α2-Macroglobulin Adsorbed to Colloidal Gold: 
A New Probe in the Study of Receptor-mediated Endocytosis

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ABSTRACT

α2-Macroglobulin (α2M) was adsorbed to colloidal gold and used as a new tool in the study of receptor-mediated endocytosis. α2M-gold is easy to prepare and is clearly visualized at the electron microscope level. When cells were incubated with α2M-gold at 0°C, gold was visualized both diffusely over the cell surface and concentrated in coated pits. After cells to which α2M-gold had been bound at 0°C were warmed, the gold was rapidly internalized into uncoated vesicles, previously termed receptosomes. After 30 min of incubation or longer, gold was found in small lysosomes and, later, in large lysosomes and very small vesicles in the region of the Golgi complex. This pattern of localization is similar to that previously described, using peroxidase-labeled anti-α2M antibodies. By incubating cells with both α2M-gold and vesicular stomatitis virus (VSV), we studied the internalization of these two markers simultaneously. VSV and α2M-gold rapidly clustered in the same coated pits and were internalized in the same receptosomes. Proteins and hormones adsorbed to gold may be useful in the study of receptor-mediated endocytosis.

A variety of hormones, proteins, and viruses enter cells by the process of concentrative adsorptive endocytosis (2, 14, 17, 19). Receptor-bound ligands rapidly cluster in clathrin-coated pits on fibroblast cell membranes and are then internalized. A newly defined organelle, termed the receptosome, has been identified as the initial intracellular location of hormone-receptor complexes (23). Receptosomes are uncoated, phase-neutral vesicles 1,500-3,000 Å in diameter that move in the cytoplasm by saltatory motion. After a delay of 15–30 min, they deliver their contents to the Golgi region and finally to lysosomes (19–23). Information in many of these previous studies was based on visualization of ligands by peroxidase- or ferritin-labeled antibodies directed against the ligand or antibodies to the ligand. Although providing useful information concerning the intracellular localization of ligands, these procedures are complex and, in the case of peroxidase, require a histochemical reaction.

α2-Macroglobulin (α2M) is a large, tetrameric protein found in plasma and other body fluids of vertebrates. Its precise biological role is unknown but it is able to form complexes with a wide variety of endopeptidases and zinc (8, 16). Previous studies using fluorescent (9, 11, 12) or ferritin- or peroxidase-labeled (20–23) α2M have demonstrated that α2M binds to membrane receptors on fibroblasts and is internalized by the coated pit-receptosome pathway outlined above. We now report that colloidal gold can be used to visualize this process. Colloidal gold is an easily visualized, discrete label for electron microscopy that has previously been adsorbed to various proteins including immunoglobulins and lectins to localize cell surface antigens (3, 7, 9). We have used α2M-gold in this study to examine the pathway of receptor-mediated endocytosis. We have then simultaneously compared the pathways of entry of α2M-gold and vesicular stomatitis virus (VSV).

MATERIALS AND METHODS

α2M was prepared from whole human plasma as previously described (18, 20). α2M was iodinated with 125I using the chloramine-T procedure (13) and used as tracer radioactivity to quantify adsorption to colloidal gold.

Normal rat kidney (NRK-2T) and Swiss mouse 3T3 cells were grown in Dulbecco-Vogt's modified Eagle's medium containing 10% (vol/vol) calf serum. For experiments, cells were plated in 35-mm Falcon tissue culture dishes (Falcon Labware, Becton, Dickinson & Co., Oxnard, Calif.) at 1.5 x 10⁵ cells/dish in 2 ml of medium supplemented with calf serum that had been heated for 1 h at 60°C. Cells were usually used 4 d after plating. At this time, confluent monolayers had formed. Cells were incubated in serum-free medium for 1 h at 37°C before any experiment, to remove most of the cellular-bound α2M derived from calf serum, and then washed extensively with serum-free medium.

Colloidal gold was prepared as previously described (9) and its pH adjusted to 6.0. The pH was measured using a pH meter (pH 6.0). 50 ml of gold solution was reacted with 12 mg (10 ml) α2M (containing tracer 125I-α2M). 1.5 ml of 1% polyethylene glycol was then added to stabilize the mixture, and the gold-bound and free α2M were
separated by centrifugation (20,000 g, 1 h). The gold was resuspended and washed several times in phosphate-buffered saline (pH 7.4) containing 1.5 mM CaCl₂ and 0.01% polyethylene glycol (PBS-Ca-PEG). The gold adsorbed to α₂M did not flocculate upon addition of 1% NaCl (unlike nonadsorbed gold), indicating that adsorption occurred (3,7,9). The gold particles appeared to be relatively homogeneous in size (100-200 A in diameter) by electron microscopy. On the basis of radioactivity associated with the gold, we estimated 400 α₂M molecules were bound to each gold particle (1.2 mg α₂M/6 mg colloidal gold). For cellular studies, α₂M-gold (resuspended at 50 µg α₂M/ml) in PBS-Ca-PEG was incubated with cell monolayers at 0°C for 4 h with or without 2 mg/ml α₂M to compete for receptor binding. Then the cell monolayers were washed five times with PBS containing 1.5 mM CaCl₂. The cells were then fixed at 0°C or warmed to 37°C for various times and fixed at 37°C. Fixation was carried out with 2% glutaraldehyde (Tousimis Research Co., Rockville, Md.) in PBS. Cells were then post-fixed in OsO₄, ethanol-dehydrated, and embedded in situ in Epon 812 (20-23). Thin sections were counterstained with lead citrate and viewed at 50 kV with a Hitachi HU-12A electron microscope.

When binding of 125I-α₂M-gold to cell monolayers was studied, cells were first incubated with the α₂M-gold at 0°C for 4 h. Then the cells were washed five times with PBS-Ca at 0°C. Radioactivity was solubilized in 0.1 N NaOH and counted in an LKB Mini-gama spectrometer (LKB Instruments, Inc., Rockville, Md.).

Monovalent, hybrid anti-α₂M/antiferritin antibodies were prepared to directly visualize α₂M bound to gold. Anti-α₂M antiserum (Miles Laboratories Inc., Elkart, Ind.) and antiferritin were purified by standard methods (ammonium sulfate fractionation and DEAE Affi-Blue (Bio-Rad Laboratories, Richmond, Calif.) chromatography) (4). Then the purified IgG fractions were pepsin digested and F(ab)² fragments were cleaved with β-mercaptoethanolamine (Sigma Chemical Co., St. Louis, Mo.), mixed, dialyzed, and oxidized under O₂ to yield hybrid F(ab)² species (1). The hybrid antibody was purified by affinity chromatography (5). Hybrid antibody (10 µg) was incubated with 0.25 ml of α₂M-gold for 15 min at room temperature in the presence or absence of 1 mg α₂M. Then the gold was pelleted by centrifugation for 15 min in an Eppendorf centrifuge 5412 (Brinkmann Instruments Inc., Westbury, N. Y.). After two washes in PBS-Ca-PEG, the α₂M-gold was incubated for 15 min at room temperature in 100 mg/ml ferritin (Sigma Chemical Co.) and rewarshed twice. The resuspended gold was spread on a Formvar-coated electron microscope grid and viewed without further treatment. Swiss 3T3 cells were incubated for 4 h at 4°C in serum-free medium with 10⁶ plaque-forming units/cell vesicular stomatitis virus (VSV) mixed with either 50 µg/ml α₂M-gold or α₂M-gold plus excess α₂M (3 mg/ml). The dishes were then washed in serum-free medium at 4°C and warmed to 37°C for 2 min. They were then fixed in 3% glutaraldehyde in PBS for 10 min at 23°C, followed by OsO₄ postfixation, ethanol-dehydration, and Epon embedding. From other studies, VSV, like α₂M, is known to be found in coated pits when observed within 30 s of warming to 37°C, and internalized into the cell 1.5-4.0 min after warming (2,17). In our experiments, 2 min was chosen as a time that would yield images of both clustering in coated pits on the surface and some internalized material in receptosomes (23).

RESULTS AND DISCUSSION

Characterization of α₂M-Gold

On the basis of the association of 125I-α₂M with colloidal gold, we calculated that ~400 molecules of α₂M were bound to each gold particle. The α₂M-gold was reacted with anti-α₂M/antiferritin antibodies and then ferritin to determine whether the immunoreactivity of α₂M was retained during the adsorption and washing procedures. Fig. 1 B shows that ferritin was associated with the colloidal gold, indicating that the α₂M was still immunoreactive. When excess α₂M was included during the incubations (Fig. 1 A), it effectively competed for binding by the antibodies, resulting in very little ferritin-gold association.

To determine whether α₂M-gold retained receptor-recognition properties, 125I-α₂M-gold was bound to 0°C to NRK-2T cell monolayers in the presence or absence of an excess of α₂M. Fig. 2 shows that cell binding measured by 125I was clearly demonstrable. It was reduced to 10% of control in the presence of an excess of α₂M. The data indicated that ~2.5 x 10⁴ particles of gold (10⁴ molecules of α₂M) were bound per cell. Similar results (data not shown) were obtained with Swiss 3T3 fibroblasts. Because the α₂M-gold is multivalent, it is not clear how many receptors were occupied by each particle of gold. It has been previously demonstrated that at 0°C a fibroblast can bind up to 6 x 10⁴ molecules of 125I-α₂M to its surface receptors. A small portion of these receptors (10%) are of high affinity and may be associated with coated pits.

Figure 3  Internalization of α2M-gold by fibroblasts. Swiss 3T3 cells were incubated with α2M-gold at 4°C as described in Materials and Methods. A shows labeling of coated pits after incubation of cells with α2M-gold for 4 h at 0°C. B shows localization of α2M-gold in uncoated vesicles (receptosomes) after cell surface labeling as in A, followed by 10 min at 37°C. For C, cells were labeled as in A and then warmed for 30 min at 37°C showing α2M-gold (arrow) located in a small lysosome. For D and E, cells were labeled as in A and then warmed for 2 h at 37°C. Gold (arrows) was visualized in secondary lysosomes (D) and small vesicles in the Golgi region (E). In F, cells were incubated for 4 h at 37°C in the continuous presence of α2M-gold. Gold (arrows) was highly concentrated in lysosomes. Lead citrate counterstain; Coated pit (cp), mitochondrion (m), receptosome (R), lysosome (ly), endoplasmic reticulum (er), Golgi complex (G), nucleus (N). Bars, 0.1 μm. (A, C, and D) × 65,000, (B) × 77,000, (E and F) × 54,000.
FIGURE 4 Co-internalization of α2M-gold and VSV. Cells incubated in the presence of both α2M-gold and VSV showed the presence of these two ligands together in the same coated pit (A), in the same uncoated endocytic receptosome adjacent to a coated pit (B), or in the same receptosome deeper in the cytoplasm (C). All of these possibilities exist simultaneously at 2 min after warming the cells from 4° to 37°C. If the cells were warmed for only a few seconds, only the image in A could be found; if warmed for 5 min, only the image in C could be found. Cells incubated with α2M-gold and VSV together with an excess of unlabeled α2M showed no gold labeling on the cells, and only VSV could be found in coated pits D. Uranyl acetate–lead citrate counterstain; arrows, VSV particles; arrowheads, α2M-gold particles. Bar, 0.1 μm. × 120,000.
Localization of \(\alpha_2\)-M-Gold in Cells

When Swiss 3T3 cells were incubated at 0°C for 5 h with \(\alpha_2\)-M-gold (Fig. 3A), the gold was visualized primarily concentrated in coated pit regions. Some gold particles were also seen distributed diffusely over the cell surface. In parallel incubations containing 2 mg/ml \(\alpha_2\)M (data not shown), both classes of surface-bound gold particles were virtually absent. A few gold particles remained associated with fibronectin or the plastic culture dish (<1%). Previous data using peroxidase-labeled, anti-\(\alpha_2\)M antibodies are in agreement with the present study (20-23): after exposure to \(\alpha_2\)M, binding to cells is concentrated in coated pits and also diffusely spread over other regions of the cell surface, depending on the concentration of \(\alpha_2\)M employed. At low concentrations of \(\alpha_2\)M, most of the ligand clusters in coated regions, whereas at close to saturating levels the diffuse component is also observed and represents the majority of the bound ligand.

After binding \(\alpha_2\)M-gold to cell surfaces at 0°C for 4 h and then washing away unbound \(\alpha_2\)M-gold, we warmed cell monolayers to 37°C for various times to determine the fate of internalized \(\alpha_2\)M-gold-receptor complexes. After cells were incubated for 10 min at 37°C, the cell surface was entirely cleared and the gold was localized exclusively in uncoated, cytoplasmic vesicles (Fig. 3B). These were easily visualized because of the intense contrast of the gold particles. The vesicles had a membrane-associated proteinaceous layer on their inner surface and are identical to those previously described by use of peroxidase-labeled antibodies to \(\alpha_2\)M and termed receptosomes (20-23). After 30 min of incubation at 37°C, the gold was found mostly in lysosomes (Fig. 3C). These lysosomes were small and homogeneous and probably represent "primary lysosomes" derived from the GERL system. After 2 h of incubation at 37°C, the gold was localized in larger, heterogeneous lysosomes (Fig. 3D). In addition to being localized in lysosomes, the gold was also localized in very small vesicles in the vicinity of the Golgi apparatus after 2 h at 37°C (Fig. 3E). Although previous studies (20-23) have localized \(\alpha_2\)M in lysosomes after 30 min or more of incubation at 37°C, the small vesicles in the region of the Golgi containing \(\alpha_2\)M after 2 h of incubation were not noted. Their function is unknown, but they could represent a step in the exocytosis of intracellular \(\alpha_2\)M, a process that is known to occur in \(\alpha_2\)M-free medium (15). If cells were incubated in the continuous presence of \(\alpha_2\)M-gold for 4 h at 37°C (Fig. 3F), the lysosome was the primary site of concentration of gold. This is in agreement with previous studies using either peroxidase-labeled \(\alpha_2\)M antibodies (20-23) and electron microscopy or fluorescence-labeled \(\alpha_2\)M (11, 12) and fluorescence microscopy. The same sequence of localizations of gold was observed when NRK-2T cells were used instead of Swiss 3T3 cells (data not shown).

Cointernalization of \(\alpha_2\)-M-Gold and VSV

The simultaneous internalization of VSV and \(\alpha_2\)M-gold was studied. Cells were incubated at 4°C with the two ligands. After washing away unbound ligands, cells were warmed to 37°C for 2 min (Fig. 4A and B). \(\alpha_2\)M-gold and VSV were often concentrated in coated pits together (Fig. 4A). Some uncoated vesicles containing \(\alpha_2\)M-gold and VSV in the immediate vicinity of coated pits were also observed (4B). This suggested that the transition of coated pits to uncoated vesicles occurs very rapidly. Fig. 4D shows that, in the presence of an excess of unlabeled \(\alpha_2\)M, virus particles but not \(\alpha_2\)M-gold were observed concentrated in coated pits. This demonstrates that the presence of \(\alpha_2\)M-gold did not somehow facilitate the concentration of VSV in coated pits. Cells incubated with the two ligands and warmed to 37°C for 2 min also showed \(\alpha_2\)M-gold and VSV within uncoated vesicles previously termed receptosomes (Fig. 4C). These receptosomes had a characteristic size and appearance which have been previously described (19, 21, 23). A previous study has demonstrated at the electron microscope level that \(\alpha_2\)M-gold and ferritin-epidermal growth factor are clustered and internalized together by this same pathway (19). Other studies (10, 19, 21, 23) have shown a clear progression of the clustered ligands present in coated pits in the 1st or 2nd min after warming to 37°C into receptosomes. This is an endocytic process that is complete over the entire cell surface within 5 min after warming to 37°C. The present study is the first clear demonstration that viruses and receptor-bound proteins and hormones share a common pathway of cellular internalization.

In summary, we have developed a new technique for the study of receptor-mediated endocytosis of \(\alpha_2\)M. \(\alpha_2\)M-colloidal gold is easy to prepare and use, and its visualization by electron microscopy is extremely clear. This technique may prove to be of general use in the study of other ligands, including hormones, which bind to membrane receptors. Because colloidal gold may be prepared in many different sizes (3, 9), the use of gold-labeled ligands may also allow simultaneous study of the binding and internalization of several proteins, hormones, and viruses.

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