Aggregation Phenomena of Amphiphilic UVB Absorptive Oligoesters Containing *p*-Alkoxycinnamate and Poly(ethylene oxide) Blocks

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Received 26 October 2008; accepted 31 July 2009
DOI 10.1002/app.31196
Published online 7 October 2009 in Wiley InterScience (www.interscience.wiley.com).

ABSTRACT: The synthesis of new amphiphilic oligoesters containing a hydrophobic block based on *p*-alkoxycinnamate and hydrophilic poly(ethylene oxide) is reported. Two hydrophobic monomers, 1,2-(bis(4-(2-carboxyvinyl)-phenoxy))ethane (**M2**) and 1,12-(bis(4-(2-carboxyvinyl) phenoxy))dodecane (**M12**), were synthesized. Four oligoesters, poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane) -*co*-(poly(ethylene oxide)200)) (**P2-200**), poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide) 400)) (**P2-400**), poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy)) dodecane)-*co*-(poly(ethylene oxide)400)) (**P12-400**), and poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-*co*-(poly(ethylene oxide)1000)) (**P12-1000**) were then constructed by reacting the **M2** or **M12** with poly(ethylene oxide) (PEO) with lengths of $\sim$ 4 (PEO 200), $\sim$ 10 (PEO 400), or $\sim$ 23 (PEO1000) units using multiple esterifications. These oligoesters possess UVB absorption properties and show good solubility in various organic solvents. Self-assembly of the oligoesters into aqueous spherical colloids could be induced through an acetone to water solvent displacement technique. © 2009 Wiley Periodicals, Inc. J Appl Polym Sci 115: 1724–1731, 2010

Key words: alkoxycinnamate; oligoester; sunscreen; colloid

INTRODUCTION

Different varieties of amphiphilic polymeric materials, both block copolymers and grafted polymers, have been synthesized and formed into countless of nanoscale architectures.[1–4] Nanostructure formation of amphiphilic polymers can be explained by the thermodynamic incompatibility between the hydrophilic and hydrophobic blocks, which makes the polymer chains to self-organize in the way that the contact between similar and dissimilar blocks are maximized and minimized, respectively.[5] Macrophase separation is prevented by the entropic forces stemming from the covalent bonds holding the hydrophilic and hydrophobic blocks together. The system, then, must reach a balance between mixing and separating[6] and this usually results in self-assembled structures, in which microphase separation is observed. It has been demonstrated that such balance is a function of several variables, such as the chemical structure of the block copolymer, ions in the solvent, concentration, and solvent selectivity.[7–9] During the self-assembly of amphiphilic polymers in an aqueous system or other polar solvents, the hydrophilic blocks (solvent–soluble block) usually form the corona, which provides the stabilization, whilst the hydrophobic blocks (solvent–insoluble polymer block) produce the core isolating the nanoparticles from the solvent.

Esters of *p*-methoxycinnamic acid are among the popular UVB screening compounds used in various sunscreen products. The most widely used derivative in this group is the 2-*ethylhexyl*-*p*-methoxycinnamate (EHMC), which possesses a high molar absorption coefficient (ε = 22,000–24000 M^{-1} cm^{-1} at 310 nm), and shows only few allergic reactions to human skin.[10,11] Nevertheless, transdermal penetration of EHMC through human skin has been reported, leading to the reduction of UV filtering efficiency at the skin surface.[12,13] Attempts to increase the skin accumulation of organic UV absorbers include incorporations of the UV filters into delivery systems[14,15] and some alterations in the formulations.[16] In addition, a few novel polymeric sunscreens have been developed recently under the assumption that large molecules presumably will have very low transdermal absorption.[17–21] To overcome these transdermal penetration problems, we have synthesized block-type-macromolecular amphiphilic chromophores containing a

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Contract grant sponsors: Thailand Research Fund, Office of Commission for Higher Education, Chulalongkorn University Graduate Thesis Grant.

hydrophobic block based on *p*-alkoxycinnamate and hydrophilic poly(ethylene oxide). Studies of the self-assembly of the obtained oligoesters into nano/microspheres are also demonstrated and correlation between hydrophobicity to hydrophilicity ratio and particle sizes are presented.

EXPERIMENTAL

Materials

Solvents used in syntheses and spectroscopic works were reagent or analytical grades purchased from Labscan (Bangkok, Thailand) and Carlo Erba Reagents (Rodano, Italy). Solvents used for column chromatography were purified from commercial grade solvents before use by distillation. 4-Hydroxybenzaldehyde, 1,2-dibromoethane, 1,12-dibromododecane, malonic acid, all polyethylene glycol's (M_W = 200, 400, and 1000) were purchased from Acros Organics (Geel, Belgium). Potassium carbonate was purchased from Fluka Chemical Company (Buchs, Switzerland). Piperidine was purchased from Sigma Chemical Co. (Steinheirg, Germany). The membranes used for dialysis were CelluSep T4 dialysis tube (MWCO 12,000–14000, 75 mm flat width, 17.9 mL/cm volume capacity, Membrane Filtration Products, Seguin, TX, USA). Column chromatography was performed using silica gel (Merck Kieselgel 60 G) (Merck KgaA, Darmstadt, Germany). Molecular weights were determined at room temperature by gel permeation chromatography using Waters styragel HR low molecular weight column and Waters 600E Multisolvent Delivery System (Waters, MA, USA), with tetrahydrofuran as a mobile phase. The IR spectra were recorded on a Nicolet Fourier Transform Infrared spectrophotometer (FTIR) using an Impact 410 (Nicolet Instrument Technologies, Madison, WI, USA). ^{1}H and ^{13}C-nuclear magnetic resonance (NMR) spectra were obtained using a Varian Mercury spectrometer (Varian Company, Palo Alto, CA, USA). A thermogram of each sample was obtained by differential scanning calorimetry using a DSC 204 (Netzsch Group, Selb, Germany). UV spectra were obtained with the aid of UV 2550 UV/VIS spectrophotometer (Shimadzu Corporation, Kyoto, Japan). MALDI mass spectra were recorded on an Ultraflex MALDI-TOF mass spectrometer (Bruker Daltonics, Bremen, Germany) with either sinapinic acid (m/z = 224.07) or 2,5-dihydroxybenzoic acid (m/z = 154.03). ESI-MS analyses were performed with Waters Micromass Quattomicro API ESCi (Waters, MA, USA).

Synthesis of monomers

1,2-(Bis(4-(formylphenoxy))ethane) (1)

In a two-necked round bottom flask, attached with a condenser and purged with N_2, 4-hydroxybenzaldehyde (6.1 g, 0.05 moles) was dissolved in acetonitrile (70 mL). Potassium carbonate (10 g) and 1,2-dibromoethane (13.0 g) were added and the mixture was refluxed until no 4-hydroxybenzaldehyde could be detected by TLC. The reaction mixture was then evaporated and the residual solute dissolved in 100 mL dichloromethane, washed three times with water and dried with anhydrous sodium sulfate to remove the water. The crude product was then purified by column chromatography on silica gel using dichloromethane / hexane (40 : 60 (v/v)) as the eluent. The product was obtained as white solid: 68%.

R_f: 0.40 (SiO_2, EtOAc/hexane, 1 : 1). ^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 9.91 (s, 2H, Ar—C**H**O), 7.87 (d, J = 8.58 Hz, 4H, Ar—**H**), 7.06 (d, J = 8.58 Hz, 4H, Ar—**H**), 4.45 (s, 4H, —C**H$_2$**—O—Ar). MS (m/z): calculated for $C_{16}H_{12}O_4$, 270; found, 270 $[M]^+$.

1,12-(Bis(4-(formylphenoxy))dodecane) (2)

1,12-(Bis(4-(formylphenoxy))dodecane) **(2)** was prepared using the same procedure mentioned earlier, except that 1,2-dibromoethane was replaced by 1,12-dibromododecane (4.7 g). Product obtained as white solid: 68%.

R_f: 0.70 (SiO_2, EtOAc/hexane, 1 : 1). ^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 9.92 (s, 2H, Ar—C**H**O), 7.87 (d, J = 8.58 Hz, 4H, Ar—**H**), 7.03 (d, J = 8.58 Hz, 4H, Ar—**H**), 4.08 (s, 4H, —C**H$_2$**—O—Ar), 1.85–1.34 (br, 20H, —C**H$_2$**—). MS (m/z): calculated for $C_{22}H_{18}O_4$, 410; found, 410 $[M]^+$.

1,2-(Bis(4-(2-carboxyvinyl)phenoxy))ethane (M2)

In a two-necked round bottom flask, attached with condenser, compound **1** (13.50 g, 0.05 mole) was dissolved in pyridine (50 mL) and then malonic acid (20.80 g, 0.20 mole) and piperidine (1 mL) were added. The mixture was heated at 78 – 80°C for 74 h. After being cooled, most of the solvent was removed and the mixture was acidified with 200 mL of 2 *M* HCl. The solid product separated by suction filtration and washed with water was white solid: 70%.

m.p. 310–315°C, UV-Vis (λ_{max}): 308 nm (ε_{max} = 44,000 $M^{-1}cm^{-1}$), IR (KBr, thin film, cm^{-1}): 3200–2400, 1677, 1599, 1509, 1241, ^{1}H-NMR (400 MHz, DMSO-d_6, δ, ppm): 12.23 (s, 1H, —COO**H**), 7.58 (d, J = 8.58 Hz, 4H, Ar—**H**), 7.48 (d, J = 16.38 Hz, 2H, Ar—C**H**=), 6.96 (d, J = 8.58 Hz, 4H, Ar—**H**), 6.32 (d, J = 16.38 Hz, 2H, Ar—C**H**=), 4.31 (s, 4H, —C**H$_2$**—O—Ar) ppm, ^{13}C-NMR (100 MHz, DMSO-d_6, δ, ppm): 168.3 (—**C**OOH), 160.4 (—**C**—), 144.1 (Ar—**C**H=), 130.4 (aromatic carbons), 127.5 (—**C**—), 117.1 (=**C**H—COOH), 115.3 (aromatic carbons), 66.9 (—**C**H$_2$—O—Ar). MS (m/z): calculated for $C_{20}H_{18}O_6$, 354; found, 353 $[M—H]^-$.

1,12-(Bis(4-(2-carboxyvinyl)phenoxy))dodecane (M12)

1,12-(Bis(4-(2-carboxyvinyl)phenoxy))dodecane **(M12)** was prepared from compound **2** using the same procedure as described earlier for the **M2** preparation, except that compound **1** was replaced with compound **2** (20.50 g). The product was obtained as white solid: 60%.

m.p. 202–205°C. UV–Vis (dimethylformamide) λ_{max}, nm (ε): 308 (45,000). IR (KBr, thin film, cm^{-1}): 3200−2400, 1671, 1593, 1511, 1246. ^{1}H-NMR (400 MHz, DMSO-d_6, δ, ppm): δ7.58 (d, J = 8.58 Hz, 4H, Ar—**H**,), 7.50 (d, J = 16.38 Hz, 2H, Ar—C**H**=), 6.92 (d, J = 8.58 Hz, 4H, Ar—**H**), 6.34 (d, J = 16.38 Hz, 2H, Ar—C**H**=), 3.97 (s, 4H, —C**H$_2$**—O—Ar), 1.68−1.24 (br, 20H, —C**H$_2$**—). ^{13}C-NMR (100 MHz, DMSO-d_6, δ, ppm): 168.3 (—**C**OOH), 160.8 (—**C**—), 144.0 (Ar—**C**H=), 130.3 (aromatic carbons), 127.4 (—**C**—), 117.0 (=**C**H—COOH), 115.2 (aromatic carbons), 68.0 (—**C**H$_2$—O—Ar), 29.4−25.9 (—**C**H$_2$—). MS (m/z): calculated for $C_{30}H_{38}O_6$, 494; found, 493 $[M—H]^-$.

Synthesis of oligoesters

Poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide)200)) (P2-200)

A mixture of monomer **M2** (0.354 g, 1 mmol) and freshly distilled thionyl chloride (15 mL) was refluxed for 3 h in a two-necked round bottom flask attached with a condenser and a drying tube. Unreacted thionyl chloride was then removed by evaporation under reduced pressure resulting in 1,2-(bis(4-(2-chlorocarbonyl vinyl)phenoxy))ethane. Poly(ethylene oxide), $\overline{M_n}$ = 200, (0.02 g, 1 mmol) and 20 mL acetonitrile were then added, and the mixture was refluxed for 28 h. The reaction mixture was cooled to room temperature, the solvent was removed by reduced pressure evaporation and the residual solute dissolved in 50 mL ethyl acetate, washed three times with water and then dried with anhydrous sodium sulfate. The product was yellowwax-like solid.

^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 7.65 (d, J = 15.60 Hz, Ar—C**H**=), 7.47 (d, J = 7.9 Hz, Ar—**H**), 6.95 (d, J = 8.0 Hz, Ar—**H**), 6.35 (d, J = 15.60 Hz, Ar—C**H**=), 4.36−4.34 (—C**H$_2$**—O—Ar, —COO— C**H$_2$**—), 3.78−3.63 (—C**H$_2$**—O—). IR (NaCl, cm^{-1}): 1705, 1599, 1510, 1244. UV–Vis (dimethylformamide) λ_{max}, nm (ε): 311 (51,000). DSC: T_g = −18.8°C, T_m = 91.1°C.

Poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide)400)) (P2-400), Poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-*co*-(poly(ethylene oxide)400)) (P12-400), and Poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy)) dodecane)-*co*-(poly(ethylene oxide)1000)) (P12-1000)

Poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide)400)) (**P2-400**) (yellow-oil) and poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-*co*-(poly(ethylene oxide)400)) (**P12-400**) (yellow wax) were prepared from 1,2-(bis(4-(2-chlorocarbonylvinyl)phenoxy))ethane **(M2)** and 1,12-(bis(4-(2-chlorocarbonylvinyl)phenoxy)) dodecane (**M12**), respectively, using the same procedure as described earlier for the **P2-200** preparation, except that poly (ethylene oxide), $\overline{M_n}$ = 200 was replaced with poly(ethylene oxide), $\overline{M_n}$ = 400, (0.04 g, 1 mmol). Poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane) -*co*-(poly(ethylene oxide)1000)) (**P12-1000**) (yellow wax) was prepared from 1,12-(bis(4-(2-chlorocarbonylvinyl)phenoxy)) dodecane **(M12),** using similar proceedure except that poly(ethylene oxide), $\overline{M_n}$ = 400 was replaced with poly(ethylene oxide), $\overline{M_n}$ = 1000, (0.10 g, 1 mmol).

*Poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-co-(poly(ethylene oxide)400))**(P2-400)***. ^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 7.66 (d, J = 15.60 Hz, Ar—C**H**=), 7.49 (d, J = 7.8 Hz, Ar—**H**), 6.95 (d, J = 7.8 Hz, Ar—**H**), 6.36 (d, J = 15.6 Hz, Ar—C**H**=), 4.36 (d, —C**H$_2$**—O—Ar, —COO—C**H$_2$**—), 3.79−3.60 (—C**H$_2$**—O—). IR (neat, cm^{-1}): 3700−3300, 1705, 1603, 1514, 1244. UV–Vis (dimethylformamide) λ_{max}, nm: 311. DSC: T_g= −20.1°C

*Poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-co-(poly(ethylene oxide)400))**(P12-400)***. ^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 7.66 (d, J = 15.60 Hz, Ar—C**H**=), 7.46 (d, J = 7.8 Hz, Ar—**H**), 6.89 (d, J = 7.8 Hz, Ar—**H**), 6.34 (d, J = 15.60 Hz, Ar—C**H**=), 4.35 (—C**H$_2$**—O—Ar), 3.98 (—COO—C**H$_2$**—), 3.70 (—C**H$_2$**—O—), 1.8 (br, —C**H$_2$**—). IR (NaCl, cm^{-1}): 3700−3300, 1709, 1603, 1501, 1248. UV–Vis (dimethylformamide) λ_{max}, nm: 311. DSC: T_g = −50.7°C, T_m = 79.0°C.

*Poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-co-(poly(ethylene oxide)1000))**(P12-1000)***. ^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 7.66 (d, J = 15.60 Hz, Ar—C**H**=), 7.47 (d, J = 7.8 Hz, Ar—**H**), 6.86 (d, J = 7.8 Hz, Ar—**H**), 6.34 (d, J = 15.60 Hz, Ar—C**H**=), 4.36 (—C**H$_2$**—O—Ar), 3.98 (—COO—C**H$_2$**—), 3.70 (—C**H$_2$**—O—), 1.76 (br, —C**H$_2$**—). IR (NaCl, cm^{-1}): 3700−3300, 1708, 1600, 1500, 1247. UV–Vis (dimethylformamide) λ_{max}, nm: 311. DSC: T_g = −58.7°C.

Poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide)400)) at higher concentration (P2-400c)

1,2-(Bis(4-(2-chlorocarbonylvinyl)phenoxy))ethane was prepared as aforementioned. Polymerization was also carried out using the same procedure as described for **P2-400** preparation except that only 5 mL of CH_3CN was used instead of 20 mL. the product obtained as yellow-oil.

^{1}H-NMR (400 MHz, $CDCl_3$, δ, ppm): 7.66 (d, J = 15.60 Hz, Ar—C**H**=), 7.49 (d, J = 7.8 Hz, Ar—**H**), 6.95

(d, $J = 7.8$ Hz, Ar—**H**), 6.36 (d, $J = 15.6$ Hz, Ar—C**H**=), 4.38–4.34 (—C**H$_2$**—O—Ar, —COO—C**H$_2$**—), 3.79–3.60 (—C**H$_2$**—O—). UV–Vis (dimethylformamide) λ_{max}, nm: 311. DSC: $T_g = -15.82°C$

Particle formation

Preparation of the particles from **P2-200**, **P2-400**, **P12-400,** and **P12-1000** was carried out by a solvent displacement technique. Twenty milligrams of the oligoester were dissolved in 5 mL acetone. The solution (4000 ppm) was dialyzed against deionized water (Milli-Q®).

Particle size, zeta potential, SEM, and TEM analyses

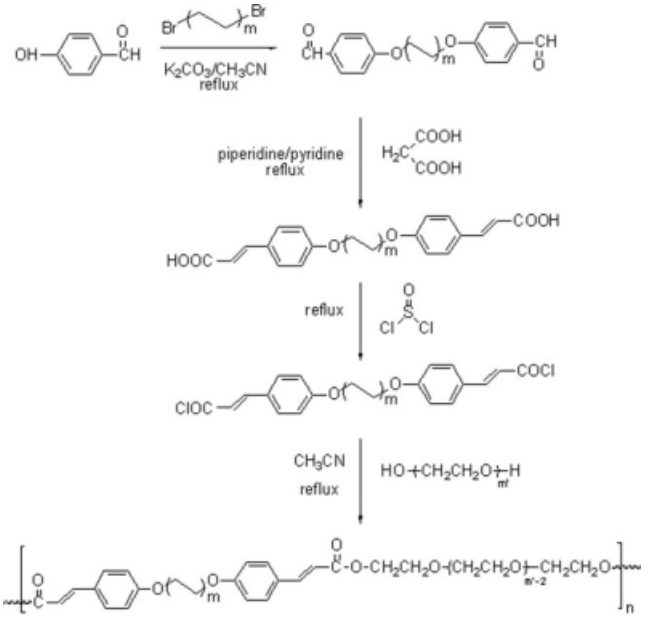
transmission electron microscopic (TEM) photographs were acquired on a TEM (JEM-2100, JEOL, Japan) with an accelerating voltage of 100–120 kV in conjunction with selected area electron diffraction.

Scanning Electron Microscopic (SEM) photographs were obtained using SEM (JSM-6400, JEOL, Japan). A drop of the nanoparticle suspension was placed on a glass slide and dried over night. After mounting the slide on an aluminum pin, the sample was coated with a gold layer under vacuum at 15 kV for 90 sec. The coated sample was then mounted on a SEM stud for visualization. The accelerating voltage used was 15 kV.

The particle sizes of the particles in water were acquired by Zetasizer nanoseries (Mulvern Instruments, Worcestershire, UK) equipped with He-Ne laser beam at 632.8 nm (scattering angle of 173°). The concentration of particles in water was diluted to about 0.1 mg/mL. Each measurement was repeated five times with the average value ±1 S.D. being reported.

RESULTS AND DISCUSSION

1,2-(Bis(4-(formyl phenoxy))ethane) **(1)** and 1,12-(bis(4-(formyl phenoxy))dodecane) **(2)** were successfully synthesized by the S_N2 reactions between 4-hydroxybenzaldehyde and 1,2-dibromoethane or 1,12-dibromododecane. These dialdehydes were then reacted with malonic acid using the Knoevenagel condensation reaction to produce 1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane (**M2**) or 1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane (**M12**) (Scheme 1). The UV absorption spectra of **M2** and **M12** showed a maximum absorption peak at 308 nm ($\varepsilon_{308\ nm}$ = 44,000 (**M2**) and 45,000 (**M12**) $M^{-1}cm^{-1}$). The ε values of both monomers were essentially double the value of 2-ethylhexyl-*p*-methoxy cinnamic acid (22,000 $M^{-1}cm^{-1}$), confirming that both **M2** and **M12** most likely contain two cinnamoyl moieties in their



Scheme 1 Synthesis of **M2** ($m = 1$), **M12** ($m = 6$), **P2-200** ($m = 1$, $m' \sim 4$), **P2-400** ($m = 1$, $m' \sim 10$), **P12-400** ($m = 6$, $m' \sim 10$), and **P12-1000** ($m = 6$, $m' \sim 23$).

molecules. The monomers were found to be soluble in pyridine, DMF, and DMSO.

The poly((1,2-(bis(4-(2-carboxyvinyl)phenoxy))-ethane)-*co*-(poly(ethylene oxide)200)) (**P2-200**), poly ((1,2-(bis(4-(2-carboxyvinyl)phenoxy))ethane)-*co*-(poly(ethylene oxide)400)) (**P2-400**), poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-*co*-(poly(ethylene oxide)400)) (**P12-400**), and poly((1,12-(bis(4-(2-carboxyvinyl)phenoxy))dodecane)-*co*-(poly(ethylene oxide)1000)) (**P12-1000**) were prepared by copolymerizations between **M2** or **M12** with poly(ethylene oxide) that had a number–average molecular weight ($\overline{M_n}$) of 200, 400 or 1000. While **M2** and **M12** themselves were not soluble in CH_3CN, their acid chloride derivatives were, allowing the condensation polymerizations to take place in CH_3CN. The FTIR spectra (Fig. 1) of all oligoesters showed the characteristic absorptions of conjugated ester groups to be around 1705–1709 cm^{-1} and 1000–1300 cm^{-1}. The ^{1}H-NMR spectra of **P2-200** and **P2-400** show —C**H$_2$**—O— resonance at ~ 3.7 ppm, indicating the presence of polyethylene oxide (Fig. 2). The appearance of —COO—C**H$_2$**— resonance at ~ 4.3 ppm also confirms the successful esterifications. The ^{1}H-NMR spectra of **P12-400** and **P12-1000** also show resonances at ~ 3.7 ppm (—C**H$_2$**—O—) and ~ 3.9 ppm (—COO—C**H$_2$**—), indicating polyethylene oxide chain (Fig. 2).

Progress of the polymerization reaction followed by analyzing the $\overline{M_n}$ of the reaction mixture at various reaction times using gel permeation chromatography. The polymerization was completed within few hours and the $\overline{M_n}$ for **P2-200**, **P2-400P12-400**,

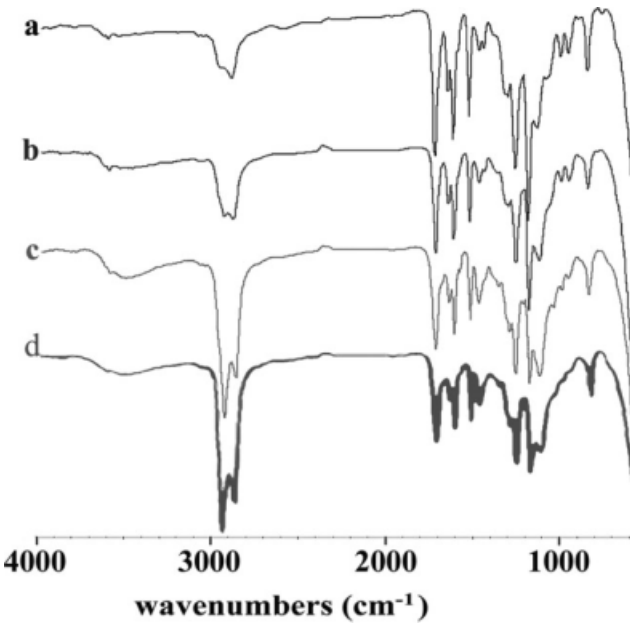


Figure 1 FTIR spectra of a) P2-200, b) P2-400, c) P12-400, and d) P12-1000.

and **P12-1000** were found to be 2100, 2600, 2100, and 2600 Daltons, respectively (Fig. 3). It was speculated that the low $\overline{M_n}$ values were the result of ring closure from intramolecular reactions between the two ends of the same chain. Therefore, polymerization at a higher monomer concentration **(P2-400c)** was carried out and the oligomer so obtained **(P2-400c)** was found to possess an average $\overline{M_n}$ of 4800, compared with the $\overline{M_n}$ of 2600, obtained with a lower reaction concentration of the monomers **(P2-400)**. This result supports the above speculation of intramolecular ring closure and indicated a possible mechanism (reactant concentration) for control of the size of the product. For further confirmation, the potentially cyclized products were analyzed by mass spectrometry. The MALDI-TOF MS spectra of the four oligomers gave *m/z* values of 688, 732, and 776 for **P2-400**, 828, 872, and 916 for **P12-400**, and finally 468, 512, and 556 for **P2-200**. Together with the lack of a broad absorption band around 2300–3600 cm^{-1} (—COOH) in the FTIR spectra of the oligomers (Fig. 1), these data confirm the complete condensation reactions.

All oligoesters showed similar UV absorption wavelengths (λ_{max} of 310 nm in acetone) to their corresponding monomers and are soluble in many organic solvents such as acetonitrile, acetone, ethyl acetate, tetrahydrofuran, chloroform, and dichloromethane. This solubility is probably related to their low molecular weight, resulting from polymerization under dilute condition as stated above. Solubility of oligoesters in acetone enables self-assembly of these oligomers through the displacing of acetone with water as discussed below. Thus, no attempt was

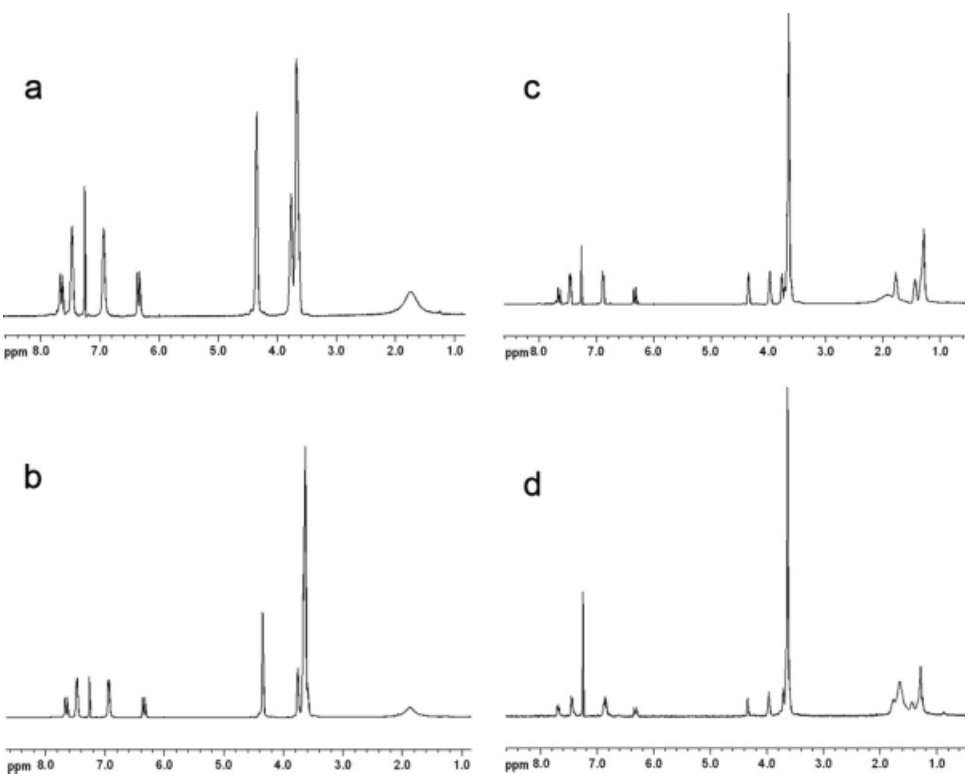


Figure 2 ^{1}H-NMR of a) P2-200, b) P2-400, c) P12-400, and d) P12-1000.

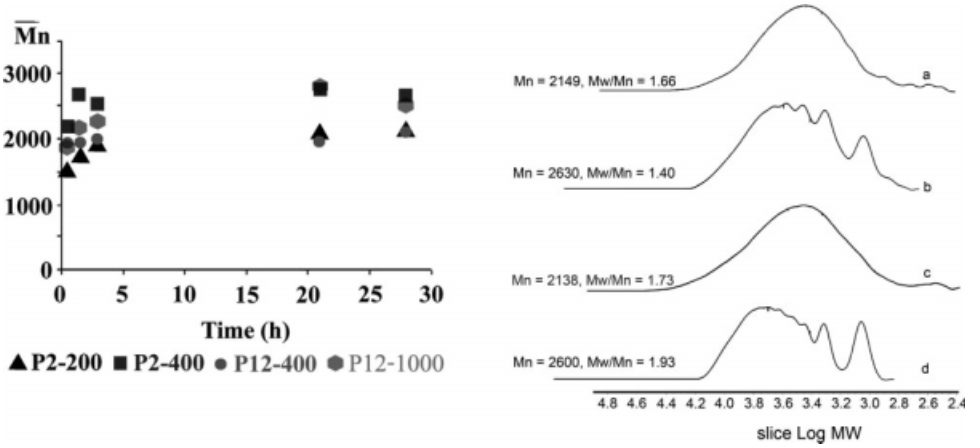


Figure 3 Molecular weight information of the synthesized oligoesters. Left: Number-average molecular weight ($\overline{M_n}$) of oligoesters obtained at various reaction times. Right: Gel permeation chromatograms of a) **P2-200**, b) **P2-400**, c) **P12-400**, and d) **P12-1000**.

made to increase the molecular weight of the products. Instead, study was geared toward the formation of nano- and micro-spheres for application in cosmetics and pharmaceutical area.

The four synthesized oligoesters, **P2-200**, **P2-400**, **P12-400**, and **P12-1000**, could be self-assembled into submicron- / micron-size-particles by the solvent displacement technique (displacing acetone with water). The particles obtained at the concentration of 0.40% (w/v) oligoester were aqueous colloidal suspensions with mean hydrodynamic diameters of $\sim$ 400–600 nm for **P2-200**, **P2-400**, and **P12-1000** (Fig. 4). Interestingly, **P12-400** suspension showed micro-size-particles ($\sim$ 3 μm). The SEM and TEM images indicate micelle-like-spherical architecture for all four self-assembled particulates (Fig. 5). These results agree well with the fact that all four oligomers possess hydrophilic weight fraction (*f factor*) of more than 40%.[22] Self-assembly of these oligomers in water should result in particles with hydrophobic *p*-alkoxycinnamate core and water soluble PEO corona. When the hydrophobic block was ethoxycinnamate or ((1,2-(bis(4-(2-carboxyvinyl)phenoxy))-ethane), changing the PEO block length from $\sim$ 4 to $\sim$ 10 ethylene oxide units resulted in a slight decrease of the particle sizes (comparing **P2-200** and **P2-400** particles). A higher hydrophilic to hydrophobic ratio, or a longer hydrophilic block in **P2-400**, compared to **P2-200**, provides enough tethered PEO chains on the particles' surfaces to afford stability to the smaller particles. However, when the length of the hydrophobic block was increased to dodecoxycinnamate or ((1,12-(bis(4-(2-carboxyvinyl)phenoxy))-dodecane), the length of PEO block was found to significantly affect the particle sizes. In the case of **P12-400**, in which the PEO block length is $\sim$ 10 ethylene oxide units, the hydrophilic to hydrophobic ratio is probably too low to provide enough of a PEO corona for the stabilization of nano-size particles, thus the micron-size particles were observed. When the PEO block length increased to the average

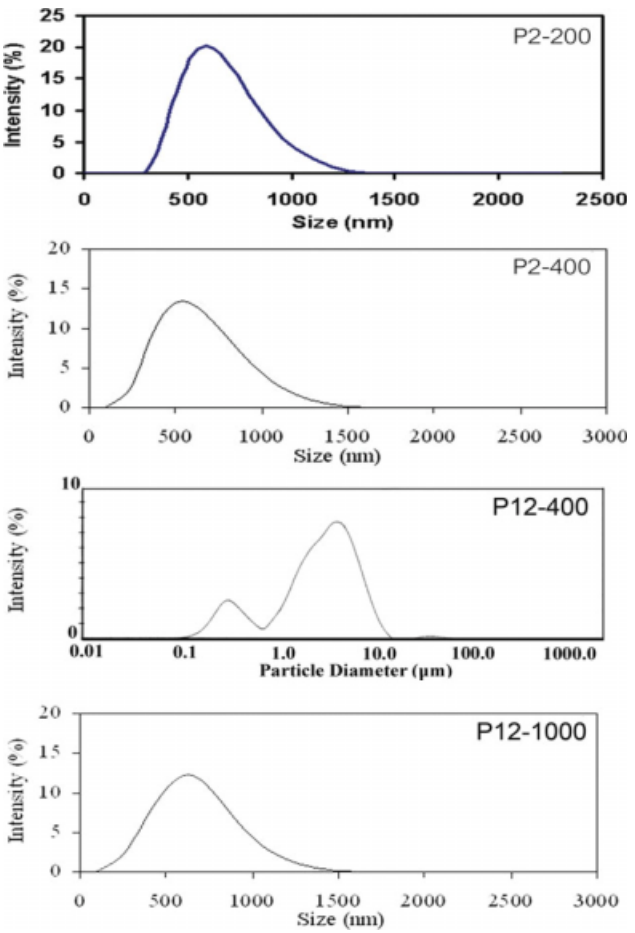


Figure 4 Size distribution profiles obtained from dynamic light scattering analysis of **P2-200**, **P2-400**, **P12-400**, and **P12-1000** particles. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

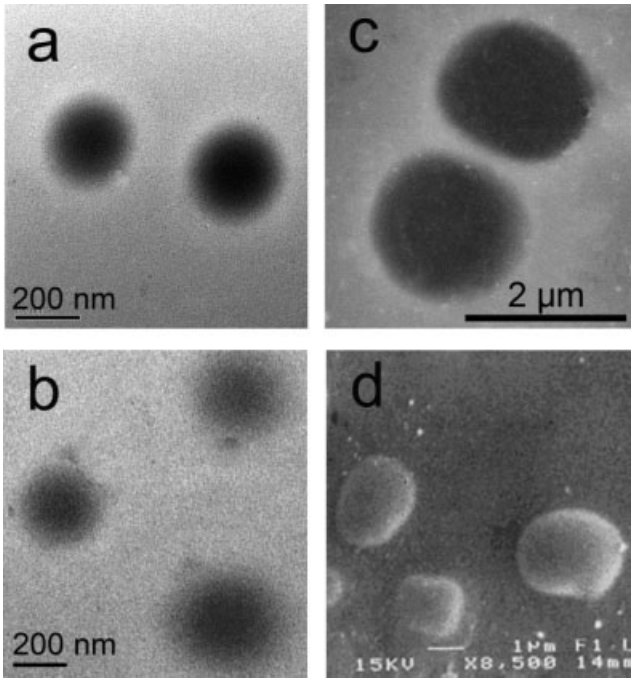


Figure 5 TEM images of **P2-200** (a), **P2-400** (b), **P12-400** (c), and SEM image of **P12-400** (d) particles.

number of 23 ethylene oxide units in the **P12-1000**, the hydrophilic to hydrophobic ratio increased to a level, such that there were sufficient tethered PEO chains to cover the surface of the smaller size particles (500 nm) and stabilize them (model in Fig. 6).

The above explanation could be simplified using the length of the alkoxy group and the ethylene oxide unit (2 m and m′ in scheme 1 and Table I) in each oligomeric structure. Higher 2 m/m′ ratio in **P12-400** (Table I) indicated not enough hydrophilic corona to stabilize small size particles, thus micro-size particles were observed. In contrast, the smallest 2 m/m′ ratio in **P2-400** structure corresponded to enough PEO chains to cover surfaces of smaller particles. As a result, **P2-400** gave the smallest self-assembled spherical particles among the four oligomeric assemblies.

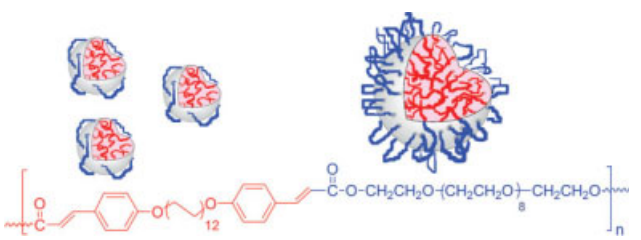
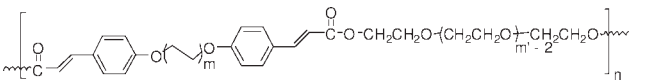


Figure 6 Representative drawing explaining the formation of bigger spheres for **P12-400**; the unstable submicron-size particles without enough PEO on their surfaces (left) and the more stable micron-size sphere with enough PEO covering on the surface (right). The size of the spheres and the size of the oligoester chains are not in a real proportion. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

TABLE I
Particles′ Size and the Ratio Between the Length of the Alkoxy Group (2 m) and the Ethylene Oxide Unit (m′) of the Four Oligomers



Samples	2m/m′	Particle size
P2-200	0.5	614.5 ± 3.21
P2-400	0.2	601.2 ± 2.89
P12-400	1.2	3260 ± 29.2
P12-1000	0.5	631.1 ± 2.90

CONCLUSIONS

We have synthesized amphiphilic block oligoesters with various hydrophobic to hydrophilic ratios based on *p*-ethoxycinnamate and *p*-dodecoxycinnamate as the hydrophobic blocks and polyethylene oxide of various lengths as the hydrophilic block. Self-assembly of the obtained UVB absorptive oligomers into spherical structures were carried out by displacing acetone with water. The yellow-oil **P2-400** and the yellow wax **P2-200** and **P12-1000** could self-assemble into spherical particles of submicron sizes whereas the yellow wax **P12-400** could self-assemble into spherical microparticles. In addition, relationship between size of the self-assembled spheres and oligomeric structures was observed. Good water dispersibility of these UVB absorptive spheres should enable direct application in water-base formulations, thus, these particles are potential UVB absorptive carriers for cosmetics and pharmaceutical applications.

References

1. Zhang, L. F.; Eisenberg, A. Science 1995, 268, 1728.
2. Yu, Y. S.; Eisenberg, A. J Am Chem Soc 1997, 119, 8383.
3. Cornelissen, J.; Fischer, M.; Sommerdijk, N.; Nolte, R. J. M. Science 1998, 280, 1427.
4. Borsali, R.; Minatti, E.; Putaux, J. L.; Schappacher, M.; Deffieux, A.; Viville, P.; Lazzaroni, R.; Narayanan, T. Langmuir 2003, 19, 6.
5. Leibler, L. Macromolecules 1980, 13, 1602.
6. Alexandridis, P.; Spontak, R. J. Curr Opin Colloid Interface Sci 1999, 4, 130.
7. Zhang, L.; Yu, K.; Eisenberg, A. Science 1995, 268, 1777.
8. Houga, C.; Giermanska, J.; Lecommandoux, S.; Borsali, R.; Taton, D.; Gnanou, Y.; Meins, J.-F. L. Biomacromolecules 2009,10, 32.
9. Rowan, S. J. Nat Mater 2009, 8, 89.
10. Kimura, K.; Katoh, T. Contact Derm 1995, 32, 304.

11. Schauder, S.; Ippen, H. Contact Derm 1997, 37, 221.
12. Jiang, R.; Roberts, M. S.; Collins D. M.; Benson, H. A. E. Br J Clin Pharmacol 1999, 4, 635.
13. Hany, J.; Nagel, R. Deutsche Lebensmittel-Rundschau 1995, 91, 341.
14. Yener, G.; Incegul, T.; Yener, N. Int J Pharm 2003, 258, 203.
15. Calderilla-Fajardo, S. B.; Cazares-Delgadillo, J.; Villalobos-Garcia, R.; Quintanar-Guerrero, D.; Ganem-Quintanar, A. Drug Dev Ind Pharm 2006, 32, 107.
16. Chatelain, E.; Gabard, B.; Surber, C. Skin Pharmacol Appl Skin Physiol 2003, 16, 28.
17. Mitchell, K.; Mitchnick, M. (SunSmart, Inc.). U.S. Pat. 5,587,148 (1996).
18. Pattanaargson, S.; Hongchinnagorn, N.; Hirunsupachot, P.; Sritana-anant, Y. Photochem Photobiol 2004, 80, 322.
19. Anumansirikul, N.; Wittayasuporn, M.; Klinubol, P.; Wanichwecharungruang, S. P. Nanotechnology 2008, 19, 205101.
20. Richard, H.; Ledue, M. (Societe L'Oreal S.A.). U.S. Pat. 6,080,880 (2000).
21. Ledue, M.; Richard, H.; Lagrange, A. (Societe L'Oreal S.A.). U.S. Pat. 6,376,679 (2002).
22. Discher, D. E.; Eisenberg, A. Science 2002, 297, 967.