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Precise Synthesis of ABCDE Star Quintopolymers by Combination of Controlled Polymerization and Azide−Alkyne Cycloaddition Reaction

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Ⓢ *Supporting Information*

ABSTRACT: A facile approach based on integrated utilization of ring-opening polymerization (ROP), reversible addition−fragmentation chain transfer (RAFT) process, and azide−alkyne cycloaddition reaction was efficiently used to construct amphiphilic 5-arm ABCDE star quintopolymers. The miktoarm stars are composed of poly(ethylene glycol) (A), poly(ε-caprolactone) (B), polystyrene (C), poly(L-lactide) (D), poly(N,N-dimethylaminoethyl methacrylate) (E$_1$), poly-(methyl methacrylate) (E$_2$), and poly(methyl acrylate) (E$_3$). Alkyne-in-chain-functionalized BC and DE diblock copolymers were synthesized by successive ROP and RAFT process.

Selective [3 + 2] click reaction between two-azide-end-functionalized PEG and BC copolymer gave azide-core-functionalized ABC star terpolymer, and a subsequent click reaction with DE copolymer afforded well-defined ABCDE stars with well-controlled molecular weight, low polydispersity, and precise composition, as evidenced from ^{1}H NMR, GPC, and GPC-MALLS analyses. DSC analyses revealed part of polymer segments in ABCDE stars were compatible. This general methodology has some advantages such as straightforward synthesis, mild reaction conditions, versatile polymerizable monomers, and high yields, which is promising for the construction of numerous functional star copolymers with multiple compositions and precise microstructures.
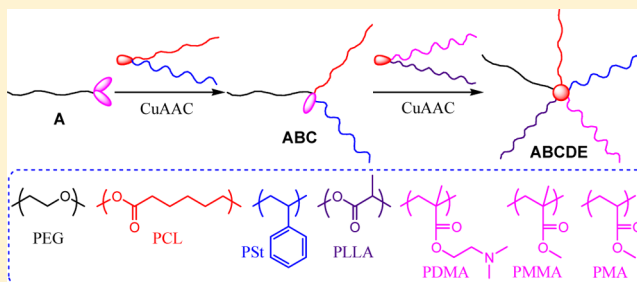
■ INTRODUCTION

Facile synthesis and properties of copolymer materials with precise compositions, complex topologies, and versatile functionalities are an enduring focus of current polymer science.[1−10] Tremendous advances in advanced polymer synthesis enable efficient modular syntheses of well-defined complex macromolecular architectures involving block, star, hyperbranched, dendritic, dendrimer-like, and brush copolymers. Among them, star copolymers, especially miktoarm or heteroarm stars (abbreviated as μ stars), have been extensively investigated due to their variable chain length and arm number, rich chemical variability, versatile properties, and potential applications in many fields.[11−40] Because of their branched architectures and heterophase structures, μ stars with different arm segments are liable to undergo microphase separation at molecular level and self-assemble into novel and intriguing periodical suprastructures and supramolecular assemblies in nanoscale, which are generally distinct from those formed by their corresponding linear analogues.[41−68] The advent of multicompartment micelles originated from self-assembly of μ stars in selective solvents represents an important advance toward hierarchical self-assembly with multiple functions and multiscale designed architectural features.[62−68] With increasing chemical components, star copolymers are liable to form more complex self-assembled nanostructures and exhibit novel physicochemical properties and functions, and thus they can hold great promise as next-generation functional polymers for potential applications in nanoscience and nanotechnique.[40,68] The continuous development of general and efficient methods to synthesize multicomponent stars can not only afford limitless examples of miktoarm stars but also promote the advance in supramolecular chemistry, materials science and technology, and polymer physics based on multiphase and multicomponent copolymer materials.

Living anionic polymerization (LAP) is unquestionably the best (in terms of low heterogeneity of the products) and most mature method to synthesize multicomponent and multiarm stars thus far.[1−4,16−40] Hirao and colleagues have successfully developed a versatile methodology to synthesize μ stars, which was based on iterative approach comprising repeated "arm introduction−regeneration of the same reaction site" processes.[28−40] With this methodology, arm segments could be successively introduced by repeating the reaction sequence to afford μ stars with many arms and multiple compositions, and numerous well-defined star-branched copolymers involving 5-arm ABCDE, 6-arm ABCDEF, and even 7-arm ABCDEFG

Scheme 1. Synthesis of ABCDE Star Quintopolymers by Combination of ROP, RAFT, and CuAAC
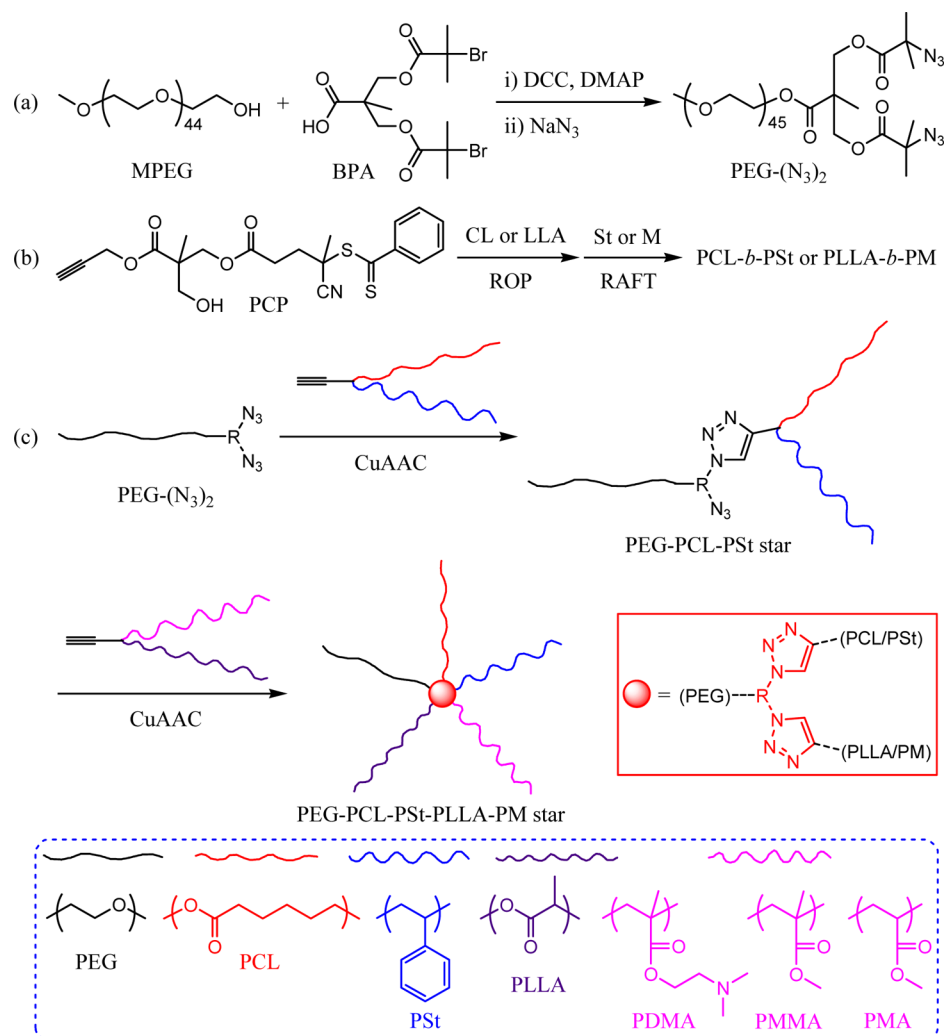
stars were achieved by combination of LAP and linking chemistry.[28−40] These pioneering researches enable precise synthesis of complex star-branched copolymers with polymer segments such as poly(4-methylphenyl vinyl sulfoxide), polyacetylene, polymethacrylates, poly(4-vinylphenol), poly(2-vinylpyridine), polystyrene, and its derivatives under high-vacuum conditions.[28−40] Until now, the examples of μ stars with chemical compositions up to five or more are scarce,[33−40] and the types of segment compositions are also relatively limited. Therefore, it is very timely to further explore more facile methods to construct functional miktoarm stars.

Recent advances in "living" and controlled polymerization techniques such as nitroxide-mediated polymerization,[5] atom transfer radical polymerization,[6−9] reversible addition−fragmentation chain transfer (RAFT) polymerization,[10,69−72] and ring-opening polymerization (ROP)[73−75] have enabled facile synthesis of numerous star polymers with controlled compositions and variable functionalities. When these techniques are combined with highly efficient linking reactions such as azide−alkyne cycloaddition click reaction,[76,77] star and branched polymers with extended compositions such as 4-arm ABCD star copolymers[78−81] and ABCDE-type H-shaped quintopolymers[82−84] were successfully obtained. As compared with LAP, these techniques are noticeably advantageous for their mild reaction conditions, wide range of monomers, and

tolerance to moistures and functionalities, and thus they may be more promising for the synthesis of μ stars. It is therefore surprising that star quintopolymers have not been successfully achieved by these approaches thus far, possibly because of the difficulty in multistep syntheses.

Herein, we report on facile synthesis of amphiphilic 5-arm ABCDE star quintopolymers by combination of ROP, RAFT process, and copper(I)-catalyzed azide−alkyne cycloaddition reaction (CuAAC). A clickable trifunctional reagent propargyl 5-cyano-5-phenylthiocarbonylsulfanyl pentanoyloxy-2-hydroxy-methyl-2-methylpropanoate (PCP) was synthesized and utilized as both ROP initiator and RAFT agent to prepare alkyne-in-chain-functionalized diblock copolymers, and the alkyne moiety was further used as a core reagent to construct the target μ stars via click chemistry (Scheme 1). To confirm the generality and versatility of this methodology, various polymer segments involving hydrophilic poly(ethylene glycol) (PEG, A), biodegradable poly(ε-caprolactone) (PCL, B) and poly(L-lactide) (PLLA, D), polystyrene (PSt, C), and poly-(meth)acrylate-type segments such as poly(N,N-dimethylami-noethyl methacrylate) (PDMA, E_1), poly(methyl methacrylate) (PMMA, E_2), and poly(methyl acrylate) (PMA, E_3) were chosen as model building blocks of star polymers, and sequential [3 + 2] click reactions[76] using two-azide-chain-end-functionalized PEG and alkyne-functionalized block

copolymers as raw materials were performed to generate the target stars. The isolated μ stars and their precursors were characterized by GPC, GPC-MALLS, ^{1}H NMR, IR, and differential scanning calorimetry (DSC). The success of this methodology further paves ways for facile construction of many types of μ stars with rich compositions and precise microstructures due to its mild reaction conditions, versatile polymerizable monomers, and high yield, which underlies systematic researches on revealing structure−property relationships of functional μ stars.

■ EXPERIMENTAL SECTION

Materials. All solvents, monomers, and other chemicals were purchased from Sigma-Aldrich unless otherwise stated. Methyl acrylate (MA, 99%), N,N-dimethylaminoethyl methacrylate (DMA, 99%), methyl methacrylate (MMA, 99%), ε-caprolactone (CL, 99%), and styrene (St, 99%) were distilled over CaH$_2$ under reduced pressure before use. L-Lactide (LLA, 99%) was recrystallized twice from toluene. 2,2′-Azobis(isobutyronitrile) (AIBN, 98%) was recrystallized twice from ethanol. CuBr (98%) was purified by stirring in acetic acid and washing with ethanol and then dried in vacuo. Toluene was distilled over Na and benzophenone and stored under nitrogen. Poly(ethylene glycol) monomethyl ether (MPEG, M_n = 2000), tin(II) 2-ethylhexanoate ((Sn(Oct)$_2$, 95%), N,N,N',N'',N''-pentamethyldiethylenetriamine (PMDETA, 99%), 2,2-bis(hydroxylmethyl)propionic acid (98%), triethylamine (99.5%), sodium azide (99%, Alfa Aesar), propargyl alcohol (99%), and 2-bromoisobutyryl bromide (98%) were used as received. 4-(Dimethylamino)pyridine (DMAP), N,N'-dicyclohexylcarbodiimide (DCC), N,N-dimethylformamide (DMF), and other chemicals with analytical grade were purchased from Sinopharm Chemical Reagent and used as received. Propargyl 2,2-bis(hydroxymethyl)propanoate (PHP),[82] 2,2-bis(2′-bromo-2′-methylpropionyloxymethyl)propionic acid (BPA),[85] and 4-cyanopentanoic acid-4-dithiobenzoate (4-CPDB)[86] were synthesized and purified according to literature methods. 4-(Chloromethyl)-phenyltrimethoxysilane (95%) was purchased from ABCR GmbH & Co. KG, Germany. Silica gel (Qingdao Haiyang Chemical Co., Ltd.) had an average particle size of 10 μm, BET specific surface area of 297.1 m^2/g, and average pore size of 11.5 nm. Azide- and alkyne-functionalized silica particles were synthesized according to previous methods,[87,88] and the loadings were 0.612 mmol of N$_3$ per g of Si−N$_3$ and 0.398 mmol of alkyne per g of Si-alkyne.

Synthesis of Propargyl 5-Cyano-5-phenylthiocarbonylsulfanylpentanoyloxy-2-hydroxymethyl-2-methylpropanoate (PCP). To a round flask were added propargyl 2,2-bis-(hydroxymethyl)propanoate (3.0 g, 17.4 mmol), DCC (3.59 g, 17.4 mmol), DMAP (0.21 g, 1.7 mmol), and 100 mL of dichloromethane (DCM) under nitrogen. The mixture cooled with an ice−water bath was stirred for 20 min and followed by slow addition of 25 mL of DCM solution containing 4-CPDB (3.5 g, 12.5 mmol) in 1 h. The reaction mixture was further stirred at room temperature overnight. After filtration, the solution was washed with deionized water (30 mL × 3) and dried with MgSO$_4$ overnight. The crude product was purified by flash column chromatography eluting with hexane/DCM (2:1, v/v), and PCP was obtained as a red-brown oil (2.88 g, 53% yield). ^{1}H NMR (CDCl$_3$): δ 7.92 (d, J 7.6, 2H, PhH), 7.58 (t, J 7.2, 1H, PhH), 7.41 (t, J 8.0, 2H, PhH), 4.74 (s, 2H, CH$_2$O), 4.35 (m, 2H, CH$_2$O), 3.73 (s, 2H, CH$_2$OH), 2.71 (m, 2H, CH$_2$), 2.62 and 2.42 (m, each 1H, CH$_2$), 2.51 (m, 1H, CH), 1.94 (s, 3H, CH$_3$), 1.25 (s, 3H, CH$_3$). ^{13}C NMR (CDCl$_3$): δ 222.2 (C=S), 173.5, 171.5 (C=O), 144.4, 133.2, 128.6, 126.7, 118.5, 77.2, 75.4, 66.2, 64.8, 52.6, 48.2, 45.6, 33.3, 29.7, 24.2, 17.4. FT-IR (KBr): 3529, 3280, 3058, 2984, 2935, 2856, 2231, 2128, 1742, 1656, 1589, 1524, 1446, 1382, 1314, 1232, 1181, 1126, 1081, 1048, 995, 929, 868, 780, 688 cm^{-1}.

Synthesis of Two-Azide-End-Functionalized PEG. MPEG (5.0 g, 2.5 mmol), 2,2-bis(2′-bromo-2′-methylpropionyloxymethyl)-propionic acid (BPA, 2.16 g, 5.0 mmol), and DMAP (0.20 g, 1.6 mmol) were dissolved in 80 mL of DCM under nitrogen, and then a solution of DCC (1.55 g, 7.5 mmol) in 50 mL of DCM was added

dropwise to the solution in 1 h. The mixture was further stirred at room temperature for 30 h. After filtration, the solution was concentrated and precipitated in cold diethyl ether thrice. PEG-(Br)$_2$ (5.61 g, 93% yield) was obtained as white powders. The bromide functionality was determined to be 2.02 by ^{1}H NMR. PEG-(Br)$_2$: ^{1}H NMR (CDCl$_3$): δ 4.35 (m, CH$_2$O), 3.65 (s, CH$_2$CH$_2$O of PEG), 3.38 (s, CH$_3$O), 1.92 (s, CH$_3$), 1.35 (s, CH$_3$). FT-IR (KBr): 2885, 1739, 1628, 1467, 1338, 1280, 1244, 1111, 949, 843 cm^{-1}.

NaN$_3$ (1.3 g, 20 mmol) was added to a solution of PEG-(Br)$_2$ (5.0 g, 2.07 mmol) in 50 mL of DMF, and the mixture was stirred in an oil bath thermostated at 50 °C for 48 h. The mixture was filtered, and the filtrate was evaporated to remove most of DMF. The crude product was dissolved in 50 mL of DCM, and then the solution was washed with deionized water (5 mL × 2) and dried with MgSO$_4$ overnight. The organic phase was concentrated and precipitated in cold diethyl ether thrice. PEG-(N$_3$)$_2$ (4.4 g, 90% yield) was obtained as white powders. PEG-(N$_3$)$_2$: ^{1}H NMR (CDCl$_3$): δ 4.35 (m, CH$_2$O), 3.65 (s, CH$_2$CH$_2$O of PEG), 3.38 (s, CH$_3$O), 1.46 (s, CH$_3$), 1.34 (s, CH$_3$). FT-IR (KBr): 2873, 2113, 1743, 1643, 1469, 1385, 1351, 1252, 1108, 1039, 950, 847, 762, 663 cm^{-1}.

Synthesis of One-Alkyne-Functionalized PCL and PLLA Macro Chain Transfer Agents. PCP (0.434 g, 1.00 mmol), CL (6.84 g, 59.9 mmol), and Sn(Oct)$_2$ (0.081 g, 0.20 mmol) were added to a Schlenk tube under nitrogen, and toluene was added until the total volume was 20.0 mL. The tube was degassed by three freeze−pump−thaw cycles and then placed in an oil bath thermostated at 90 °C for 24 h. The reaction mixture was precipitated in a large amount of methanol thrice. After drying in vacuum oven at 40 °C until constant weight, PCL was obtained in 95.2% yield. Number-average molecular weight and polydispersity index of PCL estimated by GPC and NMR analysis were $M_{n,GPC}$ = 11 600, M_w/M_n = 1.12, and $M_{n,NMR}$ = 7080. PLLA macro CTA was synthesized and purified according to a similar procedure.

PCL: ^{1}H NMR (CDCl$_3$): δ 7.92, 7.58, and 7.41 (m, PhH), 4.73 (s, HC≡CCH$_2$), 4.28 (s, CH$_2$O), 4.25 (s, CH$_2$O), 4.06 (t, J6.8, CH$_2$O of PCL), 0.8−2.8 (m, CH$_2$ of PCL and CH, CH$_2$ and CH$_3$ originated from initiator). FT-IR (KBr): 3438, 2946, 2866, 2354, 2095, 1724, 1472, 1420, 1398, 1368, 1295, 1243, 1188, 1108, 1065, 1046, 961, 933, 841, 732, 710 cm^{-1}.

PLLA: ^{1}H NMR (CDCl$_3$): δ 7.92, 7.58, and 7.41 (m, PhH), 5.17 (m, CH of PLLA), 4.73 (s, HC≡CCH$_2$), 4.37 (m, CH$_2$O), 4.27 (m, CH$_2$O), 2.2−2.8 (m, C≡CH and CH$_2$CH$_2$CO), 1.94 (s, CH$_3$), 1.59 (d, J7.2, CH$_3$ of PLLA), 1.29 (s, CH$_3$). FT-IR (KBr): 3510, 2998, 2947, 2341, 1751, 1621, 1457, 1386, 1361, 1294, 1214, 1134, 1098, 1044, 956, 922, 872, 756, 694 cm^{-1}.

Synthesis of Alkyne-in-Chain-Functionalized PCL-b-PSt and PLLA-b-PM Diblock Copolymers. In a typical polymerization, St (2.08 g, 20.0 mmol), PCL (0.94 g, 0.133 mmol), and AIBN (4.3 mg, 0.026 mmol) were added to a glass tube with a magnetic stirring bar, and toluene was added until the total volume was 6.7 mL. The tube was sealed with a rubber septum, and the contents were flushed with nitrogen for 15 min. The tube was subsequently immersed into an oil bath thermostated at 80 °C for 24 h. The reaction mixture was precipitated in methanol thrice. Monomer conversion was obtained to be 28.8% by gravimetry. Number-average molecular weight and polydispersity index of PCL-b-PSt copolymer estimated by GPC and NMR analyses were $M_{n,GPC}$ = 14 800, M_w/M_n = 1.10, and $M_{n,NMR}$ = 11 400. Other PLLA-b-PM (M = DMA, MMA and MA) copolymers were synthesized and purified according to similar procedures.

PCL-b-PSt: ^{1}H NMR (CDCl$_3$): δ 7.3−8.0 (m, PhH), 6.2−7.2 (m, PhH of PSt), 4.73 (s, 2H, HC≡CCH$_2$), 4.24 (m, CH$_2$O), 4.20 (m, CH$_2$O), 4.06 (t, J6.4, CH$_2$O of PCL), 0.8−2.8 (m, CH$_2$ of PCL, CH and CH$_2$ of PSt, and CH, CH$_2$ and CH$_3$ originated from initiator). FT-IR (KBr): 3438, 3060, 3026, 2944, 2865, 2336, 2090, 1725, 1061, 1493, 1471, 1453, 1420, 1397, 1367, 1295, 1244, 1188, 1108, 1066, 1047, 962, 933, 907, 841, 759, 733, 699 cm^{-1}.

PLLA-b-PDMA: ^{1}H NMR (CDCl$_3$): δ 7.2−8.0 (m, PhH), 5.17 (m, CH of PLLA), 4.73 (s, HC≡CCH$_2$), 4.35 (m, CH$_2$O), 4.27 (m, CH$_2$O), 4.06 (t, J1.2, CH$_2$O of PDMA), 2.57 (s, CH$_2$N of PDMA), 2.29 (s, CH$_3$N of PDMA), 0.6−2.2 (m, CH$_3$ of PLLA, CH$_2$ and CH$_3$

of PDMA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3509, 2946, 2821, 2769, 1765, 1619, 1465, 1388, 1358, 1293, 1098, 1044, 1015, 963, 918, 871, 854, 779, 754, 692 cm^{-1}.

PLLA-*b*-PMMA: ^{1}H NMR (CDCl$_3$): δ 7.2–8.0 (m, Ph*H*), 5.17 (m, C*H* of PLLA), 4.73 (s, HC≡CC*H*$_2$O), 4.37 (m, C*H*$_2$O), 4.24 (m, C*H*$_2$O), 3.60 (s, C*H*$_3$O of PMMA), 0.5–2.8 (m, C*H*$_3$ of PLLA, C*H*$_2$ and C*H*$_3$ of PMMA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3510, 2997, 2951, 2339, 2081, 1759, 1732, 1629, 1455, 1362, 1272, 1242, 1191, 1136, 1094, 1045, 989, 871, 842, 753, 695 cm^{-1}.

PLLA-*b*-PMA: ^{1}H NMR (CDCl$_3$): δ 7.2–8.0 (m, Ph*H*), 5.17 (m, C*H* of PLLA), 4.73 (s, HC≡CC*H*$_2$O), 4.37 (m, C*H*$_2$O), 4.24 (m, C*H*$_2$O), 3.67 (s, C*H*$_3$O of PMA), 0.6–2.8 (m, C*H*$_3$ of PLLA, C*H* and C*H*$_2$ of PMA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3507, 2998, 2954, 2336, 1736, 1622, 1456, 1386, 1362, 1268, 1216, 1134, 1087, 1044, 974, 922, 872, 828, 756, 694 cm^{-1}.

Synthesis of One-Azide-Functionalized PEG−PCL−PSt Star Terpolymer via Selective Click Reaction between PEG-(N$_3$)$_2$ and PS-*b*-PCL. In a typical run, PEG-(N$_3$)$_2$ (1.21 g, 0.50 mmol), PSt-*b*-PCL (0.708 g, 0.10 mmol), and PMDETA (21.0 μL, 0.10 mmol) were dissolved in DMF (24 mL) in a Schlenk tube. The reaction mixture was degassed by three freeze−pump−thaw cycles, and then CuBr (14.4 mg, 0.10 mmol) was added under nitrogen. The tube was subsequently immersed into an oil bath thermostated at 60 °C for 20 h. The reaction mixture was diluted with 40 mL of THF and passed through alumina column to remove copper salt. The polymer solution was concentrated and precipitated into methanol thrice, and PEG−PCL−PSt star was obtained in 98% yield. Apparent M_n and polydispersity index of ABC star estimated by GPC were $M_{n,GPC}$ = 16 600 and M_w/M_n = 1.08. Number-average molecular weights given by GPC-MALLS ($M_{n,MALLS}$) and NMR ($M_{n,NMR}$) analyses were 14 200 and 13 900, respectively. ^{1}H NMR (CDCl$_3$): δ 7.3–8.0 (m, Ph*H* and C*H*N), 6.2–7.2 (m, Ph*H* of PSt), 5.24 (s, C*H*$_2$O), 4.30 and 4.24 (m, C*H*$_2$O), 4.06 (t, *J* 6.8, C*H*$_2$O of PCL), 3.65 (s, C*H*$_2$C*H*$_2$ of PEG), 3.38 (s, C*H*$_3$O), 0.6–2.8 (m, C*H*$_2$ of PCL, C*H* and C*H*$_2$ of PSt, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3433, 3060, 3025, 2934, 2866, 2113, 1726, 1633, 1603, 1493, 1454, 1420, 1384, 1369, 1296, 1245, 1194, 1167, 1106, 1046, 961, 841, 760, 733, 700 cm^{-1}.

Synthesis of 5-Arm PEG−PCL−PSt−PLLA−PM Star Quintopolymers via Click Reaction between PEG−PCL−PSt and PLLA-*b*-PM. In a typical run, PEG−PCL−PSt (0.50 g, 0.036 mmol), PLLA-*b*-PDMA (0.79 g, 0.030 mmol), and PMDETA (13 μL, 0.062 mmol) were dissolved in DMF (13 mL) in a Schlenk tube. The reaction mixture was degassed by three freeze−pump−thaw cycles, and then CuBr (8.9 mg, 0.062 mmol) was added under nitrogen. The tube was subsequently immersed into an oil bath thermostated at 60 °C for 30 h, and then 0.30 g (0.18 mmol of azide functionality) of Si−N$_3$ and 0.45 g (0.18 mmol of alkyne functionality) of Si-alkyne were added to the tube under nitrogen. The reaction was further performed at 80 °C for 20 h under vigorous stirring. The mixture was diluted with 30 mL of THF and passed through alumina column. The polymer solution was concentrated under reduced pressure and precipitated into a large amount of methanol. After drying in a vacuum oven at 40 °C, 1.02 g (84% yield) of PEG−PCL−PSt−PLLA−PDMA (S1) star quintopolymer was obtained. Apparent M_n and polydispersity index of S1 estimated by GPC were $M_{n,GPC}$ = 35 100 and M_w/M_n = 1.09. Number-average molecular weights determined by GPC-MALLS and NMR analyses were 42 000 and 40 300, respectively. Other 5-arm stars were synthesized and purified according to similar procedures.

PEG−PCL−PSt−PLLA−PDMA (S1): ^{1}H NMR (CDCl$_3$): δ 7.3–8.0 (m, Ph*H* and C*H*N), 6.2–7.2 (m, Ph*H* of PSt), 5.16 (m, C*H* of PLLA and C*H*$_2$O), 4.1–4.5 (m, C*H*$_2$O), 4.07 (m, C*H*$_2$O of PCL and PDMA), 3.65 (s, C*H*$_2$C*H*$_2$ of PEG), 3.38 (s, C*H*$_3$O), 2.58 (t, *J* 2.4, C*H*$_2$N of PDMA), 0.6–2.5 (m, C*H*$_2$ of PCL, C*H* and C*H*$_2$ of PSt, C*H*$_2$ and C*H*$_3$ of PDMA, C*H*$_3$ of PLLA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3430, 3067, 2949, 2822, 1760, 1732, 1604, 1459, 1386, 1362, 1275, 1193, 1135, 1097, 1043, 1015, 957, 871, 855, 754, 700 cm^{-1}.

PEG−PCL−PSt−PLLA−PMMA star (S2): ^{1}H NMR (CDCl$_3$): δ 7.3–8.0 (m, Ph*H* and C*H*N), 6.2–7.2 (m, Ph*H* of PSt), 5.17 (m, C*H* of PLLA and C*H*$_2$O), 4.1–4.5 (m, C*H*$_2$O), 4.06 (m, C*H*$_2$O of PCL), 3.65 (s, C*H*$_2$C*H*$_2$ of PEG), 3.60 (s, C*H*$_3$O and PMMA), 3.38 (s, C*H*$_3$O), 0.6–2.4 (m, C*H*$_2$ of PCL, C*H* and C*H*$_2$ of PSt, C*H*$_2$ and C*H*$_3$ of PMMA, C*H*$_3$ of PLLA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3512, 3067, 2998, 2944, 2856, 1761, 1732, 1603, 1493, 1453, 1385, 1362, 1276, 1243, 1192, 1134, 1092, 1042, 987, 964, 910, 872, 842, 825, 808, 753, 700 cm^{-1}.

PEG−PCL−PSt−PLLA−PMA star (S3): ^{1}H NMR (CDCl$_3$): δ 7.3–8.0 (m, Ph*H* and C*H*N), 6.2–7.2 (m, Ph*H* of PSt), 5.16 (m, C*H* of PLLA and C*H*$_2$O), 4.1–4.5 (m, C*H*$_2$O), 4.06 (m, C*H*$_2$O of PCL), 3.65 (s, C*H*$_2$C*H*$_2$ of PEG and PMA), 3.38 (s, C*H*$_3$O), 2.31 (m, C*H*$_2$O of PCL and C*H* of PMA), 0.6–2.2 (m, C*H*$_2$ of PCL, C*H* and C*H*$_2$ of PSt, C*H*$_2$ of PMA, C*H*$_3$ of PLLA, and C*H*, C*H*$_2$ and C*H*$_3$ originated from initiator). FT-IR (KBr): 3510, 3059, 2945, 2857, 1760, 1735, 1633, 1562, 1544, 1524, 1493, 1458, 1384, 1271, 1193, 1106, 1042, 957, 872, 827, 756, 700 cm^{-1}.

Characterization. The apparent number-average molecular weight ($M_{n,GPC}$) and polydispersity index (M_w/M_n) of polymer samples were measured on a Waters 150-C gel permeation chromatography equipped with three Ultrastyragel columns with 10 μm bead size at 35 °C. Their effective molecular weight ranges were 100–10 000 for Styragel HT2, 500–30 000 for Styragel HT3, and 5000–600 000 for Styragel HT4. The pore sizes are 50, 100, and 1000 nm for Styragels HT2, HT3, and HT4, respectively. THF was used as an eluent at a flow rate of 1.0 mL/min, and the samples were calibrated using PMMA standard samples. Gel permeation chromatography with multiple angle laser scattering detection (GPC-MALLS) systems was used to determine the absolute number-average molecular weight ($M_{n,MALLS}$) of star copolymers, in which GPC was conducted in THF at 35 °C with a flow rate of 1.0 mL/min, and three TSK-GEL H-type columns (pore size 15, 30, and 200 Å, with molecular weight range of 100–1000, 300–20 000, and 5000–400 000 g/mol, respectively) with 5 μm bead size were used. Detection consisted of a RI detector (Optilab rEX) and a multiangle (14°−145°) laser light scattering (MALLS) detector (DAWN HELLOS) with the He−Ne light wavelength at 658.0 nm. The refractive index increment d*n*/d*c* for samples were measured off-line by Optilab rEX refractive index detector (λ = 658 nm) at 25 °C using a series of different concentration solutions, and the data were collected and processed by use of ASTRA software from Wyatt Technology. MALDI-TOF MS spectra were recorded using Bruker Autoflex III, and α-cyano-4-hydroxycinnamic acid was used as the matrix for the ionization operated in the reflection mode. ^{1}H (400 MHz) and ^{13}C (100 MHz) NMR spectra were recorded on a Varian spectrometer at 25 °C using CDCl$_3$ as a solvent. Fourier transform infrared (FT-IR) spectra were recorded on a Perkin-Elmer 2000 spectrometer using KBr disks. Differential scanning calorimetry (DSC) analysis was performed using a SDT 2960 simultaneous DSC-TGA of TA Instruments, and the heating rate was 10 °C/min under nitrogen.

■ RESULTS AND DISCUSSION

The synthesis of multicomponent star copolymers with chemical compositions up to five or more is still challenging to date.[33−40] This study aimed at developing a facile method to synthesize well-defined amphiphilic ABCDE stars comprising PEG (A), PCL (B), PSt (C), PLLA (D), PDMA (E$_1$), PMMA (E$_2$), and PMA (E$_3$) segments. To this end, a trifunctional reagent propargyl 5-cyano-5-phenylthiocarbonylsulfanyl penta-noyloxy-2-hydroxymethyl-2-methylpropanoate (PCP) was synthesized, which acted as ROP initiator, RAFT agent, and core reagent during the synthesis. Integrated utilization of ROP, RAFT, and CuAAC enabled straightforward synthesis of ABCDE star quintopolymers via sequential [3 + 2] click reactions between prefabricated polymers with functional azide and alkyne moieties. In brief, successive ROP and RAFT polymerization gave alkyne-functionalized BC and DE diblock

copolymers, selective cycloaddition between excess two-azide-end-functionalized PEG (PEG-(N$_3$)$_2$) (A) and alkyne-in-chain-functionalized PCL-b-PSt (BC) copolymer afforded one-azide-core-functionalized PEG−PCL−PSt (ABC) star and then followed by a subsequent click reaction between ABC star and DE copolymer to generate the target ABCDE stars. The detailed syntheses are described below.

Synthesis of PEG-(N$_3$)$_2$. Terminal diazide functionalized PEG (PEG-(N$_3$)$_2$) was synthesized by two-step reactions. The esterification between MPEG (M_n = 2000) and 2,2-bis(2′-bromo-2′-methylpropionyloxymethyl)propionic acid (BPA) performed in DCM at ambient temperature afforded two-bromide-end-functionalized PEG (PEG-(Br)$_2$), followed by azidation in DMF at 50 °C for 48 h to yield PEG-(N$_3$)$_2$. The resonance signals of CH_3O and $(CH_3)_2$CBr of terminal moieties quantitatively appeared at δ 3.38 and 1.92 in the ^{1}H NMR spectrum of PEG-(Br)$_2$. After azidation, the resonance signal at 1.92 ppm completely disappeared, a new signal at 1.46 ppm corresponding to $(CH_3)_2$CN$_3$ appeared (Figure 1), and
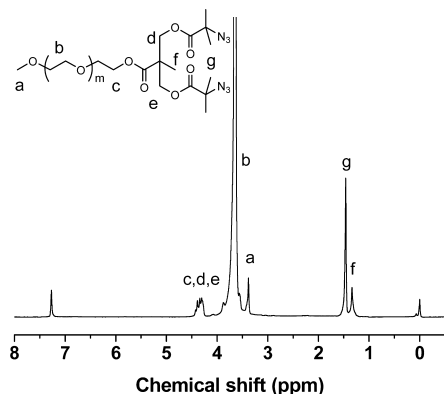

Figure 1. ^{1}H NMR spectrum of PEG-(N$_3$)$_2$.

the azide functionality of PEG-(N$_3$)$_2$ was determined to be 1.99 by ^{1}H NMR analysis, corresponding to the successful end-group transformation. The IR spectrum of PEG-(N$_3$)$_2$ (Figure 2a) revealed a strong absorbance peak of the azide moiety at 2113 cm^{-1}.

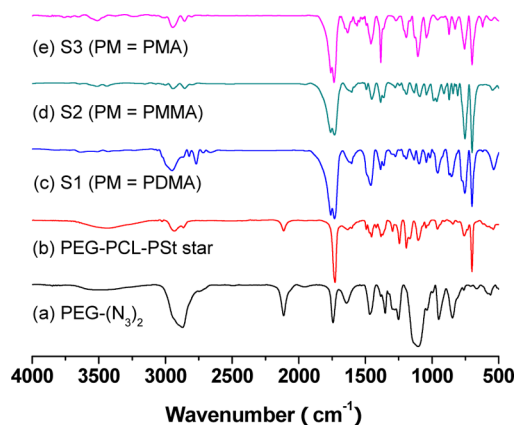MALDI-TOF MS spectra (Figure 3) indicated the presence of various PEG-based polymers with m/z values in the range of

Figure 2. IR spectra of PEG-(N$_3$)$_2$ (a), PEG−PCL−PSt star terpolymer (b), and PEG−PCL−PSt−PLLA−PM star quintopolymers (c−e).

1375.9−2608.9 (MPEG), 1878.0−2978.1 (PEG-(Br)$_2$), and 1416.0−2946.9 (PEG-(N$_3$)$_2$). In Figure 3A, the mass of each peak could be expressed as 32.04 (CH$_4$O) + 44.025n + 22.99 (Na$^+$), where n is the number of CH$_2$CH$_2$O units. From the expanded view of the spectrum in Figure 3A, m/z peaks with highest intensity appeared at 1992.3 (n = 44) and 2036.3 (n = 45), which was in good accordance with the expected M_n value of 2000. The mass of each peak in Figure 3B could be expressed as 446.13 (C$_{14}$H$_{22}$Br$_2$O$_6$) + 44.025n + 22.99 (Na$^+$), and m/z peaks with highest intensity were noted at 2406.4 (n = 44) and 2450.4 (n = 45), corresponding to the expected shifting of 414.1 m/z from MPEG to PEG-(Br)$_2$. Multiple peaks in the MALDI-TOF MS spectrum of PEG-(N$_3$)$_2$ (Figure 3C) were originated from loss of N$_2$ from the azide moieties due to fragmentation in the presence of higher laser power. In Figure 3C, peaks a−f in the range of 2164.5−2198.5 could be ascribed to M + 1.01 (H$^+$) − 56.02 (2N$_2$) (m/z 2164.5, a, n = 42), M + 22.99 (Na$^+$) − 28.01 (N$_2$) (m/z 2170.4, b, n = 41), M + 1.01 (H$^+$) (m/z 2176.5, c, n = 41), M + 22.99 (Na$^+$) − 56.02 (2N$_2$) (m/z 2186.4, d, n = 42), M + 1.01 (H$^+$) − 28.01 (N$_2$) (m/z 2192.5, e, n = 42), and M + 22.99 (Na$^+$) (m/z 2198.5, f, n = 41), where M = 370.36 (C$_{14}$H$_{22}$N$_6$O$_6$) + 44.025n. These results strongly confirmed both PEG-(Br)$_2$ and PEG-(N$_3$)$_2$ were of high purity and almost quantitative functionality.

Synthesis of Alkyne-Functionalized BC and DE Diblock Copolymers. One-alkyne-functionalized PCL-b-PSt (BC) and PLLA-b-PM (DE, PM = PDMA, PMMA and PMA) copolymers were synthesized by successive ROP and RAFT process (Table 1). ROP of CL and LLA initiated by PCP using Sn(Oct)$_2$ catalyst afforded PCL ($M_{n,NMR}$ = 7080) and PLLA ($M_{n,NMR}$ = 9500) with well-controlled molecular weight and relatively low polydispersity. The ^{1}H NMR spectra of PCL (Figure 4A) and PLLA (Figure 5A) revealed characteristic resonance signals originated from PCP initiator at δ 7.92, 7.58, 7.41 (PhH), 4.73 (HC≡CCH_2O), and 2.51 (C≡CH), resonance signals of PCL segment appeared at δ 4.06 (CH_2O), 2.31 (CH_2CO), 1.65, and 1.38 (CH_2CH$_2$CH$_2$), and resonance signals of PLLA segment appeared at δ 5.17 (CH) and 1.58 (CH_3). By comparing integration areas at δ 5.17 (CH of PLLA), 4.73 (CH_2O resulting from PCP moiety), and 4.06 (CH_2O of PCL), the number-average molecular weight determined by ^{1}H NMR ($M_{n,NMR}$) was obtained. The $M_{n,NMR}$ values of both samples agreed well with theoretically calculated results ($M_{n,th}$), as expected from a controlled polymerization.

PCL and PLLA were then used as macro chain transfer agents (CTAs) to mediate RAFT polymerization of vinyl monomers, and diblock copolymers with one alkyne functionality at the junction point were obtained. In ^{1}H NMR spectra of PCL-b-PSt (Figure 4B) and PLLA-b-PM (Figure 5B and Figures S4 and S5), resonance signals of propargyl moiety were quantitatively observed. In addition to typical signals of PCL and PLLA segments, characteristic resonance signals of propargyl moiety were observed at δ 4.73 (HC≡CCH_2O) and 2.51 (C≡CH), and resonance signals of the second block were noted at δ 6.2−7.2 (PhH of PSt), 4.07 (CH_2O of PDMA), 2.58 (CH_2N of PDMA), 2.30 ((CH_3)$_2$N of PDMA), 3.60 (CH_3O of PMMA), and 3.65 (CH_3O of PMA). On this basis, the $M_{n,NMR}$ values were determined by comparing integration areas of characteristic protons of propargyl and polymer segments. As compared with PCL and PLLA, the GPC traces of diblock copolymers completely shifted to higher molecular weight side (Figures 6 and 7). The resultant block copolymers possessed relatively low polydispersity (1.08 < M_w/M_n < 1.12),
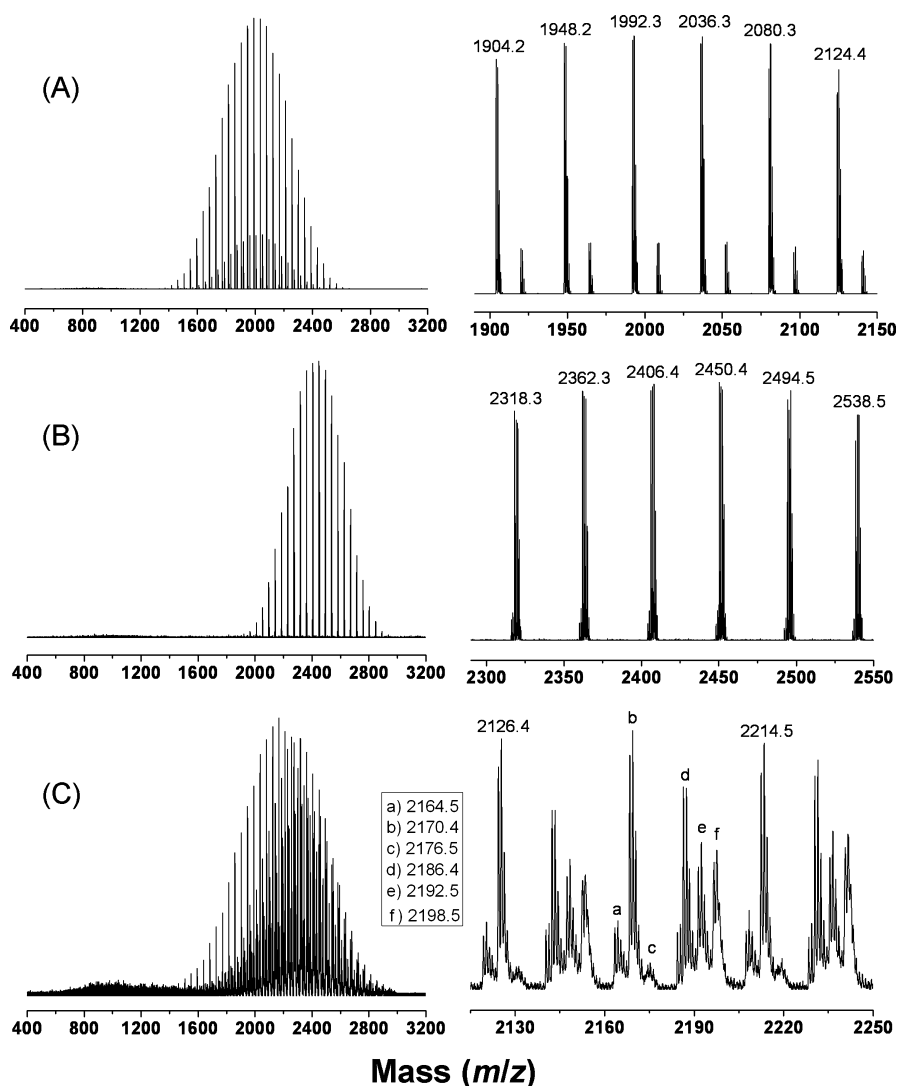
Figure 3. MALDI-TOF MS spectra of MPEG (A), PEG-(Br)$_2$ (B), and PEG-(N$_3$)$_2$ (C).

Table 1. Results for Synthesis of Alkyne-Functionalized PCL (B), PLLA (D), PCL-b-PSt (BC), and PLLA-b-PM (DE) Copolymers[a]

run	polymer	I or CTA	M	DP$_0$[b]	C (%)	$M_{n,th}$[c]	$M_{n,GPC}$[d]	M_w/M_n[d]	$M_{n,NMR}$[e]	dn/dc[f]
1	B	PCP	CL	60	95.2	6 950	11 600	1.12	7 080	0.0797
2	BC	PCL	St	150	28.8	11 600	14 800	1.10	11 400	0.1294
3	D	PCP	LLA	80	79.5	9 590	9 480	1.13	9 500	0.0568
4	DE$_1$	PLLA	DMA	120	91.2	26 700	22 800	1.11	26 300	0.0703
5	DE$_2$	PLLA	MMA	130	90.5	21 300	20 400	1.08	21 000	0.0745
6	DE$_3$	PLLA	MA	100	92.6	17 500	19 200	1.12	17 600	0.0658

[a]Reaction conditions: $[M]_0:[PCP]_0:[Sn(Oct)_2]_0 = DP_0:1:0.2$, $[M]_0 = 3.0$ mol/L, in toluene at 90 °C for 24 h (runs 1 and 3); $[M]_0:[CTA]_0:[AIBN]_0 = DP_0:1:0.2$, $[M]_0 = 2.0$ mol/L, in toluene (runs 2, 5, and 6) or dioxane (run 4) at 80 °C for 24 h. [b]Target degree of polymerization. [c]Theoretically calculated molecular weight. [d]Apparent number-average molecular weight and polydispersity index estimated by GPC using PMMA standards. [e]Number-average molecular weight determined by NMR analysis. [f]Determined by refractive index detector in THF at 25 °C.

and their $M_{n,NMR}$ values were close to those expected. All these results revealed well-defined one-alkyne-in-chain-functionalized diblock copolymers were obtained.
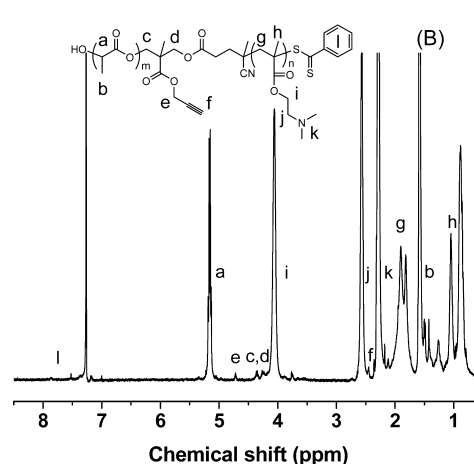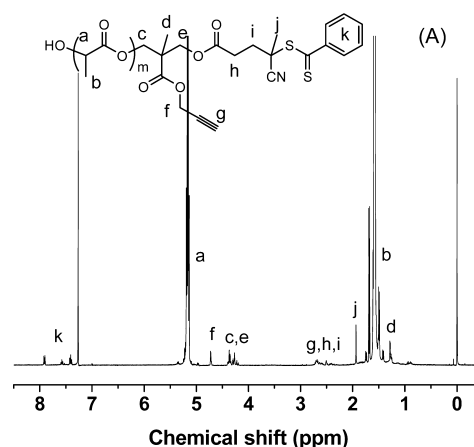
Synthesis of One-Azide-functionalized ABC Star Terpolymer via Selective Click Reaction. One-azide-core-functionalized PEG−PCL−PSt (ABC) star was synthesized by selective click reaction between PEG-(N$_3$)$_2$ and PCL-b-PSt copolymer (Table 2). Taking account of the possibility for two terminal azide moieties to simultaneously participate in the

cycloaddition reaction, 5-fold excess of PEG-(N$_3$)$_2$ was used to prepare 3-arm ABC star. The results indicated the target PEG−PCL−PSt star could be successfully achieved when the reaction was performed in DMF at 60 °C for 20 h. After reaction, excess PEG-(N$_3$)$_2$ ($M_{n,th} = 2410$, $M_{n,GPC} = 3660$, $M_w/M_n = 1.06$) was efficiently removed by repeated precipitation from THF solution to methanol due to its good solubility, and ABC star terpolymer was isolated in 98% yield.
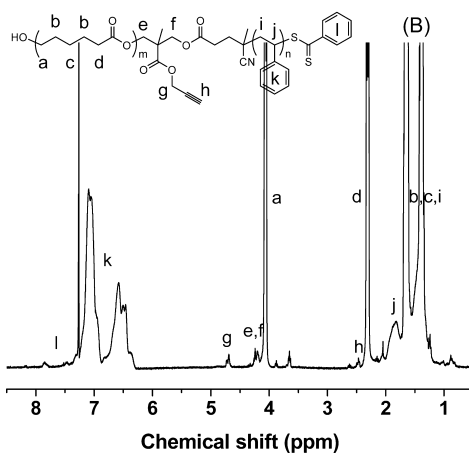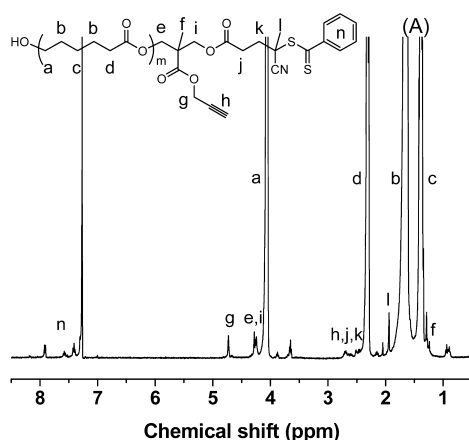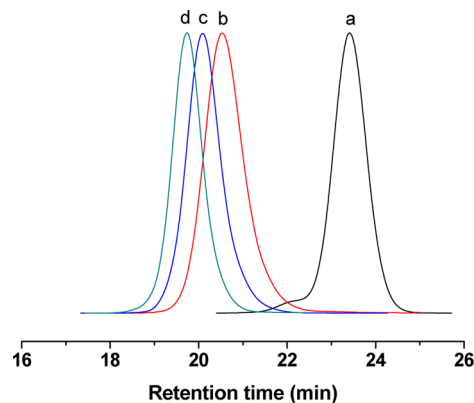
Figure 4. ^{1}H NMR spectra of alkyne-functionalized PCL (A) and PCL-*b*-PSt copolymer (B).

Figure 5. ^{1}H NMR spectra of PLLA (A) and PLLA-*b*-PDMA copolymer (B).

In ^{1}H NMR spectrum of ABC star (Figure 8), characteristic resonance signals at δ 7.84 (C*H*=C, f), 5.24 (CC*H$_2$*OC=O, g), and 1.93 ((C*H$_3$*)$_2$N, c) could be ascribed to protons in and beside the new generated 1,2,3-triazole ring, and other resonance signals appeared at δ 6.2−7.2 (Ph*H* of PSt), 4.06 (C*H$_2$*O of PCL), 3.65 (C*H$_2$CH$_2$*O of PEG), and 3.38 (terminal C*H$_3$*O of PEG, a). Although it was impossible to distinguish the remaining signals of (C*H$_3$*)$_2$CN$_3$ due to signal overlapping in ^{1}H NMR spectrum, the ratio of signal areas at δ 5.24 and 3.38 (I_g/I_a) was very close to 2/3, and the chemical composition determined by ^{1}H NMR PEG$_{45.0}$−PCL$_{58.8}$−PSt$_{42.2}$ was in good agreement with the theoretically expected value PEG$_{45.0}$−PCL$_{58.2}$−PSt$_{42.3}$ by assuming only one azide moiety of PEG-(N$_3$)$_2$ had quantitatively participate in CuAAC process (in which the subscripts denoted degree of polymerization of each block as determined by ^{1}H NMR). The dn/dc value of 0.1154 was in good agreement with the expected value (dn/dc(th) = 0.1161) by assuming the M_n value of ABC star is the sum of that of PEG-(N$_3$)$_2$ and PCL-*b*-PSt copolymer, the number-average molecular weights of ABC star terpolymer determined by ^{1}H NMR ($M_{n,NMR}$ = 13 900) and GPC-MALLS ($M_{n,MALLS}$ = 14 200) were similar, and both were very close to the theoretical value ($M_{n,th}$ = 13 800). The GPC trace of the isolated ABC star was of monomodal distribution (Figure 6d), and the polydispersity index was relatively low (M_w/M_n = 1.08). A strong absorbance peak at 2113 cm^{-1} in the IR spectrum (Figure 2b) also confirmed the presence of azide functionality in the isolated ABC star.


Figure 6. GPC traces of PEG-(N$_3$)$_2$ (a), PCL (b), PCL-*b*-PSt (c), and PEG−PCL−PSt star (d).

All the above-mentioned results revealed selective cyclo-addition click reaction using excess PEG-(N$_3$)$_2$ could afford well-defined one-azide-functionalized PEG−PCL−PSt star terpolymer with high yield and precise composition.

Synthesis of 5-Arm ABCDE μ Stars via Click Chemistry. Three ABCDE star copolymers were obtained by a subsequent [3 + 2] click reaction between slightly excess azide-function-alized ABC star and alkyne-functionalized DE copolymer. The azide−alkyne cycloaddition reaction was first performed in DMF at 60 °C for 30 h. Considering that it was difficult to quantitatively perform the click reaction due to enhanced steric
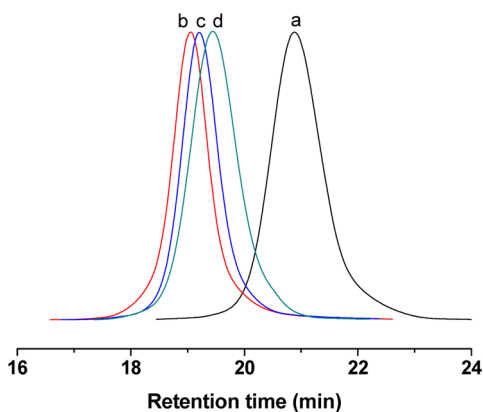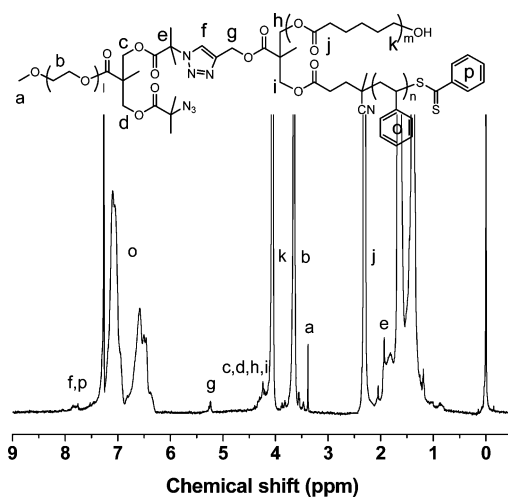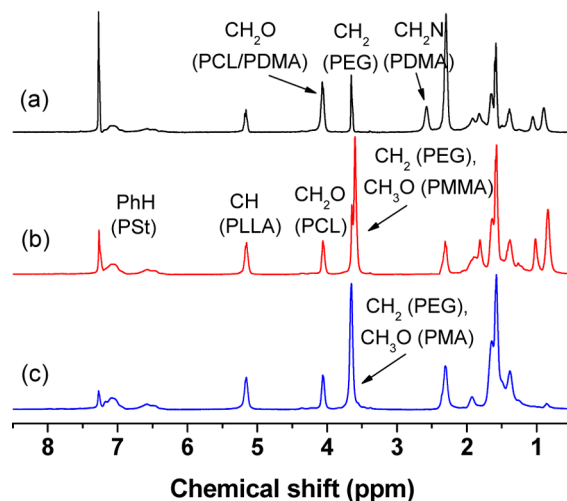
Figure 7. GPC traces of PLLA (a), PLLA-*b*-PDMA (b), PLLA-*b*-PMMA (c), and PLLA-*b*-PMA (d) copolymers.

Figure 8. ^{1}H NMR spectrum of azide-functionalized PEG−PCL−PSt star terpolymer.

**Figure 9.** ^{1}H NMR spectra of PEG−PCL−PSt−PLLA−PM (PM = PDMA, a; PMMA, b; and PMA, c) star quintopolymers.

hindrance, excess surface azide and alkyne functionalized silica particles were then added to the reaction system to perform a second click reaction, and thus the undesired polymers with reactive azide or alkyne functionality were grafted onto the surface of solid substrates, which could be easily removed by filtration.[87,88] After purification, PEG−PCL−PSt−PLLA−PDMA (S1), PEG−PCL−PSt−PLLA−PMMA (S2), and PEG−PCL−PSt−PLLA−PMA (S3) stars were isolated in 82−85% yield.

In IR spectra of ABCDE stars (Figure 2c−e), typical absorptions corresponding to characteristic groups of various segments were observed at about 1760 and 1732 ($\nu_{C=O}$), 1603 ($\nu_{C=C}$, St unit), and 700 cm^{-1} (C−H out-of-plane bending, St unit). The absorbance peak at 2113 cm^{-1} completely disappeared, corresponding to the absence of azide moiety in star copolymers obtained. In ^{1}H NMR spectra of isolated ABCDE stars, characteristic resonance signals were noted at δ 7.8−8.0 (C*H*=C of 1,2,3-triazole ring, which was partly overlapped with Ph*H*C(=S)S), 6.2−7.2 (Ph*H* of PSt), 5.16 (C*H* of PLLA and C*H*$_2$O beside 1,2,3-triazole ring), 4.06 (C*H*$_2$O of PCL and PDMA), 3.65 (C*H*$_2$C*H*$_2$O of PEG and C*H*$_3$O of PMA), 3.60 (C*H*$_3$O of PMMA), and 2.31 (C*H*$_2$CO of PCL) (Figure 9). On the basis of DP(PEG) of 45.0 (for S1) and DP(PSt) of 41.2 (for S2 and S3, in which resonance signals of C*H*$_2$C*H*$_2$O of PEG and C*H*$_3$O of PMMA and PMA were significantly overlapped), the chemical compositions of S1−S3 were determined to be PEG$_{45.0}$-PCL$_{59.2}$-PSt$_{40.2}$-PDMA$_{116.0}$-PLLA$_{64.2}$ (S1, theoretical composition PEG$_{45.0}$-PCL$_{58.8}$-PSt$_{41.2}$-PDMA$_{116.8}$-PLLA$_{63.0}$), PEG$_{45.2}$-PCL$_{59.3}$-PSt$_{41.2}$-PMMA$_{115.3}$-PLLA$_{64.4}$ (S2, theoretical composition PEG$_{45.0}$-PCL$_{58.8}$-PSt$_{41.2}$-

PMMA$_{115.8}$-PLLA$_{63.0}$), and PEG$_{45.1}$-PCL$_{59.1}$-PSt$_{41.2}$-PMA$_{92.2}$-PLLA$_{64.1}$ (S3, theoretical composition PEG$_{45.0}$-PCL$_{58.8}$-PSt$_{41.2}$-PMA$_{90.5}$-PLLA$_{63.0}$) by ^{1}H NMR, in which the expected compositions were calculated by assuming ABC star and DE copolymer were of uniform composition and both of them were reacted according to rigorous equimolar ratio. For all the star quintopolymers, the d*n*/d*c* results determined by refractive

Table 2. Results for Synthesis of ABC Star Terpolymer and ABCDE Star Quintopolymers (S1−S3) by CuAAC^a

run	polymer	yield (%)^b	$M_{n,th}{}^c$	$M_{n,GPC}{}^d$	$M_w/M_n{}^d$	$M_{n,NMR}{}^e$	$M_{n,MALLS}{}^f$	d*n*/d*c*^{g}
1	ABC	98	13 800	16 600	1.08	13 900	14 200	0.1154
2	S1	84	40 100	35 100	1.09	40 300	42 000	0.0916
3	S2	82	34 800	31 200	1.10	35 000	36 200	0.0923
4	S3	85	31 400	29 200	1.12	31 900	32 800	0.0894

^{a}Reaction conditions: [PEG-(N$_3$)$_2$]$_0$:[PCL-*b*-PSt]$_0$:[CuBr]$_0$:[PMDETA]$_0$ = 5:1:1:1, $W_{polymer}$:V_{DMF} = 0.080 g/mL, in DMF at 60 °C for 20 h (run 1); [PLLA-*b*-PM]$_0$:[PEG−PCL−PSt]$_0$:[CuBr]$_0$:[PMDETA]$_0$ = 1:1.2:2:2, $W_{polymer}$:V_{DMF} = 0.10 g/mL, in DMF at 60 °C for 30 h, and followed by a subsequent reaction with Si-alkyne and Si-N$_3$ at 80 °C for 20 h (PM = PDMA, run 2; PMMA, run 3; and PMA, run 4). ^{b}Yield of isolated star copolymer. ^{c}Theoretical molecular weight. ^{d}Apparent number-average molecular weight and polydispersity index estimated by GPC using PMMA standards. ^{e}Number-average molecular weight determined by NMR analysis. ^{f}Number-average molecular weight determined by GPC-MALLS. ^{g}Determined by refractive index detector in THF at 25 °C, d*n*/d*c* = 0.0869 (for MPEG), and the theoretical d*n*/d*c* values by assuming M_n values of star copolymers were the sum of their precursors were 0.1161 (ABC), 0.0907 (S1), 0.0931 (S2), and 0.0902 (S3).

index detector were similar to the theoretical values, the $M_{n,MALLS}$ and $M_{n,NMR}$ values were comparable, and both were close to the expected ones as a sum of $M_{n,NMR}$ of ABC star and DE copolymer. The deviation in degree of polymerization (DP) of each segment was within ±2% as determined by ^{1}H NMR, and the deviation in total molecular weights between $M_{n,th}$ and $M_{n,MALLS}$ was usually within ±5%. The isolated S1–S3 stars were of relatively low polydispersity (M_w/M_n = 1.09–1.12), and their GPC traces only exhibited monomodal distribution, which completely shifted to higher molecular weight side as compared with their precursors ABC and DE (Figure 10).
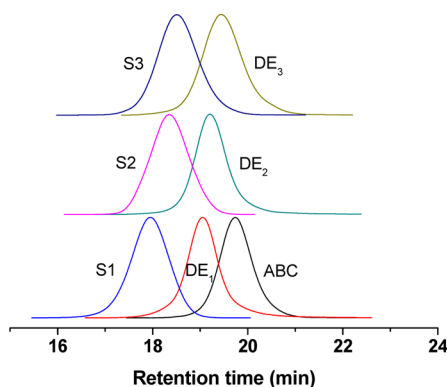
Figure 10. GPC traces of PEG–PCL–PSt star (ABC), PLLA-*b*-PDMA (DE₁), PLLA-*b*-PMMA (DE₂), PLLA-*b*-PMA (DE₃) and PEG–PCL–PSt–PLLA–PM stars (PM = PDMA, S1; PMMA, S2; PMA, S3).

All the results confirmed the click reaction between ABC star and DE copolymer had been efficiently performed. Therefore, the modular synthesis strategy involving two-step azide–alkyne cycloaddition reactions could successfully afford the target ABCDE μ stars with predetermined molecular weight, low polydispersity, and precise composition.

DSC Analyses of ABCDE Stars and Their Precursors. Glass transition temperature (T_g) and melting temperature (T_m) of μ stars and their precursors were determined by DSC analysis (Table 3). PEG-(N₃)₂ was of one melting peak at 52.6 °C in DSC curve (Figure 11a). PCL showed a T_m at 51.9 °C (Figure S6a), and a melting peak at 53.4 °C was noted in the DSC curve of PCL-*b*-PSt copolymer although the glass transition of PSt segment was difficult to distinguish (Figure

Table 3. Glass Transition (T_g) and Melting (T_m) Temperatures of Various Samples Determined by DSC

run	polymer	T_g (°C)	T_m (°C)
1	PEG-(N₃)₂ (A)		52.6
2	PCL (B)		51.9
3	PCL-*b*-PSt (BC)		53.4
4	PEG–PCL–PSt (ABC)		50.3, 53.0
5	PLLA (D)	43.7	149.0
6	PLLA-*b*-PDMA (DE₁)	23.4	128.2, 141.9
7	PLLA-*b*-PMMA (DE₂)	71.8	141.5
8	PLLA-*b*-PMA (DE₃)	37.5	140.5, 146.1
9	PEG–PCL–PSt–PLLA-PDMA (S1)	24.7	52.7, 124.9, 145.0
10	PEG–PCL–PSt–PLLA–PMMA (S2)	89.5	50.6, 138.6, 143.9
11	PEG–PCL–PSt–PLLA–PMA (S3)	24.6	52.9, 127.1, 145.4
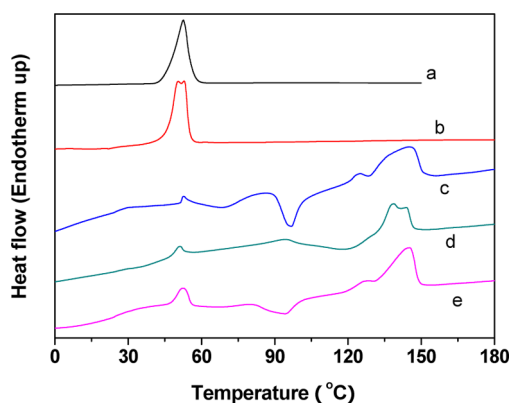
Figure 11. DSC curves of PEG-(N₃)₂ (a), PEG–PCL–PSt star terpolymer (b), and PEG–PCL–PSt–PLLA–PM (PM = PDMA, c; PMMA, d; PMA, e) star quintopolymers in second heating run.

S6b). PLLA had T_g of 43.7 °C and T_m of 149.0 °C (Figure S6c), and one or two melting peak(s) of PLLA-*b*-PM copolymers were noted in the range of 120–150 °C. Only one significant glass transition appeared in DSC curves of PLLA-*b*-PDMA (23.4 °C), PLLA-*b*-PMMA (71.8 °C), and PLLA-*b*-PMA (37.5 °C), and the T_g value was in the range between $T_{g,PLLA}$ and $T_{g,PM}$ (d–f of Figure S6), suggesting both blocks were compatible.

In the DSC curve of PEG–PCL–PSt star terpolymer (Figure 11b), two melting peaks corresponding to PEG and PCL segments appeared at 50.3 and 53.0 °C, and not notable glass transition of PSt segment was noted. For star quintopolymers S1–S3 (c–e of Figure 11), two melting areas corresponding to PEG and PCL (T_m = 50.6–52.9 °C) and PLLA (two notable peaks in the range of 124.9–145.4 °C) were noted, and only one significant glass transition appeared at 24.7 (S1), 89.5 (S2), and 24.6 °C (S3). These results indicated part of polymer segments in ABCDE stars were compatible although some glass transitions may be overlapped with melting and cold crystallization peaks in the range 40–120 °C.

■ **CONCLUSION**

A facile approach involving ROP, RAFT process, and CuAAC was successfully utilized to synthesize amphiphilic ABCDE star quintopolymers. A clickable trifunctional agent PCP was used to synthesize alkyne-in-chain-functionalized diblock copolymers via successive ROP and RAFT polymerization and followed by sequential azide–alkyne cycloaddition reactions to afford 5-arm PEG–PCL–PSt–PLLA–PM stars. The target μ stars possessed predetermined molecular weight, low polydispersity, and precise composition, evident from ^{1}H NMR, GPC, and GPC-MALLS analyses. DSC analyses revealed that part of the polymer segments in the ABCDE stars were compatible. Because of its mild reaction conditions, wide range of monomers, and high yield, the versatile methodology based on [3 + 2] click reactions can be generalized to construct many types of functional μ stars with chemical compositions up to five or more. These multicomponent stars are expected to have a great potential in supramolecular chemistry, materials science, and nanotechnology.

■ **ASSOCIATED CONTENT**

ⓢ Supporting Information

NMR spectra of PCP, PLLA-*b*-PMMA, and PLLA-*b*-PMA, IR spectra and DSC curves of various alkyne-functionalized

homopolymers and diblock copolymers. This material is available free of charge via the Internet at http://pubs.acs.org.

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Notes
The authors declare no competing financial interest.

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