The Binding of Vimentin to Human Erythrocyte Membranes: A Model System for the Study of Intermediate Filament-Membrane Interactions

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ABSTRACT We have characterized the association of the intermediate filament protein, vimentin, with the plasma membrane, using radioiodinated lens vimentin and various preparations of human erythrocyte membrane vesicles. Inside-out membrane vesicles (IOVs), depleted of spectrin and actin, bind 125I-vimentin in a saturable manner unlike resealed, right-side-out membranes which bind negligible amounts of vimentin in an unsaturable fashion. The binding of vimentin to IOVs is abolished by trypsin or acid treatment of the vesicles. Extraction of protein 4.1 or reconstitution of the membranes with purified spectrin do not basically affect the association. However, removal of ankyrin (band 2.1) significantly lowers the binding. Upon reconstitution of depleted vesicles with purified ankyrin, the vimentin binding function is restored. If ankyrin is added in excess the binding of vimentin to IOVs is quantitatively inhibited, whereas protein 4.1, the cytoplasmic fragment of band 3, band 6, band 4.5 (catalase), or bovine serum albumin do not influence it. Preincubation of the IOVs with a polyclonal anti-ankyrin antibody blocks 90% of the binding. Preimmune sera and antibodies against spectrin, protein 4.1, glycophorin A, and band 3 exhibit no effect. On the basis of these data, we propose that vimentin is able to associate specifically with the erythrocyte membrane skeleton and that ankyrin constitutes its major attachment site.

Eucaryotic cells possess a complex interconnecting network of microfilaments and tubules that seem to be involved in a variety of diverse functions (cell shape, contractility, locomotion, etc.). This network, referred to as the cytoskeleton, organizes the cell interior into three topologically distinct domains. The bulk of the cytoskeleton makes up a matrix which extends throughout the cytoplasm, linking neighboring organelles together and providing some internal order which may serve to coordinate activities of the different components.

A special subset of cytoskeletal proteins, some with features quite unlike those that make up the cytoplasmic matrix, are concentrated in the submembranous regions of cells and have come to be known as the membrane skeleton (2-8). In addition to providing structural stability to the overlying lipid bilayer (a function most pronounced in the case of the membrane skeletons of erythrocytes), the membrane skeleton occupies a critical position situated as it is at the interface between the surface membrane and the cell interior, and it is likely that it plays some role in relaying signals from the cell surface to different effector systems located in the cytoplasm or the nucleus.

A third region where cytoskeletal elements are concentrated is the perinuclear region. This especially applied to intermediate filaments and microtubules (1, 9-11). Thus, the interface between the nucleoplasm and the cytoplasm might be considered analogous in some ways to the cell surface membrane skeleton.

The mechanisms of assembly of the macromolecular complexes of each cytoskeletal subdomain also seem to have characteristic features. The subunits of the cytoplasmic matrix cytoskeleton assemble via mass-action-driven polymerization reactions (12). The individual molecules are designed for self-assembly and the processes are regulated by the local ionic milieu, metabolic co-factors, and accessory proteins (13).

However, our understanding of the factors that control the
assembly of the membrane skeleton and the perinuclear cytoskeleton are less clear, since in both cases filaments must link up with membranes. With respect to intermediate-sized (or 10-nm) filaments, specific contacts have been morphologically identified in specialized regions of the plasma membrane such as the desmosomal plaques (14). Also, in lens and avian erythrocytes there is some evidence in favor of a side-on or end-on attachment of the filaments to unspecialized regions of the plasma membrane (15, 16, 17). Still, the precise molecular mechanism of these interactions remains obscure.

We have found that inverted human erythrocyte membrane vesicles, or inside-out membrane vesicles, (IOVs)1 is a useful model system to explore the factors that regulate interactions between the intermediate filament subunits and membranes, because these membranes retain binding sites for the intermediate filament protein, vimentin. This protein is normally present in appreciable amounts in developing erythroblasts but not in the mature mammalian erythrocytes (18, 19). The binding of vimentin to IOVs can be studied under in vitro conditions, and the search for the receptors involved has been simplified by the fact that IOVs contain a relatively small number of protein classes.

We found that human erythrocyte IOVs bind vimentin by a specific high-affinity association with ankyrin, one of the proteins that also links spectrin to the inner surface of the membrane.

MATERIALS AND METHODS

Chemicals: Ultrapure urea, ammonium sulfate, and Tris (base) were purchased from Schwarz/Mann (Spring Valley, NY), trypsin from Miles Laboratories Inc. (Elkhart, IN), bovine serum albumin (BSA) (RIA grade) from Sigma Chemical Co. (St. Louis, MO), DEAE-cellulose from Whatman Laboratories (Clifton, New Jersey), and Bolton-Hunter reagent-[125I] from Amersham Corp. (Arlington Heights, IL).

Membranes: IOVs were obtained after a 20-min extraction of washed erythrocyte ghosts with 30–40 vol of 0.3 mM NaPO4, 0.1 mM EDTA, and 1 mM phenylmethylsulfonyl fluoride (PMSF) (pH 9.0) at 37°C. Resealed ghosts were prepared by incubating erythrocyte ghosts in 20 vol of phosphate-buffered saline (PBS). 1 mM PMSF for 20 min. At 37°C. Right-side-out vesicles were made as previously described (20) except that the medium also contained 2 mM MgCl2. ‘Stripping’ of the IOVs or partial removal of protein 4.1 was achieved by the method of Hargreaves et al. (21). All preparations were kept in 5 mM NaPO4, 1 mM PMSF on ice for a maximum of 6 d. Human blood was collected from normal donors while bovine blood was obtained from a local slaughterhouse.

Protein Purification: The purification, characterization, and radiolabeling of calf lens vimentin are described in the accompanying report. Vimentin at 100 µg/ml was primarily (8%) migrating as a homogeneous soluble species with an S coefficient of 6–7S in isokinetic sucrose gradients. Protein 4.1 and ankyrin were extracted from IOVs by 1 M KCl and further purified by ion-exchange chromatography (22). Band 4.5 was purified from ghosts obtained at 10°C with 20 vol of PBS, 1 mM PMSF at a final volume of 100 µl. 0.1 mg/ml of BSA was also included to prevent adsorption to the plastic. Vimentin was kept in low salt on ice at 0.1 mg/ml and it was adjusted to the proper salt concentration immediately prior to the assay. The mixture was incubated for 90 min at 23°C and then transferred to hard polyethylene 400-µl tubes and layered over a 150-µl sucrose cushion (4% sucrose [isotonic]). Samples were centrifuged for exactly 12 min in a mini-fuge (15,000 g), frozen in liquid N2, and the bottoms of the tubes dissected with a razor blade. The pellet containing tips and the rest of the tube were counted in a gamma counter (supernate and pellet). The peletting system was prestandardized as follows. Blank samples containing only vimentin or only membranes were processed as described above. After freezing in liquid N2, the tubes were serially dissected and the pieces counted for radioactivity or analyzed by SDS PAGE. In a different series of pretests, blank samples containing buffer and a trace quantity of bromophenol blue were pelleted, dissected, and analyzed spectrophotometrically at 700 nm. From such assays it was found that only 0.3% of [125I]-vimentin was sedimenting in the absence of membranes, >95% of the vesicles were pelleted after a 12-min spin, and no dye had penetrated the sucrose cushion by the end of the run.

Competition Assays: [125I]-vimentin (10 µg/ml; 50,000 cpm/µg) was mixed with 20 µg of IOVs and increasing amounts of various membrane polypeptides in isotonic salt (pH 7.4) at a final volume of 100 µl. Samples were processed for quantitation as described above in Binding Assays.

Blocking By Antibodies: Increasing amounts of specific antibodies up to saturating levels (empirically determined by SDS PAGE) were added to 20 µg of IOVs in PBS, 0.1 mM PMSF. After an incubation period of 60 min at 4°C, equal amounts of [125I]-vimentin (12 µg/ml) were added and the system was allowed to equilibrate for another 90 min at 23°C. Bound and nonbound vimentin was quantitated as previously described.

As assays were executed in triplicate, except those shown in Fig. 1 (six independent observations) and in Fig. 7 (duplicates).

Immuno blotting: 10% polyacrylamide SDS gels were transferred electrophoretically to nitrocellulose filters for 24 h. After transfer, the filters were washed in isotonic buffered saline and then incubated for 1 h at 37°C, and then again for 24 h at room temperature, with 3% BSA. Incubation with a 1:100 dilution of anti-ankyrin followed for 8 h at room temperature. After washing (6 changes of buffer), [125I]-protein A from Staphylococcus aureus was added and the filters were incubated for 4 h. Finally, the nitrocellulose was washed for 6 h with buffer (6 changes) and for another 8 h with 0.01% Triton X-100. Dried filters were exposed at -70°C for 5 d.

Electrophoresis: Regular 10% gels or 5–10% gradient gels were prepared according to the method of Laemmli (27). Two-dimensional gels were made as described by O'Farrell (28).

Protein Determinations: Protein was measured according to Lowry (29) using BSA as a standard.

RESULTS

Vimentin Binds Specifically to the Inner Surface of the Human Erythrocyte Membranes

Purified [125I]-vimentin (see accompanying report) binds to IOVs, prepared from human erythrocyte membranes, in a concentration-dependent, saturable manner. In contrast, the binding of vimentin to either resealed ghost membranes or right-side-out membrane vesicles is nonsaturable and in an order of magnitude less than to IOVs (Fig. 1A). When vimentin was incubated with saturating amounts of IOVs, >80% of the intermediate filament protein bound to the membranes (Fig. 1B), indicating that the vimentin bound to the erythrocyte IOVs is not a special subset of vimentin molecules. The polymerization state of vimentin played some role in the capacity of vimentin to bind to IOVs. Vimentin prepolimerized before being exposed to IOVs bound to a lesser extent than nonprepolymerized material when assessed under non-equilibrium conditions. Under these conditions, the vimentin...
concentration and the quantity of membrane vesicles were exactly the same (Fig. 1C).

An analysis of vimentin binding to IOVs at equilibrium (see below) using the Scatchard plot (Fig. 2A) suggested that vimentin bound to a single class of acceptor sites, present at an approximate concentration of 80 µg/mg of IOVs. Assuming that the smallest vimentin aggregate in solution under the conditions of incubation was a tetramer (30), the $K_D$ was estimated to be $3 \times 10^{-7}$ M. Plotting the data according to Hill (Fig. 2B) revealed no apparent cooperativity in the binding process (Hill coefficient 1.007). Additional evidence for the specificity and saturability of the binding of vimentin to IOVs was provided by quantitative competition assays, such as the ones shown in Fig. 3. The amount of iodinated vimentin that binds to erythrocyte IOVs can be almost completely blocked by the addition of unlabeled vimentin, with a calculated $K_i$ of approximately $6 \times 10^{-7}$ M. Comparable amounts of BSA (an acidic protein of approximately the same size as vimentin) were completely ineffective in influencing the binding of vimentin to IOVs, as were other unrelated membrane proteins, described below.

The effects of neutral salt solutions on the binding of vimentin to IOVs is complicated and dependent upon the concentration of vimentin used in the assays. At low vimentin concentration (10 µg/ml), binding to IOVs increased slightly when salt concentrations were raised to ~150 mM, but less protein remained bound with the membranes after salt concentration exceeded 200 mM (Fig. 4A). Magnesium ions did not influence the binding. When the incubations were carried out at higher vimentin concentrations (36 µg/ml), more vimentin was bound to IOVs in the low salt solutions (Fig. 4B) than in higher salt. Since it has been reported that vimentin polymerization does not occur below 20 mM salt (31), this experiment is consistent with the results using prepolymerized vimentin described above. When dilute solutions of vimentin were incubated with membranes, vimentin polymers would not be expected to form because of low protein concentration, and it is likely that binding under that condition reflected the true salt dependency of the vimentin-membrane interaction. When higher concentrations of vimentin were used in the incubation, the protein which should have remained nonpolymerized below 20 mM salt concentrations undoubtedly began to self-associate to a small degree as the salt concentration was raised. The varying degree of binding could be then
The association of vimentin to IOVs proceeded relatively slowly at 23°C and equilibrium was approached after a 90-min incubation (Fig. 4C). More prolonged incubations (>4 h) resulted in a decrease in the binding of vimentin to membranes, but this is probably due to proteolytic degradation of the membranes that occurs under these conditions.

**Identification of Vimentin Binding Sites**

To identify the nature of the binding site or sites on the exposed surfaces of IOVs, vesicles were treated with different proteolytic enzymes or with solvents capable of differentially extracting different classes of proteins from the membranes. Both trypsin and 1 M acetic acid markedly reduced binding of vimentin to the membrane vesicles (Table I). Extraction of IOVs with 1 M KCl, 0.4 M urea at 0°C selectively removed the bulk of protein 4.1 from the membrane while retaining 80% of the ankyrin as has been reported (21). Such vesicles stripped of most of protein 4.1 still retained the capacity to bind vimentin (Fig. 5B). In contrast, when a substantial amount of the ankyrin was stripped from the vesicles by treatment with 1 M KCl, 2.5 M urea at 37°C (14), the capacity of these stripped vesicles to bind vimentin was reduced to 25% of the original activity (Fig. 5B). When purified ankyrin was added back to the urea-stripped vesicles, much of vimentin’s original capacity to bind was restored (Fig. 5B). The reconstitution of IOVs, depleted only of spectrin and actin, with purified spectrin did not significantly change the vimentin-binding capacity of vesicles (Fig. 5A). Reconstitution with 36 μg/ml or 112 μg/ml of purified spectrin did not alter the levels of vimentin binding (not shown).

**Ankyrin Is a Vimentin Binding Site on IOVs**

To further explore the possibility that ankyrin was responsible for the binding of vimentin to IOVs, a series of competition experiments were carried out. A standard amount of vesicles were incubated with 125I-vimentin in the presence of ankyrin, protein 4.1, band 4.5, band 6, or the 43,000-mol-wt peptide derived from band 3 (23). The percentage of bound vimentin was then measured and expressed as a function of the putative competitor concentration.

Consistent with the findings described above, it was observed that a severalfold excess of ankyrin was able to inhibit 80% of the binding of the radiolabeled vimentin (Fig. 6A). This inhibition was of a competitive mode as indicated by the Dixon plots (Fig. 6B). Much less inhibition is found with the other proteins tested (Fig. 6, C–F). The amount of ankyrin needed for quantitative vimentin displacement was greater than expected, because exogenously added material reassociated with the IOVs, leaving only a fraction of it in solution to act as a competitor (not shown). Surprisingly, the 43,000-mol-wt cytoplasmic peptide of band 3 had little effect on the binding (Fig. 6C). This was unexpected since it was thought that an excess of the band 3 cytoplasmic peptide would probably displace some ankyrin from the membranes and would thereby decrease the available vimentin binding sites. However, in separate experiments it was observed that although the 43,000-mol-wt peptide displaces ankyrin from urea-stripped, ankyrin-reconstituted vesicles, that does not accounted for by the number of free ends of vimentin polymers that are actually exposed to receptor sites on the IOVs (31).

**Binding of 125I-Vimentin to Various Preparations of Erythrocyte Membranes**

| Membranes                | Percent binding with respect to control |
|--------------------------|----------------------------------------|
| Human erythrocyte IOVs   | 100                                    |
| Bovine erythrocyte IOVs  | 104                                    |
| Trypsinized IOVs (human) | 17.5                                   |
| Acetic acid-treated IOVs (human) | 3.6                             |
| Stored IOVs (human)      | 45                                     |

Bovine IOVs were prepared exactly the same way as the human IOVs. Trypsin digestion of human IOVs was achieved by a brief incubation of 2.9 mg/ml of IOVs with 0.4 μg/ml of trypsin for 10 min at 23°C. The digestion was stopped by PMSF and the membranes were pelleted and washed 3 times with 5 mM NaPO4, 1 mM EDTA, 1 mM PMSF (pH 7.5). Acetic acid treatment involved incubation of IOVs with 1 M acetic acid at 0°C, extensive wash, and brief dialysis against 5 mM NaPO4, 1 mM PMSF (pH 7.5). Stored IOVs were assayed after having been left on ice for 10 d in 5 mM NaPO4, 0.1 mM EDTA, 1 mM PMSF (pH 7.5).

**Figure 5**

(A) Binding of vimentin to spectrin-reconstituted IOVs. ○, nontreated IOV; ●, spectrin-reconstituted IOV. (B) Binding of vimentin to various membrane preparations after KCl-urea extraction or ankyrin-reconstitution. Δ, Protein 4.1-depleted IOV; ●, "stripped" IOV; ○, ankyrin-reconstituted ("stripped") IOV. For details see Materials and Methods.
in overexposed autoradiograms such an effect is not detected. The anti-ankyrin antibody. As it could be seen in Fig. 8, even tin) were immunblotted and tested for cross-reactivity with featured by a well-developed network composed largely of skeletal of immature erythrocytes (up to the orthoblast) is of physiological relevance. The cytoskeleton of immature erythrocytes (up to the orthoblast) is featured by a well-developed network composed largely of vimentin filaments, which is lost after the expulsion of the nucleus (18, 19). Since ankyrin (constitutively present in all erythrocytes) plays a pivotal role in connecting the spectrin-actin meshwork to the membrane while retaining the ability to bind vimentin, it follows that a fundamental regulatory mechanism may operate in vivo to control the selective linkage of membrane skeleton or/and the cytoskeleton to the lipid bilayer. Using various erythrocyte membrane constructs of defined protein composition and sidedness and exploiting the sensitive binding assays with purified vimentin, it seems now feasible to study the process of filament attachment on the molecular level (better depicted in the companion paper).

In addition, the main corollaries of this study could be applied to nucleated cells expressing both membrane skeleton components and the full complement of the cyto-skeleton. In fact, the widespread existence of "typical" erythrocyte membrane polypeptides in virtually every tissue examined, taken together with the limited complexity of the erythrocyte skeleton present a paradox whereby filament-membrane interactions occurring in nucleated cells might be better analyzed in a model system that involves anucleate cells.

Ankyrin as an Intermediate Filament Attachment Site

The findings presented here show that soluble vimentin purified from lens tissue specifically associates with the inner surface of the human erythrocyte membrane under in vitro conditions. By several criteria we have identified ankyrin (band 2.1) as the vimentin acceptor site on IOVs. Isolated ankyrin competes with the vimentin binding site. If added exogenously, it restores the binding function to membranes that otherwise exhibit minimal binding as a result of KCl-urea "stripping," and it exists in IOVs at approximately the same concentration as the vimentin acceptor (see also reference 21). Antibodies against ankyrin dramatically block the vimentin-membrane association while treatments known to modify ankyrin (trypsin, acetic acid) also reduce the binding of vimentin.

Although these results specifically implicate ankyrin as a vimentin attachment site, it is conceivable that other binding sites may also exist for intermediate filament subunits. As a matter of fact, since our Scatchard analysis was not extended to vimentin concentrations greater than 100 μg/ml (to prevent self-association), the existence of low-affinity sites cannot be excluded. In this regard, it is interesting that protein 4.1 shows a small but measurable ability to compete with the vimentin attachment site (approximately 30% inhibition). Although a direct interaction between vimentin and protein 4.1 could not be documented in vitro (data not shown), it is worth pointing out that a 30% increase in the binding of 125I-vimentin could be observed after treating IOVs with affinity-purified anti-protein 4.1.

Vimentin does not seem to interact directly with the spectrin-actin network. IOVs reconstituted with spectrin do not show an increase in binding of vimentin, nor have we been able to detect complexes of vimentin and spectrin or vimentin and actin that can be demonstrated by sedimentation analysis. Furthermore, vimentin does not form a ternary complex when co-incubated with spectrin and protein 4.1 as it happens in the case of actin (Correas, I., and S. D. Georgatos, unpublished observations). Since IOVs reconstituted only with spectrin show appreciable vimentin binding capacity, we would predict that under native conditions the vimentin binding site on ankyrin is not completely masked by spectrin. However, the
FIGURE 7 Blockade of vimentin binding to IOVs by specific antibodies. \(^{125}\text{I}\)-vimentin (at 12 \(\mu\text{g/ml}\)) was incubated with 20 \(\mu\text{g}\) IOVs that had been preincubated with increasing amounts of antispectrin (A), anti-ankyrin (B), or pooled normal rabbit serum (C). "100% binding" was assigned to samples containing no antibodies.

in vivo situation is complicated by a number of factors, among them the possible presence of spectrin oligomers attached to the inner surface of the membrane and to more than one site, and the possible effects of cross-linking of intermediate filaments by associated proteins (15). For these reasons the precise organization of the vimentin-ankyrin complex in situ cannot be approached only by studies of soluble proteins in vitro. The findings described above differ significantly from previous studies in which it was suggested that a direct association exists between intermediate filaments and the lipid bilayer (16). Both the binding features (saturability, number of acceptor sites, etc.) and the fact that stripped or protease-treated membranes failed to bind vimentin are inconsistent with a simple, nonspecific association with membrane lipids.

It is intriguing that ankyrin-like polypeptides have recently been identified in lens membranes (32), an observation that raises the possibility that a family of ankyrin-like proteins exist that provide attachment sites for intermediate filaments in a wide variety of eucaryotic cells. In fact, recent observations indicate that nonerythroid ankyrin occurs at a threefold excess over the membrane-associated nonerythroid spectrin (33). Thus, even if all spectrin is exclusively bound to the membrane via ankyrin, there is additional ankyrin to be used for other functions. Although we do not have a clear picture of the molecular features of the ankyrin molecule, these findings and other related observations (34) suggest that ankyrin has two functionally distinct domains, one a membrane-linking site and the other a multifunctional domain to which can be attached either spectrin or other components of the cytoskeleton. If the spectrin attachment site and the intermediate filament binding regions are physically close to one another as we suspect, regulatory "switching" phenomena may occur that could be involved with the coupling and uncoupling of membrane receptors with different components of the cytoskeletal system. It is also interesting to consider potential similarities between vimentin-ankyrin interactions and those that have been reported between intermediate filaments (neurofilaments) and microtubule-associated proteins (35). Since a certain degree of functional and structural homology exists between ankyrin and microtubule-associated proteins, the types of interactions between vimentin and ankyrin detected in the erythrocyte may reflect more general mechanisms whereby microtubules, actin filaments, and intermediate filaments form an integrated skeletal unit that regulates the structure and viscoelastic properties of both the membrane and the underlying cytoplasm.

Attachment Pattern

Vimentin filaments could bind to IOVs either by their "free ends" in an end-on fashion, or by a side-on association that could involve associations between multiple segments of the linear polymers. Since the binding of iodinated vimentin to IOVs (via ankyrin) is non-cooperative, and since bound subunits do not seem to serve as filament nucleation sites, we favor an end-on binding mechanism. When measured under nonequilibrium conditions, nonassembled vimentin binds to a larger extent to IOVs than preassembled vimentin, possibly because of the higher concentration of free polymer ends (Fig. 1 C). In contrast, with a hypothetical side-on mechanism in which each individual subunit along a polymer should be equally competent to bind, identical binding curves should be obtained regardless of the polymerization state of the vimentin preparation. The data cannot exclude a pattern whereby looping intermediate filaments attach to the membrane via short (proto)filament branches. In support of such a model, it has been observed that some intermediate filaments that connect keratin tonofilaments with desmosomal plaques have both a branching morphology and also have tiny rod-like bridges (36, 37). If the short rod-like bridges are
actual attachment points, they might also be oriented in an end-on fashion, even though the overall microscopic picture is one of a combination of end-on and side-on orientations.

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REFERENCES

1. Osborn, M., T. Born, H.-J. Koitch, and K. Weber. 1978. Three-dimensional arrangements of microfilaments, microtubules and tonofilaments. Cell. 14:477-488.

2. Repasky, E., B. L. Granger, and E. Lazarides. 1982. Widespread occurrence of avian spectrin in nonerythroid cells. Cell. 29:821-833.

3. Bennett, V., J. Davis, and W. F. Fowler. 1982. Brain spectrin, a membrane-associated protein related in structure to erythocyte spectrin. Nature (Lond.). 299:126-131.

4. Burridge, K., T. Kelly, and P. Mangeat. 1982. Nonerythroid spectrins: actin-membrane attachment proteins occurring in many cell types. J. Cell Biol. 95:478-486.

5. Goodman, S. R., J. S. Zagon, and R. R. Kulikowski. 1981. Identification of a spectrin-like protein in nonerythroid cells. Proc. Natl. Acad. Sci. USA. 78:7530-7534.

6. Glenny, J. R., Glensky, P., and Weber, K. 1982. Erythroid spectrin, brain fodrin and intestinal brush border proteins (7W 250/240) are related to molecules containing a common calmodulin-binding subunit bound to a variant cell-type specific subunit. Proc. Natl. Acad. Sci. USA. 79:4002-4005.

7. Levine, J., and M. Willard. 1981. Fodrin: axonally transported polypeptides associated with the internal periphery of many cells. J. Cell Biol. 90:631-643.

8. Ben-Ze’ev, A., A. Druet, F. Soloman, and S. Peisman. 1979. The outer boundary of the cytoskeleton: a lamina derived from plasma membrane proteins. Cell 17:859-867.

9. Nelson, W. J., and P. Traub. 1981. Fractionation of the detergent resistant filamentous network of Ehrlich ascites tumor cells. Eur. J. Cell Biol. 23:250-257.

10. Lazarides, E. 1983. Intermediate filaments as mechanical integrators of cellular space. Nature (Lond.). 293:249-256.

11. Lehto, V. P., I. Virtanen, and P. Kurki. 1978. Intermediate filaments anchor the nucleus in nuclear monolayers of cultured human fibroblasts. Nature (Lond.) 272:173-177.

12. Engel, J., H. Fasold, F. W. Hulla, A. Aechier, and A. Wegner. 1977. The polymerization and its regulation by proteins from non-muscle cells. Physiol. Rev. 52:672-737.

13. Kartenberg, J., K. Schwertheimer, R. Möll, and W. W. Franke. 1984. Attachment of vimentin filaments to denervational plaques in human meningoma cells and arachnoidal tissue. J. Cell. Biol. 98:1072-1081.

14. Kartenberg, J., K. Schwechheimer, R. Möll, and W. W. Franke. 1982. Structural association of synemin and vimentin in avian erythrocytes revealed by immunoelectron microscopy. Cell 30:261-275.

15. Granger, B. L., and E. Lazarides. 1982. Structural association of synemin and vimentin in avian erythrocytes revealed by immunoelectron microscopy. Cell 30:261-275.

16. Ramamurthi, F. C. S., I. Duns, H. J. Podemont, E. L. Bennedetti, and H. Bloemberg. 1982. Lenticular intermediate-sized filaments: biosynthesis and interaction with the plasma membrane. Proc. Natl. Acad. Sci. USA. 79:2308-2312.

17. Dellagi, K., W. Vainchenker, G. Vinc, D. Paulin, and J. C. Brouet. 1983. Alteration of vimentin intermediate filament expression during differentiation of human hemopoietic cells. EMBO (Eur. Mol. Biol. Organ.) J. 2:1509-1514.

18. Dellagi, K., W. Vainchenker, G. Vinc, D. Paulin, and J. C. Brouet. 1983. Alteration of vimentin intermediate filament expression during differentiation of human hemopoietic cells. EMBO (Eur. Mol. Biol. Organ.) J. 2:1509-1514.

19. Capetanaki, V. Y., J. Ngai, C. N. Fylyantis, and E. Lazarides. 1983. Tissue-specific expression of two mRNA species transcribed from a single vimentin gene. Cell. 35:441-420.

20. Bennett, V., and D. Branton. 1977. Selective association of spectrin with the cytoplasmic surface of human erythrocyte plasma membrane. J. Biol. Chem. 252:2753-2763.

21. Hartgraves, W. R., K. Giedd, A. Verkleij, and D. Branton. 1980. Reassociation of ankyrin with band 3 in erythrocyte membranes and lipid vesicles. J. Biol. Chem. 255:11965-11972.

22. Leto, T., and V. T. Marchesi. 1984. A structural model of human erythrocyte protein A-1. J. Biol. Chem. 259:4603-4608.

23. Bennett, V., and P. J. Stehbach. 1980. Association between ankyrin and the cytoplasmic domain of band 3 isolated from the human erythrocyte membrane. J. Biol. Chem. 255:6424-6432.

24. Coombe, S. H., E. Forthmayr, and V. T. Marchesi. 1977. Immunohistochemical evidence for the transmembrane orientation of glycoporphin A: Localization of ferritin-antibody in intact cells. J. Mol. Biol. 115:539-553.

25. Fukuda, M., Y. Eshdat, G. Taron, and V. T. Marchesi. 1978. Isolation and characterization of peptides derived from the cytoplasmic segment of band 3, the predominant intermediate membrane protein of the human erythrocyte. J. Biol. Chem. 253:2419-2428.

26. Ziparo, E., A. Lema, and V. T. Marchesi. 1978. The distribution of spectrin along the membranes of normal and echinocytic human erythrocytes. J. Cell. Sci. 34:91-101.

27. Lazarides, E. 1982. Vimentin intermediate filament expressions during differentiation of human hemopoietic cells. EMBO (Eur. Mol. Biol. Organ.) J. 2:1509-1514.

28. O’Farrell, P. H. 1975. High resolution two-dimensional gel electrophoresis of proteins. J. Biol. Chem. 250:4001-4021.

29. Lowry, O., H. C. Laybrooke, A. L. Farr, and R. J. Randall. 1951. Protein measure-ment with the folin-phenol reagent. J. Biol. Chem. 143:262-275.

30. Geisler, N., and K. Weber. 1982. The amino acid sequence of chicken muscle desmin provides a common structural model for intermediate filament proteins. EMBO (Eur. Mol. Biol. Organ.) J. 1:1649-1656.

31. Steiner, P. M., W. W. Edger, M. M. Goldstein, and R. D. Goldstein. 1978. In vitro assembly of homopolymer and copolymer filaments from intermediate filament subunits of muscle and fibroblastic cells. Proc. Natl. Acad. Sci. USA. 78:3692-3696.

32. Davis, J. A., and V. Bennett. 1982. Brain ankyrin. J. Biol. Chem. 259:13550-13559.

33. Davis, J. A., and V. Bennett. 1984. Brain ankyrin. J. Biol. Chem. 259:13550-13559.

34. Weaver, D. C., and V. T. Marchesi. 1984. The structural basis of ankyrin function. J. Biol. Chem. 259:6163-6169.

35. Heinmann, R., M. L. Shelski, and R. K. H. Liem. 1983. Specific binding of MAPS to the 68-000 dalton neurofilament protein. J. Cell Biol. 97(5 Pt. II):164a.

36. Steiner, P. M., and W. W. Edger. 1983. Mona membrane cytochemistry, Cell Biology and Pathology, H. H. Publishing Co., Inc., New York, N.Y.

37. McNutt, N. S., and R. S. Weinstein. 1973. Membrane ultrastructure at mammalian intercellular junctions. Prog. Biophys. and Mol. Biol. 36:65-101.