Soft Nanoparticles Assembled from Linear Poly(ethylene glycol) and Linear Brush Polydimethylsiloxane Diblock Copolymers

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ABSTRACT: A series of novel amphiphilic diblock copolymers composed of hydrophilic linear poly(ethylene glycol) (PEG) and linear brush hydrophobic polydimethylsiloxane (PDMS) were synthesized. Three different molecular weights of monomethyl ether PEG were initially functionalized with 2-bromoisobutyryl bromide to afford macroinitiators suitable for atom-transfer radical polymerization. The macroinitiators were characterized by gel permeation chromatography, ¹H and ¹³C nuclear magnetic resonance spectroscopic analysis and matrix-assisted laser desorption ionization time-of-flight mass spectroscopy. The three different molecular weight macroinitiators were then chain extended with monomethacryloxypropyl-terminated PDMS and photoactive 2-(methylacyloyloxy)ethyl anthracene-9carboxylate in different molar ratios to afford a series of photoresponsive amphiphilic diblock copolymers with high conversions. Self-assembly of these linear-linear brush diblock

INTRODUCTION The last decade has seen nanotechnology emerging as one of the most significant areas in research and development in both academia and industry.^{1,2} "Nanoscience" has developed into a multidisciplinary field, ranging from fundamental in-depth studies to the fabrication of next-generation functional materials for a wide range of applications. "Soft" materials such as micelles and vesicles have been extensively used in the biomedical field, whereas the application of such materials to separation technologies has been less explored.^{3,4}

Poly(ethylene glycol) (PEG) is a water-soluble polymer that has attracted much attention as a result of its biocompatibility and low toxicity.⁵ PEG has been widely employed in a copolymers in *N*,*N*-dimethylformamide afforded nanoparticles with hydrodynamic diameters ($d_{\rm H}$) ranging from 41 to 268 nm, as determined by dynamic light scattering analysis. Crosslinking and stabilization of the nanoparticles was achieved via [4+4] photodimerization of the anthracene moieties upon exposure to UV radiation at 365 nm with the reverse reaction studied at a wavelength of 254 nm. Transmission electron microscopy revealed that the self-assembled nanoparticles and their crosslinked derivatives had spherical morphologies. © 2014 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2014**, *52*, 1251–1262

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variety of biomedical applications including the preparation of biocompatible conjugates, surface modification of drug delivery vectors, and as scaffolds for tissue engineering.⁶ PEG has also been significant in the development of membranes for CO₂ separation as it possesses a high affinity towards CO₂.^{7–9} Additionally, PEG is readily available, inexpensive, and easily produced on an industrial scale. Polydimethylsiloxane (PDMS) is a class of hydrophobic rubbery polymer that has been utilized in many areas as a result of its high stability, biocompatibility, and flexibility.^{10–12} In the gas separation field, PDMS is known as one of the most permeable polymers, which results from the flexibility of the siloxane backbone.^{13–15} The formation of amphiphilic block copolymers (BCPs) can be achieved by covalently linking

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hydrophilic PEG with hydrophobic PDMS. Soft nanoparticles made of amphiphilic BCPs have found many applications as nanocarriers and nanoreactors.¹⁵⁻¹⁷ Previous studies have also reported the utilization of amphiphilic BCPs to prepare crosslinked hydrogels for tissue engineering applications.^{18,19} Several approaches have been reported to combine PEG and PDMS; mainly through covalently linking linear PEG with linear PDMS to form a diblock copolymer,^{20–22} end-capping linear PEG with linear PDMS to form a triblock copolymer,^{23,24} and end-capping linear PDMS with linear PEG to form a triblock copolymer.^{10,25,26} Other examples include a random-grafted PEG/PDMS copolymer²⁷ and a commercially available grafted PEG along a PDMS backbone. To the best of the authors' knowledge, no studies have reported the synthesis of a welldefined PEG/PDMS-grafted BCPs. This may arise from the difficulty in conducting the reaction under controlled living radical polymerization conditions.

BCP self-assembly has attracted significant interest as it has been identified as one of the key future strategies to prepare nanostructures with well-defined composition and structures.^{28,29} Past studies have mainly focused on the selfassembly of linear–linear PEG/PDMS diblock copolymers where the formation of micelles and vesicles was reported.^{20,22,30,31} These self-assembled structures have the potential to be utilized as nanocarriers in drug delivery system.³¹

The stability of nanoparticles is a crucial condition for applications such as controlled drug delivery and release.³² Without crosslinking, the nanoparticles might disintegrate upon changes in temperature or solution composition. Several approaches have been utilized to stabilize polymeric nanoparticles including core³³⁻³⁵ and shell crosslinking.^{36,37} There has been a growing interest in stabilizing nanoparticles via photocrosslinking as this provides good temporal and spatial control over the process.³⁸ Light-induced crosslinking also provides a stabilization route that avoids unwanted by-products.³² Past studies have utilized coumarin³⁹ and cinnamate groups⁴⁰ to incorporate photochromic moieties into the nanoparticles. Limited studies have utilized anthracene moieties to stabilize nanoparticles. Compared to coumarin and cinnamate groups, the [4+4] photodimerization of anthracene groups provides stability at elevated temperatures.⁴¹ Additionally, photodimerization of coumarin and cinnamate groups may be easily reversed under certain conditions.³⁸ which may be undesirable for certain applications.

In this study, we report the synthesis of soft nanoparticles assembled from linear PEG linked with a photocross-linkable PDMS brush. The photocross-linkable diblock copolymers were synthesized by chain extension of functionalized linear PEG with monomethacryloxypropyl-terminated PDMS (PDMS-MA) and photoactive 2-(methylacyloyloxy)ethyl anthracene-9-carboxylate (MEAC) via atom-transfer radical polymerization (ATRP) in different molar ratios. Selfassembly of these diblock copolymers was investigated in *N*,*N*-dimethylformamide (DMF), which is a selective solvent for the PEG block, and resulted in the formation of nanoparticles that were further stabilized by photocrosslinking via [4+4] photodimerization. The self-assembled nanoparticles and their crosslinked derivatives were characterized to determine their size, morphology, and molecular structure. The well-defined linear-linear brush diblock copolymers displayed various structures, from spherical to crew-cut aggregates or large compound micelles (LCMs), with unique particle sizes.

EXPERIMENTAL

Materials

2-Bromoisobutyryl bromide (BIBB, 98%), copper(I) bromide (CuBr, 98%), sodium trifluoroacetate (NaTFA, 98%), anhydrous tert-butanol (t-BuOH, 99.5%), anthracene-9-carboxylic *N*,*N*,*N'*,*N''*,*N''*-pentamethyldiethylenetriamine acid (99%), (PMDETA, 99%), 1 kDa PEG monomethyl ether (MeOPEG₁), and 5 kDa PEG monomethyl ether (MeOPEG₅) were purchased from Aldrich and used as received. Monomethacryloxypropyl-terminated PDMS ($M_w = 600-800$ Da) (PDMS-MA, 95%, Gelest) was stirred with basic alumina (99%, Scharlau) for 16 h and filtered prior to use. 2-Hydroxyethyl methacylate (HEMA, 98%, Aldrich) was stirred for 16 h with inhibitor remover (Aldrich) and filtered prior to use. Dichloromethane (DCM, AR), methanol (MeOH, AR), DMF (AR), chloroform (AR), sodium hydroxide (NaOH, 97%), and sodium chloride (NaCl, 97%) were purchased from Chem-Supply and used as received. Tetrahydrofuran (THF, HPLC grade, RCI Labscan) was distilled from sodium benzophenone ketyl under argon. Triethylamine (TEA, 99%, Ajax) was distilled from calcium hydride (95%, Aldrich) under argon. Deuterated chloroform (CDCl₃, 99.9%) and deuterated dimethyl sulfoxide (d_6 -DMSO, 99.9%) were purchased from Cambridge Isotope Laboratories. Trans-2-[3-(4-tert-butylphenyl)-2-methyl-2-propenylidene]-malononitrile (DCTB, Santa Cruz Biotechnology), 10 kDa PEG monomethyl ether (MeOPEG₁₀, Creative PEGWorks), thionyl chloride (SOCl₂, AR, Merck), hydrochloric acid (HCl, 37% in H₂O, Scharlau), and magnesium sulfate anhydrous (MgSO₄, 98 wt%, Scharlau) were used as received.

Instrumentation

Gel permeation chromatography (GPC) was performed on a Shimadzu liquid chromatography system fitted with a Shimadzu RID-10A refractive index detector (633 nm) and a Shimadzu SPD-10A UV-Vis detector (230 and 390 nm), using three Phenomenex Phenogel columns (500, 10⁴, 10⁶ Å porosity; bead size, 5 μ m) maintained at 50 °C. Chloroform was used as the eluent at a flow rate of 1 mL/min. Astra software (Wyatt Technology) was used to process the data and determine molecular weight characteristics based on a conventional column calibration using poly(ethylene oxide) (PEO) standards. ¹H and ¹³C NMR spectroscopic analysis was performed on a Varian Unity Plus 400 MHz spectrometer operating at 400 and 100 MHz, respectively, using the deuterated solvent resonance as reference. Matrix-assisted laser desorption ionization time-of-flight mass spectroscopy (MALDI ToF MS) was performed on a Bruker Autoflex III

Macroinitiator	M _n ^{NMR} (kDa) ^a	<i>M</i> n ^{MALDI-ToF} (kDa) ^b	M _n ^{GPC} (kDa) ^c	PDI ^c	Degree of Functionalization (%) ^d
P1 ₁	1.1	1.1	1.6	1.07	>99
P1 ₅	5.2	5.1	5.7	1.13	>99
P1 ₁₀	10.5	10.8	13.6	1.26	>99

TABLE 1 Molecular Weight Characterization of MeOPEG Macroinitiator P1

^a Number-average molecular weight calculated from ¹H NMR spectroscopic analysis.

^b Number-average molecular weight determined by MALDI ToF MS.

Mass Spectrometer operating in positive/linear mode; the analyte was dissolved in DCM at concentrations of 10 mg/mL, whereas the matrix (DCTB) and cationization agent (NaTFA) were dissolved in MeOH at concentrations of 10 and 1 mg/mL, respectively, and then mixed in a ratio of 10:1:1. A 0.3 µL aliquot of this solution was then spotted onto a ground steel target plate, and the solvent was allowed to evaporate prior to analysis. Flex Analysis (Bruker) was used to analyze the data. Dynamic light scattering (DLS) measurements were performed on a Wyatt DynaPro NanoStar fitted with a 120 mW Ga-As laser operating at 658 nm; 100 mW was delivered to the sample cell. Analysis was performed at an angle of 90° and a constant temperature of 25 ± 0.01 °C. UV–Vis analysis was performed on a Shimadzu UV-Vis Scanning Spectrophotometer (UV-2101 PC) using quartz cuvettes. Transmission electron microscopy (TEM) images were taken using a Tecnai TF30 transmission electron microscope (FEI, Eindhoven, The Netherlands) operating at 200 kV. Images were acquired digitally with a Gatan US1000 $2k \times 2k$ CCD Camera (Pleasanton, CA).

Synthesis of α -Methyl, ω -Bromo-functionalized PEG Macroinitiator P1

MeOPEG₅ (10.0 g, 2.0 mmol, 1 equiv.) was dissolved in anhydrous DCM (80 mL) under argon. The solution was cooled to 0 °C followed by the dropwise addition of TEA (4.50 mL, 32.3 mmol, 16 equiv.) and BIBB (6.88 g, 30.0 mmol, 15 equiv.). The mixture was stirred for 1 h at 0 °C. The crude product was then washed with 1 M HCl (2×80 mL), 1 M NaOH (4×80 mL), saturated NaCl (80 mL), dried (MgSO₄), filtered, and concentrated *in vacuo* (2 mbar). The dried product was redissolved in chloroform (80 mL), passed through basic alumina, and concentrated *in vacuo* (0.1 mbar) at 25 °C for 16 h to yield **P1**₅ as a white solid, 5.76 g (isolated yield, 34%). The synthetic procedure was repeated for the functionalization of MeOPEG₁ and MeOPEG₁₀ (Table 1).

¹H NMR (400 MHz, CDCl₃, δ , ppm): 1.89 (s, CH₃, $H_{\rm h}$ endgroup), 3.24 (s, CH₃, $H_{\rm a}$ end-group), 3.41–3.69 (m, CH₂CH₂O, $H_{\rm b}$, H_c , H_d , H_e , and $H_{\rm f}$), 4.23–4.25 (m, CH₂CH₂OCO, $H_{\rm g}$ endgroup) (Supporting Information Fig. S1). ¹³C NMR (100 MHz, CDCl₃, δ , ppm): 30.2, 57.0, 57.9, 64.9, 67.9, 69.5, 69.7, 71.2, and 170.7 (Supporting Information Fig. S2).

Synthesis of MEAC

Anthracene-9-carboxylic acid (2.22 g, 10.0 mmol) and thionyl chloride (SOCl₂) (30 mL) were added to a dried flask under

^c Number-average molecular weight and PDI measured from GPC-UV analysis (230 nm) relative to PEO standards.

^d Degree of functionalization determined by MALDI ToF MS.

argon. The reaction mixture was refluxed under argon for 90 min and the excess SOCl₂ was removed *in vacuo* (0.1 mbar). The resulting residue was azeotroped with benzene (3 × 10 mL), redissolved in anhydrous THF (40 mL), and cooled to 0 °C. TEA (2.4 mL, 32.7 mmol) was added, followed by the dropwise addition of HEMA (1.15 mL, 9.5 mmol) in anhydrous THF (30 mL). The reaction solution was stirred at 0 °C for 1 h, warmed to room temperature, and stirred for 20 h, and then filtered and concentrated. The crude product was redissolved in DCM (100 mL), washed with 2 M HCl (2 × 100 mL), 2 M NaOH (4 × 100 mL), saturated NaCl (100 mL), distilled water (2 × 100 mL), dried (MgSO₄), filtered, and concentrated *in vacuo* (2 mbar). The product was then dried *in vacuo* (0.1 mbar) at 30 °C for 16 h to yield MEAC as a pale yellow solid, 2.88 g (83%; purity (¹H NMR), >90%).

¹H NMR (400 MHz, CDCl₃, *δ*, ppm): 1.99–2.00 (*t*, *J* = 1.2 Hz, CH₃, *H*_c), 4.60–4.62 (*m*, CH₂, *H*_d), 4.87–4.90 (*m*, CH₂, *H*_e), 5.64–5.65 (*quin*, CH, *H*_a), 6.20–6.25 (*quin*, CH, *H*_b), 7.47–7.54 (*m*, ArH, *H*_h), 8.02–8.10 (*m*, ArH, *H*_g), 8.55 (*s*, ArH, *H*_f) (Supporting Information Fig. S3). ¹³C NMR (100 MHz, CDCl₃, *δ*, ppm): $\delta_{\rm C}$ 18.3, 62.5, 63.3, 125.0, 125.4, 126.2, 127.0, 128 (*d*), 129.7, 130.9, 135.9, 167.0, and 169.3 (Supporting Information Fig. S4).

Synthesis of PEG/PDMS Diblock Copolymers P2

PDMS-MA (0.30 g, 0.429 mmol, 8 equiv.), P15 (0.279 g, 0.054 mmol, 1 equiv.) and MEAC (53.7 mg, 0.161 mmol, 3 equiv.) were dissolved in t-BuOH (1.85 mL) at 60 °C to afford a macromonomer concentration of 0.02 M. An aliquot (0.2 mL) was taken (t_0) to monitor macromonomer and MEAC conversion. Bipyridine (16.7 mg, 0.107 mmol, 2 equiv.) was then added to the mixture and the solution was transferred to a Schlenk tube (oven-dried at 110 °C for 24 h). The mixture was then subjected to four freeze-pumpthaw cycles (thaw cycles conducted at 60 °C) and the Schlenk tube was then immersed again in liquid N_2 . Once the solution was frozen, CuBr (15.4 mg, 0.107 mmol, 2 equiv.) was added and one more freeze-pump-thaw cycle was completed. The Schlenk tube was then equilibrated at room temperature for 10 min with stirring to ensure homogeneity and then heated at 90 °C for 48 h. After cooling to room temperature, an aliquot (0.2 mL) was taken (t_{48}) to determine the macromonomer and MEAC conversion. The reaction mixture was then diluted with DCM and passed through a plug of basic alumina to remove the copper catalyst. The filtrate was concentrated in vacuo (2 mbar) before



TABLE 2 Synthesis and	Characterization	of PEG/PDMS	Diblock	Copoly	/mers
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Polymer ^a (P2 _{PEG-MW/PDMS-MW})	Macroinitiator	Molar Ratio ^b	Conversion (PDMS-MA/ MEAC) ^c	M _n ^{Theor} (kDa) ^d	M _n ^{NMR} (kDa) ^e	M _n ^{GPC} (kDa) ^f	PDI ^f
P2 _{1/5}	P1 ₁	1:5:3	95/>99	5.7	6.0	19.7	2.00
P2 _{1/8}	P1 ₁	1:10:3	92/>99	8.6	9.8	29.2	2.28
P2 _{5/4}	P1 ₅	1:4:3	94/>99	8.7	9.7	13.0	2.23
P2 _{5/7}	P1 ₅	1:8:3	96/>99	11.8	12.3	17.4	2.17
P2 _{5/9}	P1 ₅	1:12:4	92/>99	14.1	17.0	22.2	2.06
P2 _{10/9}	P1 ₁₀	1:11:4	92/>99	18.5	19.5	58.9	2.15
P2 _{10/12}	P1 ₁₀	1:16:4	90/>99	21.6	24.0	63.1	2.06
P2 _{10/15}	P1 ₁₀	1:21:5	88/>99	25.1	28.5	64.0	1.90

 $^{\rm a}$ The first subscript refers to PEG-MW in kDa and the second refers to PDMS-MW in kDa.

^b Molar ratio of [P1]:[PDMS-MA]:[MEAC].

 $^{\rm c}$ PDMS-MA and MEAC conversions were calculated from $^1{\rm H}$ NMR spectroscopic analysis.

drying *in vacuo* (0.1 mbar) at 45 °C for 16 h to yield product **P2**_{5/4} as an opaque tacky solid, 0.35 g (isolated yield, 65%). The polymer composition was varied by changing the macro-initiator, monomer, and MEAC feed ratio (Table 2).

¹H NMR (400 MHz, CDCl₃, δ , ppm): 0.04–0.09 (*m*, *H*_h), 0.51–0.55 (*m*, *H*_g), 0.86–1.04 (*m*, *H*_d, *H*_j), 1.25–1.35 (*m*, *H*_i), 1.64 (*br s*, *H*_f), 1.78 (*br s*, *H*_c), 3.38 (*s*, *H*_a), 3.38–4.12 (*m*, *H*_b), 3.87 (*br s*, *H*_e), 7.44 (*br s*, *H*_i), 7.99 (*br s*, *H*_k), and 8.43 (*br s*, *H*_m) (Fig. 2).

Self-assembly of PEG/PDMS Diblock Copolymers

The solvents used for the self-assembly studies, chloroform, and DMF, were first filtered through 0.45 μ m PTFE filters (Labquip Technologies). Copolymers were dissolved in chloroform (30 mg/mL) prior to dropwise addition of DMF to affect dissolution (0.167 mg/mL). DLS was then employed to measure the hydrodynamic diameters of the self-assembled nanoparticles. DLS was also utilized to measure the hydrodynamic diameters prior to self-assembly. For the control experiment, copolymers were dissolved in chloroform (0.167 mg/mL).

Photocrosslinking of PEG/PDMS Diblock Copolymers

After self-assembly, brush diblock copolymer samples were photocrosslinked by exposure to UV radiation with a wavelength of 365 nm over a period of 4 h. UV-Vis spectroscopy was used to monitor the progression of the [4+4] photodimerization. Samples were concentrated *in vacuo* (0.1 mbar) to remove DMF and then diluted with chloroform for postcrosslinking DLS analysis. Samples were also diluted below their CMCs to further confirm the extent of crosslinking.

Photocleavage of PEG/PDMS Diblock Copolymers

To initiate photocleavage, samples were exposed to UV radiation with a wavelength of 254 nm over a period of 20 h. UV- ^d Number-average molecular weight based on macromonomer conversion and initial feed molar ratio.

^e Number-average molecular weight determined by ¹H NMR spectroscopic analysis.

^f Number-average molecular weight and PDI measured by GPC-UV trace (230 nm) relative to PEO standards.

Vis spectroscopy was again used to monitor the progress of the photocleavage process.

Imaging of Self-assembled Nanoparticles and Their Photocross-linked Derivatives

TEM samples were prepared by drop-coating the self-assembled nanoparticles in DMF (0.167 mg/mL) and their photocrosslinked derivatives in chloroform (0.167 mg/mL) onto copper grids (10 μ L). The samples were then blotted and negatively stained by uranyl acetate aqueous solution (2 wt %) before imaging was conducted.

RESULTS AND DISCUSSION

ATRP was employed to synthesize photoresponsive amphiphilic linear PEG and brush PDMS diblock copolymers (Scheme 1). Initially, three different molecular weights of monomethyl ether PEG (MeOPEG) were functionalized to afford α -methyl, ω -bromo-functionalized PEG macroinitiators **P1** suitable for ATRP. The macroinitiators were characterized via GPC, nuclear magnetic resonance (NMR) spectroscopic analysis, and MALDI ToF MS. The PEG macroinitiators **P1** were subsequently chain extended with varying amounts of PDMS-MA macromonomer and photoactive MEAC to afford a series of novel photoresponsive amphiphilic copolymers with various degrees of polymerization (DP).

Synthesis of α -Methyl, ω -Bromo-functionalized PEG Macroinitiator

Functionalization of MeOPEG with initiating moieties was achieved through reaction with BIBB to afford α -methyl, ω -bromo-functionalized PEG macroinitiator **P1** with quantitative end-group conversion (Scheme 1). In this study, three different molecular weights of MeOPEG were functionalized and the resulting macroinitiators (**P1**₁, **P1**₅, and **P1**₁₀) were obtained in moderate yields after a rigorous purification

ARTICLE



SCHEME 1 Synthetic outline for the preparation of soft nanoparticles assembled from linear PEG and linear brush PDMS diblock copolymers. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

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FIGURE 1 MALDI ToF mass spectra of (a) 5 kDa MeOPEG and (b) its bromo-functionalized derivate, **P1**₅, recorded in linear/positive mode using DCTB and NaTFA as the matrix and cationization agent, respectively. The numbers on the peaks represent the number of EO repeat units (n, m/z = 44). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

process. A large excess of BIBB was utilized to ensure quantitative functionalization of MeOPEG.

¹H NMR spectroscopic analysis of **P1**₅ revealed a new resonance at $\delta_{\rm H}$ 1.9 ppm (Supporting Information Fig. S1) corresponding to the methyl groups of the bromo*iso*butyrate endgroup upon esterification. NMR spectroscopic analysis also confirmed the formation of the PEG macroinitiators **P1**₁ and **P1**₁₀ (Supporting Information Fig. S5).

MALDI ToF MS and NMR spectroscopy were used to determine the molecular weights of the MeOPEG macroinitiators **P1** (Fig. 1(b), Supporting Information Fig. S1, and Table 1). MALDI ToF MS spectra of the functionalized MeOPEG macroinitiators revealed a series of peaks shifted by about m/z = 150 (Fig. 1(b)) relative to their precursors (Fig. 1(a)), which corresponds to the addition of the bromo*iso*butyrate end-group. The observed mass values were found to correlate well with the sodium salts of the desired macroinitiator **P1**₅, resulting from the use of NaTFA as the cationization agent. MALDI ToF MS spectra of **P1**₁ and **P1**₁₀ also showed similar results (Supporting Information Figs. S6 and S7). All of the MALDI ToF MS spectra revealed series of peaks separated by *ca.* m/z = 44, corresponding to the repeat unit of PEG (Fig. 1(a,b)). Determination of the number-average molecular weights (M_n) via MALDI ToF MS provided values that corresponded well with those determined by NMR spectroscopy (Table 1). GPC analysis was performed on the MeO-PEG macroinitiators **P1**, and their molecular weights and



FIGURE 2 ¹H NMR spectrum (CDCI₃) of PEG/PDMS diblock copolymer **P2**_{5/9}. The asterisks denote resonances corresponding to the double bond of unreacted PDMS-MA macromonomer. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

molecular weight distributions were determined relative to a conventional column calibration with PEO standards. Despite PEG having a strong positive RI signal in chloroform, to be consistent, the UV traces were used for the analysis of all polymers, as the PDMS components in the following section have either a negative RI signal in chloroform or are isore-fractive in THF. The M_n values determined from GPC analysis were slightly higher than those calculated from MALDI ToF MS and NMR spectroscopy, which possibly results from the inaccuracy of the standard calibration method with PEO standards (Table 1).

Synthesis of PEG/PDMS Diblock Copolymers

Photoresponsive amphiphilic copolymers were synthesized via ATRP with α -methyl, ω -bromo-functionalized PEG **P1** as the macroinitiators, PDMS-MA as the macromonomer, and MEAC as the photoactive monomer. Cu(I)/PMDETA was utilized as the catalyst/ligand system for the copolymers based on the 1-kDa macroinitiator P11, whereas Cu(I)/bipyridine was used for copolymers based on the 5- and 10-kDa macroinitiators $P1_5$ and $P1_{10}$, respectively. ATRP of PDMS-MA and MEAC was initiated with $P1_1$ using THF as a solvent at various macromonomer to macroinitiator ratios to yield copolymers with high PDMS-MA conversions, up to 95% (Table 2); the reaction was conducted at 60 °C. Longer PEG chain macroinitiators (P1₅ and P1₁₀) required a more polar solvent, *t*-BuOH, and higher temperature (90 °C) to yield copolymers with high PDMS-MA conversions, up to 96% (Table 2). MEAC conversions were observed to be >99% for all the synthesized copolymers, as MEAC was a smaller molecule which resulted in less steric constraints. Additionally, a smaller quantity of MEAC was used to ensure full conversion. Confirmation of the presence of anthracene moieties within the copolymers was determined using GPC analysis coupled with UV detection at a wavelength of 390 nm owing to a strong series of absorbance peaks between 320 and 400 nm.

¹H NMR spectroscopic analysis of the copolymers (Fig. 2) revealed characteristic methylene and methyl proton resonances (ca. $\delta_{\rm H} = 1.8$ and 1.0 ppm) associated with the methacrylate polymer backbone. The peak shifts to lower retention times in the GPC traces (Fig. 3) and ¹H NMR spectroscopic analysis confirmed the synthesis of the PEG/PDMS diblock copolymers. The integral ratios of the PEG repeat unit (ca. $\delta_{\rm H}$ = 3.6 ppm), PDMS repeat unit (ca. $\delta_{\rm H}$ = 0.7 ppm), and the total molecular weight of the anthracene moieties were used to calculate the M_n^{NMR} values (Table 2). The M_n values determined from NMR spectroscopy corresponded well to the theoretical values calculated from conversion and molar feed ratios (Table 2). $M_{\rm n}$ values obtained from the GPC UV traces differed significantly from those determined by NMR spectroscopy and theoretical molecular weight calculations. This most likely arises from inaccuracies caused by using a conventional calibration method with PEO standards for copolymers containing both PEG and PDMS moieties. Unfortunately, GPC coupled with multiangle light scattering detection could not be used as the polymers did not show sufficient peak intensities.

¹H NMR spectroscopic analysis of the copolymers revealed alkene proton resonances that correspond to small amounts (<8%) of unreacted PDMS-MA macromonomer (Fig. 2). These trace amounts of unreacted macromonomers were not removed as we have previously shown that the association of unreacted PDMS-MA with high-density brushes makes the complete removal difficult.³⁵ Closer examination of the GPC traces of copolymers revealed peaks at about 31 min, which corresponded to a combination of unreacted PDMS-MA and unfunctionalized PDMS (Fig. 3). The presence of the unfunctionalized PDMS in the PDMS-MA was detected via MALDI ToF MS although the amount of unfunctionalized PDMS could not be quantified as a result of possible preferential ionization during analysis (Supporting Information Fig. S8).

Self-assembly of PEG/PDMS Diblock Copolymers

Self-assembly of the linear–linear brush diblock copolymers was conducted in DMF, which is a selective solvent for the PEG block. The intensity-average hydrodynamic diameters ($d_{\rm H}$) of the PEG/PDMS nanoparticles formed from self-assembly in DMF were determined via DLS (Supporting Information Fig. S9) and ranged from 41 to 268 nm (Table 3). Correlation function plots revealed smooth profiles for all samples, implying a continuous distribution in the measured samples (Supporting Information Fig. S9). Control experiments were conducted in chloroform to measure the size of the unimers prior to self-assembly, as chloroform is a good solvent for both blocks (Table 3 and Supporting Information Fig. S10).

Figure 4 shows the plot of intensity-average hydrodynamic diameters ($d_{\rm H}$) of assembled particles versus the molecular weight of poly(PDMS-MA) brush block for various PEG block





FIGURE 3 GPC ultraviolet (UV) traces at 230 (—) and 390 nm (---) of PEG/PDMS diblock copolymers and their precursor macroinitiators **P1** and PDMS-MA macromonomer. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary. com.]

molecular weights. All three series (**P2**₁, **P2**₅, and **P2**₁₀) show an increasing trend in $d_{\rm H}$ with an increase in poly(PDMS-MA) brush block molecular weight. Interestingly, the **P2**₁ series has a much greater increase relative to the other series. Furthermore, the overall $d_{\rm H}$ decreased with an increase in the PEG block molecular weight from **P2**₁ to **P2**₁₀ series, which is not consistent with that normally observed for ordinary BCP self-assembly.^{42,43}

For the **P2**₁₀ series with PEG M_n of 10.5 kDa, the d_H of the self-assemblies increased from 41 to 47 nm as the molecular weight of the poly(PDMS-MA) block increased from 9 to 15 kDa. Judging from the molecular weight of each block and the size of the particles, the assembly structure is likely to be that of spherical micelles with the poly(PDMS-MA) brush block forming the core and PEG block forming the protective coronal shell. In comparison, for the **P2**₁ series with PEG M_n of 1.1 kDa, the assembled particle sizes were significantly larger (e.g., 151 and 268 nm) relative to the theoretical max-

imum micelle diameter, which was based on twice the calculated contour length of each copolymer (Table 3). Therefore, it is proposed that different assembled structures are formed in this case.

In amphiphilic BCP self-assembly, LCMs or crew-cut aggregates are formed when BCPs with one block that is far shorter than the other blocks are assembled in selective solvents for the shorter block.^{42,43} For example, Eisenberg⁴³ observed such aggregates for the assembly of polystyrene-*b*poly(acrylic acid) (PS_{200} -*b*-PAA₄) in a selective solvent for PAA. In these LCMs, PAA is located on the surface of the particles as well as within the particles as isolated domains. Similarly, the nanoparticles formed from the **P2**₁ series of linear-linear brush diblock copolymers observed in this study are likely to form similar LCMs. Interestingly, the particle size increased substantially to 268 nm when the molecular weight of poly(PDMS-MA) was increased from 5 to 8 kDa in the **P2**₁ series self-assemblies. This behavior is the first

		Unimers (CHCI ₃)	Self-asser (DMI	nblies =)	Photocros Assemi (CHC)	slinked olies I ₃)	Theoretical Maximum
Polymer	PDMS (wt %) ^a	<i>d</i> _H (nm)	PDI	<i>d</i> _H (nm)	PDI	<i>d</i> _H (nm)	PDI	Micelle Diameter (nm) ^b
P2 _{1/5}	63	0.8	0.03	151	0.17	165	0.20	20 ^c
P2 _{1/8}	78	0.9	0.03	268	0.17	275	0.24	20 ^c
P2 _{5/4}	36	0.8	0.02	72	0.10	78	0.26	74 ^c
P2 _{5/7}	50	1.0	0.02	80	0.14	88	0.24	74 ^c
P2 _{5/9}	60	1.0	0.02	85	0.15	90	0.24	74 ^c
P2 _{10/9}	41	1.2	0.03	41	0.04	54	0.18	142 ^c
P2 _{10/12}	52	1.3	0.02	42	0.04	54	0.17	143 ^d
P2 _{10/15}	58	1.3	0.03	47	0.07	50	0.19	145 ^d

TABLE 3 Intensity-Average Hydro	dynamic Diameters of PEG/PDMS	Diblock Copolymer Self-assemblies
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 $^{\rm a}$ wt % PDMS calculated from number-average molecular weight measured by $^{\rm 1}{\rm H}$ NMR spectroscopic analysis.

^b Theoretical maximum micelle diameter was calculated as twice of each copolymer's contour length, representing the maximum possible diameter for spherical micelles.

such observation for LCMs formed from linear–linear brush BCPs. TEM images of **P2**_{1/5} showed a spherical morphology and diameters of 50–220 nm (Fig. 5(a)), which is in agreement with the results of DLS ($d_{\rm H} = 151$ nm, polydispersity index [PDI] = 0.17). The spherical morphology of the particles and the relatively polydisperse system is in agreement with the reported LCM morphology.

For the **P2**₅ series with a PEG block of M_n of 5.2 kDa, a similar trend to that of the **P2**₁₀ series was observed; however, the particle sizes are bigger. Therefore, these particles are likely to represent a transition from spherical micelles to LCMs. Again, particles with spherical morphologies were observed in TEM images (Fig. 5(c)).

Eckert and Webber⁴⁴ observed similar aggregation behavior when a random polystyrene-*alt*-maleic anhydride-*graft*-PEO



FIGURE 4 Intensity-average hydrodynamic diameter ($d_{\rm H}$) of self-assembled nanoparticles as a function of poly(PDMS-MA) number-average molecular weight determined from NMR spectroscopic analysis. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

 $^{\rm c}$ Contour length was calculated based on the stretched PEG backbone and stretched grafted PDMS side chain.

 $^{\rm d}$ Contour length was calculated based on the stretched PEG backbone and stretched grafted PDMS backbone.

was utilized for self-assembly in an aqueous NaCl solution. When the DP of the PEG branch was reduced, a substantial increase in particle size (or aggregation number) was observed. The reduction in the number of PEG-grafted side chains also reduced the stabilization capacity of the particles, resulting in an increase in particle size. This reported trend is similar to the trend observed in this study when the molecular weight of PEG block is reduced.

Photocrosslinking of PEG/PDMS Diblock Copolymers

Crosslinking of the soft nanoparticles was conducted to covalently stabilize the structure and prevent disassembly in good solvents for both the PEG and the PDMS blocks. All of the samples were photocrosslinked using UV radiation. The anthracene moieties incorporated into the PDMS segment of the BCP are photosensitive and photodimerize upon exposure to UV radiation at wavelengths >300 nm (Scheme 2).⁴¹ The [4+4] photodimerization of anthracene forms an orthosubstituted benzene molecule. Once dimerized, it does not absorb light at wavelengths >300 nm, making the reaction easy to monitor spectrophotometrically.⁴⁵ It is well known that the dimerization predominantly occurs in a "head-tohead" arrangement as shown in Scheme 2.^{41,46}

Samples containing self-assemblies in DMF were exposed to UV radiation with a wavelength of 365 nm for 4 h and then they were tested for their UV absorbance between 300 and 420 nm to monitor the progress of the photodimerization (Fig. 6 and Supporting Information Fig. S11). A decrease in UV absorption is indicative of anthracene moieties losing their conjugated structure owing to dimerization. The extent of crosslinking was found to vary between 81 and 91% (Table 4). A small fraction of nondimerized anthracene moieties residing within the dense PDMS core were unable to couple, possibly as a result of steric hindrance within the



FIGURE 5 TEM images of (a) P2_{1/5}, (b) photocrosslinked P2_{1/5}, (c) P2_{5/7}, and (d) photocrosslinked P2_{5/7}. Scale bars = 200 nm.

core. However, 100% dimerization is not required to effect successful stabilization of the assemblies.

Samples were concentrated to remove DMF, and then diluted with chloroform to verify the extent of crosslinking; chloroform is a good solvent for both blocks. From DLS analysis, similar single peaks were detected, which implied that all of the self-assembled copolymers had been crosslinked. Additionally, correlation function plots revealed smooth profiles, verifying no aggregation in the measured samples (Supporting Information Fig. S12). Dilution of the samples below their CMCs (Supporting Information Table S1) showed no evidence of dissociation which further confirmed successful crosslinking of the nanoparticles (Supporting Information Fig. S13).

DLS analysis revealed that the $d_{\rm H}$ values were found to increase slightly from the uncrosslinked values recorded for all of the crosslinked nanoparticles. Rearrangement of the anthracene moieties to undergo crosslinking possibly forces



SCHEME 2 Mechanism for photodimerization and photocleavage anthracene of molecules.



FIGURE 6 UV–Vis spectra of $P2_{5/4}$ upon exposure to UV radiation (365 nm) for 4 h. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

the chains into a larger and less well-packed structure, leading to a slight increase in particle size (Table 3). The photocrosslinking also led to an increase in PDI, implying a more dispersed nanoparticle size distribution (Table 3).

The reversibility of the crosslinked anthracene moieties was investigated by monitoring the UV absorption of the photocrosslinked **P2** under irradiation at a lower wavelength of 254 nm for 20 h. Results indicated that on average only 15% of the dimerized anthracene moieties were converted back to the unimolecular state (Supporting Information Table S2 and Supporting Information Fig. S14). These results are in agreement with the previously published results which suggest that the presence of the carbonyl functionality inhibits the complete photocleavage process.^{47,48}

TEM images of the crosslinked **P2**_{1/5} and **P2**_{5/7} nanoparticles (Figure 5(b,d)) revealed nanoparticles with spherical morphologies of 70–240 and 60–100 nm in diameters, which is again in agreement with the results from DLS ($d_{\rm H} = 165$ nm, PDI = 0.20, and $d_{\rm H} = 88$ nm, PDI = 0.24, respectively).

CONCLUSIONS

Well-defined photocrosslinkable diblock copolymers based on PEG and PDMS were successfully prepared. A range of molecular weights of monomethyl ether PEG were quantitatively functionalized with alkyl bromides to afford macroinitiators suitable for ATRP. Subsequently, ATRP with these PEG initiators, a PDMS-MA macromonomer, and an anthracenebased monomer was employed to synthesize photocrosslinkable diblock copolymers with different molecular weight poly(PDMS-MA) blocks in high conversions (88-96%). Selfassembly of these diblock copolymers in DMF resulted in the formation of nanoparticles, which were subsequently crosslinked via [4+4] photodimerization. TEM analysis showed that the self-assembled diblock copolymers and their crosslinked derivatives had spherical morphologies. DLS studies revealed that the assembly configuration of the nanoparticles is heavily reliant on the individual block lengths of the linear-linear brush diblock copolymers, and is likely to vary

TABLE 4 Extent of Photodimerization	of the Anthracene
Groups for more than 4 h	

Polymers	Extent of Photodimerization (%)
P2 _{1/5}	91
P2 _{1/8}	87
P2 _{5/4}	81
P2 _{5/7}	86
P2 _{5/9}	86
P2 _{10/9}	86
P2 _{10/12}	88
P2 _{10/15}	82

from spherical micelles to LCMs. The synthetic approach outlined in this article is a viable strategy to synthesize stable soft nanoparticles that can be utilized for different applications such as additives for membrane to improve their gas separation performance.

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