Polymersomes

Single-Vesicle Patterning of Uniform, Giant Polymersomes into Microarrays

*Neha P. Kamat, Steven J. Henry, Daeyeon Lee, and Daniel A. Hammer**

Studies with artificial cells, or protocells, in which synthetic particles are designed to replicate cellular processes, are moving beyond single particles to the engineering of coordinated action among multiple particles.[1] Cells often display multicellular communication and coordinate their activities, such as in quorum sensing[2] and paracrine signaling.[3] Vesicles are an ideal particle to serve as a structural model for a protocell. The design and construction of multi-vesicle systems to induce interparticle communication, however, is challenging. Minimally, such a system requires spatial control of vesicle positioning, the encapsulation of the signaling agents, and functionalization of the responding vesicle for signal detection. Patterning vesicles with spatial precision on a substrate would enable the design and development of structurally well-defined communication systems, and have utility in other technological applications, such as building biosensor arrays. Here, we demonstrate for the first time the patterning of individual, monodisperse, and functionalized giant polymersomes. Using microfluidics, we prepare functionalized vesicles of controlled size with high encapsulation efficiency and use microcontact printing to immobilize polymersomes in controlled spatial arrangements. Finally, we demonstrate the sensory capability of the resulting array.

Vesicles, comprised of bilayer membranes surrounding an aqueous lumen, are architecturally similar to cells, and provide the spatial compartmentalization that enable cells to perform a variety of metabolic and sensory functions. Patterning vesicles has facilitated diverse applications ranging from bioenergetic reactions[4] to diagnostic assays based on specific chemical recognition.[5] Arrays of both lipid[6] and polymer vesicles[4b,7] have been built. Vesicles with thick membrane cores are particularly useful because they are able to incorporate hydrophobic solutes in the core of the membrane as well as aqueous solutes in the vesicle lumen. Polymersomes, bilayer vesicles made from di-block copolymers, not only have hyperthick membrane cores, but possess additional advantages over lipid vesicles, including increased membrane strength and the flexibility to design a wide range of physical and chemical properties into the polymer through chemical synthesis.[8]

Beyond technological and medical applications, immobilized bilayer vesicles can also be used to construct systems that reproduce specific functions of cells, like triggered gene expression or chemical reaction cascades.[4a,9] Cellular mimicry with synthetic vesicles is quickly advancing to replicate more complex cellular behaviors, such as particle-to-particle (vesicle-to-vesicle) communication.[8] For example, theoretical work by Balazs and co-workers[1a,10] has proposed that inanimate, cell sized capsules can be engineered to communicate and induce movement of one another through the exchange of soluble cues that dynamically modulate the underlying adhesive environment. A key technological advance needed to test these principles is the assembly of arrays of vesicles with precise spatial organization.

To date, the majority of studies conducted with immobilized vesicles has been limited to small vesicles (with diameters ≤400 nm). Large, micron-sized vesicles, however, are closer to the dimensions of biological cells and are therefore appropriately sized for the study of vesicle-cell communication at a biologically-relevant length scale. Yet, patterning large vesicles has proven difficult. When larger, single, micron-scale vesicles have been immobilized, the vesicle size has generally not exceeded several microns.[6b] Arrays that are assembled with polydisperse vesicles limit the precision of the intended pattern. Classical vesicle preparation methods, like thin-film hydration, have made it difficult to prepare monodisperse giant vesicles with high encapsulation efficiencies, and have consequently limited our ability to pattern uniform arrays of large vesicles. The advent of vesicle production methods using microfluidic techniques now enables the generation of single, giant, monodisperse polymersomes.[11] These vesicles, formed through solvent evaporation from double emulsion templates, have near perfect encapsulation efficiencies and highly uniform diameters.[12]

We prepared polymersomes from microfluidic-generated, water-in-oil-in-water (W/O/W) double emulsions that contain the amphiphilic diblock copolymer PEO_{30}-*b*-PBD_{46} (MW 1300 and 2500, respectively). We previously verified the unilamellar structure of these vesicles and elimination of organic solvent from their membranes.[13] A sucrose solution, toluene and chloroform mixture, and phosphate buffered saline (PBS) made up the inner, middle, and outer phases, respectively, of the double emulsions. Though we have previously shown that polymersomes can be formed without the use of stabilizers, in order to increase yield in this study, the outer phase contained either 1 wt% bovine

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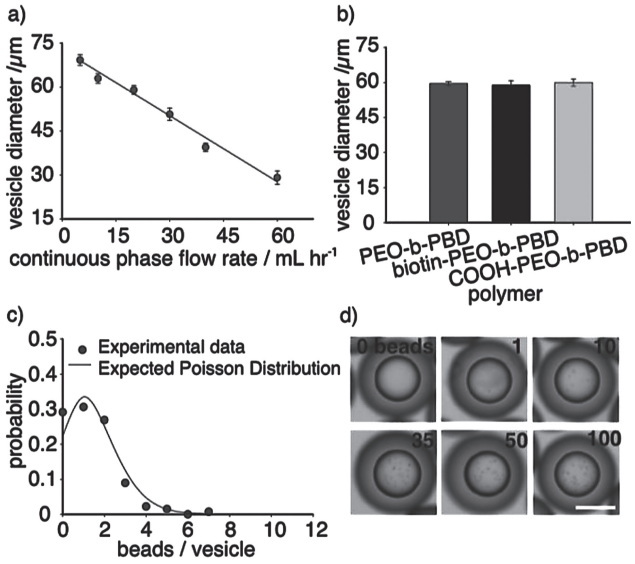

Figure 1. Controlling vesicle size and loading. (a) The diameter of polymersomes formed with a microfluidic capillary device is a linear function of the continuous flow rate used to prepare double emulsions ($n > 50$ vesicles for each data point, error bars are standard deviation (s.d.). (b) Vesicle diameter is invariant with respect to the polymer formulations tested at a given flow rate ($n > 100$). (c) Vesicles made to encapsulate a single bead follows the expected Poisson distribution, where $\langle bead/vesicle \rangle_{expected} = 1.5$ ($n = 134$ vesicles, $\langle bead/vesicle \rangle_{actual} = 1.3$, C. O. V. = 0.9). (d) Double emulsions are prepared with 1 μm carboxyl modified polystyrene beads in the interior aqueous compartment at loading quantities calculated in white. Scale bar is 50 μm.

serum albumin (BSA) or 0.1 wt% Pluoronic F-127. By tuning the continuous phase flow rate, we can robustly control the diameter of the resulting vesicles over a range of 20–70 micrometers (**Figure 1**a). While small adjustments to the inner and middle flow rates are required to form double emulsions at each continuous flow rate, we find the outer flow rate is the dominant variable in dictating vesicle size (S1c). Polymersome diameter was found to be a linear function of this continuous phase flow rate and was invariant with respect to the polymer formulations tested at a given continuous phase flow rate (Figure 1b). Changing the polymer solution from a control PEO_{30}-*b*-PBD_{46}, to biotin-functionalized PEO_{30}-*b*-PBD_{46}, to carboxy-terminated PEO_{30}-*b*-PBD_{46} resulted in the same average diameter of 59.0 ± 0.5 μm demonstrating the consistency of our preparation method regardless of small changes in polymer chemistry.

For applications in which arrays of vesicles are to be used as bioreactors or deliver a specific chemical, maintaining a high encapsulation efficiency and controlling the concentration of encapsulated reactants is critical.[14] To illustrate the control microfluidic methods afford in precise payload encapsulation, we prepared double emulsions with different numbers of 1 μm carboxylated polystyrene beads. An inner phase solution is prepared to contain the appropriate volume fraction of beads that results in the desired number of particles encapsulated. By determining the actual distribution of beads loaded in a population of vesicles that were prepared to have approximately 1 bead in their interior, we can assess the reproducibility and variation of particle loading in its most variable (i.e. low number) regime. When the volume fraction of particles in a given volume is low and randomly distributed, the distribution of bead loading is expected to follow a Poisson model.[15] This distribution was experimentally seen for the volume fraction corresponding to a mean of 1.3 ± (1.2) beads/vesicle (Figure 1c). Having validated that the encapsulated number of beads can be dictated by the starting volume fraction of the inner phase solution and given that the diameter of the inner aqueous droplet is constant, we produced populations of vesicles with controlled numbers of encapsulated beads (calculated loading values are reported in Figure 1d).

In order to adhere vesicles specifically to a patterned surface, the membranes must be functionalized with an appropriate ligand complementary to a receptor immobilized on a surface. Polymers can be modified prior to vesicle production or after membrane assembly.[16] If functional groups are sufficiently hydrophilic, we can advantageously assemble vesicles with pre-functionalized polymer where the number of reactive molecules on a vesicle is known and reproducible between batches. In this study, we demonstrated that microfluidic polymersomes could be functionalized through both aforementioned routes. As shown in **Figure 2**, PEO_{30}-*b*-PBD_{46} polymers conjugated to biotin were assembled into vesicles.

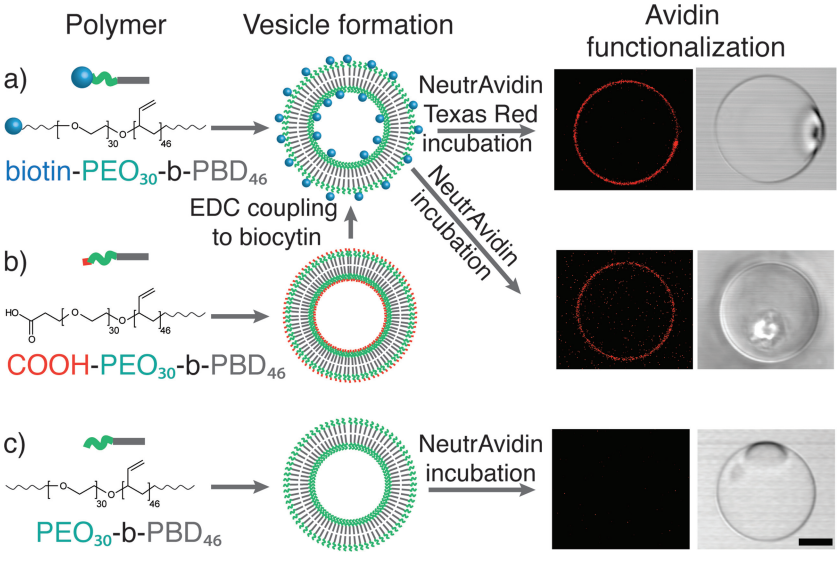

Figure 2. Functionalizing polymersomes. (a) The diblock copolymer used to prepare polymersomes is modified prior to vesicle formation to contain a reactive biotin group. (b) Polymer membranes are modified to contain biocytin post-vesicle formation via an EDC-mediated coupling to carboxyl-conjugated polymer. Polymersomes prepared through either route contain available biotin groups on the membrane surface that bind Texas-Red labeled-NeutrAvidin upon incubation (fluorescent (left) and phase (right) images appear of a representative vesicle functionalized with NeutrAvidin). (c) Control polymersomes prepared with a polymer that does not contain a reactive group do not bind avidin. Scale bar is 25 μm.

Alternatively, polymersomes made with carboxy-terminated PEO_{30}-*b*-PBD_{46} polymer could also be modified after vesicle preparation using an EDC/NHS-mediated coupling reaction to link biocytin to the carboxylic acid groups.[17] The latter method results in biotin present only on the outer leaflet of the vesicle, allowing the creation of asymmetric membranes with differing functionalities. Both methods of modification were verified to yield vesicles in which biotin was accessible for binding to Texas Red-labeled NeutrAvidin (NAv). Given the reduced number of steps required to produce biotin-functionalized vesicles from pre-modified polymer, this route was employed to prepare vesicles in subsequent patterning studies.

We next set out to spatially organize biotin-modified polymersomes via immobilization onto NAv-printed surfaces. Microcontact printing is a powerful tool for the precise and complex spatial organization of adhesive ligands on surfaces.[18] Substrates for polymersome array generation were prepared by microcontact printing NAv onto poly(dimethylsiloxane) (PDMS)-spin coated glass coverslips. NAv islands were 50 μm in diameter with 100 μm spacing (**Figure 3**a_1). Unstamped regions of the substrate were blocked with the non-ionic triblock copolymer Pluoronic F-127 (PEO_{106}-*b*-PPO_{106}-*b*-PEO_{106}), which results in the presentation of PEO groups on bare PDMS not occupied by adhesive ligand. Vesicles that were ~55 μm in diameter were incubated on the substrate. Gentle movement of the microscope stage created a convective flow of PBS across the substrate face inducing non-adherent vesicles to move. Moving vesicles were either captured by printed NAv islands (Figure 3b_1 and Figure S3 in supporting information) or glided along the PEO blocked regions between islands. The high mobility of vesicles on F-127 blocked PDMS (Movie S1) is attributed to the steric repulsion between PEO chains at the vesicle-substrate interface.

Selective biological adhesion requires a combination of adhesive and repulsive interactions. In the absence of blocking by Pluronic, vesicles failed to specifically pattern, adhering to both bare PDMS and NAv islands (Figure 3c_1). To explore the role of biotin-avidin specificity on patterning, non-biotinylated vesicles were incubated with NAv printed surfaces. To our surprise, non-biotinylated polymersomes could still be patterned (Figure 3d_1). The repulsive interactions between the blocking F-127 and the PEO chains on the polymersome drove vesicles onto NAv islands, regions of the substrate that minimized the energetically unfavorable repulsive forces between PEO groups. Capture of non-biotinylated polymersomes on NAv islands suggests a level of favorable non-specific interaction[19] between PEO and NAv, which is verified by the absence of vesicle motion on continuous fields of the ligand (Figure S6 and Movie S2).

We hypothesized that non-specific interactions between vesicles and NAv patches could be tuned by changing the surface area over which they occur. To test this hypothesis, NAv was printed with a decreased island size (Figure 3a_1). On smaller islands biotinylated vesicles were again specifically patterned when substrates were blocked (Figure 3b_2), and bound non-specifically to bare PDMS when left unblocked (Figure 3c_2). When non-biotinylated control vesicles were incubated with the smaller islands of NAv, however, they failed to pattern as previously observed on large 50 μm islands. Instead, these vesicles were found to be continuously motile during observation as indicated by the superimposed trajectories (Figure 3d_2 and Movie S2). By decreasing the island size, we effectively eliminated the contribution of nonspecific PEO-NAv interaction allowing us to attribute the high fidelity patterning of biotinylated vesicles to biotin-avidin binding exclusively. Ultimately, we have shown that NAv-printed PDMS, blocked with Pluronic F-127, is an ideal platform for the spatial patterning of giant biotinylated polymersomes.

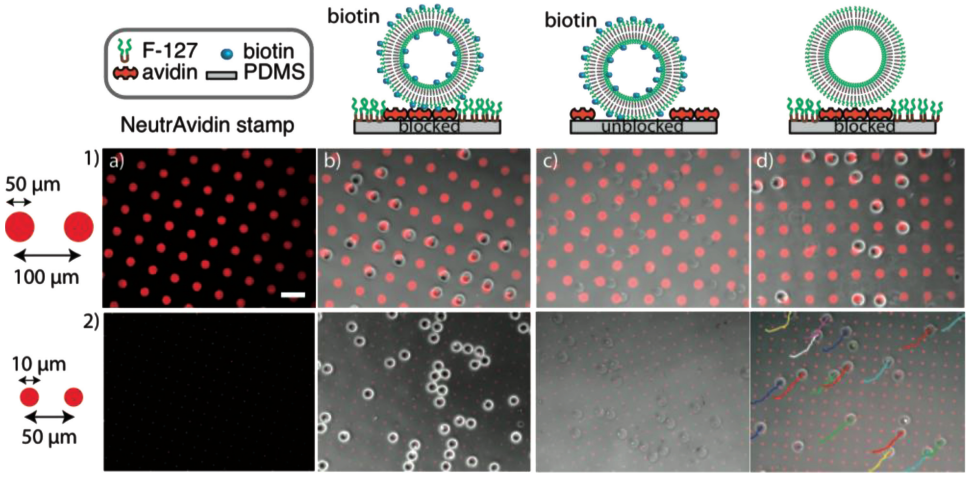

Figure 3. Patterning single polymersomes. Giant polymersomes that are functionalized with biotin are patterned in an array by incubation and immobilization onto micropatterned islands of NeutrAvidin (a) Fluorescence image of the NeutrAvidin microcontact-printed array which has islands with a (1) 50 μm diameter and 100 μm spacing or a (2) 10 μm diameter and 50 μm spacing. Scale bar is 100 μm. (b-d) Fluorescence microscopy image of the NeutrAvidin stamp overlayed with a phase image of polymersomes. (b) Biotinylated polymersomes incubated with a NeutrAvidin stamped and F-127 blocked surface are specifically patterned. (c) On unblocked PDMS, biotinylated vesicles fail to pattern, binding nonspecifically to bare PDMS. (d) Non-biotinylated control vesicles pattern on a printed and blocked surface provided the island size is sufficiently large. When present, colored tracks indicate the trajectories of mobile vesicles on stamped substrates (b-d).

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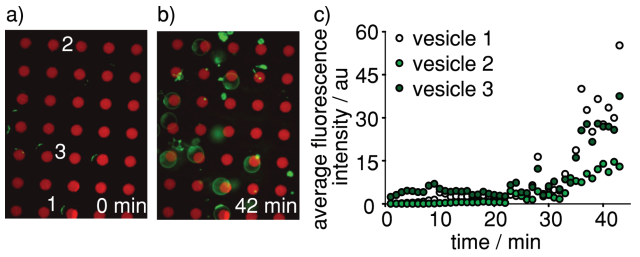

Figure 4. Creating sensor arrays. Biotin functionalized vesicles were patterned onto an array of NeutrAvidin with islands 50 μm in diameter and 100 μm in spacing. (a) At time = 0, when Biotective Green Reagent is added to the system, the vesicles do not fluoresce. (b) At time = 42 min, Biotective Green Reagent has bound biotin on the surface of vesicles and the fluorescence signal from the reagent increases and occurs selectively at the vesicle surface. (c) Fluorescence signals from the reagent were tracked at the surface of three vesicles (numbers correspond to panel a) over the course of a 40 minute imaging session.

Having successfully patterned giant microfluidic vesicles, we sought to demonstrate the array's future applicability to the design of systems capable of inter-vesicle communication. Towards this end, we demonstrate the vesicle array can be used as a biosensing platform. Immobilized polymersomes can report the presence of a soluble molecule added to the vesicle array by capturing the molecule at the vesicle membrane. Biotective Green reagent, an avidin analogue, was used as the bioactive ligand. This molecule is labeled with a fluorescent donor molecule that is quenched through FRET interactions with an acceptor molecule located in the biotin-binding pockets of the reagent. Upon binding biotin, the quencher molecules become displaced and the signaling ligand fluoresces. When this reagent was added to an array of immobilized biotinylated polymersomes, the ligand was captured at the polymersome surface (**Figure 4**b). Fluorescent signals from three representative vesicles over the course of 40 minutes are shown in Figure 4c.

Our system provides a significant advance in the engineering of vesicle-based assemblies. To the best of our knowledge, there has been no previous demonstration of the ability to chemically control the spatial organization of single giant polymersomes. We show, by patterning vesicles of precisely controlled diameter and payload encapsulation, that individual polymersomes can be positioned into multi-vesicle arrays that are geometrically governed by the underlying adhesiveness of the surface. In the future, the printing of multiple adhesive ligands[20] or oligonucleotides[21] on a single substrate will enable the patterning of multiple populations of vesicles, each with a distinct biorecognition capability. The precise patterning of giant functionalized polymersomes is an important step towards realizing the full potential of increasingly complex artificial cell systems.

Experimental Section

Reagents: A polyethylene oxide-polybutadiene diblock copolymer, PEO_{30}-*b*-PBD_{46}, was used for polymersome formation (Polymer Source, Montreal, Canada). Biotinylated polymer was previously functionalized in our laboratory, in which biotin was conjugated onto the terminal polyethylene oxide of PEO_{30}-*b*-PBD_{46} via an intermediate 4-fluoro-3-nitrobenzoic acid linkage that yielded polymer that was approximately 65% biotin-modified. Biocytin, Pluronic F-127, and bovine serum albumin (BSA) were purchased from Sigma. NeutrAvidin-Texas Red conjugate and Biotective Green Reagent were purchased from Life technologies and were used to pattern substrates and demonstrate vesicle communication, respectively.

Polymersome Preparation: Giant polymersomes were prepared via double emulsion templates. Water-in-oil-in-water (W/O/W) double emulsions were produced using glass microcapillary devices, described previously.[13] The inner aqueous phase consisted of a sucrose solution (290 mOsm), the middle, organic phase consisted of 1 mg/mL polymer in a mixture of toluene and chloroform (72:28 v/v), and the outer, aqueous phase consisted of phosphate buffered saline (PBS) (290 mOsm) containing either 1 wt% BSA or 0.1 wt% F-127. For functionalization studies, polymersomes were prepared with Pluronic F-127 as the stabilizer to ensure carboxy-linked biocytin modification occurs with the carboxy group on the polymer and not on any residual surfactant (e.g. BSA) that remains in the membrane). For all other studies, BSA was used as the stabilizer. The three fluid streams were co-focused to generate PEO_{30}-*b*-PBD_{46} double emulsions that were collected in 2 mL of PBS inside 20 mL glass vials. The vials were left loosely capped on a rocker overnight and subsequently tightly capped and rocked until use, generally between 1–2 weeks after formation. The control over vesicle size was demonstrated by changing the outer aqueous phase flow rate between 10–70 mL/h.

Polymersome Functionalization: To demonstrate functionalization of giant, double emulsion-templated polymersomes, polymer vesicles were formed from either carboxy-terminated diblock copolymer, COOH- PEO_{30}-*b*-PBD_{46} or biotin-functionalized polymer. In the former case, following polymersome formation, the carboxy-terminated polymer membranes were functionalized via an EDC mediated coupling to biocytin. For polymersomes made with either biotin-conjugated polymer or covalently linked to biocytin post-vesicle formation, NeutrAvidin-Texas Red was incubated with the vesicles to demonstrate the ability to functionalize biotin after biotin conjugation to the vesicle surface.

Substrate Fabrication: Micropatterned substrates containing NeutrAvidin-Texas Red islands were fabricated as described by Desai et al.[20a] Briefly, glass coverslips were spin-coated with poly(dimethylsiloxane) (PDMS, Sylgard 184, Dow-Corning) prepolymer components at 10:1 (base:curing agent) ratio by weight followed by baking overnight at 60 °C. PDMS stamps were cast against a silicon wafer upon which was etched the negative relief of our desired island array using common photolitopgraphy techniques. The stamps were cured for a few hours at 90 °C, removed from the mask and inked with NeutrAvidin-Texas Red (100 μg/mL) for 1 h. Stamps were rinsed and applied to the substrate, as described previously. Square NeutrAvidin lattices consisted of circular islands either 50 μm in diameter and laterally spaced by 100 μm (50 μm × 100 μm) or of 10 μm diameter islands spaced by 50 μm (10 μm × 50 μm). Texas Red-labeled NeutrAvidin was used to visualize the resulting pattern and uniformity of the printed protein. Vesicle adhesion was restricted to the NeutrAvidin islands by blocking the unprinted surface with 0.2 wt% Pluoronic F-127 for at least 10 min and washing thoroughly with PBS without dewetting the printed and blocked surface.

Vesicle Patterning: Polymersomes made with biotin-conjugated polymer were incubated on NeutrAvidin patterned substrates at a density of 80 vesicles/mm^2 and subjected to gentle rotation on a motorized microscope stage. The convection of fluid induced by the stage motion was found to effectively clear unbound vesicles from the patterned and blocked PDMS substrate provided the island pitch allowed egress. Vesicles made with unmodified PEO_{30}-*b*-PBD_{46} were used as a control of biotin-avidin specificity as described in the text.

Supporting Information

Supporting Information is available from the Wiley Online Library or from the author.

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Supporting Information

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Supporting Information

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Keywords: polymersomes, double emulsions, microarrays, biosensor, patterning

Supporting Information Figures:

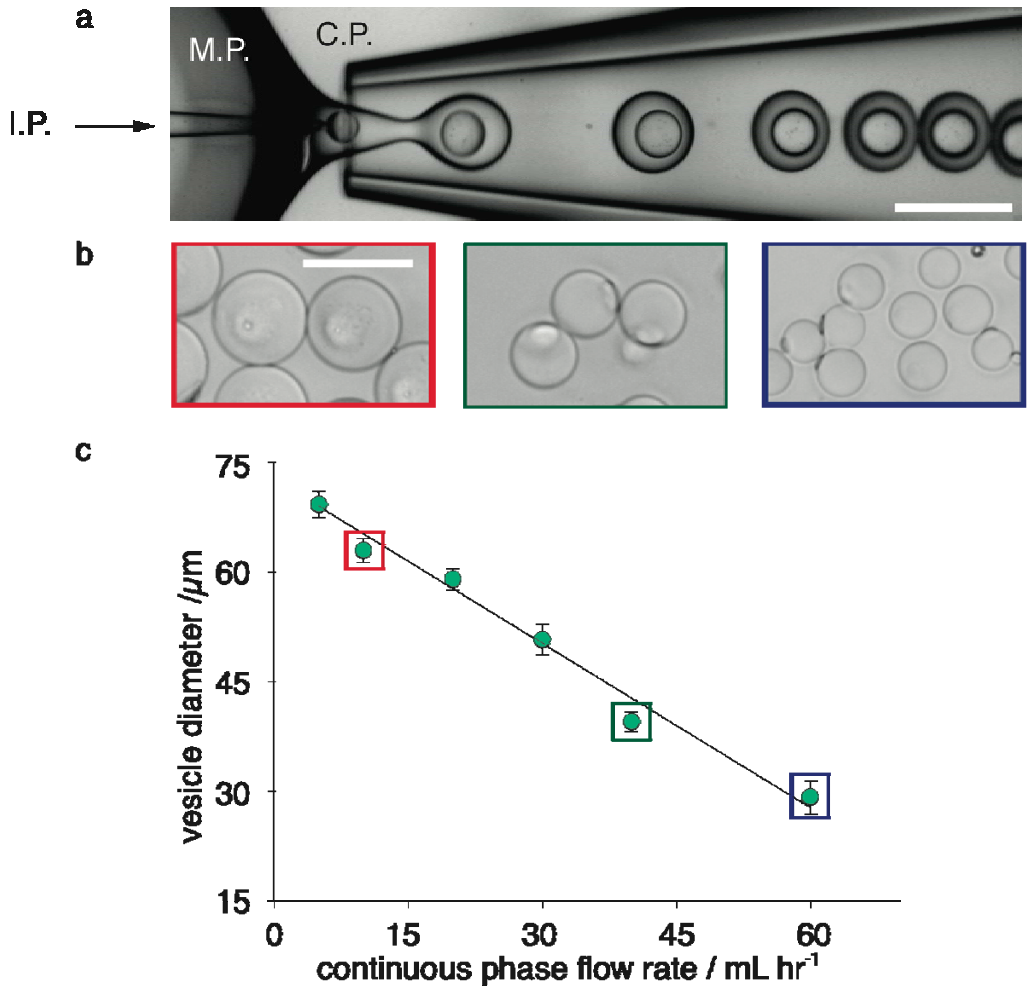

Figure S1: Controlling vesicle diameter by adjusting the continuous phase flow rate.

(a) A microcapillary device is used to prepare polymersomes by first generating double emulsions.[1] The inner phase (I.P.), middle phase (M.P.) and continuous phase (C.P.) are co-focused to create the double emulsions. (b,c) The diameter of polymersomes can be controlled by changing the flow rates of the different fluid phases. The C.P. flow rate is the dominant variable in dictating vesicle size. Using a device with an inner capillary diameter of 32.6 μm and an outer capillary diameter of 151 μm, polymersomes were prepared with diameters ranging from 20-70 microns. Phase microscopy images of representative polymersomes are depicted for 3 different populations of vesicles appearing in graph c. (n > 50 vesicles for each data point, error bars are standard deviation (s.d.). The I.P., M.P. and C.P. flow rates for each population of vesicles that appears on graph c were: (1) 0.55, 5.0 and 5 mL hr^{-1} (2) 1, 7 and 10 mL hr^{-1} (3) 1, 7 and 20 mL hr^{-1} (4) 1.5, 7 and 30 mL hr^{-1} (5) 1.2 , 7.5 and 40 mL hr^{-1} and (6) 0.55, 5 and 60 mL hr^{-1}. Scale bar is 70 μm.

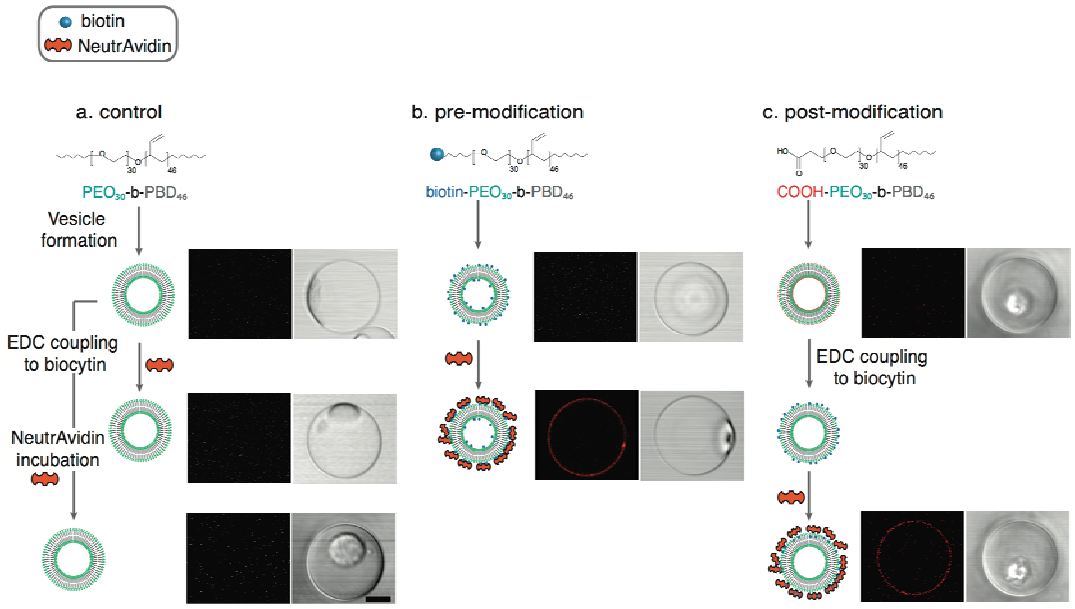

Figure S2: NeutrAvidin functionalization of polymersomes made from biotin-modified polymer.

For functionalization studies, polymersomes were prepared with Pluronic F-127 as the stabilizer to ensure carboxy-linked biocytin modification occurs with the carboxy group on the polymer and not on any residual surfactant that remains in the membrane.(a) Polymersomes that are PEO terminated are not functionalized with NAv. The lack of carboxyl groups on the vesicle surface ensures that EDC mediated reactions to biocytin do not result in biocytin linkage to the polymer membrane. (b) Polymersomes can be made by using polymer that already contains biotin. In this case biotin is available on both the inner and outer leaflets of the membrane and is able to bind NAv upon incubation. (c) Carboxy-terminated polymersomes are also functionalized with biocytin after vesicle formation. In this case, biotin is only added to the outer leaflet of the vesicle. This EDC-mediated coupling could be used to link other amine-containing proteins or molecules to a polymersome surface. Scale bar is 20 µm.

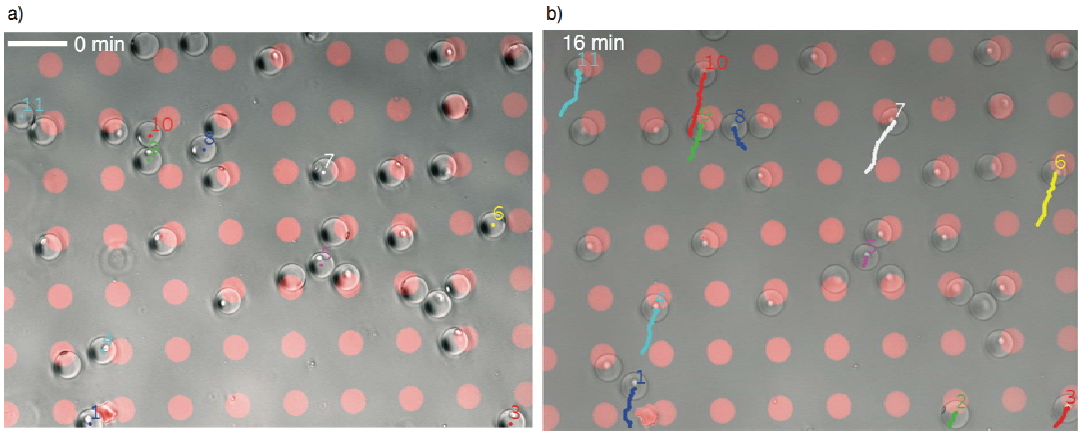

Figure S3: Polymersome capture on NAv-printed surfaces.

(Left) Polymersomes are patterned by incubating vesicles on a NAv-printed surface and placing both the biotinylated polymersomes and the NAv surface on a microscope stage. Low -level motion of the microscope stage that is rotating between different imaging positions creates a convective flow in the polymersome sample. Polymersomes moving along the NAv printed surface are mobile on the blocked regions that contain Pluoronic F-127, but are captured by the NAv islands. Overtime, the capture of biotinylated vesicles and movement of non-captured vesicles out of the field of view results in the patterning of polymersomes. Trajectories for mobile vesicles appear in colored tracks that are overlayed onto the merged image of vesicles and the NAv stamp. Vesicles numbered 2, 3, 4, 6, 7, 9, 10, and 11 are captured by NAv islands. Vesicles 5 and 8 are trapped by two patterned vesicles and unable to move to find a NAv island or exit the field of view. Increasing the spacing between NAv islands would allow unbound vesicles to egress more readily. The possibility of utilizing geometric confinement as a patterning force, however, is made compelling but this observation of entrapment. Scale bar is 20 μm. The full time course depicting this vesicle capture can be seen in SI Movie 1.

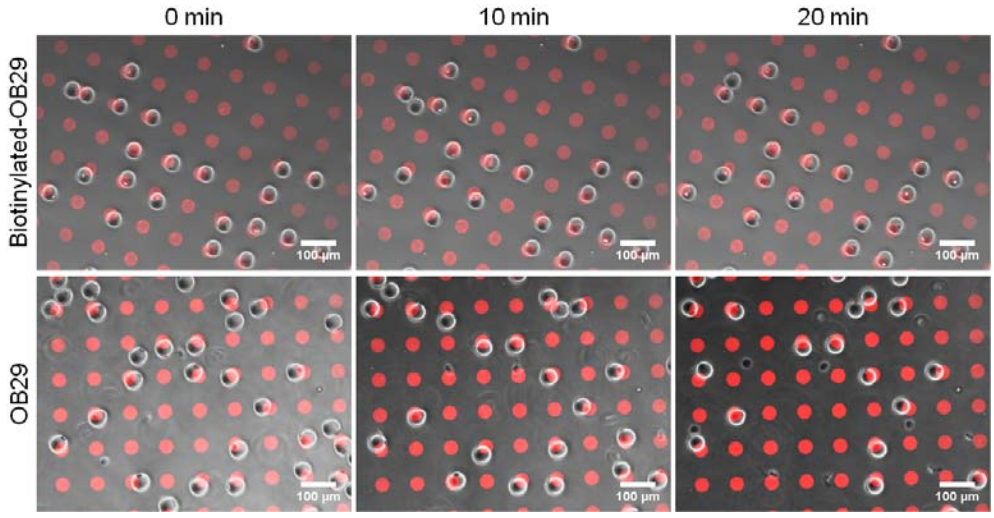

Figure S4: Polymersomes patterned on NeutrAvidin islands of 50 um diameter and 100 um pitch.

Sustained vesicle patterning in the non-biotinylated case motivated our hypothesis that another driving force such as the repulsive interaction between PEO chains on the vesicles and PEO chains on the blocked substrate was at play.

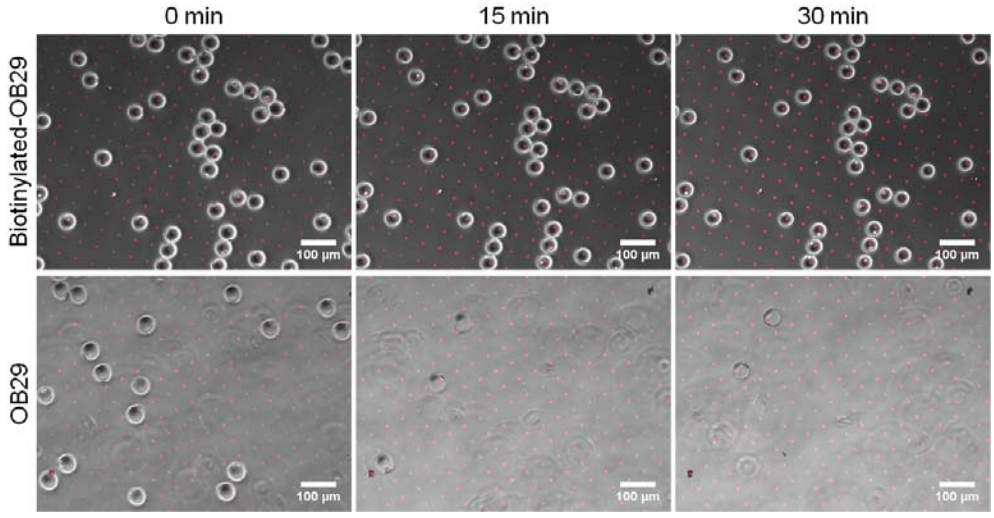

Figure S5: Polymersomes patterned on smaller NeutrAvidin islands of 10 um diameter and 50 um pitch.

Unlike previously, where non-biotinylated vesicles remained patterned, here, reduction in island size prevents patterning of these same control vesicles. That biotinylated vesicles retain their pattern during stage motion suggests the biotin-avidin interaction is stronger than the non-specific PEO-NAv interaction.

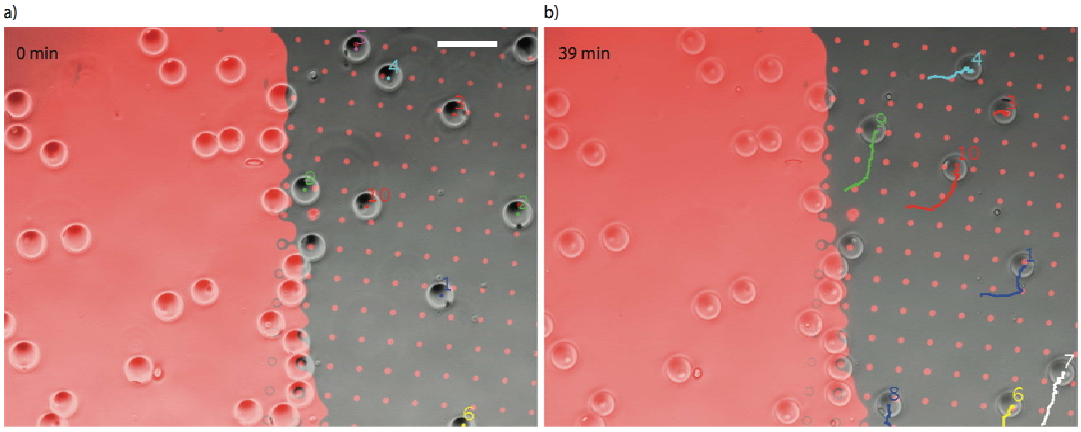

Figure S6: Effect of NAv surface area on non-specific binding.

To illustrate the effect of available protein surface area on non-specific binding, NAv was printed in a uniform field on the left side of the PDMS substrate and printed in islands on the right side. The fluorescent image of NeutrAvidin (red) is overlayed with the phase image of polymersomes. The substrate was blocked with PDMS and incubated with non-biotinylated polymersomes. Though polymersomes do not contain biotin, they are immobilized through non-specific interactions on the uniform field of NAv. When the area of interaction is decreased to a 10 µm island size, however, the vesicles are mobile and move freely across the substrate. The tracks of motile vesicles are indicated by overlaying the colored vesicle trajectories onto the merged image of the polymersomes and NAv stamp. The full time course of this phenomenon can be seen in SI Movie 2.

Supporting Information movies

SI Movie 1: Polymersome motility on a) bare PDMS b) F-127 blocked PDMS and c) NAv islands

(a) Biotin-modified polymersomes bind nonspecifically to bare PDMS and are immobile. (b) Biotin-modified polymersomes are mobile on Pluronic F-127 blocked PDMS, due to steric repulsion between PEO groups on the vesicle surface and PEO groups on Pluoronic F-!27. (c) Biotin-modified polymersomes are mobile on blocked PDMS and are captured onto NeutrAvidin islands as they move across the NAv-patterned and F-127 blocked surface.

SI Movie 2: Effect of NAv surface area on non-specific polymer binding.

See Figure S6 for details.

References:

[1] N. P. Kamat, M. H. Lee, D. Lee, D. A. Hammer, Soft Matter 2011.

The table of contents entry

Giant, cell-sized polymersomes are functionalized and patterned at the single vesicle level. Microfluidic methods are employed to generate uniform diameter vesicles with high loading efficiencies and microcontact printing is used to generate patterns of adhesive ligand. A simple sensory capability is demonstrated with the immobilized array of vesicles.

TOC Keyword: Positioning artificial polymer membranes

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Single vesicle patterning of uniform, giant polymersomes into microarrays

ToC figure