normal endocytic pathway with transport to yolk platelets. Selective targeting to the storage pathway appears to be dependent both on receptor occupancy and on selective ligand proteolysis (Opresko and Karpf, 1987). Fluid phase markers, on the other hand, in the absence of vitellogenin, are routed to the degradative pathway. In the work described in this paper, we have used HRP as a fluid phase marker.

In the last few years, it has become apparent that GTP binding proteins play an important role in endocytosis, and that a series of GTPases act in concert to effect transport from cell surface to lysosomes or the TGN. A large number of studies have shown that GTPγS can impair transport by interfering with budding or the fusion events, consistent with the conclusion that a large repertoire of GTPases is required for efficient endocytosis (Gomperts and Fernandez, 1985; Mayorga et al., 1989; Goda and Pfeffer, 1988; Damke et al., 1995).

Numerous reports indicate that several small GTPases regulate endocytosis. Most of these studies have employed transient overexpression of proteins using recombinant virus encoding the proteins of interest. This approach has been extremely useful in studying transport but is somewhat limited because usually only one variable can be changed at a time. We have developed an in vivo assay by microinjection of purified proteins into *Xenopus* oocytes followed by endocytosis of HRP. This approach takes advantage of the high endocytic capacity of oocytes and allows one to examine the effect of one or more proteins that can be injected simultaneously. These studies have led to some unexpected findings.

Two experiments, one with GTPγS and another with aluminum fluoride, indicate that one or more GTPases are involved in oocyte endocytosis and that GTP hydrolysis by at least one GTPase is required. Aluminum fluoride is a potent and reversible activator of the heterotrimeric GTP binding proteins (Chabre, 1990; Colombo et al., 1994), although recent experiments (Mittal et al., 1996) indicate that, under certain circumstances, low molecular weight GTPases can be affected by AlF_4. Heterotrimeric GTPases have been implicated in transport along the secretory pathway (Burgoyne, 1992) and in endocytosis (Colombo et al., 1992).

Rab4 and Rab5 are associated with early endosomes, and Rab5, in particular, has been shown to play a role in the regulation of endocytosis. As shown in Fig. 3 *a*, Rab5:Q79L, a GTPase-defective mutant, enhances HRP uptake. This result suggests that the GTP form of Rab5 is the molecular switch for endocytosis in oocytes as reported for other cells (Barbieri et al., 1994; Stenmark et al., 1994). Rab5:Q79L has been shown to induce HRP uptake in BHK cells (Li et al., 1994) and to enhance fusion between early endosomes in an in vitro reconstitution assay (Stenmark et al., 1994; Barbieri et al., 1994). Thus, enhanced uptake of HRP by oocytes is probably due to enhanced fusion between early endosomes. In contrast, Rab5:S34N, the dominant-negative mutant, inhibited HRP uptake. This is in agreement with the observation that Rab5:S34N inhibits both endocytosis, when overexpressed in mammalian cells, and in vitro endosome fusion. The inhibition of HRP uptake by Rab5:S34N may be due to competition for the Rab5-specific exchange factor, as suggested for ras-specific GEF (Feig and Cooper, 1988; Hwang et al., 1993; Schweighoffer et al., 1993).

The COOH-terminal motif of Rab proteins serves as a recognition site for isoprenylation that is important for membrane attachment and biological function (Li et al., 1994; Burstein et al., 1992). It has been shown that deletion of three or four residues from the COOH-terminal domain of Rab5 completely abolishes prenylation. The data presented in the Fig. 3 *a* show that Rab5:ΔC did not significantly affect HRP uptake in oocytes. This is probably due to the fact that this protein is not prenylated and unable to bind to target membranes. This was further confirmed by the Western blot analysis (Fig. 3 *b*). A band corresponding to Rab5 was detected in the membrane preparation of oocytes injected with Rab5:Q79L but not Rab5:ΔC4 where most of the protein was detected in the cytosol. In vitro prenylation experiments confirmed that oocyte cytosol has the capacity, in the presence of added substrate, to prenylate Rab GTPases (data not shown). These results indicate that the oocyte has the ability to carry out prenylation, and that COOH-terminal isoprenylation is required for the binding of the Rab proteins and for their biological activity.

To further characterize endocytosis in microinjected oocytes, we examined NSF. NSF fusion protein is required for efficient fusion of endosomes in vitro. Mutants of NSF that fail to bind or to hydrolyze ATP are effective inhibitors of endosome fusion in vitro (Colombo et al., 1996). NSF and associated SNAP molecules (Wilson et al., 1992; Sollner et al., 1993) are required in multiple intracellular vesicle fusion events (Becker et al., 1989; Diaz et al., 1989; Sztul et al., 1993; Sogaard et al., 1994). The results presented in Fig. 5 *a* show that anti-NSF antibody inhibits Rab5:Q79L-induced HRP uptake in oocytes. (Western blot experiments not shown indicate that the mAb used recognizes a frog protein of the same apparent molecular weight

Published March 24, 1997

as NSF.) Injection of anti-NSF into control cells produced a modest decrease in uptake. The role of NSF was further confirmed by coinjecting wild-type NSF or NSF mutants (D1E-Q, D1K-A) along with Rab5:Q79L. The results show that NSF activates endocytosis of HRP mediated by Rab5 and suggest that NSF may be rate limiting in Rab5-sensitive pathways. This is the first report of activation of a transport pathway by NSF in vivo. To confirm the role of NSF, we used two NSF mutants that are known to block NSF function. These mutant proteins inhibited uptake, suggesting that ATP binding and hydrolysis by NSF is required for function in oocytes as in mammalian cells (Whiteheart et al., 1994). However, why anti-NSF antibodies effectively block Rab-induced endocytosis and yet only modestly inhibit control uptake is unclear. It is likely that endogenous NSF and endogenous Rab GTPases are more efficient than the injected mammalian counterparts. This might explain why antibody inhibition of uptake is only modest in control cells since the antibody would be competing with endogenous factors for binding to NSF. Similarly, exogenous Rabs might be more easily competing for interaction with the docking and fusion machinery than endogenous Rabs by the anti-NSF antibody.

Recently, it has been shown in mammalian cells that Rab7 regulates transport between the early and late endosomes (Feng et al., 1995). Similar results were also obtained in yeast using Ypt7, a yeast homologue of mammalian Rab7. Schimmoller and Riezmann (1993) have shown that Ypt7 regulates the transport between the late endosome to the vacuole. Moreover, it has been shown that Ypt7 is also involved in the homotypic fusions between the vacuole in the yeast (Hass et al., 1995; Mayer et al., 1996). All these studies have shown that Rab7 in mammalian cells or Ypt7 in yeast initiates the degradation of the marker proteins by enhancing transport to a late endosome/prelysosome or lysosomal compartment. Our data demonstrate that injected Rab7 WT stimulates HRP uptake. Rab7:T22N, the dominant-negative mutant of Rab7 (Feig et al., 1988; Nuoffer et al., 1994; Riederer et al., 1994), was found to be mildly inhibitory for HRP uptake when injected alone but was fully able to block the stimulatory effect of Rab7. As outlined above for inhibition by anti-NSF antibodies, it is likely that the exogenous mammalian Rab7-negative mutant would more effectively antagonize injected mammalian wild-type Rab7 than the corresponding endogenous Rab. The results presented in Fig. 7 *a* show that when Rab7 was injected into HRP preloaded cells, only 20% of the injected HRP activity was recovered at the indicated times in Rab7:WT-injected cells compared with controls. This rapid inactivation of HRP may be due to loss of enzymatic activity, actual degradation, or both. In Fig. 7 *b*, we show that Rab7-injected cells degrade ^{125}I-HRP more rapidly than control cells, but the degradation was not commensurate with the loss of HRP activity in Rab7-injected cells. Thus, the loss of HRP activity in Rab7-injected cells is probably due to inactivation and degradation of the marker protein. The results in Fig. 7 *b* also confirm that the loss of activity in Rab7-injected cells is not due to the recycling or regurgitation of HRP. Rab7 probably mediates the rapid degradation of the marker protein by stimulating transport to a late endosome/prelysosomal compartment (Fig. 7). Thus, kinetically, Rab7 function is different from that of Rab5 because the latter does not stimulate inactivation. The rapid inactivation of HRP in Rab7-injected cells is effectively blocked by monensin. Monensin may block the transport of the marker protein from an early compartment to the degradative compartment, or it may inhibit the degradation of the ligand by increasing the pH of the lysosome-like compartment. The latter is consistent with the finding that monensin blocks the transport of markers to a later compartment described by Opresko and Karpf (1987). An effect of Rab7 on transport to late compartments is further strengthened by localization of WGA–gold in large multivesicular endosomes deep inside the oocyte when the cells were injected with Rab7:WT. These data are consistent with that of Wall and colleagues (Wall and Patel, 1987), who demonstrate that multivesicular bodies are found along the endocytic pathway. One issue that remains unresolved is whether the degradation of the marker protein occurs in late endosomes or lysosomes. GTPγS has been shown to block the transport from late endosomes to lysosomes, implicating GTPases in this process (Mullock et al., 1994). It is also possible that Rab7 is involved in both processes. Interestingly, homotypic fusion of the vacuole has been shown to require Ypt7 (Hass et al., 1995), and recently Rab7 was found, in part, to be localized in lysosomes (Meresse et al., 1995).

The results with the Rab coinjection experiments suggest that Rab7 mediates endocytosis through the early endosome and that the effect of Rab7 is downstream of Rab5. Similar results have been reported in the yeast where Ypt51p, Ypt52p, and Ypt53p, functional homologues of mammalian Rab5, mediate the degradation of the yeast pheromone α-factor via delivery to the vacuole. A null *Ypt7* mutant delayed the onset of α-factor degradation threefold, while a triple mutation *Ypt51*,*Ypt52*,*Ypt53* delayed α-factor degradation more than sixfold (Singer-Kruger et al., 1994; Wichmann et al., 1992). The fact that α-factor is accumulated in the triple mutant in the early endosome, whereas the Ypt7 mutant accumulated in the late endosome, suggested that Ypt51 function is upstream of Ypt7 (Schimmoller and Riezman, 1993). These conclusions are similar to our findings in oocytes where we show that Rab7-mediated uptake is blocked by the Rab5-negative mutant, but the Rab5-mediated uptake remains unaffected in the presence of the Rab7-negative mutant. We speculate that Rab5 fills an intracellular compartment, perhaps an early endosomal sorting compartment. Internalized solute present in the early endosomal compartment may recycle to the cell surface or be transported to a later compartment en route to lysosomes. Rab5 would be expected to increase the flux of ligand through the early compartment. Rab7 stimulates transport from the early endosome to a later compartment where inactivation and/or degradation occurs. If Rab7 were rate limiting in the pathway and the magnitude of the Rab7 effect was dependent on the concentration of solute or ligand present in the early endosomal compartment, Rab7 would be expected to increase endocytosis and to act additively with Rab5. The relationship between sequentially acting Rabs, the levels of expression, the use of common factors (e.g., GDP dissociation inhibitor), and the regulation by respective guanine nucleotide exchange factors poses interesting and important questions that concern the overall regulation of intracellular transport.

We thank Rita Boshans for technical help and Mike Mueckler for introducing us to oocytes. We also thank Angela Wandinger-Ness and Marisa Colombo for critically reading the manuscript.

P.D. Stahl is supported by grants from the National Institutes of Health. A. Mukhopadhyay is supported by an associateship from DBT, Government of India.

Received for publication 27 November 1996 and in revised form 14 December 1996.

References

Alvarez-Dominguez, C., M.A. Barbieri, W. Beron, A. Wandinger-Ness, and P.D. Stahl. 1996. Phagocytosed live *Listeria monocytogenes* influences rab5-regulated *in vitro* phagosome-endosome fusion. *J. Biol. Chem.* 271:13834–13843.

Balch, W.E. 1990. Small GTP-binding proteins in vesicular transport. *Trends Biochem. Sci.* 15:473–477.

Barbieri, M.A., G. Li, M.I. Colombo, and P.D. Stahl. 1994. Rab5, an early acting endosomal GTPase, supports *in vitro* endosome fusion without GTP hydrolysis. *J. Biol. Chem.* 269:18720–18722.

Barbieri, M.A., G. Li, L.S. Mayorga, and P. Stahl. 1996. Characterization of Rab5:Q79L-stimulated endosome fusion. *Arch. Biochem. Biophys.* 326:64–72.

Barr, F.A., A. Leyte, and W.B. Huttner. 1992. Trimeric G proteins and vesicles formation. *Trends Cell Biol.* 2:91–94.

Barsagi, D., and J.R. Feramisco. 1986. Induction of membrane ruffling and fluid phase pinocytosis in quiescent fibroblasts by ras proteins. *Science (Wash. DC).* 233:1061–1068.

Becker, C.J.M., M.R. Bloch, B.S. Glick, J.E. Rothman, and W.E. Balch. 1989. Vesicular transport between the endoplasmic reticulum and the Golgi stack requires the NEM sensitive factor. *Nature (Lond.).* 339:397–398.

Beron, W., C. Alvarez-Dominguez, L. Mayorga, and P.D. Stahl. 1995. Membrane trafficking along the phagocytic pathway. *Trends Cell Biol.* 5:100–104.

Bourne, H.R. 1988. Do GTPases direct membrane traffic in secretion? *Cell.* 53: 669–671.

Bourne, H.R., D.A. Sanders, and F. McCormick. 1990. The GTPase superfamily: a conserved switch for diverse cell functions. *Nature (Lond.).* 348:125–132.

Bucci, C., R.G. Parton, I.H. Mather, H. Stunnenberg, K. Simons, B. Hoflack, and M. Zerial. 1992. The small GTPase Rab5 functions as a regulatory factor in early endocytic pathway. *Cell.* 70:715–728.

Burgoyne, R.D. 1992. Trimeric G proteins in Golgi transport. *Trends Biochem. Sci.* 17:87–88.

Burstein, E.S., W.H. Brondyk, and I.G. Macara. 1992. Amino acid residues in Ras-like GTPase rab3A that specify sensitivity to factors that regulate the GTP/GDP cycling of Rab3A. *J. Biol. Chem.* 267:22715–22718.

Busson, S., L. Ovtracht, and P. Gounon. 1989. Pathway and kinetics of vitellogenin-gold internalization in the *Xenopus* oocyte. *Biol. Cell.* 67:37–49.

Chabre, M. 1990. Aluminium fluoride and beryllofluoride complex: a new phosphate analog in enzymology. *Trends Biochem. Sci.* 15:6–10.

Chavrier, P., R.G. Parton, H.P. Hauri, K. Simons, and M. Zerial. 1990. Localization of low molecular GTP binding proteins to exocytic and endocytic compartments. *Cell.* 62:317–329.

Colombo, M.I., S. Gonzalo, P. Weidman, and P.D. Stahl. 1991. Characterization of trypsin-sensitive factor(s) required for endosome-endosome fusion. *J. Biol. Chem.* 266:23438–23445.

Colombo, M.I., L. Mayorga, P.J. Casey, and P.D. Stahl. 1992. Evidence of a role for heterotrimeric GTP-binding proteins in endosome fusion. *Science (Wash. DC).* 255:1695–1697.

Colombo, M.I., J. Lenhard, L. Mayorga, W. Beron, H. Hall, and P.D. Stahl. 1994. Inhibition of endocytic transport by aluminium fluoride implicates GTPases as a regulator of endocytosis. *Mol. Membr. Biol.* 11:93–100.

Colombo, M.I., M. Taddese, S.W. Whiteheart, and P.D. Stahl. 1996. A possible predocking attachment site for N-ethylmaleimide-sensitive fusion protein. Insights from in vitro endosome fusion. *J. Biol. Chem.* 271:18810–18816.

Cresswell, P. 1994. Assembly, transport, and function of MHC class II molecules. *Annu. Rev. Immunol.* 12:259–293.

Damke, H., T. Baba, A.M. van der Bliek, and S.L. Schmid. 1995. Clathrin-independent pinocytosis is induced in cells overexpressing a temperature-sensitive mutant of dynamin. *J. Cell Biol.* 131:69–80.

Desjardins, M., J.E. Celis, G. van Meer, H. Dieplinger, A. Jahraus, G. Griffiths, and L.A. Huber. 1994. Molecular characterization of phagosome. *J. Biol. Chem.* 269:32194–32200.

Diaz, R., L. Mayorga, and P.D. Stahl. 1988. *In vitro* fusion of endosomes following receptor-mediated endocytosis. *J. Biol. Chem.* 263:6093–6100.

Diaz, R., L.S. Mayorga, P.J. Weideman, J.E. Rothman, and P.D. Stahl. 1989. Vesicle fusion following receptor mediated endocytosis requires a protein active in Golgi transport. *Nature (Lond.).* 339:398–400.

Feig, L.A., and G.M. Cooper. 1988. Inhibition of NIH 3T3 cell proliferation by a mutant ras protein with preferential affinity for GDP. *Mol. Cell. Biol.* 8: 3235–3243.

Feng, Y., B. Press, and A. Wandinger-Ness. 1995. Rab7: An important regulator of late endocytic membrane traffic. *J. Cell Biol.* 131:1435–1452.

Germain, R.N. 1994. MHC-dependent antigen processing and peptide presentation: providing ligand for T lymphocyte activation. *Cell.* 76:287–299.

Goda, Y., and S.R. Pfeffer. 1988. Selective recycling of the mannose-6-phosphate/IGF II receptor to trans-Golgi network in vitro. *Cell.* 55:309–320.

Goldstein, J.L., M.S. Brown, R.G. Anderson, D.W. Russell, and W.J. Schneider. 1985. Receptor mediated endocytosis: concepts emerging from the LDL receptor system. *Annu. Rev. Cell. Biol.* 1:1–39.

Gomperts, B.D., and J.M. Fernandez. 1985. Techniques for membrane permeabilization. *Trends Biochem. Sci.* 10:414–417.

Goud, B., A. Zahraoui, A. Tavitian, and J. Saraste. 1990. Small GTP-binding protein associated with Golgi-cisternae. *Nature (Lond.).* 345:553–556.

Gravotta, D., M. Adesnik, and D.D. Sabatini. 1990. Transport of influenza HA from the *trans*-Golgi network to apical surface of MDCK cells permeabilized in their basolateral plasma membrane: energy dependence and involvement of GTP binding proteins. *J. Cell Biol.* 111:2893–2908.

Griffiths, G., R. Matteoni, R. Back, and B. Hoflack. 1990. Characterization of the cation-independent mannose-6-phosphate receptor enriched prelysosomal compartment in NRK cells. *J. Cell. Sci.* 95:441–461.

Grovel, J.P., P. Chavrier, M. Zerial, and J. Gruenberg. 1991. Rab5 controls early endosome fusion in vitro. *Cell.* 64:915–925.

Hass, A., D. Scheglmann, T. Lazar, D. Gallwitz, and W. Wickner. 1995. The GTPase Ypt7 of *Saccharomyces cerevisiae* is required on both partner vacuoles for the homotypic fusion step of vacuole inheritance. *EMBO (Eur. Mol. Biol. Organ.) J.* 14:5258–5270.

Hwang, Y.-W., J.M. Zhong, P. Poullet, and A. Parmeggiani. 1993. Inhibition of SDC25 C-domain-induced guanine nucleotide exchange by guanine ring binding domain mutants of v-H-ras. *J. Biol. Chem.* 268:24692–24698.

Li, G., and P.D. Stahl. 1993. Structure-function relationship of small GTPase rab5. *J. Biol. Chem.* 268:24475–24480.

Li, G., A. Barbieri, M.I. Colombo, and P.D. Stahl. 1994. Structural features of the GTP-binding defective Rab5 mutants required for their inhibitory activity on endocytosis. *J. Biol. Sci.* 269:14631–14635.

Li, G., C. D'Souza-Schorey, M.A. Barbieri, R.L. Roberts, A. Klippel, L.T. Williams, and P.D. Stahl. 1995. Evidence for phosphatidylinositol 3-kinase as a regulator of endocytosis via activation of rab5. *Proc. Natl. Acad. Sci. USA.* 92:10207–10211.

Lombardi, D., T. Soldati, M.A. Riederer, Y. Goda, M. Zerial, and S.R. Pfeffer. 1993. Rab9 functions in transport between late endosomes and trans-Golgi network. *EMBO (Eur. Mol. Biol. Organ.) J.* 12:677–682.

Ludwig, T., G. Griffiths, and B. Hoflack. 1991. Distribution of newly synthesized lysosomal enzymes in the endocytic pathway of normal rat kidney cells. *J. Cell Biol.* 115:1561–1572.

Mayer, A., W. Wickner, and A. Hass. 1996. Sec 18p (NSF)-driven release of Sec 17p (*L*-SNAP) can precede docking and fusion of yeast vacuoles. *Cell.* 85:83–94.

Mayorga, L.S., R. Diaz, and P.D. Stahl. 1989*a.* Regulatory role for GTP-binding protein in endocytosis. *Science (Wash. DC).* 244:1475–1478.

Mayorga, L.S., R. Diaz, M.I. Colombo, and P.D. Stahl. 1989*b.* GTPγS stimulation of endosome fusion suggests a role for a GTP binding protein in priming of vesicles before fusion. *Cell Regul.* 1:113–124.

Mayorga, L., M.I. Colombo, M. Lennartz, E.J. Brown, K.H. Rahman, R. Weiss, P.J. Lennon, and P.D. Stahl. 1993. Inhibition of endosome fusion by phospholipase A_2 (PLA_2) inhibitors points to a role for PLA_2 in endocytosis. *Proc. Natl. Acad. Sci. USA.* 90:10255–10259.

Meresse, S., J.P. Grovel, and P. Chavrier. 1995. The rab7 GTPase resides on a vesicular compartment connected to lysosome. *J. Cell Sci.* 108:3349–3358.

Mittal, R., M.R. Ahmadian, R.S. Goody, and A. Wittinghofer. 1996. Formation of a transition-state analog of the Ras GTPase reaction by Ras-GDP, tetrafluoroaluminate, and GTPase-activating proteins. *Science (Wash. DC).* 273:115–117.

Mullock, B.M., J.H. Perez, T. Kuwana, S.R. Gray, and J.P. Luzio. 1994. Lysosomes can fuse with a late endosomal compartment in a cell-free system from rat liver. *J. Cell Biol.* 126:1173–1182.

Nuoffer, C., H.W. Davidson, J. Matteson, J. Meinkoth, and W.E. Balch. 1994. A GDP-bound rab1 inhibits protein export from the endoplasmic reticulum and transport between Golgi compartments. *J. Cell Biol.* 125:225–237.

Olkkonen, V.M., P. Dupree, I. Killisch, A. Lutcke, M. Zerial, and K. Simons. 1993. Molecular cloning and subcellular localization of three GTP-binding proteins of the rab subfamily. *J. Cell Sci.* 106:1249–1261.

Opresko, L., and R.A. Karpf. 1987. Specific proteolysis regulates fusion between endocytic compartments in *Xenopus* oocytes. *Cell.* 51:557–568.

Opresko, L., H.S. Wiley, and R.A. Wallace. 1980. Differential postendocytotic compartmentation in *Xenopus* oocytes is mediated by a specifically bound ligand. *Cell.* 22:47–57.

Pfeffer, S.R. 1994. Rab GTPases: master regulators of membrane trafficking. *Curr. Opin. Cell Biol.* 6:522–526.

Qui, Y., X. Xu, A. Wandinger-Ness, D.P. Dalke, and S.K. Pierce. 1994. Separation of subcellular compartments containing distinct functional forms of MHC class II. *J. Cell Biol.* 125:595–605.

Rabinowitz, S., H. Horstmann, S. Gordon, and G. Griffiths. 1992. Immunocytochemical characterization of the endocytic and phagolysosomal compartments in peritoneal macrophages. *J. Cell Biol.* 116:95–112.

Riederer, M.A., T. Soldati, A.D. Shapiro, J. Lin, and S.R. Pfeffer. 1994. Lysosome biogenesis requires rab9 function and receptor recycling from endosomes to *trans*-Golgi network. *J. Cell Biol.* 125:573–582.

Rothman, J.E. 1994. Mechanisms of intracellular protein transport. *Nature (Lond.).* 372:55–63.

Schimmoller, F., and H. Riezman. 1993. Involvement of Ypt7p, a small GTPase, in traffic from late endosome to vacuole in yeast. *J. Cell Sci.* 106:823–830.

Schweighoffer, F., H. Cai, M.C. Chavellier-Multon, I. Fath, G. Cooper, and B. Tocque. 1993. The *Saccharomyces cerevisae* SDC25 C-domain gene product overcomes the dominant inhibitory activity of Ha-ras Asn-17. *Mol. Cell. Biol.* 13:39–43.

Singer-Kruger, B., H. Stenmark, A. Dusterhoft, P. Philippsen, J.S. Yoo, D. Gallwitz, and M. Zerial. 1994. Role of three rab-like GTPases, Ypt51p, Ypt52p and Ypt53p, in the endocytic and vacuolar protein sorting pathways of yeast. *J. Cell Biol.* 125:283–298.

Sogaard, M., K. Tani, R. Ye, S. Geromanos, P. Tempst, T. Kirchhausen, J.E. Rothman, and T. Sollner. 1994. A rab protein is required for the assembly of SNARE complexes in the docking of the transport vesicles. *Cell.* 78:937–948.

Sollner, T.S., W. Whiteheart, M. Brunner, H. Erdjument-Bromage, S. Geromanos, P. Tempst, and J.E. Rothman. 1993. SNAP receptor implicated in vesicle targetting and fusion. *Nature (Lond.).* 362:318–324.

Stenmark, H., R.G. Parton, O. Steele-Mortimer, A. Lutcke, J. Gruenberg, and M. Zerial. 1994. Inhibition of rab5 GTPase activity stimulates membrane fusion in endocytosis. *EMBO (Eur. Mol. Biol. Organ.) J.* 13:1287–1296.

Swick, A.G., M. Janicot, T. Cheneval-Kastelic, J.C. McLenithan, and M.D. Lane. 1992. Promoter-cDNA directed heterologous protein expression in *Xenopus laevis* oocytes. *Proc. Natl. Acad. Sci. USA.* 89:1812–1816.

Sztul, E., M. Colombo, P. Stahl, and R. Samanta. 1993. Control of protein traffic between distinct plasma membrane domain. Requirement for a novel 108,000 protein in the fusion of transcytotic vesicles with the apical membrane. *J. Biol. Chem.* 268:1876–1885.

Tisdale, E.J., J.R. Bourne, R. Khosravi-Far, C.J. Der, and W.E. Balch. 1992. GTP binding mutants of rab1 and rab2 are potent inhibitors of vesicular transport from the endoplasmic reticulum to the Golgi complex. *J. Cell Biol.* 119:749–761.

Toumikoski, T., M.A. Felix, M. Doree, and J. Gruenberg. 1989. Inhibition of endocytic vesicle fusion in vitro by the cell-cycle control protein kinase cdc2. *Nature (Lond.).* 342:942–945.

van der Sluijs, P., M. Hull, A. Zahraoui, A. Tavitian, B. Goud, and I. Mellman. 1991. The small GTP-binding protein Rab4 is associated with early endosomes. *Proc. Natl. Sci. Acad. USA.* 88:6313–6317.

Wall, D.A., and S. Patel. 1987. Multivesicular bodies play a key role in vitellogenin endocytosis. *Dev. Biol.* 119:275–289.

Whiteheart, S.W., K. Rossnagel, S.A. Buhrow, M. Brunner, R. Jaenicke, and J.E. Rothman. 1994. *N*-ethylmaleimide–sensitive fusion protein: a trimeric ATPase whose hydrolysis of ATP is required for membrane fusion. *J. Cell Biol.* 126:945–954.

Wichmann, H., L. Hengst, and D. Gallwitz. 1992. Endocytosis in yeast: evidence for the involvement of a small GTP binding protein (Ypt7). *Cell.* 71: 1131–1142.

Wilson, D.M., P.G. Whiteheart, M. Wiedmann, M. Brunner, and J.E. Rothman. 1992. A multisubunit particle implicated in membrane fusion. *J. Cell Biol.* 117:531–538.

Wolters, G., L. Kuijpers, J. Kacaki, and A. Schuurs. 1976. Solid phase enzyme-immunoassay for the detection of hepatitis B surface antigen. *J. Clin. Pathol. (Lond.).* 29:873–879.

Yamashiro, D.J., B. Tycko, S.R. Fluss, and F.R. Maxfield. 1984. Segregation of transferrin to a mildly acidic (pH 6.5) para-Golgi compartment in the recycling pathway. *Cell.* 37:789–800.

Zerial, M., and H. Stenmark. 1993. Rab GTPase in vesicular transport. *Curr. Opin. Cell Biol.* 5:613–620.