

Real-Time Analysis of the Effects of Cholesterol on Lipid Raft Behavior Using Atomic Force Microscopy

Jared C. Lawrence, David E. Saslow, J. Michael Edwardson, and Robert M. Henderson

Department of Pharmacology, University of Cambridge, Cambridge, United Kingdom

ABSTRACT Cholesterol plays a crucial role in cell membranes, and has been implicated in the assembly and maintenance of sphingolipid-rich rafts. We have examined the cholesterol-dependence of model rafts (sphingomyelin-rich domains) in supported lipid monolayers and bilayers using atomic force microscopy. Sphingomyelin-rich domains were observed in lipid monolayers in the absence and presence of cholesterol, except at high cholesterol concentrations, when separate domains were suppressed. The effect of manipulating cholesterol levels on the behavior of these sphingomyelin-rich domains in bilayers was observed in real time. Depletion of cholesterol resulted in dissolution of the model lipid rafts, whereas cholesterol addition resulted in an increased size of the sphingomyelin-rich domains and eventually the formation of a single raftlike lipid phase. Cholesterol colocalization with sphingomyelin-rich domains was confirmed using the sterol binding agent filipin.

INTRODUCTION

Cholesterol is an essential component of eukaryotic cell membranes, and plays numerous roles in membrane function (Simons and Ikonen, 2000). Recently, it has been suggested that cholesterol is involved in the assembly and maintenance of sphingolipid-rich microdomains or “rafts,” which are proposed to act as platforms for the preferential sorting of proteins (Simons and Ikonen, 1997). The raft hypothesis is based on the observation that detergent-resistant membranes, which are enriched in sphingolipids and cholesterol, can be isolated using cold non-ionic detergents (Brown and London, 1998, 2000; Brown and Rose, 1992).

Model membrane studies have shown that lipid-lipid interactions are sufficient to induce the formation of raftlike domains (Dietrich et al., 2001a; Saslow et al., 2002). It is well established that phase separation can occur in binary lipid mixtures consisting of lipids that have different phase transition temperatures. Typically, a gel phase, which is characterized by tightly-packed lipids that have limited lateral mobility, co-exists with a fluid or liquid-disordered phase in which the lipids are loosely packed and have a high degree of lateral mobility. Addition of cholesterol has been reported to modify the gel phase component of such systems resulting in the so-called liquid-ordered phase in which the lipids are still tightly packed but acquire a relatively high degree of lateral movement (Sankaram and Thompson, 1990). Lipid rafts are proposed to exist in a state similar to the liquid-ordered phase surrounded by a fluid lipid matrix.

To investigate lipid raft characteristics in model membranes, sphingomyelin (SM) is commonly combined with a fluid-phase lipid, such as dioleoylphosphatidylcholine (DOPC), and cholesterol. SM lipids typically have long,

saturated acyl chains that facilitate close packing, an important feature of lipid raft organization (Ahmed et al., 1997; Brown and London, 2000). For this reason, SM-enriched domains in a bilayer are thicker than areas enriched in more fluid, unsaturated lipids, which have kinked chains that effectively shorten the molecules. SM lipids also have significantly higher phase transition temperatures than phosphocholine lipids (e.g., the transition temperature of brain SM is 37–41°C). In addition, there is a favorable interaction between SM and cholesterol, and there is strong evidence that they are colocalized in cell membranes, where cholesterol is thought to promote the formation and stability of lipid rafts (Simons and Ikonen, 2000; Slotte, 1999). The SM/cholesterol interaction is most likely strengthened by hydrogen bonding between the 3'-OH group of cholesterol and the amide of the SM head group (Bittman et al., 1994). Currently, the requirement for cholesterol in raft formation is unclear. For instance, it has been reported that raft domains disappear after cholesterol depletion from the plasma membrane in experiments using cultured cells (Cernea et al., 1993; Ilangumaran and Hoessli, 1998). However, cholesterol-independent raft domains have also been reported in both model membranes (Milhiet et al., 2002; Saslow et al., 2002), and in the brush border membrane of enterocytes (Hansen et al., 2001).

In vitro studies of lipid raft behavior have mainly used fluorescence microscopy to monitor the distribution of fluorescent raft markers (Dietrich et al., 2001a,b; Samsonov et al., 2001; Wang et al., 2000). However, recently, the direct visualization of raftlike domains in model membranes has been achieved using atomic force microscopy (AFM; Milhiet et al., 2001, 2002; Rinia et al., 2001; Saslow et al., 2002). AFM is a particularly suitable technique for studying supported lipid layers because of its ability to discriminate Ångstrom-scale height differences between lipid domains, and also to visualize surfaces under aqueous conditions (Dufrene et al., 1997). Previously, AFM has been used to investigate model raft domains at a number of fixed

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Address correspondence to Dr. R. M. Henderson, Dept. of Pharmacology, University of Cambridge, Tennis Court Road, CB2 1PD, UK. Tel.: 44-1223-334033; Fax: 44-1223-334040; E-mail: rmh1003@cam.ac.uk.

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cholesterol concentrations. These studies have provided useful information about the effect of cholesterol on raft thickness and area. In the present study, we have used AFM to analyze in real time the effects of manipulating cholesterol levels in supported model membranes containing DOPC and SM. In addition, we have used the cholesterol binding agent filipin, to reveal the lateral distribution of cholesterol in supported lipid bilayers containing model rafts.

MATERIALS AND METHODS

Materials

1,2-Dioleoyl-*sn*-glycero-3-phosphatidylcholine (DOPC), brain sphingomyelin (SM), and cholesterol (Avanti Polar Lipids, Birmingham, AL, USA) were used as received. Methyl- β -cyclodextrin (M β CD), water-soluble cholesterol (M β CD loaded with cholesterol) and filipin complex (minimum 75% filipin III) were purchased from Sigma (UK). Water was obtained from a Millipore water purification system.

Formation of supported lipid monolayers

Lipid monolayers were formed by the Langmuir-Blodgett method using a Nima Series 2011 trough (Coventry, UK). Lipid solutions consisting of SM/DOPC (1:1 mol/mol) with varying amounts of cholesterol were prepared in chloroform at a total lipid concentration, including cholesterol, of 1 mg/ml. To prepare lipid monolayers for transfer onto a freshly cleaved mica support (Goodfellow, Huntingdon, UK), the lipid solution was deposited onto the air-water interface of the Langmuir-Blodgett trough using water as the subphase. Monolayers were compressed to a surface pressure of 30 mN/m, released, and then recompressed three times, and allowed to rest for 10 min on the third compression before being transferred to mica at 10 mm/min. Cholesterol extraction experiments were performed using a subphase containing 10 mM M β CD dissolved in water.

Formation of supported lipid bilayers

Vesicles were prepared by combining DOPC, SM, and cholesterol from chloroform stocks. The chloroform was evaporated under a stream of nitrogen gas and the lipids were rehydrated overnight in water to give a total concentration of 2 mg/ml. The lipid mixture was then vortexed to produce large multilamellar vesicles from which small unilamellar vesicles were prepared by sonicating in a heated (50°C) bath sonicator (Decon Laboratories, Hove, UK) for 30 min. Supported lipid bilayers were formed by depositing 10 μ l of vesicle solution followed by 50 μ l of buffer (100 mM NaCl, 50 mM HEPES, 2 mM CaCl₂, pH 7.6; HBS) onto mica. After 3–5 min incubation at room temperature (22°C), the sample was gently rinsed with the same buffer and transferred to the AFM.

Filipin treatment of supported lipid bilayers

Supported lipid bilayers were preformed on a mica substrate and treated with filipin complex (100 μ M) diluted from a dimethyl sulfoxide stock (final dimethyl sulfoxide concentration 1.3% v/v). Incubation of the bilayer with filipin was conducted at room temperature in the dark for 30 min. The samples were gently rinsed with buffer before imaging.

Atomic force microscopy

A Nanoscope III Multimode AFM (Digital Instruments, Santa Barbara, CA, USA) equipped with a J-scanner was used for all imaging. Monolayers were imaged in air in either contact mode using oxide-sharpened DNP-S

cantilevers with a spring constant of 0.06 N/m (Digital Instruments) or tapping mode using silicon cantilevers (NCH Pointprobes, Nanosensors, Wetzlar-Blankenfeld, Germany). Supported lipid bilayers were imaged in HBS in fluid tapping mode using oxide-sharpened DNP-S cantilevers with a spring constant of 0.32 N/m (Digital Instruments). For fluid tapping mode imaging the cantilever oscillation was tuned to a frequency between 8–9 kHz and the drive amplitude was adjusted to produce a RMS amplitude of \sim 0.3–0.5 V. Force was minimized by adjusting the setpoint to just below the jumpoff point of the tip. The scan rate was typically 1–2 Hz. All scanning was carried out at room temperature (22°C). Images were flattened using the Nanoscope III software.

RESULTS

To investigate raft behavior in lipid monolayers, the Langmuir-Blodgett technique was used to transfer monolayers containing SM/DOPC (1:1 mol/mol), with varying amounts of cholesterol, to a mica support for AFM imaging. Separate microdomains were observed in monolayers in the absence of cholesterol (Fig. 1 *A*) and also in monolayers containing 10 and 20 mol% cholesterol (Fig. 1, *B* and *C*), as described previously (Milhiet et al., 2001). The percentage surface area occupied by the thicker SM-rich domains (*lighter gray areas*) increased with increasing cholesterol concentration ($24 \pm 2\%$, $33 \pm 2\%$, and $43 \pm 6\%$ ($n = 5$) for 0, 10, and 20 mol% cholesterol, respectively). The step height between the DOPC-rich and the SM-rich areas was \sim 0.5 nm, although this value was strongly dependent on the tip characteristics and whether tapping- or contact-mode AFM was used. At a concentration of 33 mol% cholesterol, the two phases began to coalesce (Fig. 1 *D*), and at 50 mol% cholesterol no distinct domains could be detected (Fig. 1 *E*). To further investigate the relationship between cholesterol concentration and the presence of discrete SM-rich domains, the cholesterol-sequestering agent methyl- β -cyclodextrin (M β CD; 10 mM) was used to extract cholesterol from a monolayer (SM/DOPC 1:1 mol/mol) containing 50 mol%

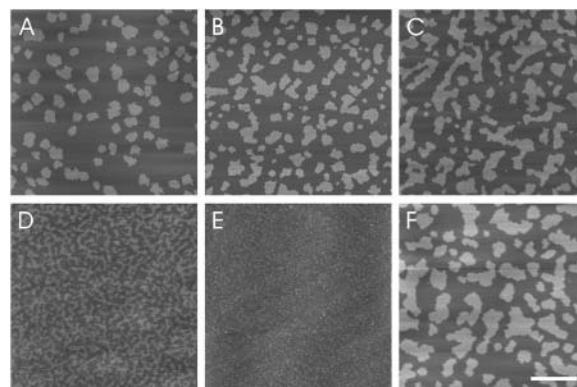


FIGURE 1 Effect of cholesterol on raft behavior in SM/DOPC monolayers. SM/DOPC monolayers (1:1 mol/mol) containing varying amounts of cholesterol were deposited onto mica from the air-water interface using the Langmuir-Blodgett method at a surface pressure of 30 mN/m. (*A*) No cholesterol, (*B*) 10 mol% cholesterol, (*C*) 20 mol% cholesterol, (*D*) 33% mol cholesterol, (*E*) 50 mol% cholesterol, and (*F*) 50 mol% cholesterol monolayer deposited from a subphase containing 10 mM M β CD. Scale bar: 500 nm.

cholesterol. After partial cholesterol depletion from the monolayer (cholesterol was extracted away from the air-water interface into the subphase), SM-rich domains were reformed, and could be visualized after transfer to a mica support (Fig. 1 *F*). In a control experiment, M β CD treatment was found to have no effect on either the lipid domain structure or the surface pressure of a cholesterol-free SM/DOPC monolayer (data not shown). Hence, in our experiments, M β CD was specifically extracting cholesterol.

We next used real-time AFM imaging to investigate the effect of manipulating the cholesterol content of supported lipid bilayers. Initially, bilayers were formed on a mica substrate via vesicle fusion. As with the monolayers, separate domains could be detected in the bilayers (SM/DOPC, 1:1 mol/mol) both in the absence of cholesterol and also at 10, 20, and 33 mol% cholesterol (data not shown). We could not form bilayers successfully from vesicles containing 50 mol% cholesterol. Whereas microdomains in monolayers were of a similar size and occupied a similar area between repeat experiments, microdomains in bilayers exhibited a much greater variation in both these attributes. Typically, the SM-rich domains in bilayers were more irregularly shaped, with a greater variation in size, from the nanometer to micrometer range. It is not known how the microdomains in supported bilayers are related to microdomains in the vesicles before vesicle fusion. For example, a vesicle with a diameter of 50 nm would contribute $\sim 0.008 \mu\text{m}^2$ in the supported bilayer. Some domains are much larger than this, indicating that some lipid rearrangement must occur after fusion. However, there was no detectable reorganization or diffusion of the SM-rich microdomains over the time scale investigated, of up to several hours.

When supported bilayers (10 mol% cholesterol/SM/DOPC) were treated with M β CD (10 mM) to deplete them of cholesterol, the SM-rich domains were found to dissolve into the surrounding fluid lipid bilayer (Fig. 2). To confirm that the rearrangement of the bilayer after M β CD treatment was due to cholesterol extraction, a SM/DOPC bilayer containing no cholesterol was treated using M β CD in a similar manner. In this instance, no loss of domains was observed (data not shown). When water-soluble cholesterol (50 $\mu\text{g}/\text{ml}$) was added to preformed bilayers (10 mol% cholesterol/SM/DOPC), the size of SM-rich domains was observed to increase over time, and the height difference between the DOPC-rich and SM-rich regions was reduced from an initial value of 0.7–0.8 nm to a point where separate lipid domains could no longer be detected (Fig. 3). By treating a cholesterol-saturated bilayer (Fig. 4 *A*) with M β CD (20 mM), it was possible to observe the behavior of the bilayer as the cholesterol concentration decreased from high concentrations (no rafts) through to intermediate concentrations, at which separate SM-rich domains reappeared. As the cholesterol concentration decreased further, the domains again dissolved into the surrounding bilayer (Fig. 4 *B*) as in Fig. 2. Unfortunately, it was not possible

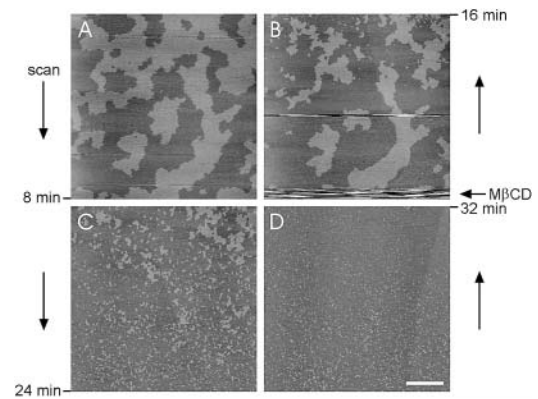


FIGURE 2 Effect of cholesterol depletion on lipid rafts in supported lipid bilayers. (A) SM/DOPC (1:1 mol/mol) bilayer containing 10 mol% cholesterol. Lipid rafts can be clearly seen. (B) Addition of M β CD (10 mM) at the beginning of the scan resulted in the loss of lipid raft domains in the bilayer. The disturbance at the bottom of the scan shows the point at which the M β CD was injected. Images B–D were captured sequentially by scanning over the same area of the sample. The directions of the scans and the times elapsed at the end of each scan are indicated. Scale bar: 1 μm .

to quantitate the cholesterol concentration or the rate of extraction during the AFM imaging.

The cholesterol-binding agent filipin was used to examine the lateral distribution of cholesterol in supported lipid bilayers. Filipin had no effect on supported lipid bilayers that lacked cholesterol (Fig. 5 *A*); however, in bilayers containing 10 mol% cholesterol a highly ordered and striated array could be seen, which was exclusively localized to the SM-rich areas (Fig. 5 *B*). The filipin-induced features protruded

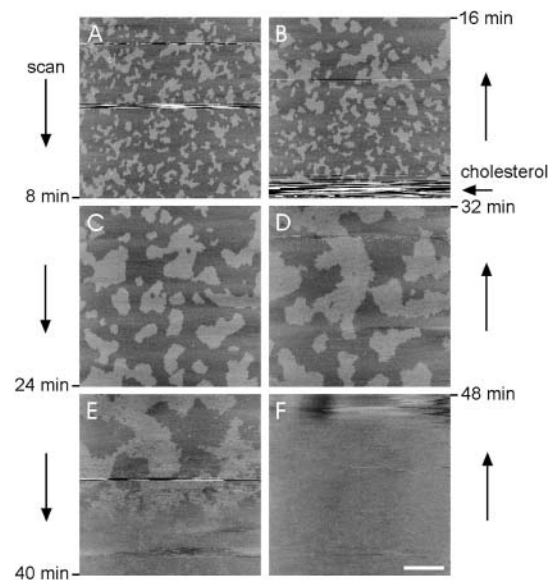


FIGURE 3 Effect of cholesterol addition on lipid rafts in supported lipid bilayers. (A) SM/DOPC (1:1 mol/mol) bilayer containing cholesterol (~ 10 mol%). (B) Water-soluble cholesterol (50 $\mu\text{g}/\text{ml}$) was added at the beginning of the scan and the system was allowed to equilibrate briefly before capturing sequential images (B–F). The directions of the scans and the times elapsed at the end of each scan are indicated. Scale bar: 1 μm .

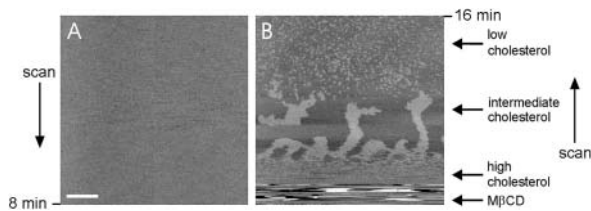


FIGURE 4 Effect of cholesterol depletion from a cholesterol-saturated supported bilayer. (A) Image of supported lipid bilayer after treatment with water-soluble cholesterol. (B) $M\beta CD$ (20 mM) was injected at the beginning of the scan. The disturbance indicates the point of injection. Initially, a high-cholesterol bilayer was present, exhibiting no lateral heterogeneity. After ~ 2 min, discrete rafts were observed, and then, after further cholesterol extraction, the rafts “melted” into the surrounding fluid bilayer. The directions of the scans and the times elapsed at the end of each scan are indicated. Scale bar: 500 nm.

0.6–0.8 nm above the lipid surface. High-resolution images of the striated filipin-induced array are shown in Fig. 5, C and D. A height profile taken perpendicular to the array (Fig. 5 E) highlights the well-defined bumps and grooves, which have a periodicity of ~ 4.3 nm. The extent of filipin binding to cholesterol-containing bilayers did not appear to be a function of time, at least for incubations of up to several hours. Some larger aggregates attached to the filipin-induced arrays were observed in some instances. We are uncertain of what these represent, but they may be aggregates of filipin similar to those reported previously (Santos et al., 1998).

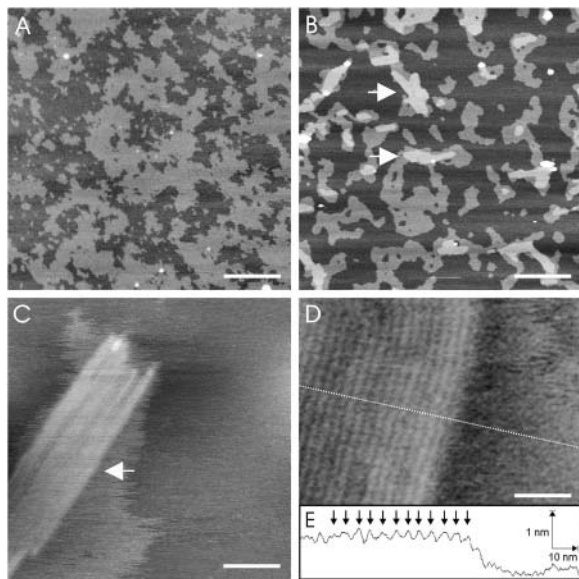


FIGURE 5 Filipin binding to lipid rafts. (A) SM/DOPC (1:1 mol/mol) supported lipid bilayer in the absence of cholesterol incubated with filipin complex (100 μM). (B) SM/DOPC (1:1 mol/mol) supported lipid bilayer containing 10 mol% cholesterol incubated with filipin complex. Filipin-induced features (arrows) are localized to raft areas, highlighting the preferential distribution of cholesterol with lipid raft domains. (C and D) Higher resolution images of the highly ordered array (arrow in C) located on the lipid raft domains. (E) Height profile along the dotted line in D of the filipin-induced array, highlighting the striated pattern, which has a periodicity of ~ 4.3 nm. Scale bars: 500 nm in A and B, 100 nm in C, and 30 nm in D.

DISCUSSION

Rafts enriched in SM and cholesterol are proposed to exist in the exoplasmic leaflet of the plasma membrane, where the majority of cell SM is located. A current view is that rafts represent liquid-ordered microdomains in the cell membrane and that depletion of cholesterol, which is required for the liquid-ordered phase, leads to dissolution of these microdomains into the liquid-disordered fluid membrane. However, several recent reports have questioned the role of cholesterol in rafts, because separate lipid domains have been observed in the absence of cholesterol (Ahmed et al., 1997; Hansen et al., 2001; Milhiet et al., 2002; Saslowky et al., 2002). In the present study, we set out to investigate the effects of manipulation of cholesterol levels on raft behavior, exploiting the ability of AFM to generate structural information under near-physiological conditions, and in real time.

As a first step, we demonstrated an increase in the area of SM-rich raftlike domains in monolayers containing increasing amounts of cholesterol, indicating that cholesterol colocalizes with SM, and that cholesterol addition may promote the recruitment of dissolved SM in the DOPC-rich phase into the SM-rich phase, as suggested previously (Rinia et al., 2001). Discrete lipid SM domains were not detected in monolayers containing 33 and 50 mol% cholesterol, suggesting that high cholesterol levels may suppress raft formation (Milhiet et al., 2002). We also investigated the effect of cholesterol extraction on the presence of lipid rafts. Cholesterol was extracted into the subphase of the Langmuir-Blodgett trough from a monolayer containing a high cholesterol concentration (50 mol% cholesterol/SM/DOPC) using $M\beta CD$ without disrupting the integrity of the lipid leaflet, at least while being held at constant pressure at the air-water interface. After transfer to a solid support, separated SM-rich domains were detected, providing evidence that rafts can be reformed from monolayers initially containing high cholesterol concentrations if the cholesterol concentration is reduced.

Separate domains were detected in supported lipid bilayers formed from mixtures containing SM/DOPC (1:1 mol/mol) in the absence and at varying concentrations of cholesterol, as reported previously (Milhiet et al., 2002; Rinia et al., 2001). The cholesterol content of preformed bilayers was manipulated using either water-soluble cholesterol or $M\beta CD$, and the effects of these agents were monitored in real time. Interestingly, separate SM-rich lipid domains could be detected in bilayers prepared from vesicles which did not contain cholesterol, and these domains were not affected by $M\beta CD$ treatment. In contrast, when a supported lipid bilayer containing a high cholesterol concentration was treated with $M\beta CD$, separate lipid domains were observed only at an intermediate cholesterol concentration, whereas at both high and low cholesterol concentrations the bilayer appeared homogeneous. The observation that SM-rich domains can be detected in SM/DOPC bilayers, whereas separate do-

mains disappear after cholesterol depletion from bilayers initially containing cholesterol, is intriguing. One possibility to account for this result is that the removal of cholesterol from a cholesterol-containing bilayer leaves holes in the bilayer, which creates a drop in lateral pressure, leading to dissolution of the lipid domains. Unfortunately, we have no way of measuring the surface pressure of supported bilayers. However, significant changes in surface pressure would only occur if the bilayers were tightly attached to the mica support, in such a way as to reduce the mobility of the lipids. In a previous study (Saslowsky et al., 2002), we have shown that bilayers are in fact separated from the support by a hydration layer, which should allow free lipid movement. This mobility of the lipids is amply demonstrated by the rapid dispersal of the liquid-ordered domains after cholesterol depletion (<8 min; see Fig. 4 *B*), which indicates that liquid-ordered and fluid lipids can rearrange in the bilayer fairly readily (Samsonov et al., 2001). Hence, it is likely that changes in lateral pressure in the bilayer will be minimal. An alternative possibility is that cholesterol removal causes a dissolution of the SM-enriched liquid-ordered domains into the surrounding fluid (DOPC-enriched) phase. Subsequent formation of gel-phase domains by SM, similar to those produced in the absence of cholesterol (see Fig. 5 *A*), is likely to be a slow process (Giocondi et al., 2001), and may not be detectable over the time course of our experiments.

After cholesterol addition to the bilayer we suggest that the homogeneous bilayer is likely to be in a single raftlike lipid phase, whereas at a low cholesterol concentration the bilayer will be in a liquid-disordered, fluid state. A similar conclusion was drawn from a previous study, in which the distribution of a fluorescent lipid probe in lipid monolayers at low, intermediate, and high cholesterol concentrations was examined (Dietrich et al., 2001b). At both low and high cholesterol concentrations the lipid probe exhibited a homogeneous distribution, although at high concentrations the diffusion rate of the probe was reduced, pointing to the existence of a liquid-ordered rather than a liquid-disordered phase. As reported here, separate lipid domains, indicated by the heterogeneous distribution of the lipid probe, were detected only at intermediate cholesterol concentrations.

The mechanism by which the separate lipid domains formed a single phase is unclear, but may involve a number of factors. Cholesterol is known to thicken phosphocholine (PC) bilayers by orientating the lipids in a more perpendicular fashion to the bilayer plane. In contrast, cholesterol does not affect the length of the SM molecules in the bilayer (Sprong et al., 2001). For example, the bilayer thickness for SM (C18:0) and SM (C24:0) is 46–47 Å and 52–56 Å respectively, in the presence or absence of cholesterol (Maulik and Shipley, 1995; 1996). However, bilayers containing egg PC have a thickness of 35 Å which is increased to 40 Å in the presence of cholesterol (Nezil and Bloom, 1992). Therefore, in the present study, cholesterol addition, using water-soluble cholesterol, would have resulted

in thickening of the DOPC-rich but not the SM-rich areas. In addition to the thickening of the DOPC-rich regions, the fact that the shape and size of SM-rich domains changes after cholesterol addition points to a reorganization of the lipids in the bilayer. This may occur through recruitment of SM from the fluid phase into the SM-rich domains, thereby increasing the size and causing smaller domains to coalesce with one another. The distribution of DOPC and SM in the single raftlike phase remains an interesting question.

The lipid raft hypothesis predicts that rafts are enriched in both SM and cholesterol, a notion which was originally based on the finding that detergent-resistant membrane fragments contained both of these constituents (Brown and London, 2000). Independent of the raft theory, there is a growing body of evidence that suggests SM and cholesterol interact selectively within the plasma membrane (Slotte, 1999). For example, a study using cyclodextrin to deplete cell membrane cholesterol showed that the rate of cholesterol depletion was greatly enhanced by initial SM degradation, but was not changed significantly after phosphocholine degradation (Ohvo et al., 1997). Similarly, cholesterol esterification activity was shown to increase after SM degradation, but was not changed by cell surface degradation of phosphocholine (Pörn and Slotte, 1990).

We used the cholesterol marker filipin to investigate cholesterol distribution between SM-rich and DOPC-rich regions in supported lipid bilayers. The colocalization of the filipin-induced features with SM-rich domains strongly suggests that the cholesterol is predominantly located within these areas of the bilayer. It is well established that the site of action of filipin is the cell membrane and that exposure to filipin causes membrane leakage (Bolard, 1986). However, the nature of the molecular interaction between filipin and biological membranes has remained an open question. In this study, filipin interaction with cholesterol-containing supported lipid bilayers revealed a highly-ordered, striated array located solely on SM-rich domains. How this array promotes membrane leakage is not clear. Two possibilities are that the interfacial region at the boundaries of the filipin-induced features could be a site of increased permeability, or alternatively filipin could cause bilayer deformation due to an increase in the lipid bilayer surface pressure (Severs and Robenek, 1983). Based on the amphiphilic nature of filipin, it is thought to be only partially inserted into the bilayer (Elias et al., 1979; Severs and Robenek, 1983). Hence, in the topographical AFM images, the striated array would consist of an aggregated filipin structure located at the water-bilayer interface. Surprisingly, the filipin-induced features shown here differ considerably from those seen in a previous AFM study which reported both circular protrusions and doughnut-shaped lesions in supported dipalmitoyl phosphatidylethanolamine/cholesterol bilayers (Santos et al., 1998). This discrepancy may be due to the different lipids used and consequent differences in the interactions between the lipids and cholesterol.

An interesting aspect of polyene compounds, including filipin, nystatin, and amphotericin B, is that they incorporate more extensively into lipids in the gel phase than in the fluid phase (Castanho and Prieto, 1992; Castanho et al., 1999). In the present study we observed filipin binding to liquid-ordered rafts in the presence of cholesterol. In the absence of cholesterol the SM-rich regions exist in a gel phase (Sankaram and Thompson, 1990); however, no filipin binding to these more-rigid bilayer regions was detected by AFM.

Several studies have reported that raft markers such as glycosylphosphatidylinositol-anchored proteins can be redistributed after cholesterol depletion from cells (Cerneus et al., 1993; Ilangumaran and Hoessli, 1998). Recently, preferential sorting of proteins into raftlike domains has also been detected in model membranes (Dietrich et al., 2001b; Saslowky et al., 2002), and we believe insights provided by the current model will be applicable to further studies investigating dynamic protein-raft interactions.

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