

A simplified method for the preparation of detergent-free lipid rafts

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Abstract Lipid rafts are small plasma membrane domains that contain high levels of cholesterol and sphingolipids. Traditional methods for the biochemical isolation of lipid rafts involve the extraction of cells with nonionic detergents followed by the separation of a low-density, detergent-resistant membrane fraction on density gradients. Because of concerns regarding the possible introduction of artifacts through the use of detergents, it is important to develop procedures for the isolation of lipid rafts that do not involve detergent extraction. We report here a simplified method for the purification of detergent-free lipid rafts that requires only one short density gradient centrifugation, but yields a membrane fraction that is highly enriched in cholesterol and protein markers of lipid rafts, with no contamination from nonraft plasma membrane or intracellular membranes.—Macdonald, J. L., and L. J. Pike. A simplified method for the preparation of detergent-free lipid rafts. *J. Lipid Res.* 2005. 46: 1061–1067.

Supplementary key words caveolin • cholesterol • epidermal growth factor receptors • flotillin • Gq

Lipid rafts are low-density plasma membrane domains that are involved in a number of cellular processes, such as trafficking (1) and cell signaling (2–5). A variety of proteins have been shown to be selectively enriched in lipid rafts. These include glycosylphosphatidylinositol (GPI)-anchored proteins (6–10) and dually acylated proteins (11–15) that appear to be targeted to rafts as a result of their posttranslational modification with lipids. Several transmembrane proteins, including flotillin (16), receptor tyrosine kinases (17–19), and G protein-coupled receptors (20–25) have also been shown to be enriched in lipid rafts, although the targeting mechanisms for such proteins are not well defined. Caveolin, the structural protein of the subclass of lipid rafts known as caveolae (26, 27), is also typically found in low-density plasma membrane fractions. Together, these proteins are used as markers for lipid rafts during biochemical fractionation

procedures designed to isolate these plasma membrane domains.

Lipid rafts contain high levels of sphingolipids and cholesterol and probably exist in a liquid-ordered phase (28). Because of the presence of cholesterol and sphingomyelin, as well as the preponderance of saturated acyl chains in lipid rafts (29, 30), the acyl chains in these domains tend to be well ordered and tightly packed. This physical property gives rise to the known ability of lipid rafts to withstand disruption by nonionic detergents (6, 31). The high lipid:protein ratio of such detergent-resistant lipid rafts makes them significantly lower in density than other solubilized membrane proteins and allows them to be isolated from other membrane proteins by centrifugation through density gradients.

Early preparations of lipid rafts used 1% Triton X-100 to extract whole cells and the low-density, detergent-resistant material was separated from other solubilized membrane fractions by centrifugation on a 5% to 30% sucrose density gradient (6). Subsequently, lipid rafts have been prepared using a variety of other detergents, including Lubrol WX, Lubrol PX, Brij 58, Brij 96, Brij 98, Nonidet P40, CHAPS, and octylglucoside (31–36). Although preparations of detergent-resistant membranes are readily isolated, several observations have raised concerns that extraction of cells with detergent may be generating clusters of raft lipids and proteins that did not exist in the intact cell. For example, examination of cells grown on coverslips and then extracted with Triton X-100 reveals a continuous membrane sheet pock-marked by large holes (37). Because rafts are thought to be <50 nm in diameter (38–40), the residual “detergent-resistant” membrane probably formed from individual rafts that coalesced as a result of the detergent treatment.

To avoid the complications associated with preparing rafts using detergent extraction procedures, several meth-

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Abbreviations: CHO, Chinese hamster ovary; EGF, epidermal growth factor; ER, endoplasmic reticulum; GPI, glycosylphosphatidylinositol.

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ods have been established for isolating rafts from cells fractionated in the absence of detergent. Song et al. (41) sonicated cells in a pH 11 sodium carbonate buffer and isolated caveolae by centrifugation of the lysate in a discontinuous 5%/35%/45% sucrose gradient. Although this procedure is relatively easy, the spin time of 16 to 20 h is long and the resulting raft fraction is significantly contaminated with other membranes. A more careful fractionation of lipid rafts and caveolae was devised by Smart et al. (42), who lysed cells in an isotonic buffer containing EDTA and purified plasma membranes on a Percoll gradient. The plasma membranes were then sonicated and the lipid rafts isolated by flotation through a 10% to 20% gradient of OptiPrep. This method results in the production of a relatively clean raft preparation. However, it is time-consuming and yields are poor. Furthermore, there is significant variability from preparation to preparation and from cell type to cell type.

Because of the drawbacks associated with existing procedures for isolating detergent-free lipid rafts, we sought to develop an improved method that would allow the rapid isolation of purified rafts in good yield. We report here that lysis of cells by shearing in an isotonic buffer containing calcium and magnesium permits isolation of a highly purified raft fraction in a single step by flotation in a 0% to 20% OptiPrep gradient.

EXPERIMENTAL PROCEDURES

Materials

OptiPrep was obtained from Granier BioOne. Percoll was obtained from Sigma Chemical Co. CII Total Cholesterol Assay Kit was from Wako. Protease inhibitor cocktail set III was from Calbiochem. Calpain inhibitor I was from Sigma. The polyclonal anti-epidermal growth factor (EGF) receptor antibody and polyclonal anti-G_q antibody were from Santa Cruz. The monoclonal anti-transferrin receptor antibody was obtained from Zymed. The monoclonal antibodies against flotillin-1 and annexin II and the polyclonal antibody against caveolin-1 were purchased from Transduction Laboratories. The polyclonal anti- β -COP antibody was from Sigma, and the polyclonal anti-calnexin antibody was from Stressgen. The monoclonal anti-prohibitin antibody was from Neomarkers. The polyclonal antibody against 5'-nucleotidase was obtained from Abgent. The α -nucleoporin antibody was the generous gift of Dr. Susan Wentz (Vanderbilt University). Horseradish peroxidase-conjugated anti-rabbit IgG was from Pierce. Horseradish peroxidase-conjugated anti-mouse IgG and chemiluminescence reagents were from Amersham.

Cells and tissue culture

Chinese hamster ovary (CHO) cells transfected with human EGF receptors and HeLa cells were grown in Ham's F12 medium containing 10% fetal calf serum. Human breast adenocarcinoma MDA-231 cells were maintained in RPMI1640 containing 10% fetal calf serum. All cells were grown in a humidified incubator in 5% CO₂.

Simplified method for the preparation of detergent-free lipid rafts

All procedures were carried out on ice. Four D150 plates of cells were washed and scraped into base buffer (20 mM Tris-HCl,

pH 7.8, 250 mM sucrose) to which had been added 1 mM CaCl₂ and 1 mM MgCl₂. Cells were pelleted by centrifugation for 2 min at 250 *g* and resuspended in 1 ml of base buffer containing 1 mM CaCl₂, 1 mM MgCl₂, and protease inhibitors at final concentrations of 0.2 mM aminoethyl-benzene sulfonyl fluoride, 1 μ g/ml aprotinin, 10 μ M bestatin, 3 μ M E-64, 10 μ g/ml leupeptin, 2 μ M pepstatin, and 50 μ g/ml calpain inhibitor I. The cells were then lysed by passage through a 22 *g* \times 3" needle 20 times. Lysates were centrifuged at 1,000 *g* for 10 min. The resulting postnuclear supernatant was collected and transferred to a separate tube. The pellet was again lysed by the addition of 1 ml base buffer plus divalent cations and protease inhibitors, followed by shearing 20 times through a needle and syringe. After centrifugation at 1,000 *g* for 10 min, the second postnuclear supernatant was combined with the first.

An equal volume (2 ml) of base buffer containing 50% OptiPrep was added to the combined postnuclear supernatants and placed in the bottom of a 12 ml centrifuge tube. An 8 ml gradient of 0% to 20% OptiPrep in base buffer was poured on top of the lysate, which was now 25% in OptiPrep. Gradients were centrifuged for 90 min at 52,000 *g* using an SW-41 rotor in a Beckman ultracentrifuge. After centrifugation, cloudiness could be seen throughout the gradient. A diffuse band was observed about one-third of the way down the gradient, and a distinct band was apparent at the interface of the 20% end of the gradient and the 25% OptiPrep bottom layer. Gradients were fractionated into 0.67 ml fractions, and the distribution of various proteins was assessed by Western blotting. Total protein in each fraction was determined by precipitation Lowry (43). Total cholesterol was determined using the Wako CII Total Cholesterol assay kit.

Preparation of other types of detergent-free rafts

Detergent-free rafts were prepared using the carbonate gradient method of Song et al. (41). Briefly, two D150 plates of cells were washed and scraped into phosphate-buffered saline. After pelleting the cells for 2 min at 250 *g*, 2 ml 500 mM sodium carbonate, pH 11.0, containing protease inhibitors as above were added to the cell pellet. Cells were lysed by 20 strokes in a Dounce homogenizer using a tight-fitting pestle, followed by 10 passages through a 23 *g* needle and, finally, sonication three times for 15 s in a Branson Sonifier 250. The homogenate was mixed with an equal volume (2 ml) of MES-buffered saline (25 mM MES, pH 6.5, 150 mM NaCl) containing 90% sucrose and placed in the bottom of a test tube. Four milliliters of MES-buffered saline containing 35% sucrose was layered on top, followed by 4 ml of MES-buffered saline containing 5% sucrose. Gradients were centrifuged for 16 h at 175,000 *g* in an SW41 rotor. Tubes were fractionated into 12 1 ml fractions.

Rafts were also prepared by the sequential linear gradient method of Smart et al. (42). Four D150 plates of cells were washed and scraped into buffer A (20 mM Tris, pH 7.8, 0.25 M sucrose, 1 mM EDTA) containing protease inhibitors as above. Cells were lysed in 1 ml buffer A using 10 strokes in a Dounce homogenizer, followed by 10 passages through a 23 *g* needle. The lysate was centrifuged for 10 min at 1,000 *g* and the supernatant collected. The pellet was lysed as before in 1 ml buffer A. After centrifugation, the two postnuclear supernatants were combined and placed on top of 8 ml 30% Percoll and centrifuged for 30 min at 84,000 *g* in a Beckman Ti75 rotor. A visible band approximately one-third of the distance down the tube was collected and used as the plasma membrane fraction. This fraction was adjusted to 2 ml with buffer A and then sonicated with six pulses at 50% duty cycle using a Branson Sonifier 250. After a 1 min rest, the sample was sonicated with a second set of six pulses. The procedure was repeated for a total of 18 1 s pulses. The sonicate was

mixed with 1.8 ml buffer A containing 50% OptiPrep plus 0.2 ml buffer A. An 8 ml gradient of 10% to 20% Opti-Prep in buffer A was poured on top, and the tubes were centrifuged for 90 min at 52,000 *g*. Gradients were fractionated and protein distribution analyzed by Western blotting.

RESULTS

Figure 1 compares the distribution of several membrane proteins in two earlier detergent-free lipid raft membrane preparations. The distribution of marker proteins in the carbonate step gradient of Song et al. (41) is shown on the left, and the distribution of the same proteins in the sequential linear gradient procedure of Smart et al. (42) is shown on the right. As can be seen from the figure, in the carbonate step gradient procedure, raft proteins, including flotillin, caveolin, Gq, and the EGF receptor are present in fractions 4 and 5, which represent the interface between the 5% and 35% sucrose pads. However, this “raft” fraction also contains a significant amount of transferrin receptor, a nonraft plasma membrane protein, and β -COP, a Golgi marker. The fraction appears to be relatively free of contamination by endoplasmic reticulum (ER) membranes, as evidenced by the absence of calnexin from fractions 4 and 5.

In contrast to the carbonate step gradient rafts, the low-density membranes derived from the sequential linear gradient procedure are not contaminated with either ER or Golgi markers. A significant portion of these intracellular membranes are removed during the initial plasma membrane purification in the Percoll gradient (data not shown), and the remainder are readily separated from the

raft membranes in the second OptiPrep gradient. The raft protein markers flotillin, caveolin, and Gq were broadly distributed in the gradient, but approximately one-third of each was found in the upper third of the gradient. Approximately one-quarter of the EGF receptor was also found in the lowest-density fractions. If only the lightest five fractions of the OptiPrep gradient are pooled, a relatively clean raft fraction can be obtained. However, the preparation requires a full day to complete, and yields are often poor. More importantly, there is significant day-to-day and cell-to-cell variability in the fraction of raft markers that can be recovered in the low-density portion of the gradient.

Because the method of Smart et al. (42) provided a cleaner preparation of rafts, we used this as the starting point for our method and modified the procedure to optimize for purity, yield, and ease of preparation. The method that was developed omits the initial purification of plasma membranes over the Percoll gradient and employs a single OptiPrep gradient to separate lipid rafts from other membrane fragments. The key to obtaining these separations was the removal of EDTA and the inclusion of calcium and magnesium in the washing and lysis buffer. However, divalent cations were absent from the OptiPrep gradient used to separate the membrane fractions. **Figure 2** shows the distribution of several membrane proteins across the density gradient in this modified procedure.

Most raft membrane markers were found primarily in fractions 1 through 3 of the gradient. This included ras, Gq, GPI-anchored 5'-nucleotidase, and the EGF receptor. Flotillin was recovered over a somewhat broader density range, but a significant fraction of this marker was still found in the lightest fractions of the gradient. Flotillin has

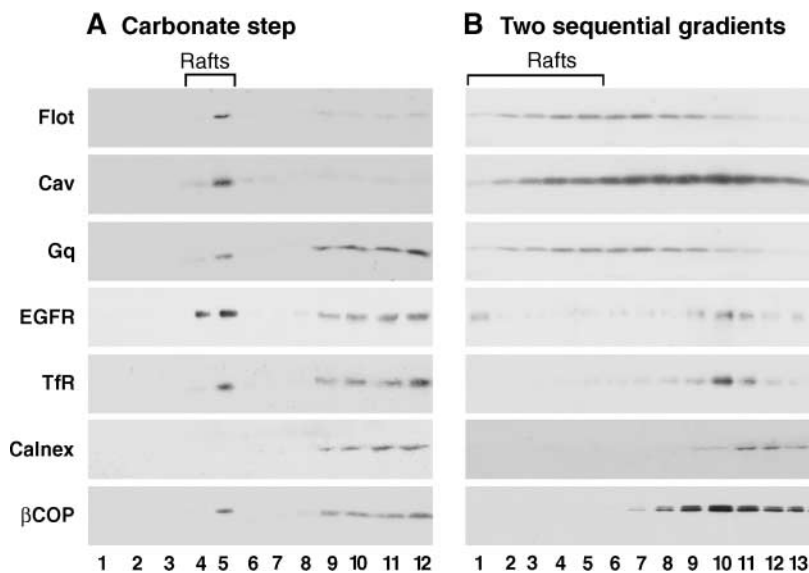


Fig. 1. Distribution of membrane proteins in previous detergent-free protocols. Raft preparations were isolated from Chinese hamster ovary (CHO) cells as described in Experimental Procedures. A 100 μ l aliquot of each gradient fraction was analyzed by SDS polyacrylamide gel electrophoresis followed by Western blotting for the indicated protein. A: Protein distribution in the carbonate step gradient procedure of Song et al. (41). B: Protein distribution in the Percoll/OptiPrep linear gradient procedure of Smart et al. (42). Flot, flotillin; Cav, caveolin; EGFR, epidermal growth factor receptor; TfR, transferrin receptor; Calnex, calnexin.

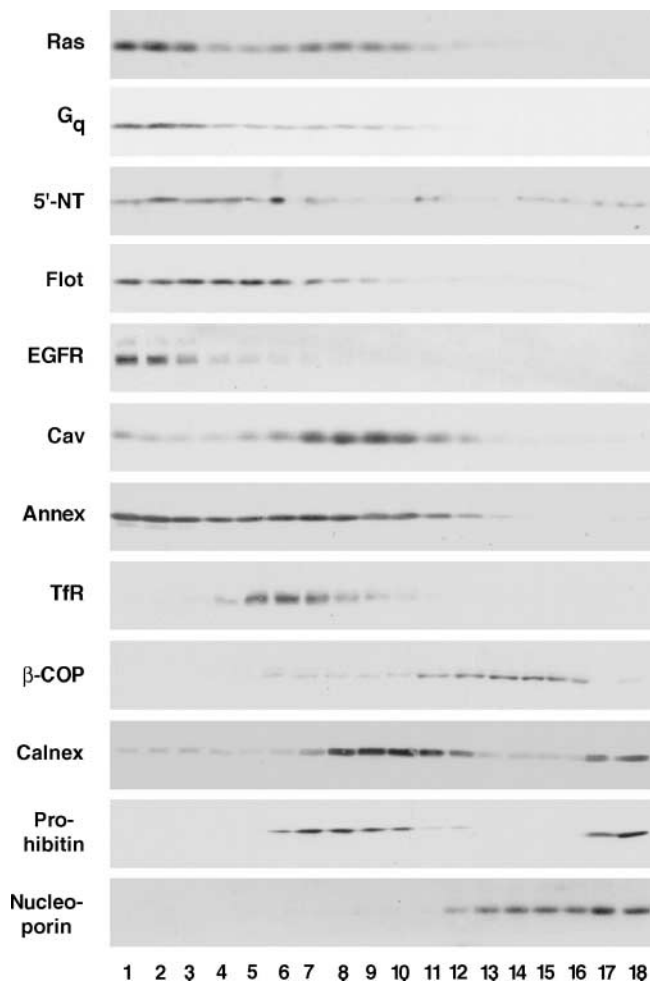


Fig. 2. Distribution of membrane proteins in new detergent-free protocol. CHO cells were lysed and the membranes separated as described in Experimental Procedures. A 100 μ l aliquot of each gradient fraction was analyzed by SDS polyacrylamide gel electrophoresis followed by Western blotting for the indicated protein. Annex, annexin II; 5'-NT, ecto-5'-nucleotidase. All other abbreviations are as in Fig. 1.

been reported to be present in cellular compartments other than lipid rafts (44–46). Thus, its presence throughout the gradient probably reflects its varied intracellular distribution. These raft fractions correspond to a concentration of 0% to 5% OptiPrep. Because the base buffer contains \sim 9% sucrose, the material recovered in these fractions is similar in density to the membranes isolated using detergent extraction and sucrose density gradient centrifugation (6).

The peripheral membrane protein, annexin II, was recovered in both the low-density raft fractions and in the higher-density portion of the gradient. Interestingly, although some caveolin was found in the top three fractions, this marker protein was recovered primarily in fractions 7 through 10, well outside the main lipid raft fractions. Importantly, the transferrin receptor, a marker for nonraft plasma membrane, was well separated from the major lipid raft fractions, indicating that nonraft plasma membrane did not significantly contaminate the

major lipid raft fractions. Furthermore, β -COP and calnexin, the Golgi and ER markers, respectively, were also well separated from the lipid rafts, as were prohibitin, a marker for mitochondria, and α -nucleoporin, a marker for nuclear membranes. Thus, this procedure cleanly separates intracellular membranes from plasma membrane lipid rafts.

To determine the reproducibility of the fractionation method, rafts were prepared on three separate days using the above protocol. Fractions were analyzed for marker proteins by Western blotting and the blots quantitated to determine the fraction of the various markers that were recovered in the lipid raft fraction (fractions 1 through 3). The results are shown in **Fig. 3**. On average, nearly 70% of the EGF receptor and 60% of Gq were recovered in the lipid raft fractions. A somewhat lower fraction, 40% to 50%, of ras and flotillin was found in the raft fractions, whereas about 35% of 5'-nucleotidase and annexin II was recovered in rafts. All nonraft markers, including those for plasma membrane and intracellular organelles, were present at less than 5%. Daily variation in recovery was generally 15% or less. Thus, the method reproducibly recovers raft proteins and purifies them away from nonraft markers.

Figure 4 shows the distribution of total protein and cholesterol across the OptiPrep gradient. As can be seen from the figure, relatively little protein was present in the raft fractions. The bulk of the protein was found at the bottom of the gradient. Cholesterol levels in the low-density frac-

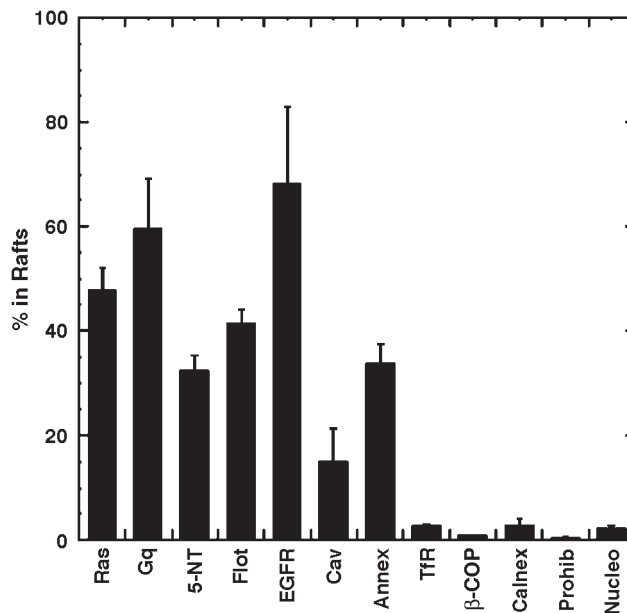


Fig. 3. Percent recovery of membrane proteins in the raft fraction. Lipid rafts from CHO cells were prepared using the simplified method and fractions analyzed for marker proteins as in Fig. 2. The Western blots were scanned and quantitated using ImageJ. The percent recovery of a protein in the raft fraction was calculated by adding the amount of a marker protein in fractions 1 through 3 and dividing this by the total amount of that protein recovered in all 18 fractions. Values represent the mean \pm SD from three separate experiments.

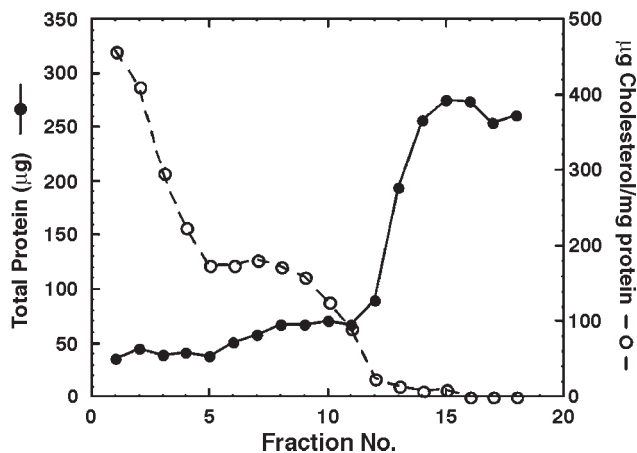


Fig. 4. Distribution of protein and cholesterol across the OptiPrep gradient. Protein and cholesterol content of each fraction were determined as indicated in Experimental Procedures. Closed circles, total protein content of each fraction; open circles, micrograms cholesterol per milligram protein in each fraction.

tions were high. When plotted as micrograms cholesterol per milligram protein, it can be seen that the light fractions are significantly enriched in this sterol, as compared with the higher-density fractions. The protein yield in the raft fractions was approximately twice that obtained using the method of Smart et al. (42). Because the amount of cholesterol per milligram protein is similar in the two preparations (~900–1,000 nmol/mg protein), the level of purity of the two preparations is similar. Thus, we estimate

that the recovery of raft material in our preparations is about twice that obtained using the Smart et al. method.

The one-step OptiPrep gradient separation method was applied to two additional cell types, MDA-231 and HeLa cells, to determine whether the procedure produced equivalently good separation and recovery of lipid rafts in other cell systems (Fig. 5). In both cell lines, the lipid raft marker proteins floated to fractions 2 through 5, somewhat denser than those found in CHO cells. However, the rafts were still well separated from nonraft plasma membranes marked by the transferrin receptor. In addition, markers for intracellular membranes were also distributed well away from the raft fractions. Thus, the procedure yielded similar results in terms of separation of rafts from nonraft membranes in other cell types.

DISCUSSION

We report here on a new method for the isolation of detergent-free lipid rafts from cultured cell lines. The procedure represents a simplification of the methodology of Smart et al. (42). Although this earlier method generates a fairly clean raft fraction, it requires three ultracentrifugation steps and a full 8 h to produce a concentrated raft fraction. In addition, we have observed that the sonication step prior to the OptiPrep gradient introduces significant variability into the preparation. Over-sonication results in the recovery of all proteins in the high-density portion of the gradient, whereas under-sonication fails to separate the raft membranes from the plasma membrane. The

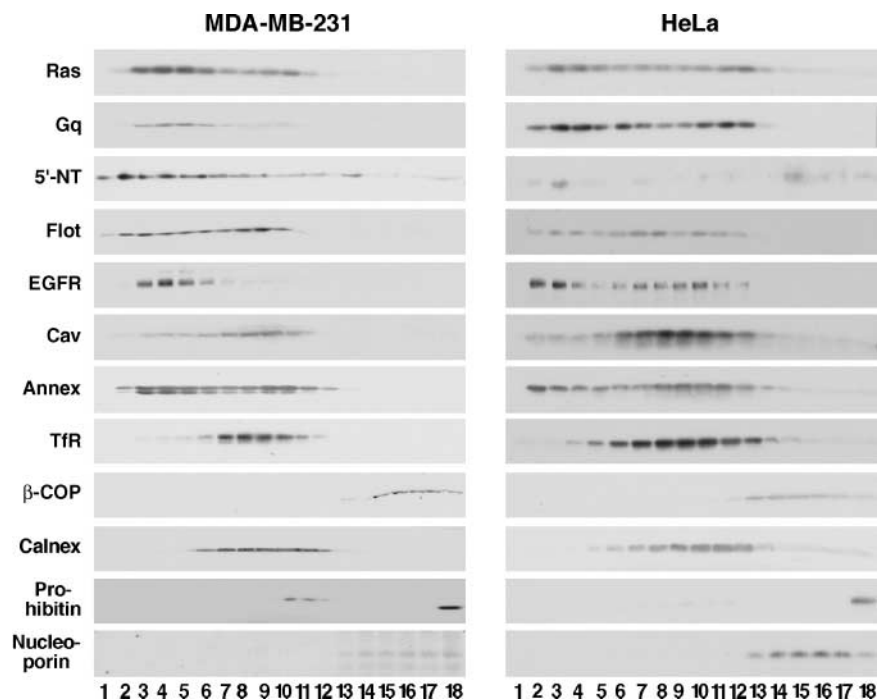


Fig. 5. Application of the detergent-free raft isolation procedure to MDA-231 and HeLa cells. MDA-231 and HeLa cells were lysed and membranes separated as outlined in Experimental Procedures. A 100 µl aliquot of each gradient fraction was analyzed by SDS polyacrylamide gel electrophoresis followed by Western blotting for the indicated protein.

amount of sonication necessary to achieve good separation varies from cell line to cell line and also differs with different growth or treatment conditions. This lack of consistency is the major impediment to applying this methodology to the study of lipid rafts.

Our method requires just one short (90 min) ultracentrifugation and omits the sonication step. Thus, it is much faster than the earlier methods. In addition, because there is only one fractionation step, losses are reduced and yields are significantly increased. Analysis of protein marker distribution can easily be accomplished using half as many cells (two D150 plates) as are required for the method of Smart et al. (42). If a concentrated raft fraction is desired, this is readily achieved by separating the lysates on a 5% to 20% OptiPrep gradient rather than the 0% to 20% OptiPrep gradient used here. The narrower gradient results in the recovery of all raft markers in fraction 1 and does not affect the separation from other cellular membranes.

Most importantly, this new methodology yields consistent results. Raft markers are always separated from non-raft plasma membrane and intracellular membrane markers, and the fractional recovery of a raft marker in the low-density fractions is reproducible from experiment to experiment. Membranes from different cell lines appear to have different average densities; thus, the rafts and other membranes are recovered at slightly higher or slightly lower positions in the density gradients. However, their relative separation is similar, and the recovery of raft markers in the raft fractions is consistently high. At most, a minor adjustment in the boundaries of the OptiPrep gradient would be necessary to produce an optimal separation of rafts from other membranes in different cell lines.

The key change in the protocol was the removal of EDTA from the washing and lysis buffers and the addition of calcium and magnesium. Lysing the cells in buffer containing EDTA followed by separation on a 0% to 20% OptiPrep gradient did not lead to the separation of rafts from the plasma membrane. The reason for the difference in the behavior of lipid rafts under these lysis conditions is not clear, but it is possible that rafts are stabilized by divalent cations, making their isolation easier.

The rafts isolated using the new method exhibit the characteristics typical of this membrane domain. The purified rafts are highly enriched in cholesterol, a key lipid component of such domains. They are also enriched in traditional raft marker proteins, including the GPI-anchored protein, 5'-nucleotidase, and the acylated protein G_q. The rafts also contain transmembrane domain proteins known to be present in lipid rafts, such as flotillin (16) and the EGF receptor (18). Annexin II, a peripheral membrane protein previously shown to be raft associated (47), was also found in the raft fractions. The nonraft plasma membrane marker, transferrin receptor, as well as markers for intracellular membranes (β -COP, calnexin, prohibitin, and nucleoporin) were excluded from the raft fraction. Thus, this procedure appears to yield a clean fraction of membranes that has all the characteristics of lipid rafts.

Interestingly, caveolin was recovered in fractions of a significantly higher density than other raft marker proteins. The basis for this separation is not clear, but it is possible that the association of caveolae with the actin cytoskeleton is not disrupted by the lysis procedure, resulting in the generation of relatively heavy caveolar membranes. It is noteworthy that this is the first biochemical isolation of lipid rafts in which they were physically separated from caveolae without recourse to immunoaffinity purification. This may, therefore, be a useful procedure for determining whether a protein partitions into lipid rafts or caveolae.

In summary, we have developed a simple and rapid method for the isolation of lipid rafts without employing detergents. The availability of a procedure for isolating large amounts of detergent-free lipid rafts will permit easier and more extensive biochemical characterization of these domains. ■■

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REFERENCES

1. Helms, J. B., and C. Zurzolo. 2004. Lipids as targeting signals: lipid rafts and intracellular trafficking. *Traffic*. **5**: 247–254.
2. Smart, E. J., G. A. Graf, M. A. McNiven, W. C. Sessa, J. A. Engelman, P. E. Scherer, T. Okamoto, and M. P. Lisanti. 1999. Caveolins, liquid-ordered domains, and signal transduction. *Mol. Cell. Biol.* **19**: 7289–7304.
3. Pike, L. J. 2003. Lipid rafts: bringing order to chaos. *J. Lipid Res.* **44**: 655–667.
4. Simons, K., and D. Toomre. 2000. Lipid rafts and signal transduction. *Nat. Rev. Mol. Cell Biol.* **1**: 31–41.
5. Saitiel, A. R., and J. E. Pessin. 2003. Insulin signaling in microdomains of the plasma membrane. *Traffic*. **4**: 711–716.
6. Brown, D. A., and J. K. Rose. 1992. Sorting of GPI-anchored proteins to glycolipid-enriched membrane subdomains during transport to the apical cell surface. *Cell*. **68**: 533–544.
7. Cinek, T., and V. Horejsi. 1992. The nature of large noncovalent complexes containing glycosyl-phosphatidylinositol-anchored membrane glycoproteins and protein tyrosine kinases. *J. Immunol.* **149**: 2262–2270.
8. Sargiacomo, M., M. Sudol, Z. Tang, and M. P. Lisanti. 1993. Signal transducing molecules and glycosyl-phosphatidylinositol-linked proteins form a caveolin-rich insoluble complex in MDCK cells. *J. Cell Biol.* **122**: 789–807.
9. Zurzolo, C., W. van't Hof, G. van Meer, and E. Rodriguez-Boulan. 1994. VIP21/caveolin, glycosphingolipid clusters and the sorting of glycosylphosphatidylinositol-anchored proteins in epithelial cells. *EMBO J.* **13**: 42–53.
10. Milliet, P.-E., M.-C. Giocondi, O. Baghdadi, F. Ronzon, B. Roux, and C. Le Grimellec. 2002. Spontaneous insertion and partitioning of alkaline phosphatase into model lipid rafts. *EMBO Rep.* **3**: 485–490.
11. Shenoy-Scaria, A. M., D. J. Dietzen, J. Kwong, D. C. Link, and D. M. Lublin. 1994. Cysteine³ of Src family protein tyrosine kinases determines palmitoylation and localization in caveolae. *J. Cell Biol.* **126**: 353–363.
12. Shaul, P. W., E. J. Smart, L. J. Robinson, Z. German, I. S. Yuhanna, Y. Ying, R. G. W. Anderson, and T. Michel. 1996. Acylation targets endothelial nitric-oxide synthase to plasmalemmal caveolae. *J. Biol. Chem.* **271**: 6518–6522.
13. Moffett, S., D. A. Brown, and M. E. Linder. 2000. Lipid-dependent targeting of G proteins into rafts. *J. Biol. Chem.* **275**: 2191–2198.
14. Melkonian, K. A., A. G. Ostermeyer, J. Z. Chen, M. G. Roth, and D. A. Brown. 1999. Role of lipid modifications in targeting pro-

- teins to detergent-resistant membrane rafts. *J. Biol. Chem.* **274**: 3910–3917.
15. Zacharias, D. A., J. D. Violin, A. C. Newton, and R. Y. Tsien. 2002. Partitioning of lipid-modified monomeric GFPs into membrane microdomains of live cells. *Science*. **296**: 913–916.
 16. Bickel, P. E., P. E. Scherer, J. E. Schnitzer, P. Oh, M. P. Lisanti, and H. F. Lodish. 1997. Flotillin and epidermal surface antigen define a new family of caveolae-associated integral membrane proteins. *J. Biol. Chem.* **272**: 13793–13802.
 17. Liu, P., Y. Ying, Y-G. Ko, and R. G. W. Anderson. 1996. Localization of platelet-derived growth factor-stimulated phosphorylation cascade to caveolae. *J. Biol. Chem.* **271**: 10299–10303.
 18. Mineo, C., G. L. James, E. J. Smart, and R. G. W. Anderson. 1996. Localization of epidermal growth factor-stimulated Ras/Raf-1 interaction to caveolae membrane. *J. Biol. Chem.* **271**: 11930–11935.
 19. Gustavsson, J., S. Parpal, M. Karlsson, C. Ramsing, H. Thorm, M. Borg, M. Lindroth, K. H. Peterson, K-E. Magnusson, and P. Stralfors. 1999. Localization of the insulin receptor in caveolae of adipocyte plasma membrane. *FASEB J.* **13**: 1961–1971.
 20. Feron, O., T. W. Smith, T. Michel, and R. A. Kelly. 1997. Dynamic targeting of the agonist-stimulated m2 muscarinic acetylcholine receptor to caveolae in cardiac myocytes. *J. Biol. Chem.* **272**: 17744–17748.
 21. Seno, K., M. Kishimoto, M. Abe, Y. Higuchi, M. Mieda, Y. Owada, W. Yoshiyama, H. Liu, and F. Hayashi. 2001. Light- and guanosine 5'-3-*o*-(thio)triphosphate-sensitive localization of a G protein and its effector on detergent-resistant membrane rafts in rod photoreceptor outer segments. *J. Biol. Chem.* **276**: 20813–20816.
 22. Rybin, V. O., X. Xu, M. P. Lisanti, and S. F. Steinberg. 2000. Differential targeting of β -adrenergic receptor subtypes and adenylate cyclase to cardiomyocyte caveolae. *J. Biol. Chem.* **275**: 41447–41457.
 23. Lasley, R. D., P. Narayan, A. Uittenbogaard, and E. J. Smart. 2000. Activated cardiac adenosine A1 receptors translocate out of caveolae. *J. Biol. Chem.* **275**: 4417–4421.
 24. Igarashi, J., and T. Michel. 2000. Agonist-modulated targeting of the EDG-1 receptor to plasmalemmal caveolae. *J. Biol. Chem.* **275**: 32363–32370.
 25. de Weerd, W. F. C., and L. M. F. Leeb-Lundberg. 1997. Bradykinin sequesters B2 bradykinin receptors and the receptor-coupled $G\alpha$ subunits $G\alpha_q$ and $G\alpha_i$ in caveolae in DDT1 MF-2 smooth muscle cells. *J. Biol. Chem.* **272**: 17858–17866.
 26. Fra, A. M., E. Williamson, K. Simons, and R. G. Parton. 1995. De novo formation of caveolae in lymphocytes by expression of VIP21-caveolin. *Proc. Natl. Acad. Sci. USA*. **92**: 8655–8659.
 27. Le, P. U., G. Guay, Y. Altschuler, and I. R. Nabi. 2002. Caveolin-1 is a negative regulator of caveolae-mediated endocytosis to the endoplasmic reticulum. *J. Biol. Chem.* **277**: 3371–3379.
 28. Brown, D. A., and E. London. 2000. Structure and function of sphingolipid- and cholesterol-rich membrane rafts. *J. Biol. Chem.* **275**: 17221–17224.
 29. Fridriksson, E. K., P. A. Shipkova, E. D. Sheets, D. Holowka, B. Baird, and F. W. McLafferty. 1999. Quantitative analysis of phospholipids in functionally important membrane domains from RBL-2H3 mast cells using tandem high-resolution mass spectrometry. *Biochemistry*. **38**: 8056–8063.
 30. Pike, L. J., X. Han, K-N. Chung, and R. Gross. 2002. Lipid rafts are enriched in plasmalogens and arachidonate-containing phospholipids and the expression of caveolin does not alter the lipid composition of these domains. *Biochemistry*. **41**: 2075–2088.
 31. Schuck, S., M. Honsho, K. Ekroos, A. Shevchenko, and K. Simons. 2003. Resistance of cell membranes to different detergents. *Proc. Natl. Acad. Sci. USA*. **100**: 5795–5800.
 32. Madore, N., K. L. Smith, C. H. Graham, A. Jen, K. Brady, S. Hall, and R. Morris. 1999. Functionally different GPI proteins are organized in different domains on the neuronal surface. *EMBO J.* **18**: 6917–6926.
 33. Drevot, P., C. Langlet, X-J. Guo, A-M. Bernard, O. Colard, J-P. Chauvin, R. Lasserre, and H-T. He. 2002. TCR signal initiation machinery is pre-assembled and activated in a subset of membrane rafts. *EMBO J.* **21**: 1899–1908.
 34. Ilangumaran, S., S. Arni, G. van Echten-Deckert, B. Borisch, and D. C. Hoessli. 1999. Microdomain-dependent regulation of Lck and Fyn protein-tyrosine kinases in T lymphocyte plasma membranes. *Mol. Biol. Cell*. **10**: 891–905.
 35. Roper, K., D. Corbeil, and W. B. Huttner. 2000. Retention of prominin in microvilli reveals distinct cholesterol-based lipid microdomains in the apical plasma membrane. *Nat. Cell Biol.* **2**: 582–592.
 36. Slimane, T. A., G. Trugnan, S. C. D. van Izendoorn, and D. Hoekstra. 2003. Raft-mediated trafficking of apical resident proteins occurs in both direct and transcytotic pathways in polarized hepatic cells: role of distinct lipid microdomains. *Mol. Biol. Cell*. **14**: 611–624.
 37. Mayor, S., and F. R. Maxfield. 1995. Insolubility and redistribution of GPI-anchored proteins at the cell surface after detergent treatment. *Mol. Biol. Cell*. **6**: 929–944.
 38. Anderson, R. G. W., and K. Jacobson. 2002. A role for lipid shells in targeting proteins to caveolae, rafts, and other lipid domains. *Science*. **296**: 1821–1825.
 39. Edidin, M. 2003. The state of lipid rafts: from model membranes to cells. *Annu. Rev. Biophys. Biomol. Struct.* **32**: 257–283.
 40. Pralle, A., P. Keller, E-L. Florin, K. Simons, and J. K. H. Horber. 2000. Sphingolipid-cholesterol rafts diffuse as small entities in the plasma membrane of mammalian cells. *J. Cell Biol.* **148**: 997–1007.
 41. Song, K. S., S. Li, T. Okamoto, L. A. Quilliam, M. Sargiacomo, and M. P. Lisanti. 1996. Co-purification and direct interaction of Ras with caveolin, an integral membrane protein of caveolae microdomains. *J. Biol. Chem.* **271**: 9690–9697.
 42. Smart, E. J., Y-S. Ying, C. Mineo, and R. G. W. Anderson. 1995. A detergent-free method for purifying caveolae membrane from tissue culture cells. *Proc. Natl. Acad. Sci. USA*. **92**: 10104–10108.
 43. Peterson, G. L. 1977. A simplification of the protein assay method of Lowry et al. which is more generally applicable. *Anal. Biochem.* **83**: 346–356.
 44. Kokubo, H., J. B. Helms, Y. Ohno-Iwashita, Y. Shimada, Y. Horikoshi, and H. Yamaguchi. 2003. Ultrastructural localization of flotillin-1 to cholesterol-rich membrane microdomains, rafts, in rat brain tissue. *Brain Res.* **965**: 83–90.
 45. Lopez-Casas, P. P., and J. del Mazo. 2003. Regulation of flotillin-1 in the establishment of NIH-3T3 cell-cell interactions. *FEBS Lett.* **555**: 223–228.
 46. Reuter, A., U. Binkle, C. A. Stuermer, and H. Plattner. 2004. PrPc and reggies/flotillins are contained in and released via lipid-rich vesicles in Jurkat T cells. *Cell. Mol. Life Sci.* **61**: 2092–2099.
 47. Lisanti, M. P., P. E. Scherer, J. Vidugiriene, Z. Tang, A. Hermanowski-Vosatka, Y-H. Tu, R. F. Cook, and M. Sargiacomo. 1994. Characterization of caveolin-rich membrane domains isolated from an endothelial-rich source: implications for human disease. *J. Cell Biol.* **126**: 111–126.