Transmembrane Linkage between Surface Glycoproteins and Components of the Cytoplasm in Neutrophil Leukocytes

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ABSTRACT An experimental approach is described that enables the analysis of interactions between exogenous surface ligands and components of the cytoplasm in neutrophil leukocytes. Neutrophils treated with the nonionic detergent Lubrol PX, under controlled conditions, yield intact detergent-insoluble ghosts. Morphological analysis of neutrophil ghosts shows that they retain the original dimensions of the cell and consist almost entirely of a peripheral filamentous network, representing the submembranous cortical web, concentric to nuclear remnants. All intracellular membrane-bounded organelles, plasma membrane, and background cytoplasmic electron density are absent.

Biochemical analysis of the ghosts shows that <10% of enzyme markers for the soluble and granule fractions remain, and that >90% of total cell phospholipid is removed during detergent extraction. The major proteins remaining in the ghosts comigrate, on polyacrylamide gels in the presence of SDS, with chicken gizzard actin, myosin, filamin, and a 110-kdalton protein.

Patches and caps induced on neutrophils with either fluorescein isothiocyanate-concanavalin A or ferritin-concanavalin A retain their original location and morphology on ghosts after lysis, as determined by both fluorescence and electron microscopy. In similar experiments, but using ^{125}I-labeled lectins, 37% of total cell bound concanavalin A (Con A) and 25% succinylated Con A remain attached to the ghosts.

A major ^{125}I-labeled membrane glycoprotein (80 kdaltons) is associated with ghosts prepared from intact neutrophils iodinated in the presence of exogenous lactoperoxidase. Further ^{125}I-labeled membrane glycoproteins (217, 170, and 147 kdaltons) become associated with ghosts prepared from iodinated cells treated before lysis with Con A, but not with succinylated Con A.

These data taken together suggest that linkages exist in neutrophils between proteins exposed on the outer surface of the plasma membrane and the peripheral filamentous network independent of the presence of lipid bilayer. The implications of these findings for surface motile phenomena will be discussed.

Since the wide acceptance of a membrane structure based on the fluid mosaic model proposed by Singer and Nicolson (35), it has become apparent that the lateral mobility of some membrane proteins may be constrained or influenced by their interaction, through the lipid bilayer, with components of the cytoplasm (14). This property of certain membrane proteins can be inferred from their behavior in the presence of multivalent ligands (34) and from lateral diffusion data obtained in photobleaching experiments (30, 31, 36). In some cases these phenomena can be enhanced or inhibited by treatment of cells with agents that interfere with microtubule or microfilament integrity (13, 14), thus leading to the predominant view that these structures are somehow involved either directly or indirectly in the anchorage or movement of membrane proteins. Data supporting this view have emerged from several laboratories, showing redistribution of actin and myosin, correlated with redistribution of membrane proteins by ligand. In particular, Singer and his colleagues have shown that actin, myosin, and α-actinin are preferentially located or retained directly subadjacent to membrane protein clusters induced by ligand on the cell surface (9, 16). In fibroblasts, addition of multivalent lectins or antibodies directed against specific transmembrane

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proteins causes clustering of their respective target proteins and their relocation over stress fibers (2, 3), further consolidating the view that actomyosin-containing structures influence the location of certain membrane proteins. Recently, Flanagan and Koch (15) showed that microfilaments, isolated from detergent-lysed cells pretreated with anti-Ig antisera, were physically linked, either directly or indirectly to antibody, presumably via its antigen receptor Ig.

The evidence presented above suggests that interaction can occur between cytoplasmic components and several membrane proteins, including defined transmembrane proteins and unidentified lectin-binding glycoproteins. Thus this interaction may be regarded as a common feature of membrane structure. However, although it has inspired much speculation (1, 12, 23, 34), the nature of this interaction is little understood.

The data presented in this report show that interactions between membrane proteins and components of the cytoplasm can be retained on detergent-insoluble ghosts prepared from neutrophils. Preliminary identification of components involved in the interaction and some properties of the interaction are described.

MATERIALS AND METHODS

Isolation and Incubation of Neutrophils

Neutrophils were routinely prepared from blood collected directly from the jugular vein of pigs and prevented from coagulating by the addition of citrate and glucose. Erythrocytes were removed by gelatin sedimentation from blood, previously freed by centrifugation at 550 g_{avg} for 20 min at 23°C, from platelets, lymphocytes, and monocytes. The procedure is essentially that described by Henson (18) except that the optimal concentration of gelatin for agglutination of erythrocytes from pig's blood is 0.75% wt/vol. The purity of the cell suspension was monitored by fixing and embedding the cells, and examining 1-μm sections stained with azure II and methylene blue. Cells were counted manually by using a hemocytometer, and viability was assessed by the criterion of trypan blue exclusion. Routine yields of 1–3 × 10^6 cells/ml blood were obtained. Cells were washed, maintained, and incubated, unless otherwise stated, in Dulbecco's solution A (Na^+, 197 mM; K^+, 11 mM; PO_4^{2-}, 39 mM; Cl^-, 139 mM; pH 7.4) containing 5.5 mM glucose and 0.1 mM phenylmethylsulfonyl fluoride (PMSF).

All incubation experiments were performed with neutrophils in suspension at a density quoted in text or legend. Washes or medium changes were performed by centrifuging cells for 2 s in a Beckman microfuge (Beckman Instruments, Inc., Spinco Div., Palo Alto, Calif.), followed by removal of supernate and resuspension of cells by gentle aspiration into a plastic automatic pipette tip.

Preparation of Detergent-insoluble Ghosts

The standard lysis procedure was performed on ice in a medium containing 4% wt/vol polyethylene glycol (1,000 mol wt), 1.5% wt/vol Lubrol PX, 60 mM KCl, 50 mM PIPES, 1 mM $MgCl_2$, 2 mM PMSF, and 10 μg/ml chymostatin adjusted to pH 6.8 at 23°C by addition of NaOH. Cells were sedimented in a Beckman microfuge, then resuspended by repeated aspiration into ice-cold lysis medium at a density of 5 × 10^7 cells/ml. Cells were left for 30 s, then centrifuged again and resuspended in fresh lysis medium. Ghosts were then collected by centrifugation and either fixed for microscopy or treated as described elsewhere in the text or legends.

Lectins

Concanavalin A (Con A) was prepared from jack bean meal (Sigma [London] Chemical Company Limited, Poole, Dorset, U. K.) by affinity chromatography on Sephadex G-100 essentially according to the method of Olson and Leiner (29). Fluorescein isothiocyanate (FITC)–derivatized Con A was obtained from Miles Research Laboratories, Stoke Poges, Buckinghamshire, U. K., and succinylated Con A, and its rhodamine isothiocyanate (RITC) derivative, RITC–succinylated Con A were obtained from Vector Laboratories, Burlingame, Calif.

Various iodination procedures were evaluated to produce lectins with both a high specific ^{125}I radioactivity and maximum biological activity. Both chloramine-T- and lactoperoxidase-catalyzed (see references 21 and 27, respectively) iodination yielded products with high specific radioactivities, but the latter procedure yielded lectin with a higher biological activity as judged by binding to and specific elution from immobilized ligand. Lectins Con A and succinylated Con A (100 μg) were incubated in 50 μl of 50 mM sodium phosphate pH 7.0 at room temperature with 1.25 μg lactoperoxidase and 0.18 mM H_2O_2 for 15 min. ^{125}I-lectin was separated from free iodine by molecular exclusion chromatography on Bio-Gel P-60 (Bio-Rad Laboratories Inc., Richmond, Calif.). The iodinated lectin was then mixed with native lectin to achieve a convenient specific radioactivity for binding studies, usually ~5 × 10^5 cpm/μg. Because one of the uses for the lectins was to evaluate the binding parameters of cell surface glycoproteins, it was necessary to obtain an accurate value for the specific radioactivity of biologically active lectin. To this end the mixed native and iodinated lectins were subjected to affinity chromatography on an appropriate matrix, and bound lectin was eluted with 0.1 M glucose. The lectin peak was then dialyzed against Dulbecco's solution A containing 0.1 mM $CaCl_2$ and $MnCl_2$, and the specific radioactivity of the nondiffusible material estimated by using the protein assay of Lowry et al. (26) with lectin as standard.

Antisera were raised to Con A in rabbits by injection of 1 mg of Con A emulsified in either complete (first injection) or incomplete (subsequent injections) Freund's adjuvant at multiple sites on the dorsal surface of rabbits. Antisera were evaluated by immunodiffusion in agarose against both Con A and succinylated Con A in the presence of 0.1 M α-methyl-D-mannoside.

Characterization of Lectin-binding Sites

Preliminary experiments showed that binding of lectins to washed, paraformaldehyde-fixed cells was identical to binding to live cells at 0°C. For convenience, and to avoid any uptake of lectin by pinocytosis, binding experiments were performed on cells fixed and stored at 4°C in 2% (wt/vol) paraformaldehyde in 0.876% wt/vol NaCl, pH 7.4. Fixed cells were washed twice, then incubated at 0°C in Dulbecco's solution A, containing for 0.1 mM $MnCl_2$ and 0.1 mM $CaCl_2$, with no glucose or PMSF, at a cell density of 5 × 10^7/ml. ^{125}I-lectin was added at initial concentrations in the range 1–300 μg/ml. Cells required 30 min to equilibrate with Con A; after incubation, 50-μl aliquots of cells were centrifuged for 1 min in a Beckman microfuge through 100 μl of a 60:40 mixture of silicone oil MS550 and dinonylphthalate (SG 1.03) in 400-μl tubes. The cells pelleted, leaving the supernate on the silicone oil cushion. The free lectin concentration was calculated by removing a sample of supernate for determination of ^{125}I radioactivity. Bound lectin was determined by cutting off the tip of the tube just above the pellet and assaying for radioactivity in a gamma counter. Data were then subjected to Scatchard analysis using a computer program adapted from one originally devised by Dr. P. J. England, Department of Biochemistry, University of Bristol, U. K., which fits a linear regression line by the reduced common axis method of York (41).

Iodination of Cells

Cells were suspended into Dulbecco's solution A containing 16.5 mM glucose and 0.1 mM PMSF at 5 × 10^7 cells/ml. Proteins exposed on the outer surface of the plasma membrane were iodinated in the presence of 100 μCi/ml ^{125}I (Radiochemical Centre, Amersham, Buckinghamshire, U. K.) 25 μg/ml lactoperoxidase and 140 mU/ml glucose oxidase for 20 min at 0°C (20). Cells were washed twice in Dulbecco's solution A containing 0.1 mM PMSF, 5.5 mM glucose and 0.1 mM KI. Omission of glucose oxidase or glucose reduced incorporation of ^{125}I into TCA-insoluble material by >90%. Omission of lactoperoxidase caused an ~60% reduction in labeling, presumably because of the presence of myeloperoxidase released from cells in the medium.

Electrophoresis and Autoradiography

Whole cells freeze-thawed three times and detergent-insoluble ghosts were either added to Laemmli sample buffer (24) containing 2 mM PMSF or treated with DNase before solubilisation. Samples were triturated for a few minutes, then warmed to 100°C for 2 min, and allowed to cool, then 2 μl of 400 mg/ml iodoacetamide per 100-μl sample was added to alkylate sulfhydryl groups, and left for 30 min at room temperature. Gels were stained in Coomassie Blue and those destined for autoradiography soaked in 2% vol/vol glycerol after destaining and before drying. Dried gels were exposed to Kodak NS-2T film for between 3 and 10 d.

Assay Procedures

Protein was assayed by the method of Lowry et al. (26), using bovine serum albumin as the standard. DNA was estimated colorimetrically by the method of Burton (11). Lactate dehydrogenase was assayed by following the oxidation of NADH at 340 nm in the presence of pyruvate (7) by cell lysates (freeze-thawed three times) and detergent-insoluble ghosts. Myeloperoxidase was assayed by following the change in optical density at 440 nm by oxidation of o-toluidine (4). The reaction was carried out in 1.4 ml of 0.1 M sodium citrate, pH 5.0, containing

0.1% o-toluidine, 0.05% Triton X-100, and 1.5 mM H_2O_2. The reaction was started by addition of 0.1-ml sample, and the initial rate was determined. Acid phosphatase activity was measured by following release of p-nitrophenol from its phosphate ester at pH 4.5 (4). Neutral protease activity was measured in whole cell lysates by determining the amount of TCA-soluble dye released from sulfanilate-treated casein (37) (azocasein; Sigma [London]). Reaction mixtures contained 10 mg/ml azocasein, 50 mM PIPES, pH 6.8, 1 mM-$MgCl_2$, and 0.1% Triton X-100. Neutrophils were freeze-thawed three times, then added to a final concentration of 2.5×10^7 cells/ml. Samples were removed for assay at 1 and 2 h. All enzyme assays were linear with respect to time over the interval of measurement and with respect to the amount of sample added over the range of additions made. Total phospholipid was estimated in chloroform/methanol extracts of both ghosts and whole cells by measuring inorganic phosphate (5) released by perchloric acid hydrolysis of total lipid. Thin-layer chromatography of total cell lipids was performed on silica gel G plates (Camlab, Cambridge, U. K.) that were developed with a $CHCl_3$:MeOH:H_2O mixture (65:25:4). Lipid spots were identified by spraying the chromatogram with 2% vol/vol H_2SO_4 followed by warming the plates to 160°C for a few minutes. Glycolipids were identified on parallel plates by spraying the chromatogram with a diphenylamine reagent (39). Where the ^{125}I content of individual lipids was required, spots were scraped directly from the plates and assayed in a gamma spectrometer. Total cellular ATP was measured in perchloric acid extracts of cells by following the rate of photon release in the presence of luciferin/luciferase (Sigma FLE-50) as described previously (33).

Preparation of Cells for Microscopy

Cells incubated with fluorescent lectins or destined for phase-contrast microscopy were fixed for 10 min at 23°C by addition of paraformaldehyde to 2% wt/vol. Cells were usually centrifuged onto glass slides, mounted in 90% vol/vol glycerol in phosphate-buffered saline (PBS), and observed in a Zeiss photomicroscope III equipped with epifluorescence optics. Images were recorded onto Ilford FP4 film.

Cells or ghosts for electron microscopy were fixed directly or, in some cases, cells were incubated with ferritin-Con A (Miles Research Laboratories Limited, Stoke Poges, Buckinghamshire, U. K.) at 50 μg/ml equivalent Con A in Dulbecco's minimum essential medium before lysis. Cells and ghosts were fixed by addition of 50% Karnovsky's fixative (22). Before osmication, ghosts were treated for 10 min in 0.2% wt/vol tannic acid at 23°C. Fixed cells and ghosts were pelleted in a Beckman microfuge and processed immediately, by conventional techniques, for electron microscopy.

RESULTS

Neutrophils isolated from pig's blood by gelatin sedimentation of erythrocytes constitute >95% of the total cells and have a viability of >95%, as judged by exclusion of trypan blue. Eosinophils generally constituted the greatest single contaminating species but rarely exceeded 2% of the total cell population. The balance was made up from small numbers of erythrocytes, lymphocytes, and monocytes; a typical preparation is shown in Fig. 1. Neutrophils retained a high viability at room temperature for ~6 h, although experiments were generally initiated within 1 h of isolation.

Evaluation of the Lysis Procedure

It has been established elsewhere (see reference 19), and confirmed in this laboratory (38), that treatment of cells attached to culture dishes with nonionic detergents under controlled conditions removes the majority of membrane-bounded organelles and soluble proteins. The detergent-insoluble material remaining on the dish consists mainly of microfilaments, microtubules, and 10-nm filaments, which retain a distribution similar to that seen in fixed and permealysed cells. A similar approach for the preparation of detergent-insoluble ghosts from neutrophil leukocytes in suspension is described here.

A variety of lysis media and conditions were evaluated on the basis of the following criteria: (*a*) the balance between retention of known contractile and cytoplasmic structural proteins and the efficiency of removal of presumed soluble proteins and granule contents, (*b*) the removal of total (chloroform/methanol soluble) lipid, (*c*) the disappearance of phase-contrast cytoplasmic granularity and unmasking of the nucleus, and (*d*) the retention of lectin-induced patches.

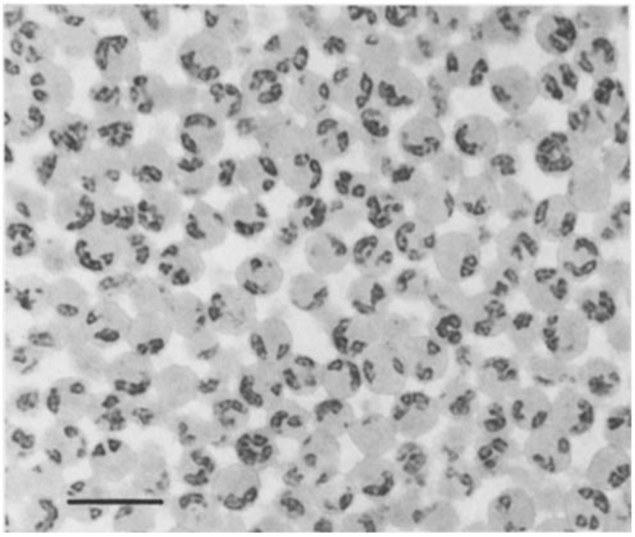


FIGURE 1 Plastic 1-μm section of typical neutrophil preparation. Neutrophils were prepared from pig's blood and treated for microscopy as described in Materials and Methods. Bar, 20 μm.

From the use of these criteria in preliminary experiments, the standard lysis conditions described in Materials and Methods were adopted. The data in Table I show that >50% of the DNA is retained in the detergent-insoluble ghosts and that removal of soluble components (represented by lactate dehydrogenase) and of granule contents (represented by myeloperoxidase and acid phosphatase activity) was extremely efficient. Only 10% of total phospholipid is retained by the ghosts. Thin-layer chromatography on silica gel plates indicated that the lipid remaining associated with the ghosts was entirely representative of total cell lipid (data not shown). Proteins remaining in the detergent-insoluble ghosts were separated by electrophoresis on polyacrylamide gels in the presence of SDS, and proteins were tentatively identified by comparison with those separated from chicken gizzard myofibrils (Fig. 2). The major proteins in the ghosts comigrated with gizzard actin, myosin, filamin, and a 110-kdalton protein. During preliminary lysis experiments it was noticed that recovery of proteins with the electrophoretic mobilities of actin-binding protein and myosin was rather variable, suggesting proteolysis during lysis. Whole-cell lysates were found to exhibit considerable proteolytic activity at neutral pH. Samples of freeze-thawed cells were assayed for protease activity, using azocasein as substrate, in the presence of a variety of inhibitors. The data in Table II suggest that there is major chymotrypsin-like protease activity present in whole-cell lysates, which can be substantially inhibited by using either PMSF or disopropylfluorophosphate (DFP) (irreversible but relatively slow acting serine protease inhibitors), together with chymostatin (a noncovalent but fast-acting peptide inhibitor of chymotrypsin-like proteases). These inhibitors were, therefore, included at 2 mM and 10 μg/ml, respectively, in the lysis medium.

Bands comigrating with α- and β-tubulin were noticeably weak or absent in SDS gels of ghost proteins. Attempts were made to enhance the stability of microtubules during lysis by the addition of EGTA, GTP, dimethylsulfoxide, and glycerol to the lysis medium and/or by extracting cells at 37°C instead of 0°C. These additional precautions, however, only marginally

TABLE I

Extraction of Cells by Lysis Medium

	Content per 10^6 cells or ghosts					
	Protein	DNA	Phospholipid	LDH	Myeloperoxidase	Acid phosphatase
	μg	*μg*	*nmol P_i*	*U/min*	*ΔOD_{440}/min*	*ΔOD_{400}/min*
Cells	47	9.6	11.50	2.56×10^{-3}	3.4×10^{-3}	7.5×10^{-4}
Ghosts	10	5.5	1.25	1.12×10^{-3}	5.0×10^{-4}	5.3×10^{-5}
% Removed by extraction	79	43	89	99.6	85	93

Cells and detergent-insoluble ghosts were prepared, and appropriate numbers of cells or ghosts were assayed as indicated above using procedures described in Materials and Methods. These data are given as the mean of triplicate analyses on a representative ghost preparation.

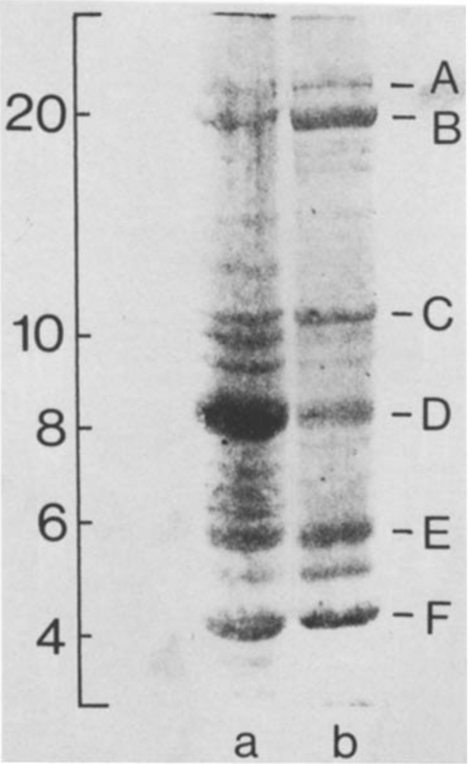


FIGURE 2 SDS polyacrylamide gels of proteins from detergent insoluble ghosts and from whole cells. Proteins from (*a*) 5 × 10^6 neutrophils and (*b*) 10^7 ghosts were separated on 6% (wt/vol) polyacrylamide gels and stained with Coomassie Blue. The scale indicates approximate molecular weight × 10^{-4}. Mean values of molecular weight for ghost proteins given in Table VIII.

TABLE II

Effects of a Variety of Inhibitors on Neutrophil Total Protease Activity

Inhibitor	Concn.	% Inhibition
DFP	0.1 mM	41
	1.0 mM	62
PMSF	0.1 mM	7
	2.0 mM	62
Chymostatin	10 μg/ml	47
	50 μg/ml	58
DFP + Chymostatin	1 mM + 20 μg/ml	85
PMSF + Chymostatin	1 mM + 20 μg/ml	80
PMSF + Chymostatin + pepstatin	1 mM + 20 μg/ml + 40 μg/ml	76
PMSF + Chymostatin + DTT	1 mM + 10 μg/ml + 5 mM	74
PMSF + Chymostatin + EDTA	1 mM + 20 μg/ml + 2 mM	72
Pepstatin	40 μg/ml	20
TPCK	1 mM	21
TLCK	1 mM	19
Ovomucoid	50 μg/ml	9
DTT	5 mM	11
2-Mercaptoethanol	5 mM	16
EDTA	2 mM	19
p-Amino benzamidine	2 mM	3
Leupeptin	100 μg/ml	25
Soybean trypsin inhibitor	1 mg/ml	12
Aprotinin	100 U/ml	0
	1,000 U/ml	39

Three-times freeze-thawed neutrophils at 2.5 × 10^7 cells/ml were incubated with azocasein at 10 mg/ml for 2 h at 37°C in the absence and presence of inhibitors and at the concentrations detailed above. Proteolysis was assessed by measuring the absorbance at 340 nm of dye released into a 5% wt/vol TCA-soluble fraction. *DTT*, dithiothreitol; *TLCK*, tosyllysylchloromethylketone; *TPCK*, tosylphenylalanylchloromethylketone.

improved the retention of tubulin in the detergent-insoluble ghosts and were not routinely adopted. It seems likely either that microtubules are particularly sensitive to the low levels of proteolytic activity remaining in the presence of inhibitors or, because neutrophil microtubules, which extend centripetally from the centrioles to near the cell periphery, are only 3–4 μm long, that even small losses by depolymerization from the distal end are sufficient to deplete the ghosts of these structures.

It is also notable that retention of proteins with the electrophoretic mobilities of actin-binding protein, myosin, and the 110-kdalton protein in ghost preparations, as judged by staining density of bands on polyacrylamide gels (Fig. 2), is relatively efficient, whereas large amounts of protein with the electrophoretic mobility of actin are lost. This is consistent with previous suggestions that much of the actin in nonmuscle cells is maintained in a soluble pool (10). The only other major polypeptide, 86,000 mol wt, which is also the major periodic acid/Schiff–positive band, is of unknown origin.

Cells and detergent-insoluble ghosts were centrifuged onto glass slides and examined by phase-contrast microscopy (Fig. 3). The ghosts show a dramatic loss of the phase-dense margin corresponding to the cell periphery and of the cytoplasmic granularity. The characteristic multilobed nuclei that are masked by large numbers of cytoplasmic granules in whole cells are clearly visible in the detergent-insoluble ghosts and appear to retain a normal morphology.

Thin sections of epoxy resin–embedded material were also examined by transmission electron microscopy. These images show clearly that the general dimensions of the cell are retained by the detergent-insoluble ghosts (Fig. 3). The ghosts appear to consist almost entirely of a filamentous network, which corresponds to the cortical microfilament network, concentric to the

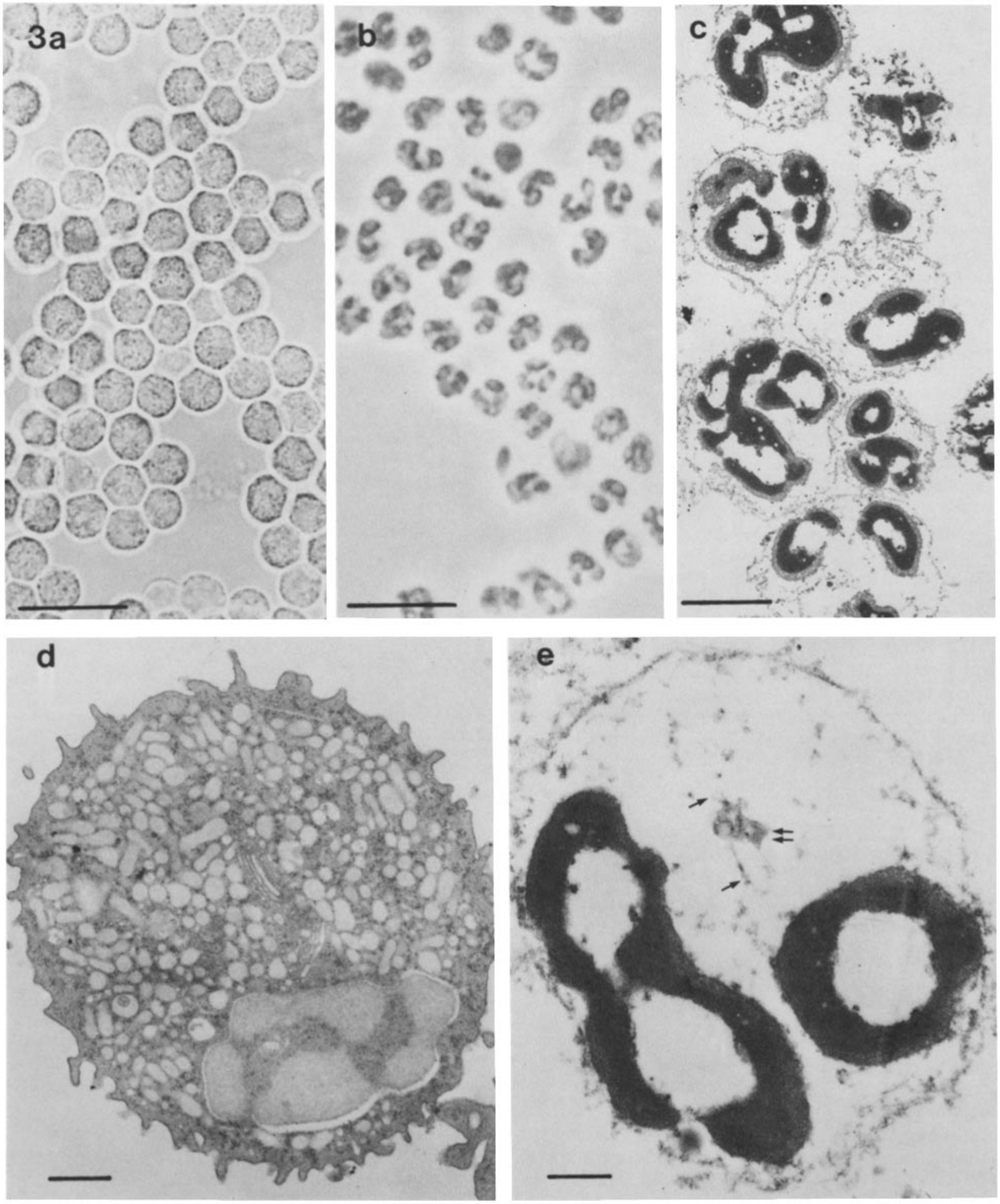


FIGURE 3 Phase-contrast and electron micrographs of neutrophils and neutrophil ghosts. Cells and ghosts were prepared as described in Materials and Methods. Material for phase-contrast microscopy was fixed in 4% (wt/vol) paraformaldehyde in 0.876% (wt/vol) NaCl then centrifuged onto glass slides and mounted in glycerol/PBS. Cells and ghosts were prepared for electron microscopy as detailed in Materials and Methods. (*a*) Phase-contrast image of intact neutrophils, (*b*) phase-contrast image of detergent-insoluble ghosts. Bar, 20 μm. (*c*) Survey electron micrograph of a section through fixed and pelleted ghosts. Bar, 5 μm. (*d*) Electron micrograph of intact neutrophil. Bar, 1 μm. (*e*) Electron micrograph of detergent-insoluble ghost. Note centriole (double arrows) and poorly preserved microtubules (single arrow). Bar, 1 μm.

nucleus. Membrane-bounded organelles, organized lipid bilayers and cytoplasmic background density are absent. In some cases, as shown in Fig. 3, the centrioles and some poorly preserved microtubles remain, but in general microtubules were rarely seen, in agreement with the electrophoretic data. The nuclear morphology remains relatively unchanged; it retains not only its shape and position relative to the cell periphery but also appears to contain heterochromatin with a distribution similar to that seen in sections of intact cells.

Effects of Lectin on Neutrophil Cell Surface Motility

Application of Con A to neutrophils results in a defined sequence of events. The lectin rapidly forms sizable clusters on the cell surface, followed in a proportion of the cells by relocation of the patches into caps (Fig. 4). Endocytosis takes place slowly ($t_{1/2}$, ~10 min) at the sites of both patching and capping. The effects of Con A can be compared with those induced by succinylated Con A, a divalent derivative of Con A (17). Succinylated Con A does not induce either patching or capping on neutrophils, but if cells treated with succinylated Con A are incubated with anti-Con A IgG, then the degree of patching and capping is restored to that observed at a similar concentration of Con A. These data suggest that the induction of patches and caps by lectin on neutrophils is highly dependent on valency. Studies on the binding parameters of lectin-binding sites confirm that both Con A and succinylated Con A bind to a similar number of sites on the cell surface (Table III).

The nature of the patching and capping phenomena on neutrophils was investigated by using a variety of inhibitors. Capping could be completely inhibited by reducing the total cellular ATP content below 20% (data not shown) of control levels in the presence of iodoacetate or 2-deoxyglucose. Capping was also prevented by incubation of neutrophils in the presence of cytochalasin D, which prevents growth onto prenucleated F-actin polymer (25), trifluoperazine, which prevents Ca^{++} activation of target enzymes in the presence of calmodulin, notably in this context of myosin light-chain kinase (32), and A23187, a Ca^{++} ionophore (Table IV). These data are consistent with the hypothesis that the force driving redistribution of patches into caps derives from an interaction between actin and myosin. None of these treatments influenced the formation of patches on neutrophils.

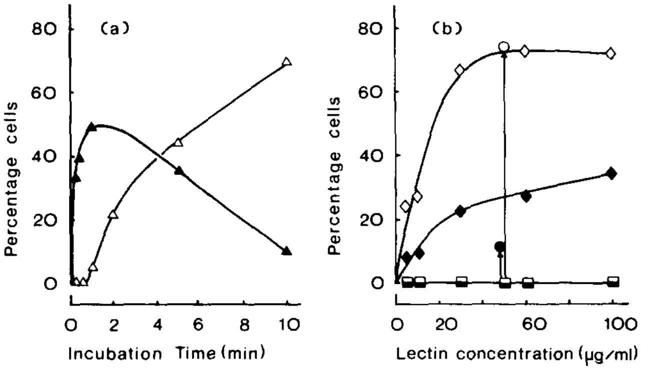


FIGURE 4 Kinetics of cap formation induced by FITC-Con A and RITC succinyl-Con A on neutrophils in suspension. Cells were preincubated for 30 min at 37°C in the presence and absence of 1 μM colchicine. Lectin was added at the recorded concentration and cells were then incubated for the times indicated at 37°C. Cells were fixed by addition to 4% (wt/vol) paraformaldehyde at ambient temperature, then examined by fluorescence microscopy. After each treatment the proportion of cells patching or capping was assessed for at least 200 cells. (*a*) Time-course of patch and cap formation after colchicine preincubation in the presence of 20 μg/ml FITC-Con A. ▲, Patches; △, caps. (*b*) Concentration and colchicine dependence of lectin-induced capping, Con A ◆, ◇; succinyl-Con A ■, □. All incubations with lectin for 5 min. To some tubes treated with 50 μg/ml succinyl-Con A at 0°C, anti-Con A γ-globulin was added (1:10 dilution of serum equivalent) at 0°C for a further 10 min, then the cells were warmed to 37°C for 5 min (●, ○). Solid symbols represent incubation in the absence and open symbols incubation in the presence of colchicine.

TABLE III

Characterization of Lectin-binding Sites on Neutrophils

Lectin	Dissociation constant (K_d + SEM × 10^8 M)	No. of sites/cell (±SEM × 10^{-5})	Correlation coefficient
Con A	6.56 ± 0.49	8.99 ± 0.42	0.974
Succinylated Con A	99.9 ± 5.56	7.33 ± 0.23	0.984

Iodinated lectins were prepared, and equilibrium binding assays performed as described in detail in Materials and Methods. Data was analyzed by using a computer program for calculating the dissociation constant and number of binding sites/cell on the basis of a reduced axis linear regression on data in the form of a Scatchard analysis. The correlation coefficient reflects the closeness of fit of the data to the calculated regression.

TABLE IV

Effects of Various Agents on Con A-induced Capping by Neutrophils

Conditions	Concentration	Number of caps as percentage of total cells, with and without colchicine (10^{-6} M)	
		−	+
	M		
Control		13	76
A23187	10^{-5}	3	31
Cytochalasin D	2×10^{-6}	6	12
2-Deoxyglucose	2.5×10^{-2}	0	7
Trifluoperazine	2×10^{-5}	0	8

Cells were incubated at 10^7/ml in the absence or presence of colchicine for 30 min at 37°C. 2-Deoxyglucose was added at t = 0 min and other inhibitors at t = 20 min. At t = 30 min, 20 μg/ml FITC-Con A was added and cells incubated for a further 5 min at 37°C. Samples of cells (10^6) were fixed in paraformaldehyde. The percentage of total cells displaying caps was estimated from counts of at least 200 cells or ghosts. No qualitative differences in the appearance of caps in control and treated cells were observed.

Lectin Attachment to Detergent-insoluble Ghosts

The work of Flanagan and Koch (15) had previously shown that linkage between microfilaments and clustered cell surface Ig on lymphocytes was stable in the presence of nonionic detergent. To determine whether lectin-induced patches or caps remained associated with detergent-insoluble ghosts, neutrophils were treated with FITC-Con A at 37°C, to allow patching and capping, and then lysed. In both cases the appearance and distributions of both patches and caps on whole cells and on ghosts prepared from the same batch of cells were identical (Fig. 5). If cells were treated with FITC-succinylated Con A, the lectin remained evenly distributed over the surface of neutrophils. Detergent-insoluble ghosts prepared from these cells also showed reduced but even fluorescence around the periphery.

The relationship between lectin-induced patches and components of the detergent-insoluble ghosts was examined in more detail by electron microscopy (Fig. 6). Cells were incubated as before but with ferritin-Con A before lysis. The

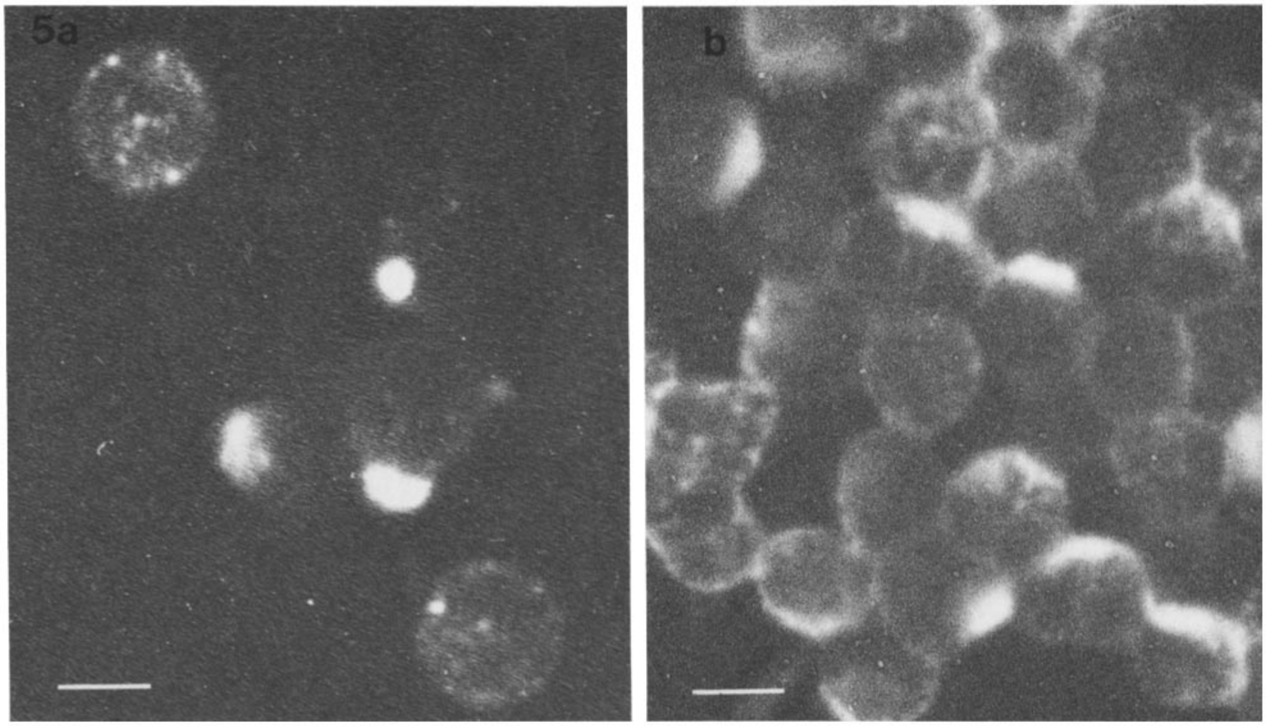


FIGURE 5 Retention of patched and capped FITC-Con A on detergent-insoluble ghosts. Cells were treated with FITC-Con A at 20 μg/ml for 5 min at 37°C. Samples of cells were fixed in 2% (wt/vol) paraformaldehyde, the remainder lysed according to the schedule in Materials and Methods, then fixed. Cells and ghosts were centrifuged onto slides and examined by fluorescence microscopy. (*a*) Capped and patched neutrophils. (*b*) Ghosts prepared from a similar preparation of cells. Bars, 5 μm.

majority of the ferritin-Con A maintains a location in the ghosts clearly reminiscent of that observed in sections of whole cells either on the cell surface as patches or within endocytic vesicles or invaginations of the plasma membrane. As there was no evidence for the presence of the intervening plasma membrane in any of the sections examined, in contrast to previous studies (12), retention of lectin on the ghosts must occur by means independent of the presence of lipid bilayer.

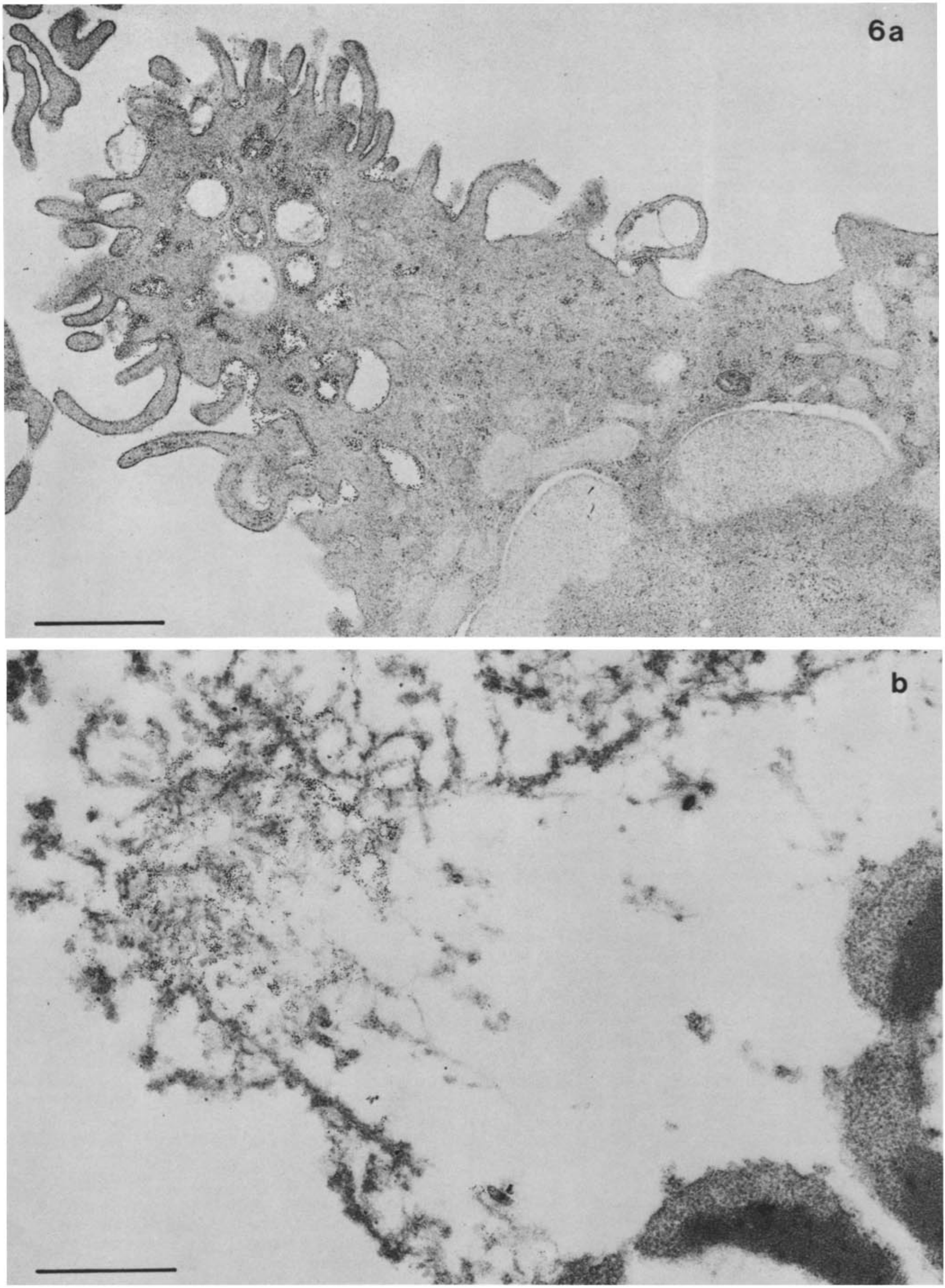
Two approaches were adopted for further analysis of the nature of lectin attachment to detergent-insoluble ghosts. First, neutrophils were incubated with ^{125}I-labeled lectins and allowed to patch and cap. Cells were then lysed, and the proportion of the original cell bound lectin remaining on the ghosts was assessed. The data are presented in Table V. It can be seen that although 40% of the total cell-bound Con A survives lysis, only 25% of the total succinyl Con A remains associated with the ghosts. The distribution of retained lectin in the ghosts has been described above (Figs. 5 and 6). Patches also remained attached to ghosts prepared from cells treated with agents that block the redistribution of patches into caps, i.e., as in Table IV (data not shown).

In the second approach, receptive groups exposed on the outer surface of the plasma membrane were labeled with ^{125}I in the presence of lactoperoxidase and glucose oxidase. Preliminary iodination experiments confirmed, in common with the experience of others (28, 40), that large amounts (~30%) of ^{125}I were taken up by the cells during iodination. However, covalent modification occurred almost exclusively to protein exposed on the cell surface. No labeling of intracellular proteins with electrophoretic mobilities corresponding to actin, myosin, or actin-binding protein was observed, and in the absence of extracellular glucose oxidase ^{125}I incorporation was reduced below 10%.

The degree of labeling of lipid molecules exposed at the outer surface of the cells was determined by separating chloroform-soluble material from whole cells and comparing the total radioactivity in this extract with total TCA-insoluble material. Less than 15% of the ^{125}I was found associated with the chloroform/methanol-extracted material. Lipids were further separated by thin-layer chromatography; Table VI shows that the proportion of ^{125}I associated with (unidentified) glycolipids in ghost preparations from lectin-treated cells was similar to that in control preparations, suggesting that a preferential association of particular ^{125}I glycolipids with these ghosts is unlikely.

If ghosts were prepared from iodinated cells incubated in either Dulbecco's solution A or medium containing lectins, significantly more TCA-insoluble ^{125}I was associated with ghosts prepared from cells incubated with lectin before lysis (Table VII). However, because 26% of the total ^{125}I-labeled TCA-insoluble material remains attached to ghosts prepared from cells incubated in the absence of lectin, the nature of this associated label was examined further.

Proteins from ghosts prepared from iodinated cells were separated on polyacrylamide gels in the presence of SDS, then subjected to autoradiography. It can be seen from Fig. 7 and Table VIII that eight consistently labeled proteins could be identified on autoradiograms of total cell proteins separated on gels. However, only one major labeled species remains associated with ghosts isolated from control cells. This protein, which has a molecular weight of 80,000, thus appears to be the predominant labeled component that is both exposed on the outer surface of the plasma membrane and attached, in the absence of ligand, to the detergent-insoluble ghosts. The possibility that the 80-kdalton protein is ^{125}I-labeled lactoperoxidase was excluded by showing that (*a*) lactoperoxidase does


6a
b

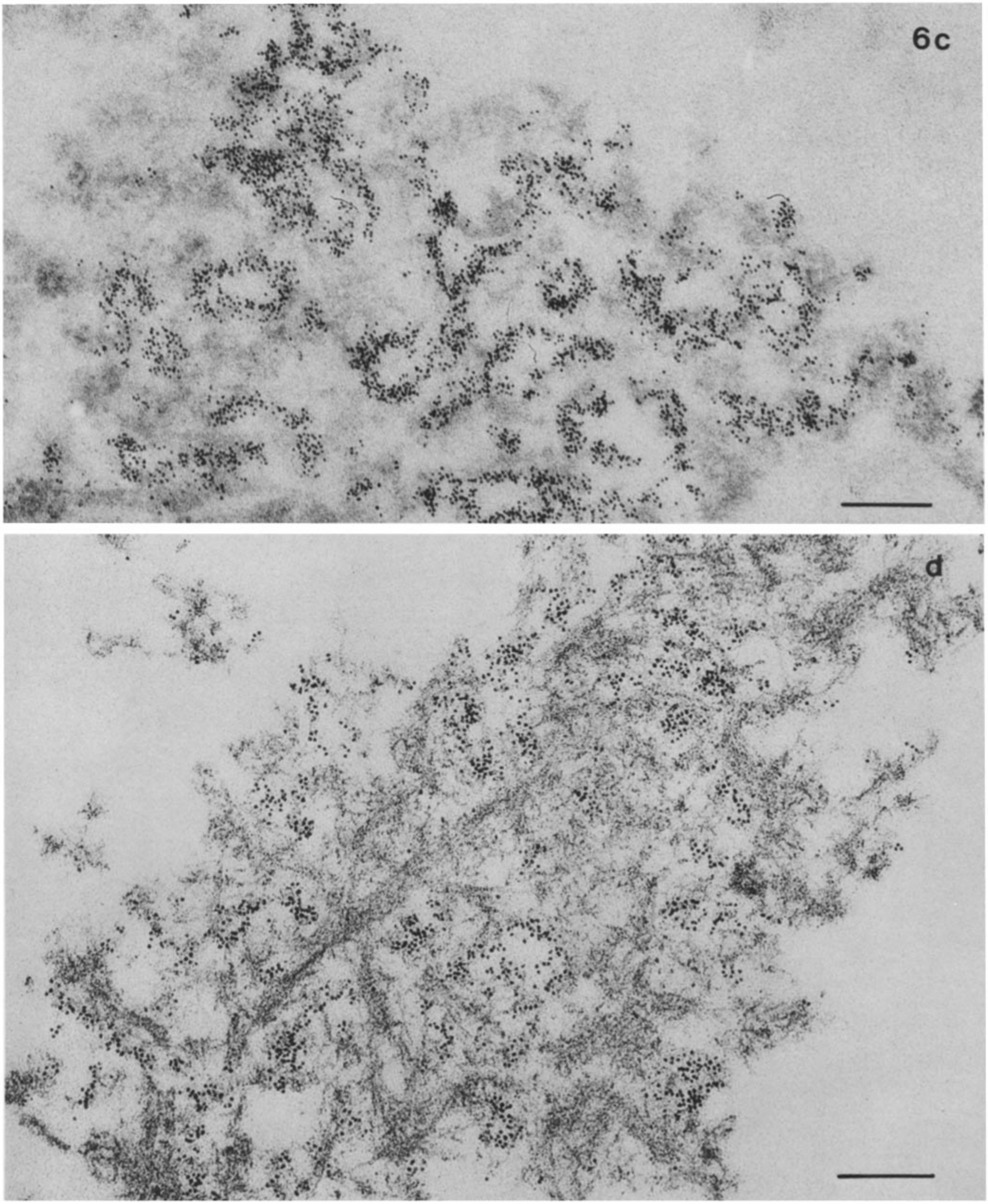


FIGURE 6 Location of ferritin-Con A on capped neutrophils and in detergent-insoluble ghosts prepared from a similar preparation. Cells were incubated with ferritin-Con A (50 µg/ml Con A equivalent) for 5 min at 37°C. Detergent-insoluble ghosts were prepared from samples of treated cells, and both cells and ghosts were fixed and prepared for electron microscopy as detailed in Materials and Methods. (*a*) Capped neutrophil. Bar, 1 µm. (*b*) Ghost prepared from capped neutrophil. Note the retention of the surface features of the capped neutrophil in the ghosts. Bar, 1 µm. (*c*) Unstained thick (interference color green) section of capped region of ghosts showing retention of the vesicular distribution of ferritin-Con A. Bar, 200 nm. (*d*) Thin section (silver interference color) stained with lead citrate of similar region showing the filamentous nature of the peripheral web. Bar, 200 nm.

TABLE V

Proportion of Cell-bound ^{125}I-Lectin Remaining Associated with Ghosts after Lysis

Lectin	% Cell-bound ^{125}I-lectin	No. binding sites/ghost
Con A	37.0 ± 4.8 (4)*	3.3×10^5
Succinyl Con A	24.5 ± 1.7 (4)*	1.8×10^5

Cells at 5×10^7/ml were incubated with ^{125}I-lectin in the absence or presence of competing sugar, 0.1 M α-methyl-D-mannoside for 5 min at 37°C. Cells were washed once at 0°C. 50-μl aliquots of cells were then centrifuged through a silicone oil cushion. Detergent-insoluble ghosts were prepared from remaining cells and similar aliquots centrifuged through silicone oil. The bottoms of the tubes were cut off and assayed for ^{125}I in a gamma spectrometer. Specific lectin binding was taken to be the difference between that observed in the absence and presence of competing sugar. The values given above are the percentage of lectin bound to cells remaining after preparation of ghosts. The significance of differences between two groups of data was determined by applying Student's *t* test.

* $P < 0.05$ Student's *t* test. Numbers in parentheses = number of trials.

TABLE VI

Iodination of Lipids Extracted from Cell and Ghosts

Lipid	Percentage total cell lipid-associated ^{125}I Cells	 Ghosts	 Con A ghosts
Sphingomyelin	7.5	1.3	1.5
Phosphatidyl choline	15.6	1.9	1.9
Glycolipids	27.4	1.7	2.1
Phosphatidyl ethanolamine	10.4	1.4	2.1
Neutral lipid	38.5	4.5	4.4

Chloroform/methanol-soluble lipid was extracted from ^{125}I-labeled cells, ghosts prepared from the same, and the extract subjected to thin layer chromatography. Spots were located and their ^{125}I content assayed as described in Materials and Methods. The glycolipid values are given as if for a single lipid; this entry, however, consists of three discreet but unidentified spots. The distribution of ^{125}I within the group was similar in all cases. Other lipids were tentatively identified by comigration with standard lipid samples. The amounts of TCA-insoluble ^{125}I and chloroform-soluble ^{125}I associated with cells and ghosts are given as follows for 10^8 cells (or ghost equivalents): (*a*) cells, TCA-insoluble ^{125}I, 152,568 cpm, chloroform-soluble, 21,096 cpm; (*b*) ghosts, TCA-insoluble 29,844 cpm, chloroform-soluble, 3,175 cpm; ghosts prepared from Con A-treated cells, TCA-insoluble 35,244 cpm, chloroform-soluble 3,430 cpm.

TABLE VII

Surface Iodinated Plasma Membrane Proteins Associated with Ghosts

Incubation conditions	TCA-insoluble ^{125}I As % of total cell ^{125}I	 As % of control ghost ^{125}I
Control cells	100	—
Control ghosts	26.8 ± 5.7 (14)	100
Con A ghosts	36.3 ± 6.2 (14)	148.8 ± 6.4 (14)*
Succinyl Con A ghosts	27.2 ± 5.3 (14)	105.2 ± 4.0 (14)*

Cells were iodinated at 5×10^7/ml on ice in the presence of lactoperoxidase and glucose oxidase, then washed twice in ice-cold Dulbecco's solution A containing 0.1 mM KI. Washed cells were then incubated with lactin for 5 min at 37°C, washed twice in ice-cold medium, and 200-μl aliquots (10^7 cells) were added to ice-cold 5% wt/vol TCA containing 1 mM KI. Ghosts were prepared from equivalent aliquots and these too were added to 5% wt/vol TCA. After standing on ice for 10 min TCA-insoluble material was collected by centrifugation and washed twice in further volumes of 5% wt/vol TCA. Pellets were then assayed for ^{125}I radioactivity. The significance of differences between two groups of data was determined by applying Student's *t* test.

* $P < 0.001$ Student's *t* test.

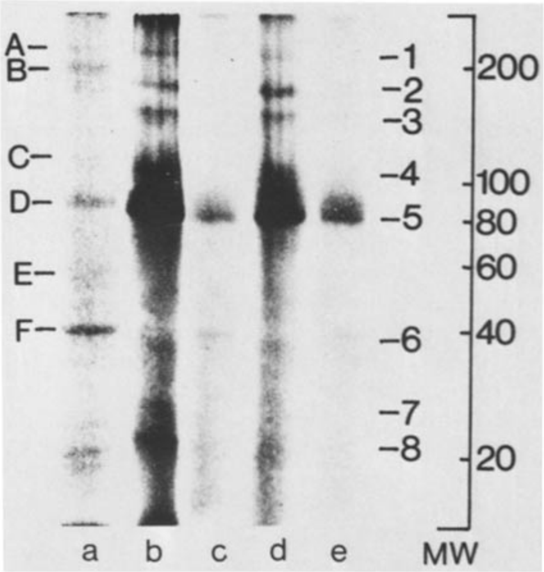


FIGURE 7 Autoradiograms of surface iodinated proteins in whole cells and ghosts. Cells were iodinated and then incubated in the presence or absence of lectin for 5 min at 37°C. Total cell and ghost proteins were subjected to electrophoresis in the presence of SDS on 7% (wt/vol) polyacrylamide gels; then the dried gels were subjected to autoradiography. The scale to the right of the gels shows approximate molecular weights $\times 10^{-3}$, derived from standard curves. Numerals and capital letters identify bands listed in Table VIII. Lane *a*, Coomassie Blue-stained ghost proteins. Lanes *b*–*e*, ^{125}I autoradiograms: (*b*) neutrophil proteins; (*c*) control ghost proteins; (*d*) ghosts prepared from cells incubated with 20 μg/ml Con A; (*e*) ghosts prepared from cells treated with 20 μg/ml succinyl-Con A. 5×10^6 cell equivalents added to each lane. The samples contained the following total ^{125}I cpm: *b*, 10.2×10^4; *c*, 2.4×10^4; *d*, 3.8×10^4; *e*, 2.5×10^4.

TABLE VIII

The Molecular Weights of Proteins Labeled on Intact Neutrophils with ^{125}I in the Presence of Lactoperoxidase and Those Present in Ghosts

^{125}I-labeled proteins*	Coomassie-Blue-stained ghost proteins‡
1. 217,154 ± 3,358	A. 220,281 ± 5,662
2. 170,494 ± 1,735	B. 200,000
3. 146,814 ± 2,271	C. 111,592 ± 1,603
4. 110,891 ± 6,676	D. 85,677 ± 2,050
5. 79,453 ± 1,056	E. 52,961 ± 1,992
6. 45,980 ± 660	F. 42,800
7. 34,033 ± 2,258	
8. 28,503 ± 3,018	

Ghost and cell proteins were separated in the presence of SDS on polyacrylamide gels and stained with Coomassie Blue, dried, then subjected to autoradiography. Molecular weights given are the mean ± SEM for four separate preparations and are derived by comparison with the mobility of myosin, 200,000 daltons; phosphorylase *b*, 95,000 daltons; bovine serum albumin, 68,000 daltons; tubulin, 54,000 and 56,000 daltons; actin, 42,800 daltons.

* Nos. *1*–*8*, indicate labeled bands on autoradiograms shown in Fig. 7, lanes *b*–*e*.

‡ Letters *A*–*F* correspond to Coomassie-Blue-stained bands in the gels shown in Figs. 2, lane *b* and Fig. 7, lane *a*. Band *A* comigrates with chicken gizzard filamin. Band *B* comigrates with chicken gizzard myosin heavy chain. Band *F* comigrates with chicken gizzard actin, Band *D* stains positively for carbohydrate with periodic acid-Schiff's reagent. The lactoperoxidase used in these experiments had a molecular weight of 87,283 ± 5,067 as measured by its relative mobility in polyacrylamide gels.

not comigrate with the 80-kdalton protein (Table VIII,‡), (*b*) the labeling efficiency of the 80-kdalton protein is not reduced if lactoperoxidase is presaturated with unlabeled iodine, and (*c*) small amounts (<10% control) of ^{125}I are incorporated into the 80-kdalton protein if lactoperoxidase is omitted from the iodination medium. The iodinated band consistently ran in front of the major 86-kdalton glycoprotein and comigrated with a minor band sometimes visible on stained gels.

The data in Table VII show that Con A induces the retention of more TCA-insoluble ^{125}I-labeled material to the ghosts than does succinyl Con A, the latter causing no increase over that observed in control ghosts. The increased label associated with the ghosts in the presence of Con A can be accounted for mainly by the presence of three labeled bands of 217, 170, and 147 kdaltons. On the other hand, the autoradiogram of ghost proteins from cells treated with succinylated Con A is similar to that of control ghost proteins (Fig. 7).

Note that the band with an apparent molecular weight of 217,000, which migrates between myosin and actin-binding protein, is similar in size to fibronectin. We have recently shown an association between fibronectin and stress fibers on the dorsal surface of detergent-insoluble ghosts prepared from ovarian granulosa cells (38).

DISCUSSION

The experiments described above were initiated to find a means of studying the molecular events occurring at the cell surface after binding and redistribution of lectin. The approach evaluated the possibility that interactions between membrane proteins and components of the cytoplasm occur in neutrophils, and, further, that these interactions can be retained and studied on detergent-insoluble ghosts.

The biochemical and morphological data show that extraction of neutrophils with Lubrol PX removes the majority of the cytoplasmic matrix components, intracellular organelles, and lipid bilayers of membrane boundaries. Only 20% of the total cell protein remains in the ghosts. For the most part this residual protein can be accounted for by the proteins, actin, myosin, actin-binding protein, a 111-kdalton protein that comigrates with a prominent band from gizzard muscle, and an unidentified 86-kdalton glycoprotein. Because the only structures observed in the ghosts are the peripheral filamentous network and a nuclear remnant, it is probable that the majority of the contractile related proteins are located in the filamentous network.

Treatment of neutrophils with Con A causes rapid clustering of lectin-binding sites on the cell surface followed, in a proportion of the cells, by relocation of these clusters into caps at one pole of the cell. Capping can be blocked by a range of inhibitors that would be expected to interfere with actomyosin-dependent motile systems. Because we can show by vectorial labeling of the cell surface that the majority of the contractile proteins are located on the cytoplasmic side of the plasma membrane, it is likely that an interaction of clusters with the peripheral network occurs through the lipid bilayer of the plasma membrane.

Comparison of cells and ghosts from cells treated with FITC- or ferritin-labeled Con A, by light and electron microscopy, show that lectin is exclusively located in clusters on the ghosts and that the size and spatial distribution of these clusters is essentially unchanged by the lysis procedure. Because electron microscopy shows that the majority of the lectin at the time of lysis is either on the surface of neutrophils or in invaginations of the plasma membrane open to the surface, it is unlikely that the patches are merely trapped within the filamentous network.

The lectin-binding species within clusters have been only partially characterized, but ghosts prepared from iodinated neutrophils treated with lectin did not contain more ^{125}I-glycolipid than control ghosts; thus it is likely that the majority of these binding sites are glycoproteins. Identification of surface glycoproteins associated with these clusters was attempted by vectorial labeling of intact cells with ^{125}I. Autoradiograms show eight or more consistently iodinated proteins exposed on the intact cell surface only one of which, the 80-kdalton protein, is efficiently retained by the ghosts. An additional three or four iodinated proteins are retained by ghosts prepared from iodinated cells incubated in the presence of Con A. These additional proteins are presumably associated with the lectin-induced clusters. The selectivity of association between surface iodinated proteins and the ghosts argues against the possibility that small amounts of intact plasma membrane survive detergent extraction. These results differ from those of Ben-Ze'ev et al. (6) who found, using mild lysis conditions, that many surface labeled proteins were retained by the extracted cells.

Quantitative estimates obtained by sectioning tube gels (data not shown) suggests that ~30% of the total cell complement of the ^{125}I-labeled 80-kdalton protein remains associated with the ghosts from untreated cells. We interpret this data to mean that this 80-kdalton protein is a component of the plasma membrane normally attached to the peripheral filamentous network in the cytoplasm of neutrophils.

In ghosts prepared from iodinated neutrophils treated with succinylated Con A, the autoradiograms show an autoradiographic pattern identical to that of control ghosts, in that the 80-kdalton protein remains attached to the ghosts but additional lectin associated proteins are absent. Because succinylated Con A does not cause clustering, we conclude that although cross-linking of surface glycoproteins is not required for attachment of the 80-kdalton protein to the ghosts, it is obligatory for retention of the additional lectin-binding proteins. The data in Table V further show that 24% of cell-bound succinylated Con A is retained by the ghosts. It is thus possible that the 80-kdalton protein is itself a binding site for Con A and that the attachment of the three or four other iodinated glycoproteins, observed in ghosts prepared from cells treated with Con A, could occur by direct cross-linking of these glycoproteins to the 80-kdalton protein. The increased efficiency of retention of the 80-kdalton protein on patched or capped ghosts through the lysis procedure, could reflect the binding advantage derived from cooperativity.

In the lateral plane, the 80-kdalton protein may be important in establishing connections with mobile binding sites exposed to the external surface before their relocation or internalization. The 80-kdalton protein fulfils the major requirements of the universal cross-linker "protein X" postulated by Bourguignon and Singer (8). However, because the 80-kdalton protein may be itself a Con A–binding protein, we are unable to use lectins to explore the possibility that the protein becomes associated with ligand induced clusters in the manner suggested by these authors. With other ligands this aspect is open to direct experimentation.

The 80-kdalton protein is both exposed on the outer surface of the plasma membrane and attached to the peripheral filamentous network, this protein must therefore itself, or in conjunction with other proteins, span the lipid bilayer. Because contraction generated by components within the peripheral filamentous network will tend to pull the network away from the plasma membrane, direct attachment of the network to a transmembrane protein (complex) may provide an important form of anchorage. Thus the 80-kdalton protein molecules may act in the manner of floats on a seine net, and, while prevented from being plucked out of the bilayer by hydrophobic/hydrophilic interactions, would be free to move laterally within the constraints imposed by their attachment to components within the cytoplasm. Contraction of the peripheral filamentous network would then act against the fluid volume within the cell via the lipid bilayer.

This model can provide a simple conceptual description of certain phenomena of surface motility and gives rise to predictions relating to the location of both the float protein and the contraction (relaxation) stimulus, aspects of which can be tested experimentally.

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REFERENCES

1. Albertini, D. F., R. D. Berlin, and J. M. Oliver. 1977. The mechanism of Con A cap formation in leukocytes. *J. Cell Sci.* 26:57–75.
2. Ash, J. F., D. Louvard, and S. J. Singer. 1977. Antibody-induced linkages of transmembrane proteins to intracellular actomyosin-containing filaments in cultured fibroblasts. *Proc. Natl. Acad. Sci. U. S. A.* 74:5584–5588.
3. Ash, J. F., and S. J. Singer. 1976. Concanavalin A-induced transmembrane linkage of Con A surface receptors to intracellular myosin-containing structures. *Proc. Natl. Acad. Sci. U. S. A.* 73:4575–4579.
4. Baggiolini, M., J. G. Hirsch, and C. de Duve. 1969. Resolution of granules from rabbit heterophil leukocytes into distinct populations by zonal sedimentation. *J. Cell Biol.* 40: 529–541.
5. Baginski, E. S., O. P. Foa, and B. Zak. 1967. Microdetermination of inorganic phosphate, phospholipids and total phosphate in biologic materials. *Clin. Chem.* 13:326–332.
6. Ben-Ze'ev, A., A. Duerr, F. Solomon, and S. Penman. 1979. The outer boundary of the cytoskeleton: a lamina derived from plasma membrane proteins. *Cell.* 17:859–865.
7. Bergmeyer, H. U., E. Bernt, and B. Hess. 1963. Lactic dehydrogenase. *Methods Enzymat. Anal.* 737–739.
8. Bourguignon, L. Y. W., and S. J. Singer. 1977. Transmembrane interactions and the mechanism of capping of surface receptors by their specific ligands. *Proc. Natl. Acad. Sci. U. S. A.* 74:5031–5035.
9. Bourguignon, L. Y. W., K. T. Tokuyasu, and S. J. Singer. 1978. The capping of lymphocytes and other cells studied by an improved method for immunofluorescence staining of frozen sections. *J. Cell Physiol.* 95:239–258.
10. Bray, D., and C. Thomas. 1976. Unpolymerised actin in fibroblasts and brain. *J. Mol. Biol.* 105:527–544.
11. Burton, K. 1956. A study of the conditions and mechanism of the diphenylamine reaction for the colorimetric estimation of deoxyribonucleic acid. *Biochem. J.* 62:315–323.
12. Condeelis, J. 1979. Isolation of Con A caps during various stages of formation and their association with actin and myosin. *J. Cell Biol.* 80:751–758.
13. de Petris, S. 1974. Inhibition and reversal of capping by cytochalasin B, vinblastine and colchicine. *Nature (Lond.).* 250:54–56.
14. Edelman, G. M., I. Yahara, and J. L. Wang. 1973. Receptor mobility and receptor-cytoplasmic interactions in lymphocytes. *Proc. Natl. Acad. Sci. U. S. A.* 70:1442–1446.
15. Flanagan, J., and G. L. E. Koch. 1978. Cross-linked surface Ig attaches to actin. *Nature (Lond.).* 273:278–281.
16. Geiger, B., and S. J. Singer. 1979. The participation of α-actinin in the capping of cell membrane component. *Cell.* 16:213–222.
17. Gunther, G. R., J. L. Wang, I. Yahara, B. A. Cunningham, and G. M. Edelman. 1973. Con A derivatives with altered biological activities. *Proc. Natl. Acad. Sci. U. S. A.* 70: 1012–1016.
18. Henson, R. M. 1971. The immunologic release of constituents from neutrophil leukocytes. *J. Immunol.* 107:1535–1557.
19. Heuser, J. E., and M. W. Kirschner. 1980. Filament organization revealed in platinum replicas of freeze-dried cytoskeletons. *J. Cell Biol.* 86:212–234.
20. Hubbard, A. L., and Z. A. Cohn. 1975. Externally disposed plasma membrane proteins. I-Iodination of mouse L cells. *J. Cell Biol.* 64:438–460.
21. Hunter, W. M., and F. C. Greenwood. 1962. Preparation of iodine-I^{131}-labeled human growth hormone of high specific activity. *Nature (Lond.).* 194:495–496.
22. Karnovsky, M. J. 1965. A formaldehyde-glutaraldehyde fixative of high osmolality for use in electron microscopy. *J. Cell Biol.* 27:137–138*A* (Abstr.).
23. Koch, G. L. E. 1980. Microfilament-membrane interactions in the mechanism of capping. *Symp. Br. Soc. Cell Biol.* 3:425–444.
24. Laemmli, U. K. 1970. Cleavage of structural proteins during the assembly of the head of bacteriophage T4. *Nature (Lond.)* 227:680–685.
25. Lin, D. C., K. D. Tobin, M. Grumet, and S. Lin. 1980. Cytochalasins inhibit nuclei-induced actin polymerization by blocking filament elongation. *J. Cell Biol.* 84:455–460.
26. Lowry, O. H., N. J. Rosebrough, A. L. Farr, and R. J. Randall. 1951. Protein measurements with Folin phenol reagent. *J. Biol. Chem.* 193:265–276.
27. Marchalonis, J. J. 1969. An enzymic method for the trace iodination of immunoglobulins and other proteins. *Biochem. J.* 113:299–305.
28. Muller, W. A., R. M. Steinman, and Z. A. Cohn. 1980. The membrane proteins of the vacuolar system. I. Analysis by a novel method to intralysosomal iodination. *J. Cell Biol.* 86:292–303.
29. Olson, M. D. J., and I. E. Leiner. 1967. Some physical and chemical properties of concanavalin-A, the phytohemagglutinin of the jack bean. *Biochemistry.* 6:105–111.
30. Schlessinger, J., D. Axelrod, D. E. Koppel, W. W. Webb, and E. L. Elson. 1977. Lateral transport of a lipid probe and labelled proteins on a cell membrane. *Science (Wash. D. C.).* 195:307–309.
31. Schlessinger, J., E. L. Elson, W. W. Webb, L. Yahara, U. Rutishauser, and G. M. Edelman. 1977. Receptor diffusion on cell surfaces modulated by locally bound Con A. *Proc. Natl. Acad. Sci. U. S. A.* 74:1110–1114.
32. Sheterline, P. 1980. Trifluoperazine can distinguish between myosin light chain kinase-linked and troponin-C-linked control of actomyosin interaction by Ca^{++}. *Biochem. Biophys. Res. Commun.* 93:194–200.
33. Sheterline, P., and J. G. Schofield. 1974. Measurement of the rate of ATP synthesis in bovine pituitary slices. *Biochim. Biophys. Acta.* 338:505–511.
34. Singer, S. J., J. F. Ash, L. Y. W. Bourguignon, and H. H. Heggeness. 1978. Transmembrane interactions and the mechanisms of transport of proteins across membranes. *J. Supramol. Struct.* 9:373–389.
35. Singer, S. J., and G. L. Nicolson. 1975. The fluid mosaic model of the structure of cell membranes. *Science (Wash. D. C.).* 175:720–731.
36. Smith, B. A., W. R. Clark, and H. M. McConnell. 1979. Anisotropic molecular motion on cell surfaces. *Proc. Natl. Acad. Sci. U. S. A.* 76:5641–5644.
37. Starkey, P. M. 1977. Elastase and cathepsin G; the serine proteases of human neutrophil leukocytes and spleen. *In* Proteinases in Mammalian Cells and Tissues. A. J. Barrett, editor. North Holland, Amsterdam. 57–89.
38. Tolson, N. D., C. R. Hopkins, P. Sheterline, and S. L. Schor. 1980. Fibronectin and the cytoskeleton of epithelial cells. *Cell Biol. Int. Rep.* 4:765.
39. Wagner, H., L. Horhammer, and P. Wolff. 1961. Thin layer chromatography of phosphatides and glycolipids. *Biochem. Z.* 334:175–184.
40. Willinger, M., and F. R. Frankel. 1979. Fate of surface proteins of rabbit polymorphonuclear leukocytes during phagocytosis. I. Identification of surface proteins. *J. Cell Biol.* 82:32–44.
41. York, D. 1966. Least squares fitting of a straight line. *Can. J. Phys.* 44:1079–1086.