Phase Diagram and Tie-Line Determination for the Ternary Mixture DOPC/eSM/Cholesterol

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ABSTRACT We propose a novel, to our knowledge, method for the determination of tie lines in a phase diagram of ternary lipid mixtures. The method was applied to a system consisting of dioleoylphosphatidylcholine (DOPC), egg sphingomyelin (eSM), and cholesterol (Chol). The approach is based on electrofusion of single- or two-component homogeneous giant vesicles in the fluid phase and analyses of the domain areas of the fused vesicle. The electrofusion approach enables us to create three-component vesicles with precisely controlled composition, in contrast to conventional methods for giant vesicle formation. The tie lines determined in the two-liquid-phase coexistence region are found to be not parallel, suggesting that the dominant mechanism of lipid phase separation in this region changes with the membrane composition. We provide a phase diagram of the DOPC/eSM/Chol mixture and predict the location of the critical point. Finally, we evaluate the Gibbs free energy of transfer of individual lipid components from one phase to the other.

INTRODUCTION

In recent years, the prevailing view of cell membrane structure has gradually evolved from the fluid mosaic model proposed by Singer and Nicolson (1) to a heterogeneous membrane model that hypothesizes the existence of domains of lipids in the liquid-ordered (l_o) phase surrounded by lipids in the liquid-disordered (l_d) phase (2). The l_o domains (also called lipid rafts) are rich in cholesterol (Chol) and saturated lipids, and are thought to play an important role in regulation of cell processes (3,4).

To gain insight into the roles of individual membrane components, many groups have focused their efforts on establishing model membrane systems containing the lipid species of interest. Vesicles constitute a well-defined model system for studying basic biophysical properties and the behavior of more complex biological membranes. Giant unilamellar vesicles (GUVs) are a particularly practical biomimetic tool for displaying membrane behavior on the cell-size scale directly under the optical microscope (5,6).

In this work, we used GUVs composed of the three major lipid components of the outer leaflet of an animal cell plasma membrane: an unsaturated phospholipid represented by dioleoylphosphatidylcholine (DOPC), a saturated phospholipid represented by egg sphingomyelin (eSM), and Chol. The most obvious way to obtain multicomponent vesicles is to prepare them from lipid mixtures. However, with this method, the composition of the different vesicles in a batch can vary drastically depending on the individual vesicle history. For example, before observation, a phase-separated vesicle may have budded and the two daughter vesicles may have attained compositions that are different from the composition of the mother vesicle. Particularly strong deviations in the vesicle composition are observed for multicomponent lipid mixtures that are not fully miscible at the temperature of observation (7,8). To overcome this problem, we use an alternative means of arriving at a specific vesicle composition, i.e., we produce vesicles with domains via electrofusion of two vesicles made of two different fully miscible lipid mixtures, as proposed previously (9).

After electrofusion, the lipids in the newly created vesicle redistribute depending on the new membrane composition as described by the phase diagram. The latter specifies which phases are present as a function of composition, temperature, and pressure. Fig. 1 shows a tentative phase diagram for the ternary mixture of DOPC, SM, and Chol at room temperature as compiled from literature data (8,10–24) and our own measurements. The reported data were obtained from membranes containing different types of SM, such as eSM, brain SM, palmitoyl (16:0) SM, and stearoyl (18:0) SM; thus, compiling a phase diagram such as the one shown in Fig. 1 is not very accurate. However, the obtained phase boundaries (Fig. 1 *B*) can be used as a rough guide for the phase state of the membranes to be studied. The joint presentation of data for palmitoyl and eSM is partially justified by the well-defined chain-melting temperature of eSM, which is close to that of palmitoyl SM (25,26), and by the high content of palmitoyl chains in eSM. Data for stearoyl and brain SM were used to establish the phase boundaries in case data for eSM or palmitoyl SM were unavailable.

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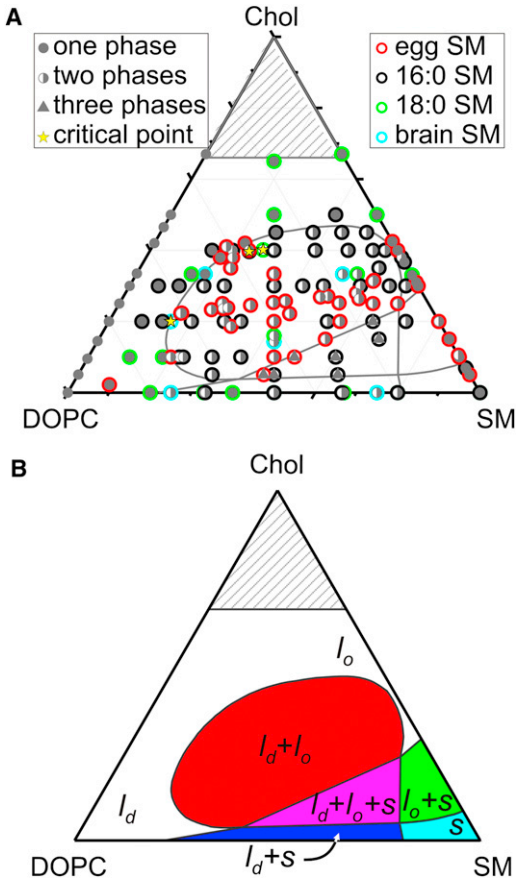

FIGURE 1 Phase diagram of the ternary mixture DOPC/SM/Chol at (23 ± 1)°C. (*A*) Data available in the literature (see text for references) and our own data were grouped according to the number of observed coexisting phases and SM type (see the two *insets*). Stars indicate reported critical points (see text for details). Tentative phase region boundaries deduced from the data are shown. A larger version of the graph is provided in the Supporting Material. (*B*) Rough estimate for the boundaries of one-, two-, and three-phase regions.

In Fig. 1 *A*, the data were grouped depending on the number of observed coexisting phases (one, two, or three) and on the SM type used (i.e., egg, brain, palmitoyl, or stearoyl SM). The stars indicate critical points reported in the literature (18,27,28). The solubility limit of Chol in phosphatidylcholine (PC) membranes was found to be 66–67 mol % (10). Above this concentration (*hatched region* in Fig. 1), Chol precipitates as monohydrate crystals and coexists with a lipid lamellar phase. At room temperature, eSM is in the gel or solid (s) phase, whereas DOPC is already in the fluid state at temperatures above −20°C. Below the solubility limit of Chol, mixtures of Chol and DOPC are fully miscible (14–16). At Chol fractions above ~30 mol %, the eSM/Chol membranes at room temperature are in the l_o state (29). At fractions between 8 mol % and 20–30 mol %, evidence for the coexistence of l_o/s in palmitoyl-SM/Chol membranes has been provided by differential scanning calorimetry (30,31) and fluorescence quenching studies (13). However, fluorescence microscopy observations of giant eSM/Chol vesicles demonstrated no phase coexistence region in this range (8), in similarity to results obtained with palmitoyl-SM/Chol mixtures (17). For the binary mixture eSM/Chol with a composition of 0/90/10 mol % (DOPC/eSM/Chol), giant vesicles appear to be in the solid phase (8). Note that further below, we will use the notation of DOPC/eSM/Chol in mol % for the membrane composition.

Knowing the boundaries of the regions in the phase diagram is not sufficient to characterize the composition of domains in a multicomponent vesicle. The domain composition is defined by the tie lines in the coexistence region. Locating the tie lines is challenging because the coexisting phases in the bilayer membrane cannot be physically isolated and then analyzed for chemical composition as is usually done, for example, with bulk solutions or alloys. So far, several methods have been applied to determine tie lines, including electron spin resonance spectroscopy (27,32,33), NMR spectroscopy (34–36), multiphoton fluorescence microscopy (37), fluorescence lifetime and anisotropy measurements (38), and low-angle x-ray scattering (39).

Here, we propose a new method for locating the tie lines in the liquid coexistence region of the phase diagram. It is based on microscopy quantification of the domain surface areas in giant vesicles produced by the fusion of two- or single-component vesicles. The method allows for direct observation of the membrane behavior under the microscope, and enables multiple tie lines to be located. In addition, one can evaluate the free energy of lipid transfer between the phases for each membrane component.

MATERIALS AND METHODS

Materials

The lipids used for vesicle preparation were 1,2-dioleoyl-*sn*-glycero-3-phosphocholine and eSM from Avanti Polar Lipids (Alabaster, AL), and Chol from Sigma (St. Louis, MO). All lipids were used without further purification, and stock solutions of lipids were stored in chloroform at –20°C until use.

The fluorescent probes 1,1′-dioctadecyl-3,3,3′,3′-tetramethylindocarbocyanine perchlorate ($DiIC_{18}$) and perylene were purchased from Molecular Probes (Leiden, The Netherlands) and Sigma-Aldrich (Steinheim, Germany), respectively. Dye stock solutions in chloroform were added to the lipid mixtures at concentrations of 0.1 mol % $DiIC_{18}$ or 0.4 mol % perylene. Perylene partitions preferentially in the l_o phase (11), whereas $DiIC_{18}$ favors the l_d phase (16).

Aqueous solutions of sucrose, glucose, sodium chloride (NaCl), and bovine serum albumin (BSA), all purchased from Sigma-Aldrich, were prepared with deionized water with a conductivity of 5.5 μS/m (Purelab Plus).

Vesicle preparation and observation

GUVs were prepared using the electroformation method described in Gracià et al. (40). In brief, a small volume (12–40 μl) of 4 mM lipid solution

in chloroform was spread on the surface of two preheated conductive glasses coated with indium tin oxide. The glasses were kept at 63–68°C in a vacuum drying oven (Heraeus Vacutherm VT 6025; Thermo Electron, Langenselbold, Germany) for at least 1 h to remove all traces of the organic solvent. The vesicles were grown at the same temperature to ensure that the lipids would be in the fluid phase and fully miscible. The two glasses were separated by a 2-mm-thick Teflon frame and assembled to form a chamber sealed with silicon grease. The chamber was filled with a sucrose solution (100 or 200 mOsm/kg). The solution osmolarities were measured with a cryoscopic osmometer (Osmomat 030; Gonotec, Germany). The conductive sides of the glasses were connected to an AC field function generator (Agilent 33220A; Agilent Technologies; Deutschland GmbH, Böblingen, Germany) and an alternating current of 1.1 V (peak-to-peak amplitude) at 10 Hz was applied for 1 h and then changed to 1.5 V at 5 Hz for another 2–5 h. In some cases, the frequency was changed to 1 Hz at the end to detach the vesicles from the glass.

For electrofusion experiments, the vesicle sucrose suspension was diluted with a mixture of 0.1 mM NaCl and glucose solution of slightly higher osmolarity than the osmolarity of the sucrose solution. This step slightly deflated the vesicles and created a sugar asymmetry between the interior and exterior of the vesicles. Due to the differences in density and refractive index between the sucrose and glucose solutions, the vesicles were stabilized by gravity at the bottom of the experimental chamber and had better contrast when observed with phase contrast microscopy.

Fluorescence microscopy snapshots were acquired with a confocal laser scanning microscope (Leica DM IRE2 or DMI 6000) using 20× Ph2 or 40× Ph2 objectives and laser excitation at 476 nm (argon laser) and at 561 nm (diode-pumped solid-state laser). Emission light was detected by a photomultiplier tube in spectral ranges of 480–533 nm (for perylene) and 564–654 nm (for $DiIC_{18}$). Electrofusion events were recorded nearly at the equatorial plane of the fusing vesicles as a time series, at approximately one image per 1.6 s (Leica DM IRE2) or one image per 0.14 s (Leica DMI 6000). For the domain formation and dynamics analysis, three-dimensional (3D) z-series of the vesicle with 0.33 μm increments were taken. To reduce possible artifacts that could arise from light-induced domain formation (41,42), illumination with low intensity was used and only a few 3D scans per vesicle were allowed. Under these conditions, no change in the size of the domains in equilibrated vesicles was observed. However, we cannot completely exclude possible effects associated with changes in the phase boundaries caused by the fluorescent dyes.

Micropipette aspiration

Micropipettes (inner diameter 5–30 μm) were prepared from glass capillaries (World Precision Instruments USA, Sarasota, FL) with the use of a micropipette puller (Sutter Instruments USA, Novato, CA) and their tips were shaped with a microforge (Narishige, Tokyo, Japan). Before use, each micropipette was coated with 1 mg/ml BSA solution to prevent vesicle adhesion to the glass. To apply suction pressure, the micropipettes were connected to water reservoirs mounted on two independent linear translational stages (M-531.DD; PI, Karlsruhe, Germany). Manipulation within the sample was achieved with the use of micromanipulators (MHW-103 and MLW-3; Narishige) secured to coarse manipulators (MMN-1; Narishige).

Vesicle electrofusion

For the electrofusion experiments, we used two vesicle populations: DOPC/Chol and eSM/Chol with a Chol concentration of 0–30 mol %. We mainly employed vesicles made of DOPC and Chol with compositions of 90/0/10 or 80/0/20 mol %, and vesicles made of eSM and Chol with a composition of 0/70/30 mol %. The DOPC/Chol membranes were stained with $DiIC_{18}$ (red false color in the confocal images), and the eSM/Chol membranes were labeled with perylene (green). We put ~50–100 μl of the DOPC/Chol and eSM/Chol vesicle suspensions into the observation chamber (see Fig. S2 of the Supporting Material) and diluted them ~10–20 times with glucose solution. The sample was left to equilibrate for 15–30 min. We then selected a pair of vesicles, one from each of the two populations, and applied an electric pulse to induce electrofusion after the vesicles had been brought together either by application of an alternating current or by means of micropipette aspiration. The field strength of the pulses was set to 110–300 V for 300 μs pulses or 200–300 V for 150 μs pulses. More details on the experimental procedure will be given elsewhere; a similar approach was already used for fusing two giant vesicles with the same membrane composition but different enclosed solutions to achieve nanoparticle synthesis in vesicles as closed containers (43). The electrofusion events were recorded by confocal microscopy.

The three-component vesicles thus obtained were observed after electrofusion, and 3D images of them were recorded. Two observation chambers were used. One was purchased from Eppendorf (Hamburg, Germany) and modified as described in the Supporting Material (see also Fig. S2, *A* and *B*). The other was made in house and used for electrofusion assisted with micropipettes (Fig. S2 *C*). The chambers were connected to a Multiporator (Eppendorf, Hamburg, Germany) that generated square-wave direct current (DC) pulses. The pulse strength and duration were set in the ranges of 5–300 V and 5–300 μs, respectively.

Image analysis

Leica Confocal Software, ImageJ, and in-house-written software were used for image analysis. The confocal series acquired after vesicle electrofusion were used to measure the surface areas of domains using an in-house-written plugin for ImageJ. An algorithm that is able to find the contour of the vesicle in the different slices using signal from both channels was developed (see Fig. 2 *A*). The shape of the vesicle was reconstructed from the contours from all slices, as shown in Fig. 2, *B* and *C*. Due to blur in images far from the equator, the upper part of the vesicle was fitted with a paraboloid; the lowest part was left flat because it corresponded to the coverslip. Occasionally, the original images were slightly skewed because of vesicle displacement in the chamber during recording of a 3D sections stack. The program corrected this by aligning the centers of the contours. Effects of possible aberrations were corrected as described in the Supporting Material.

The next step was to define the boundaries of the domains based on dye partitioning. Green color was assigned to the l_o phase labeled with perylene. Red color was assigned to the l_d phase labeled with $DiIC_{18}$. Perylene exhibited stronger photobleaching than $DiIC_{18}$. Because the green intensity was observed to decrease over the recording time, we used only the red channel to allocate the boundaries of the domains.

To determine the errors introduced by user handling during vesicle contour definition, two different investigators analyzed some of the images.

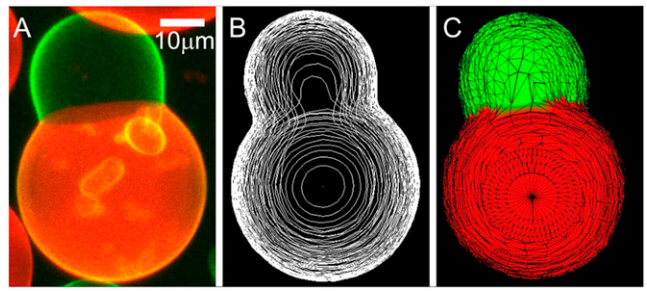

FIGURE 2 Reconstructing the 3D vesicle shape and domains from confocal images. (*A*) Maximum projection image of confocal 3D series (*top view*). The green color corresponds to the l_o phase and red indicates the l_d phase. (*B*) A set of contours from all slices. (*C*) A 3D model of the digitized vesicle surface.

Trends in domain surface fraction versus time were found to be independent of the investigator. The relative standard deviation (SD) of the domain area fractions was up to 2%. Error propagation calculations for the SD of the vesicle composition because of manual processing implied an estimate of maximum 2.0 mol % for each component.

The composition of the vesicle created by electrofusion was calculated from the measured domain areas (for details see the Supporting Material). Our estimates are based on the assumption that right after fusion, the compositions of the initial domains are still identical to the corresponding compositions of the two vesicles before fusion. We measure the initial area of these domains and, knowing the molecular surface area of each lipid in the different phases, calculate the respective number of molecules in the fused vesicle and consequently its composition. For the areas per lipid, we used available data interpolated to our conditions (51 $Å^2$ for SM (44), 27 $Å^2$ for Chol (44,45), and 70 or 66 $Å^2$ for DOPC in mixtures with 10 or 20 mol % of Chol (46,47), respectively). The composition error associated with the uncertainty in the values for the area per lipid was estimated to be maximum 0.6 mol % for an individual lipid (see Supporting Material for details).

Taking into account the errors from manual image processing and area per lipid uncertainty, the maximal SD in the vesicle composition was estimated to be 2.1 mol %.

RESULTS AND DISCUSSION

Compositional inhomogeneity of vesicles prepared from ternary lipid mixtures

The most commonly used method to obtain multicomponent vesicles is to prepare them directly from premixed lipid solutions. However, when prepared in this way, giant vesicles from the same batch can exhibit significant compositional differences, especially if their composition belongs to a region of phase coexistence (7,8,48,49). First, small compositional deviations between the vesicles could arise during the formation process (18). The growing vesicles are typically connected to the substrate via lipid tubes (43) with high membrane curvature, which may promote lipid sorting. Second, the membrane composition depends on the individual vesicle history, which is not known. Before a vesicle is observed under the microscope, budding of some part of the membrane might occur, which would change the overall composition of the vesicle. Generally, vesicles are formed at temperatures at which all components are fully miscible. Phase separation achieved by subsequent temperature quenching below the phase transition temperature of one of the components gives rise to a line tension of the domain boundary between the two phases, which can lead to budding (50). If the explored membrane composition is located close to the boundary of the region of coexisting phases, even small compositional deviations in the vesicle batch will affect the lipid miscibility. When observed by fluorescence microscopy, vesicles both with and without domains can be detected in the same batch (7) (see also Fig. 3 *A* and Fig. S3). For membrane compositions located deeper in the two-phase coexistence region, the deviations in the vesicle composition in a batch can be well demonstrated by the distribution of the area fraction of one of the domain types. If all vesicles had the same composition,

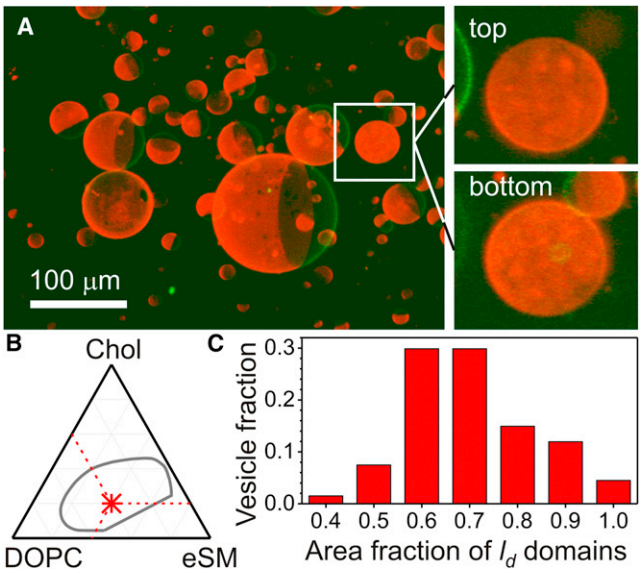

FIGURE 3 Compositional inhomogeneity of vesicles prepared from DOPC/eSM/Chol 40/40/20 observed at 23°C. (*A*) 3D projections reconstructed from confocal series. Vesicles with this composition exhibit phase separation, as observed for all vesicles on the image except for the framed one. This vesicle has no domains (see zoomed projections of the top and bottom vesicle hemispheres). (*B*) Membrane composition in the Gibbs triangle. The gray curve shows the boundary of the l_o-l_d coexistence region. (*C*) Distribution of the area fraction of red (l_d) domains over a population of ~70 vesicles from the same batch.

they should exhibit the same domain surface area fractions. However, the observed distribution of area fractions is often quite broad, as we show for vesicles made of DOPC/eSM/Chol 40/40/20. Inspection of Fig. 3 *C* shows that only 60% of the vesicles have nearly the same domain surface area ratio, i.e., nearly the same lipid composition. The obvious conclusion is that the composition of an observed vesicle made from the ternary lipid mixture can differ significantly from the composition of the starting lipid mixture used for the vesicle preparation.

Electrofusion of single- or two-component vesicles as a method to create three-component vesicles with well-defined compositions

To deal with the problem outlined in the previous section and to produce three-component vesicles with specific and precisely controlled composition, we established a new, to our knowledge, method as proposed earlier (9). Ideally, the scenario would be to fuse three single-component vesicles with certain areas. However, Chol by itself does not form a bilayer in an aqueous environment. Thus, we use a couple of vesicles, at least one of which contains Chol. The necessary condition to exclude deviations in the membrane composition during the formation of these vesicles is that the lipids in the starting mixtures are fully miscible at the working temperature (in this case, room

temperature). This approach lowers the complexity of the systems. Here, we used vesicles made of pure DOPC, DOPC/Chol (90/0/10 and 80/0/20), and eSM/Chol (0/80/20 and 0/70/30). The mixtures belong to regions in the phase diagram where no macroscopic phase separation is observed with fluorescence microscopy. Thus, by starting with single- or two-component homogeneous vesicles made of different lipids of known composition and forcing them to fuse with each other (e.g., via electrofusion), one can obtain three-component vesicles with precisely controlled composition. Of course, the size of the fusing vesicles affects the final vesicle composition.

The success of vesicle electrofusion depends on the membrane properties. It is generally assumed that fusion is initiated by localized membrane breakdown or electroporation (51). Therefore, to realize fusion, the vesicles have to porate at nearly the same parameters of the external field, i.e., they must have comparable values of the critical poration potential. The electroporation conditions for DOPC and SM membranes doped with Chol were found to be specific for the type of lipid and Chol content, as will be described elsewhere (see also Portet and Dimova (52)).

For successful electrofusion of two vesicles, the vesicles have to be correctly positioned, i.e., aligned in the field direction and in close contact at their poles facing the electrodes, because the probability of poration is highest at the poles. In the case of electrofusion of vesicles stabilized by gravity at the chamber bottom, it is only possible to fuse two vesicles of comparable size (within a difference of a few micrometers). We bring the vesicles together and align them by applying weak AC fields (an effect similar to that observed with cells that align in the field direction in pearl chains). An example of producing a two-domain vesicle by electrofusion is given in Fig. 4, *A–C*. Two single-phase vesicles are subjected to an electric pulse and fused. The resulting vesicle composition can be located precisely in the Gibbs triangle (Fig. 4 *D*).

When there are large differences in the sizes of the vesicles, or when two particular vesicles have been selected for fusion, the above protocol becomes ineffective. In this case, one can manipulate the vesicles, for example, by using micropipettes to bring them together and align them in the field direction. One can also apply this protocol to vesicles of arbitrary compositions by adjusting the membrane tension to match the vesicle poration thresholds. One example of electrofusion assisted by micropipettes is given in Fig. 4, *E–H*. In this example, the newly formed vesicle has a composition belonging to the single-phase (l_d) region in the phase diagram. The green domain quickly dissolves within ~5 min after fusion (see Fig. 4 *H*).

The examples given above demonstrate that by using the electrofusion method, one can create vesicles with compositions located anywhere in the phase diagram. This approach allows one to observe domain formation and dynamics, as well as to calculate the precise vesicle composition from the domain areas independently of the vesicle history.

Tie-line determination

As mentioned in the Introduction, several methods for tie-line determination have been previously reported. However, all of these methods have some shortcomings. Some of them involve the use of deuterated samples, which affects the hydrogen bonding in the system (53). Others are based on the use of bilayer stacks or multilamellar vesicles, and thus the bilayer hydration, interbilayer interactions, and/or interactions with the substrate can influence the results. Still others use small unilamellar vesicles, in which case membrane curvature might affect the thermodynamic behavior of the membranes. In addition, with nonimaging

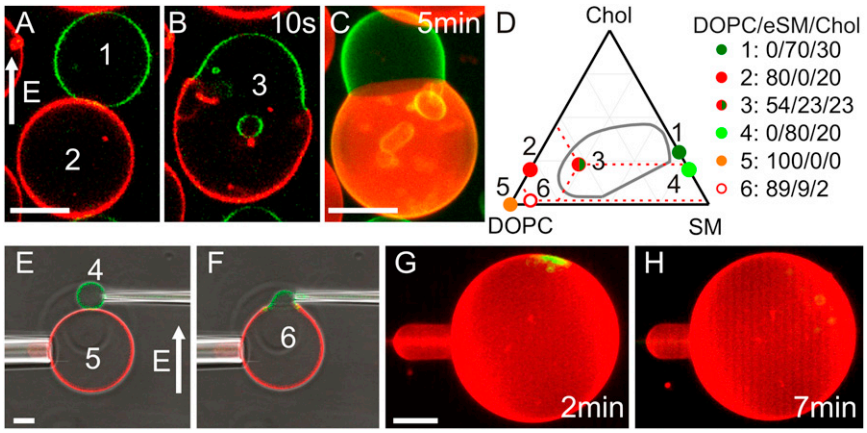

FIGURE 4 Electrofusion of single- or two-component vesicles provides a novel (to our knowledge) protocol to create three-component vesicles with precisely controlled composition. (*A–C*) Fusion of two freely suspended vesicles observed with confocal microscopy: cross sections (*A* and *B*) and a 3D projection (*C*). Vesicle 1 in panel *A* is composed of eSM/Chol (0/70/30). Vesicle 2 is made of DOPC/Chol (80/0/20). The two vesicles were subjected to an electric pulse (400 kV/m, 150 μs; arrow indicates the field direction) and fused to form vesicle 3 shown in *B* and *C*. The duration of time after application of the electric pulse is indicated in the upper-right corners. (*D*) Compositions of the vesicles in the images. The numbered compositions in the Gibbs triangle correspond to the numbered vesicles in *A*, *B*, *E*, and *F*. (*E–H*) Electrofusion of two vesicles brought into contact via micropipettes, as observed with an overlay of phase contrast images and confocal cross sections (*E* and *F*) or 3D projections (*G* and *H*). The initial vesicles differ significantly in size. Vesicle 4 is made of eSM/Chol (0/80/20) and has a radius of 17 μm. Vesicle 5 is composed of DOPC and has a radius of 52 μm. After application of an electric pulse (250 kV/m, 100 μs) the vesicles fuse to form vesicle 6, which is located in the single-phase region (*D*). The lipids mix quickly after the fusion, as shown in image *H*, which was taken 7 min after the pulse. All scale bars correspond to 20 μm.

methods, one cannot directly observe the sample to check that the vesicles have attained the same phase or exhibit similar area fractions for the different membrane domains. The only microscopy-based method that does not have these disadvantages is apparently so demanding that only a single tie line in the two-fluid-phase coexistence region can be located (37). Furthermore, the measurements are performed on giant vesicles prepared from ternary mixtures. As noted above, the composition of such vesicles is likely to vary over a wide range.

We propose a new, to our knowledge, method for tie-line determination in the l_o-l_d coexistence region of the phase diagram of ternary lipid mixtures. Three-component vesicles in this region were obtained via electrofusion of single- and/or two-component vesicles as explained above. Domain surface areas obtained from the 3D confocal scans recorded right after electrofusion were used to calculate the composition of the fused vesicle as described in "Image analysis" above and in the Supporting Material. The method for tie-line determination is based on quantifying the domain areas in the obtained three-component vesicle after equilibration. The mean equilibration time, beyond which the domain areas remain constant, was found to depend on the vesicle composition and was of the order of 30–120 min, being longer for vesicles with larger fraction of the l_o phase.

Briefly, the tie-line searching procedure involves the following steps: From the confocal image recorded right after fusion, we measure the domain surface areas and calculate the precise composition of the vesicle (see above). Then, we draw a hypothetical tie line through this composition point in the phase diagram. The intersection of this tie line with the phase boundary yields the hypothetical compositions of the two fluid phases. Taking the respective areas per molecule of the lipids in the phases, we calculate the hypothetical areas of the domains in the vesicle. If these areas correspond to the experimentally measured ones (taking into account the experimental accuracy), the hypothetical tie line can be considered a trial tie line (see the Supporting Material for a detailed protocol and a mathematical description of the searching procedure). In this way, several trial tie lines can be drawn through the composition point of the measured vesicle. The choice of valid tie lines can be then made under the conditions that 1), tie lines through different points do not cross each other inside the coexistence region; and 2), the boundary between the l_o-l_d two-phase and the s-l_o-l_d three-phase coexistence regions represents a tie line (called the end tie line).

Images of 13 fused vesicles exhibiting coexisting liquid phases were used to determine tie lines in the region of l_o-l_d coexistence. However, four out of 13 experimental points produced no valid trial tie lines. Thus, we questioned the reliability of the binodals for the l_o-l_d two-phase coexistence region as deduced from the literature data (see Fig. 1). The data in this region of the phase diagram were obtained predominantly from fluorescence microscopy experiments on giant vesicles. The uncertainty in the lipid composition of vesicles made from ternary lipid mixtures was estimated to be 2 mol % for each lipid species (18), suggesting similar uncertainty in the position of the coexistence curve in Fig. 1. Furthermore, most of the literature data are for 16:0 SM, whereas we used eSM. The vesicle preparation procedure could also affect the collected data (48).

To accommodate these uncertainties, we allowed for some adjustments of the binodals for the liquid-liquid coexistence region. By displacing the binodals in 0.5 mol % steps, we found that the first sets of valid trial tie lines for all 13 experimental points had a variation of 2 mol % from the binodal bounding the l_d region and 4.5 mol % from the one bounding the l_o region. Deviations >2 mol % from the l_d side were not considered, because this would leave some of the studied vesicle compositions outside the coexistence region. From the obtained nonintersecting trial tie lines, we selected a set that minimized the difference between the calculated and measured domain area fractions for the liquid-ordered or -disordered phases (see Fig. 5 and Supporting Material). We consider this set to be our best approximation of the tie-lines field. The exact coordinates of the tie lines determined in this way are given in Table S2.

Using the newly found tie-line end points, we revised the binodal facing the l_o-phase region as shown by the solid curve in Fig. 5. The shift of this binodal is understandable, considering that the majority of the experimental points used to define this binodal (as we initially did in Fig. 1)

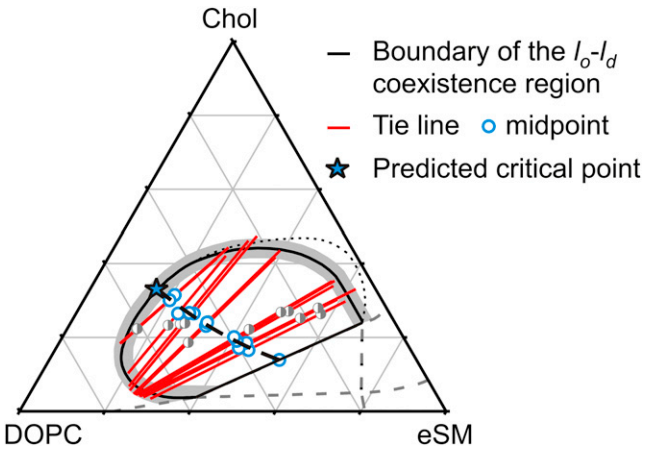

FIGURE 5 Phase diagram of the DOPC/eSM/Chol mixture at 23°C. Half-solid circles in gray indicate the compositions of the fused vesicles (see also Fig. S5 C) whose images were used to locate tie lines (*red*) within the l_o-l_d coexistence region. The latter region is indicated by the solid black curve shown with ±2 mol % deviation in gray (the *dotted black line* represents the initial binodal as defined in Fig. 1). The gray dashed lines show tentative boundaries for the rest of the phase coexistence regions. The blue open circles indicate the midpoints of the found tie lines, and the dashed black curve serves as a guide to the eye to connect them. It is extrapolated to the boundary of the l_o-l_d coexistence region to predict the location of the critical point as indicated by the star. At this critical point, the composition of the mixture is 52/15/33.

were obtained on 16:0 SM. Compared with 16:0 SM, eSM contains lipids with longer saturated chains that melt at higher temperature (the exact composition of eSM is 84% of 16:0 SM, 6% of 18:0 SM, 2% of 20:0 SM, 4% of 22:0 SM, and 4% of 24:0 SM eSM). Thus, it is to be expected that the presence of longer saturated chains will lead to an expansion of the l_o single-phase region at the expense of the l_o-l_d coexistence region. An analogous expansion can be observed when one compares the phase diagrams of DOPC/di16:0 PC/Chol (18) and DOPC/di18:0 PC/Chol (54).

From the binodals of the l_o-l_d coexistence region, and by applying the lever rule, we can also predict the approximate location of the critical point by extrapolating a curve passing through the midpoints of the found tie lines (see Fig. 5). The critical point deduced in this manner is located between those reported for the ternary mixtures with palmitoyl SM (18) and brain SM (27). It is closer to the former, which is to be expected given the compositional similarity of the lipids.

A compositional analysis of the l_o and l_d phases on the basis of our tie-line data (Table S2) reveals that in general, the l_o phase is mainly enriched in the saturated eSM and Chol, and the l_d phase is highly enriched in unsaturated DOPC (64–71 mol %) and further contains eSM and Chol but in much smaller amounts compared with the respective fractions in the l_o phase. The Chol content averages ~30–47 mol % in the l_o phase and 3–18 mol % in the l_d phase. On a qualitative level, our results agree well with published data suggesting that the l_o phase is strongly enriched in saturated lipids and moderately enriched in Chol, and the l_d phase is strongly enriched in unsaturated lipids (27,34,35).

Let us now consider the inclination of the tie lines as defined by their angle with respect to the compositional lines of constant Chol content. The end tie line toward the three-phase coexistence region has an angle of 24° (Table S2). The tie lines closest to the end tie line are approximately parallel to it. The angle of the subsequent tie lines increases up to 50° but then decreases to 41.5° for the two tie lines closest to the critical point. A similar nonmonotonous change in the inclination of the tie lines was previously reported for a DOPC/brain SM/Chol system (27). Such a behavior of the tie-line inclination does not seem to violate any thermodynamic rule for ternary mixtures, but it may also be related to the fact that many SM molecules with different chain composition are present in eSM and brain SM.

The inclinations of the tie lines are related to the difference in lipid mole fractions between each phase, which reflects the favorable or unfavorable interactions between the lipids. Relatively small tie-line inclinations imply a small difference in the Chol concentration and a large difference in the fractions of eSM and DOPC in the l_o and l_d phases. This might suggest that phase separation is driven by the interaction and alignment of eSM chains, leading to the exclusion of other lipids from the SM surroundings. Inclination angles close to 60° imply that the eSM concentration is similar in the two phases, whereas the mole fractions of DOPC and Chol differ significantly, which may indicate a steric incompatibility of DOPC and Chol. Our results suggest that the dominant mechanism of lipid phase separation in the coexisting l_o-l_d region depends on the particular membrane composition. When the DOPC amount averages half of the lipid content, the tie lines have a large inclination angle (up to 51°), implying that phase separation may be driven mainly by the steric incompatibility of DOPC and Chol. The decreasing slope of the tie lines closer to the end tie line at the three-phase coexistence region and those close to the critical point region suggests that in this case, phase separation may be driven mainly by the mutual attraction of eSM chains and the alignment of these chains.

Thermodynamics of lipid transfer

Our approach for creating multicomponent vesicles with known composition has a further advantage in that it enables us to characterize the thermodynamics of lipid mixing. After fusion, the vesicle composition is changed, followed by lipid redistribution via long-range diffusion. The driving force for this diffusion is the gradient in the chemical potentials of the lipids. At equilibrium, the chemical potential of each component has to be the same in every phase.

We refer to the initial domain that is enriched in DOPC immediately after fusion as the pre-l_d phase, and the domain that is initially enriched in eSM as the pre-l_o phase. From the initial domain compositions and the final equilibrated ones as specified by the tie lines, we conclude that DOPC diffuses from the pre-l_d domain to the pre-l_o domain, completing the formation of the l_o phase. eSM molecules diffuse in the opposite direction, contributing to the l_d phase formation. Quantitatively, the lipid transfer can be characterized in the following way. Based on the determined tie lines, we can evaluate the free energy of transfer between the phases for each lipid as (55,56):

$$\Delta G = -k_B T \ln K$$

Here, $k_B T$ is the thermal energy and K is the molar partition coefficient calculated as

$$K = \frac{\left([L]_{lo}/V^L_{lo}\right)}{\left([L]_{ld}/V^L_{ld}\right)}$$

where $[L]_{lo}$ and $[L]_{ld}$ are the mole fractions of lipid L in the l_o or l_d phases, respectively, and V^L_{lo} and V^L_{ld} are the volumes of the corresponding lipid phases. We define V^L_{lo} and V^L_{ld} as the sums of the products of the number of molecules and molecular volume of the corresponding lipid over all lipids located in the corresponding phase. The molecular volumes were taken as $V^{Chol}_{lo} \equiv V^{Chol}_{ld} = 630$ Å^3 for Chol, $V^{DOPC}_{lo} \equiv V^{DOPC}_{ld} = 1289$ Å^3 for DOPC, and $V^{eSM}_{lo} = 1165$ Å^3 and

$V_{ld}^{eSM} = 1176$ Å^3 for eSM depending on the Chol content (above or below 0.2 mol of Chol, respectively, corresponding to the l_o or l_d phase, respectively) (57). The values obtained for ΔG^{DOPC}, ΔG^{eSM}, and ΔG^{Chol} are of the order of 2 k_BT (see Table S2). The values of ΔG are negative for eSM and Chol but positive for DOPC. This means that partitioning from l_d into l_o is energetically favorable for eSM and Chol but energetically unfavorable for DOPC. The free energy of transfer ΔG is a measure of the relative affinity a particular lipid has to the l_o or l_d phase. The free-energy difference associated with thermodynamic fluctuations in an equilibrium system is typically of the order of the thermal energy, k_BT. The magnitudes of the free energies of transfer for DOPC and eSM are close to the magnitude of the thermal energy, suggesting that these molecules move between phases without a significant energy cost. On the other hand, the values of the free energy for Chol reveal a weak preference of Chol for the l_o phase. This implies that phase separation may have an impact on the sorting of Chol in cells.

CONCLUSIONS

We have shown that electrofusion of vesicles with different compositions provides a useful method for creating multicomponent vesicles with precisely controlled composition. The conventional method for vesicle electroformation produces vesicles with compositions that can vary over a wide range, as judged from the distribution in the area fraction of the domains. This variation is illustrated for vesicles made of DOPC/eSM/Chol 40/40/20 in Fig. 3. For this mixture, the average value and SD for the area fraction of red (l_d) domains is given by 0.71 ± 0.13. In contrast, the novel, to our knowledge, method developed here leads to an average value and SD for the area fraction of 0.62 ± 0.02 for the same ternary composition. Thus, the SD is reduced by more than a factor of 6. The remaining SD of ± 0.02 reflects the uncertainties in the estimates for the binodals and tie-line inclinations.

Using this electrofusion method, one can create vesicles with not only a precisely controlled composition but also a composition located anywhere in the phase diagram. Consecutive electrofusion events even allow one to create multidomain vesicles, as shown in Fig. S6.

By fusing two vesicles with different compositions and observing the lipid redistribution between the phases, we were able to establish a new (to our knowledge) method for tie-line determination. Our method is based on 1), knowing the precise composition of the vesicles before fusion; 2), measuring the surface areas of the different domains after fusion; and 3), matching tie lines and binodals by an iterative procedure. The approach is direct, facile, and not very experimentally demanding from an experimental viewpoint. It consists of quantifying the domain areas in vesicles recorded with confocal microscopy. We determined a set of tie lines in the l_o-l_d coexistence region of DOPC/eSM/Chol ternary membranes and predicted the tentative location for the critical point.

SUPPORTING MATERIAL

Supporting analysis, two tables, six figures, and references (58–60) are available at http://www.biophysj.org/biophysj/supplemental/S0006-3495(13)00241-5.

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