Design of Click Polyesters and Hybridization of Bioactive Glass

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Contents

General Introduction

Even though many different kinds of polymers have been synthesized, their properties characterized, and used in commercial applications, polyesters still constitute a useful class of polymers. Specifically, aliphatic polyesters are expected to soon replace conventional plastics, because they are biodegradable and are mechanically strong.[1] Although polyesters are usually produced by polycondensation of diols and dicarboxylic acids or hydroxycarboxylic acids,[2] or by ring-opening polymerization of a lactone,[3] the former method requires severe reaction conditions even when a customized catalyst is used,[4] and the latter uses highly strained cyclic monomers, which makes it difficult to synthesize polyesters with specific functionalities and/or properties. We have reported on low-temperature polycondensations of diols and dicarboxylic acids,[5] which allowed us to use thermally labile monomers that contained functional groups.[6]

It is still unusual to find examples dealing with new synthetic strategies and catalysts[7] for the synthesis of aliphatic polyesters under environmentally benign conditions. Click chemistry, introduced by Sharpless and his colleagues,[8] is used to efficiently prepare many different types of organic compounds.

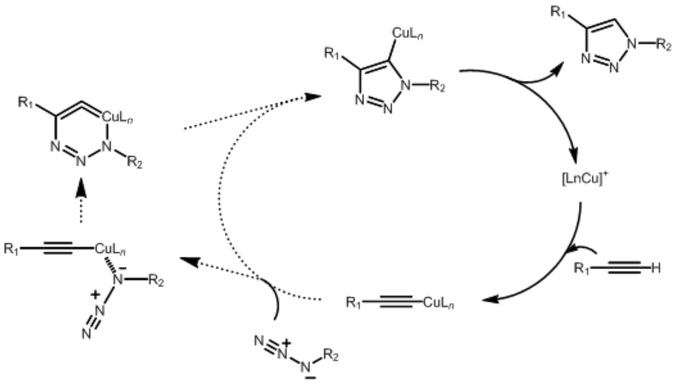


Figure 1. Proposed mechanism of the azide/alkyne click reaction.

The Cu(I)-catalyzed click 1,3-dipolar cycloadditions between azides and alkynes[9] proceed readily under mild conditions, without producing by-products, and with great chemoselectivities. Additionally, these Cu(I)-catalyzed azide-alkyne cycloadditions (CuAAC) are usually highly regioselective, e.g., the formation of 1,4-disubstituted 1,2,3-triazoles (Figure 1). Although there have been many reports concerning the improvement of reaction conditions for click-type syntheses,[10] and click reactions have been used to synthesize biologically active substances,[11] its application to polymer synthesis (click polymerization) has been limited.[12] Polyesters are a major class of polymeric materials, nevertheless click chemistry has not been used to synthesize polyesters.

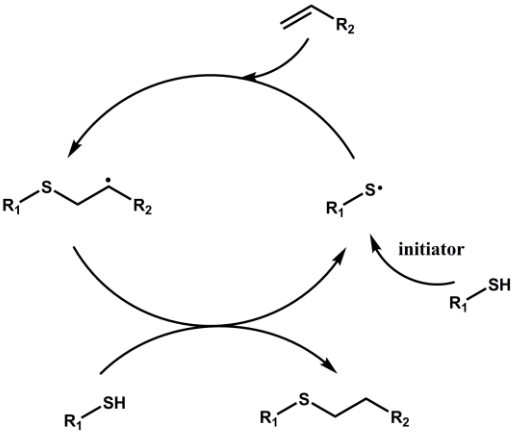
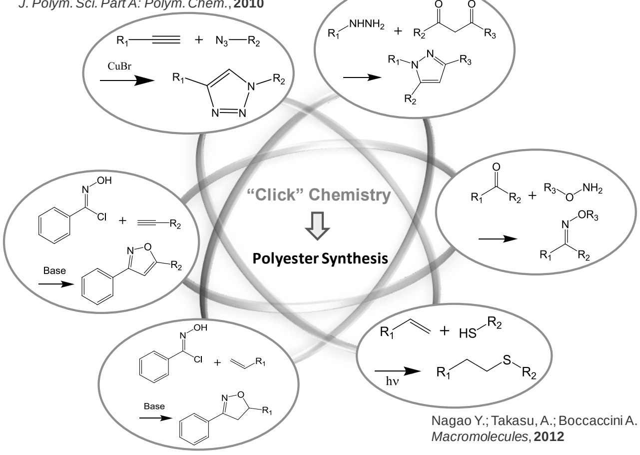


Figure 2. Reaction cycle for one round of a thiol−ene click reaction.

It has been also well-known that the thiol−ene click reaction is an efficient method for the production of many types of polymers.[13] Thiol−ene click polymerizations proceed via a thiyl-radical-mediated mechanism, involving alternating propagation and chain-transfer steps (Figure 2). The reactions are highly efficient, proceed rapidly, even in the presence of oxygen, and do not require metal catalysts. One round of polymerization involves the addition of a thiyl radical to a vinyl, followed by abstraction of a hydrogen from a second thiol to give a thioether, and regenerate the thiyl radical. Thiol−ene click polymerization can be used in conjunction with many different thiol- and vinyl-containing compounds, which should allow for orthogonal and site-selective functionalization of polymers. Thiol−ene click polymerization might be an attractive route to synthesize polymers that can be used in applications that require materials with specific physical and/or chemical properties.[14] Sulfur-containing polymers have excellent optical properties and biocompatibility.[15] Introduction of sulfurs into a polyester should increase their refractive index, thermal stability, and affinity towards metals in comparison with the analogous non-sulfur-containing polyesters.[16, 17]

In this thesis, we demonstarted two different synthetic approaches of fine-tuning designer polyesters (“Click Polyester”), which will be described in chapter 1 (Cu(I)-catalyzed click 1,3-dipolar cycloadditions) and chapter 2

Nagao Y.; Takasu, A.
Macromol. Rapid Commun., **2009**
J. Polym. Sci. Part A: Polym. Chem., **2010**



Nagao Y.; Takasu, A.; Boccaccini A. R.
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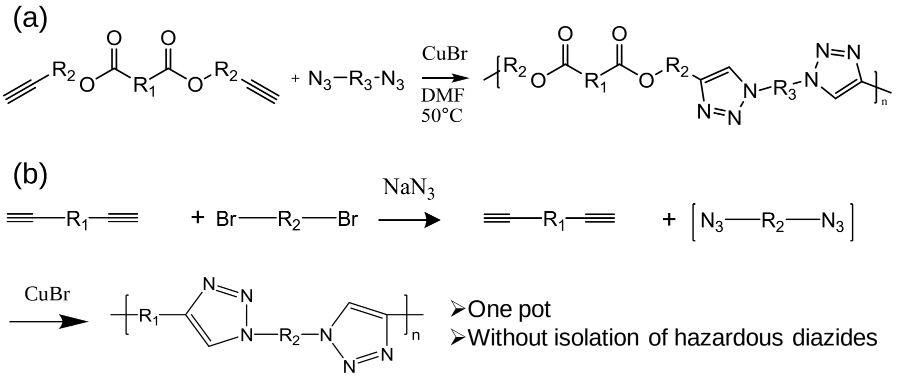
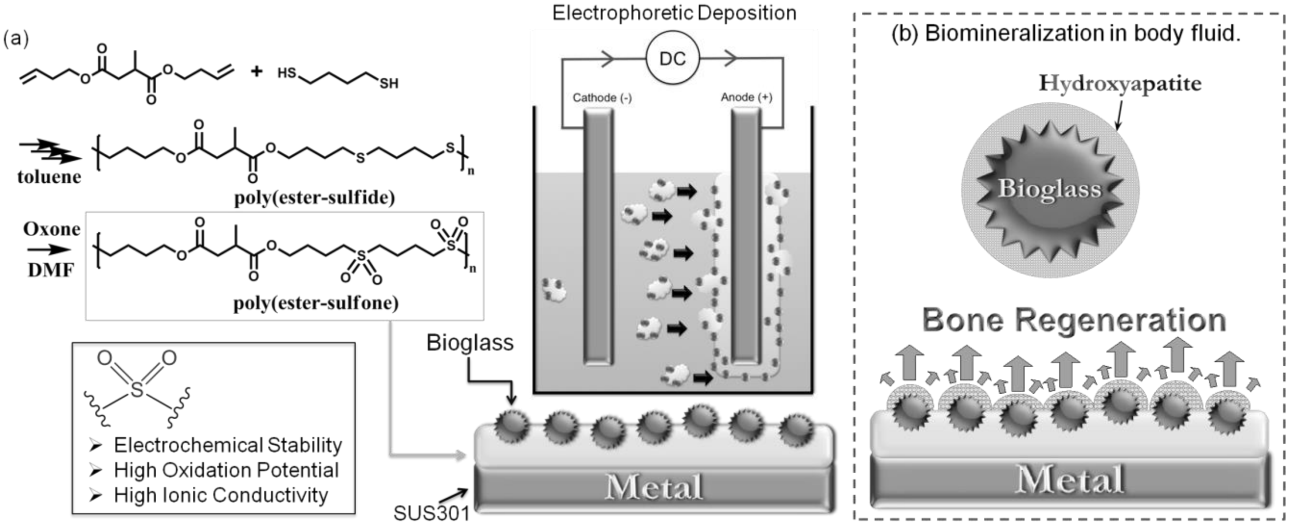
(thiol−ene click reaction). Moreover, we performed further applications of click polyesters in chapter 3 and 4. Each digest is as follows.

Scheme 1. Synthesis of click polyesters (a) by CuAAC and (b) via *in situ* azidation.



In chapter 1, we describe the use of CuAAC to synthesize polyesters (Scheme 1a). We analyzed the thermal properties of the resulting poly(ester-triazole)s to clarify the relationship with the polymer structure including position of the triazole rings. Additionally we discuss the rapid and safe synthesis of the poly(ester-triazole) via *in situ* azidation using microwave irradiation (Scheme 1b). The small molecular weight, organic azides that are used for CuAAC are explosive compounds.[18] Handling purified small azides is not a safe procedure, and they, therefore, should not be purified. To avoid the hazardous procedure, we developed a practical way, in which azide reactants are generated *in situ* from their parent halides[19] and then react immediately with Cu(I) acetylides, to form the corresponding 1,4-disubstituted-1,2,3-triazoles. Microwave heating shortens reaction time from hours to minutes, increase yields, and improves reproducibility.[20] With the use both of microwave irradiation and *in situ* azidation, we demonstrated simple, safe, and rapid procedure for click polyester via CuAAC.

Figure 3. (a) Anode-selective electrophoretic deposition of bioglass/sulfone-containing click polyester composite. (b) Process of biomineralization in body fluid.



In chapter 2, we present a thiol−ene click polymerization for the synthesis of a series of sulfide-containing polyesters that were then converted to the corresponding polyesters contained main-chain sulfone via oxone oxidation (Figure 3). Thiol-ene click polymerization might be an attractive candidate to synthesize polymers that can be used in applications that require materials with specific physical and/or chemical properties.[21] Sulfur-containing polymers have excellent optical properties and biocompatibility.[22] Introduction of sulfurs into polyester should increase their refractive index, thermal stability, and affinity towards metals in comparison with the analogous non-sulfur-containing polyesters.[23] Also given the electrical characteristics of sulfone, i.e., electrochemical stability, oxidation potential, and ionic conductivity, we were able to deposit a 45S5Bioglass/poly(ester-sulfone) composite film onto a stainless steel anode selectively by electrophoretic deposition (EPD). EPD is based in the controlled electric–field-induced deposition of charged particles or molecules in an orderly manner onto an electrode.[24] Nano- to micrometer films can be made, including those formed by organic/inorganic composites. 45S5Bioglass was the first silicate material found to bind directly to bone.[25] When in contact with a biological fluid, a thin layer of carbonate hydroxyapatite—a substance similar to carbonated calcium-deficient hydroxyapatite, the main mineral found in bone, dental enamel, and dentine—can form on the surface of Bioglass.[26]

This bioactive glass/poly(ester-sulfone) composite might therefore find use as a surface coating for implantable medical devices on which a hydroxyapatite layer can form post implantation to strengthen the interface between the implant and host bone.

Ascribed to excellent electrostatic properties of sulfone groups, low-molecular weight sulfone compounds, such as tetramethylene sulfone and ethyl methyl sulfone, are used as aprotic polar solvent for electrochemical devices (liquid electrolyte).[27] In chapter 3, we apply the thiol−ene click polymerization to prepare sulfone contained polyester-gel, and examined the electrophoretic behavior (Figure 4). We found an interesting phenomenon that deposition of the gel is achieved via eletrophoretic motion of polar sulfone to the anode in the heterogeneous state. The advantages and characteristics of employing this gel indicate the potential of the materials for use as solid electrolyte.[28]

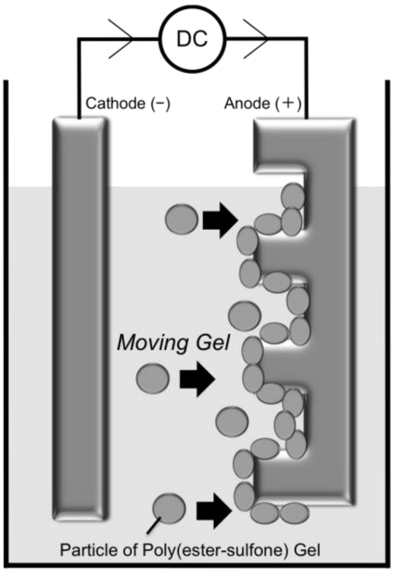
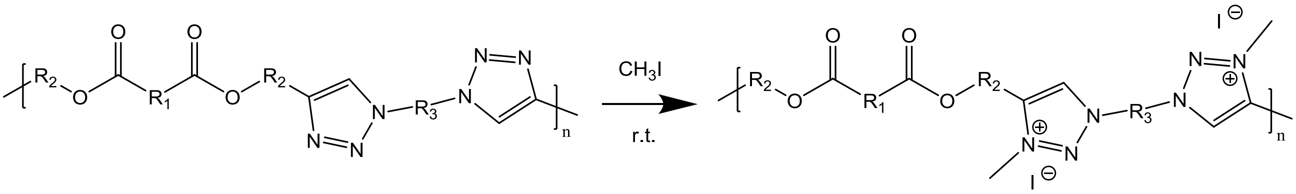


Figure 4. Smart gel coating by EPD.

Scheme 2. Ionization of poly(ester-triazole).



It is known that 1,4-disubstituted triazole formed by azide−alkyne click reaction can be easily quaternized with methyl iodide to the corresponding triazolium.[29] In chapter 4, applied this unique transformation, we led the poly(ester-triazole) to ionic polyesters directly. Polymerized ionic liquids (PILs) possess excellent ionic conductivity compared to non-ionized polymer, nevertheless they are solid, of course show lower conductivity than ionic liquids.[30] Moreover, PILs have other characteristic such as thermal, mechanical and chemical stability.[31] For these reasons, PILs have been actively investigated to apply in the fields of polymer chemistry and material science. Utilizing these processabilities, the applications to ion conducting membranes, electrical device and actuator are expected.[32]

In this thesis, we describe the use of fidelity of click chemistry for the controlled synthesis of functional polyesters. By selecting the click reaction under mild conditions, we introduced expected functional building blocks into the main chain of polyester. The introduced functional blocks play interesting roles in thermal, electrostatic, and electrophoretic properties, and hybridization with inorganic materials.

Reference

(1) (a) Lenz, R. W. *Adv. Polym. Sci.* **1993**, *107*, 1-40. (b) Koeshark, V. V. ; Vinogradora, S. V. *Polyester ; Pergamon Press : New York* **1995**.

(2) (a) Carothers, W. H.; Dorough, G. L. *J. Am. Chem. Soc.* **1930**, *52*, 711-721. (b) Takiyama, E.; Niikura, I.; Hatano, Y. Japan Patent 189,823, 1995. (c) Miura, M.; Watanabe, H.; Fujiwara, M. Japan Patent 53, 695, 1995. (d) Buzin, P.; Lahcini, M.; Schwarz, G.; Kricheldord, H. R. *Macromolecules*, **2008**, *41*, 8491-8495. (e) Garaleh, M.; Lahcini, M.; Kricheldorf, H. R.; Weidner, S. M. *J. Polym. Sci.; Part A: Polym. Chem.* **2009**, *47*, 170–177.

(3) (a) Kricheldorf, H. R.; Kreiser-Saunders, I. *Macromol. Chem. Phys.* **1990**, *191*, 1057-1066. (b) Lofgren, A.; Albertsson, A. C.; Dubois, P.; Jerome, R. *J. Macromol. Sci.; Rev. Macromol. Chem. Phys.* **1995**, *35*, 379-418. (c) Kim, S.; Han, Y. K.; Kim, Y. H.; Hong, S. I. *Macromol. Chem. Phys.* **1992**, *193*, 1623-1631.

(4) (a) Ajioka, M.; Enomoto, K.; Suzuki, K.; Yamaguchi, A. *Bull. Chem. Soc. Jpn*, **1995**, 68, 2125-2131. (b) Ni: Mochizuki, M.; Mukai, K.; Yamada, K.; Ichise, N.; Murase, S.; Iwaya, Y. *Macromolecules* **1997**, *30*, 7403-7407. (c) $HfCl_4(THF_2)$: Ishihara, K.; Ohara, S.; Yamamoto, H. *Science* **2000**, *290*, 1140-1142. (d) Sn distannoxane: Ishii, M.; Okazaki, M.; Shibasaki, Y.; Ueda, M. *Biomacromolecules* **2001**, *2*, 1267-1270.

(5) (a) Takasu, A.; Oishi, Y.; Iio, Y.; Inai, Y.; Hirabayashi, T. *Macromolecules* **2003**, *36*, 1772-1774.(b) Takasu, A.; Iio, Y.; Oishi, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2005**, *38*, 1048-1050. (c) Takasu, A.; Iio, Y.; Mimura, T.; Hirabayashi, T. *Polym. J.* **2005**, *37*, 946-953. (d) in water: Takasu, A.; Takemoto, A.; Hirabayashi, T. *Biomacromolecules* **2006**, *7*, 6–9. (e) PLA: Takasu, A.; Narukawa, Y.; Hirabayashi, T. *J. Polym. Sci.; Part A: Polym. Chem.* **2006**, 44, 5247–5253. (f) combination with ROP: Takasu, A.; Tsuruta, H.; Narukawa, Y.; Shibata, Y.; Oshimura, M.; Hirabayashi, T. *Macromolecules.* **2008,** *41*, 4688-4693. (g) microwave-assisted: Yamada, S.; Takasu, A. *Polym. J.* **2011**, *43*, 1003-1007.

(6) (a) hydroxyl: Takasu, A.; Shibata, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2007**, *40*, 151–153. (b) hydroxyl: Shibata, Y.; Takasu, A. *J. Polym. Sci.; Part A: Polym. Chem.* **2009**, *47*, 5747-5759. (c) mercapto: Yamamoto, K.; Takasu, A. *Macromolecules* **2010**, *43*, 8519-8523. (d) disulfide: Sato, Y.; Takasu, A. *Polym. J.* **2010**, *42*, 956-959.

(7) Takasu, A.; Makino, T.; Yamada, S. *Macromolecules.* **2010**, *43*, 144-149.

(8) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, 40, 2004-2021.

(9) Rostovtsev, V. V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2002**, *41*, 2596-2599.

(10) Chan, T. R.; Hilgraf, R.; Sharpless, K. B.; Fokin, V. V. *Org. Lett.* **2004**, *17*, 2853.

(11) (a) review: Pieteres, R. J.; Rijkers, D. T. S.; Liskamp, R. M. J. *QSAR Comb. Sci.* **2007**, *26*, 1181. (b) review: Tron, G. C.; Pirali, T.; Billington, R. A.; Canonico, P. L.; Sorba, G.; Genazzani, A. A. *Med. Res. Rev.* **2008**, *28*, 278.

(12) (a) adhesive polymer : Diaz, D. D.; Punna, S.; Holzer, P.; Mcpherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. G. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4392. (b) polyketone: Tang, B. Z.; Qin, A.; Jim, C. K. W.; Lu, W.; Lam, J. W. Y.; Häussler, M.; Dong, Y.; Sung, H. H. Y.; Williams, I. D.; Wong, G. K. L. *Macromolecules* **2007**, *40*, 2308-2317. (c) helical polymer: Kobayashi, S.; Itomi, K.; Morino, K.; Iida, H.; Yashima, E. *Chem. Comm.*, **2008**, 3019-3021. (d) poly(ethylene glycol): Liu, X.-M.; Thakur, A.; Wang, D. *Biomacromolecules* **2007,** *8*, 2653-2658. (e) biomass-based polymer: Michinobu, T.; Inazawa, Y.; Hiraki, K.; Katayama, Y.; Masai, E.; Nakamura, M.; Ohara, S.; Shigehara, K. *Chem. Lett.* **2008**, 154-155. (f) review: Binder, W. H.;

Sachsenhofer, R. *Macromol. Rapid Commun.* **2007**, *28,* 15-54. (g) review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2008**, *29,* 952-981. (h) review: Johnson, J. A.; Finn, M. G.; Koberstein, J. T.; Turro, N. J. *Macromol. Rapid Commun.* **2008**, *29,* 1052-1072. (i) new "click" chemistry: Koyama, Y.; Yonekawa, M.; Takata, T. *Chem. Lett.* **2008**, *37,* 918-919. (j) Lee, Y. G.; Koyama, Y.; Yonekawa, M.; Takata, T. *Macromolecules* **2009**, *42*, 7709-7717. (k) α-azide-ω-alkyne monomers: Binauld, S.; Damiron, D.; Hamaide, T.; Pascault, J. P.; Fleury, E.; Drockenmuller, E. *Chem. Comm.,* **2008**, 4138-4140.

(13) (a) Jacobine, A. F. In radiation Curing in Polymer Science and Technology III; Fouassier, J. D.; Rabek, J. F., Eds.; Elsevier: London, **1993**, *7*, 219-268. (b) Hoyle, C. E.; Lee, T. Y.; Roper, T. *J. Polym. Sci.; Part A: Polym. Chem.* **2004**, *42*, 5301–5338.

(14) (a) Wilderbeek, H. T. A.; Goossens, J. G. P.; Bastiaansen, C. W. M.; Broer, D. J. *Macromolecules* **2002**, *35*, 8962-8968. (b) Wilderbeek, H. T. A.; Meer, M. G. M.; Bastiaansen, C. W. M.; Broer, D. J. *J. Phs. Chem. B* **2002**, *106*, 12874-12883. (c) Killops, K. L.; Campos, L. M.; Hawker, C. J. *J. Am. Chem. Soc.* **2008**, *130*, 5062-5064. (d) Kwinsnek, L.; Nazarenko, S.; Hoyle, C.E. *Macromolecules* **2009**, *42*, 7031-7041. (e) Kloxin, C. J.; Scott, T. F.; Bowman, C. N. *Macromolecules* **2009**, *42*, 2551-2556. (f) Shin, J.; Matsushima, H.; Chan, J. W.; Hoyle, C. E. *Macromolecules* **2009**, *42*, 3294-3301. (g) Lluch, C.; Ronda, J. C.; Galia, M.; Lligadas, G.; Cádiz, V. *Biomacromolecules* **2010**, *11*, 1646-1653.

(15) (a) Santerre, J. P.; Brash, J. L. *Macromolecules* **1991**, *24*, 5497-5503. (b) Marianucci, E.; Berti, F.; Pilati, F.; Manaresi, P. *Polymer* **1994**, *35*, 1564-1566. (c) Rydholm, A. E.; Bowman, C. N.; Anseth, K. S. *Biomaterials* **2005**, *26*, 4495-4506. (d) Rydholm, A. E.; Reddy, S. K.; Anseth, K. S.; Bowman, C. N. *Biomacromolecules* **2006**, *7*, 2827-2836.

(16) Lu, C.; Cui, Z.; Wang, Y.; Li, Z.; Guan, C.; Yang, B.; Shen, J. *J. Mater. Chem.* **2003**, *13*, 2189-2195.

(17) Huang, Y.; Paul, D. R. *Macromolecules* **2006**, *39*, 1554-1559.

(18) Bräse, S.; Gil, C.; Knepper, K.; Zimmermann, V. *Angew. Chem., Int. Ed.* **2005**, *44,* 5188–5240.

(19) (a) Feldman, A. K.; Colasson, B.; Fokin, V. V. *Org. Lett.* **2004**, *22*, 3897-3899. (b) Appukkuttan, P.; Dehaen, W.; Fokin, V. V.; Eycken, E. V. *Org. Lett.* **2004**, *23*, 4223-4225.

(20) Kappe, C. O. *Angew. Chem. Int. Ed.* **2004**, *43*, 6250-6284.

(21) (a) Wilderbeek, H. T. A.; Goossens, J. G. P.; Bastiaansen, C. W. M.; Broer, D. J. *Macromolecules* **2002**, *35*, 8962-8968. (b) Wilderbeek, H. T. A.; Meer, M. G. M.; Bastiaansen, C. W. M.; Broer, D. J. *J. Phs. Chem. B* **2002**, *106*, 12874-12883. (c) Killops, K. L.; Campos, L. M.; Hawker, C. J. *J. Am. Chem. Soc.* **2008**, *130*, 5062-5064. (d) Kwinsnek, L.; Nazarenko, S.; Hoyle, C.E. *Macromolecules* **2009**, *42*, 7031-7041. (e) Kloxin, C. J.; Scott, T. F.; Bowman, C. N. *Macromolecules* **2009**, *42*, 2551-2556. (f) Shin, J.; Matsushima, H.; Chan, J. W.; Hoyle, C. E. *Macromolcules* **2009**, *42*, 3294-3301. (g) Lluch, C.; Ronda, J. C.; Galia, M.; Lligadas, G.; Cádiz, V. *Biomacromolecules* **2010**, *11*, 1646-1653.

(22) (a) Santerre, J. P.; Brash, J. L. *Macromolecules* **1991**, *24,* 5497-5503. (b) Marianucci, E.; Berti, F.; Pilati, F.; Manaresi, P. *Polymer* **1994**, *35*, 1564-1566. (c) Rydholm, A. E.; Bowman, C. N.; Anseth, K. S. *Biomaterials* **2005**, *26*, 4495-4506. (d) Rydholm, A. E.; Reddy, S. K.; Anseth, K. S.; Bowman, C. N. *Biomacromolecules* **2006**, *7,* 2827-2836.

(23) (a) Lu, C.; Cui, Z.; Wang, Y.; Li, Z.; Guan, C.; Yang, B.; Shen, J. *J. Mater. Chem.* **2003**, *13*, 2189-2195. (b) Huang, Y.; Paul, D. R. *Macromolecules* **2006**, *39*, 1554-1559.

(24) (a) Boccaccini, A. R.; Keim, S.; Ma, R.; Zhitmirsky, L. I. *J. R. Soc. Interface* **2010**, *7*, 581-613. (b) Sarker, P.; Nicholson, P. S. *J. Am. Ceram. Soc.* **1996**, *79*, 1987-2002. (c) Roether, J. A.; Boccaccini, A. R.; Hench, L. L.; Maquet, V.; Gautier, S.; Jérôme, R. *Biomaterials*, **2002**, *23*, 3871-3878. (d) Corni, I.; Neumann, N.; Novak, S.; König, K.; Veronesi, P.; Chen, Q.; Ryan, M. P.; Boccaccini, A. R. *Surf. Coat. Technol.* **2009**, *203*, 1349-1359. (e) Pishbin, F.; Simchi, A.; Ryan, M. P.; Boccaccini, A. R. *Surf. Coat. Technol.* **2011**, *205*, 5260-5268. (f) Rodriguez, H. H.; Vargas, G.; Cortés D. A. *Ceram. Int.* **2008**, *34*, 1303-1130. (g) Van der Biest, O. O.; Vandeperre, L. J. *Annu. Rev. Mater. Sci.* **1999**, *29*, 327-352. (h) Boccaccini, A. R.; Zhitomirsky, I. *Curr. Opin. Solid State Mater. Sci.* **2002**, *6*, 251-260. (i) Ma, R.; Zhitomirsky, I. *J. Alloy Compd.* **2011**, *509*, S510-S513. (j) Wang, Y.; Deen, I.; Zhitomirsky, I. *J. Colloid Interface Sci.* **2011**, *362*, 367-374. (k) Boccaccini, A. R.; Peters, C.; Roether, J. A.; Eifler, D.; Misra S. K.; Minay, E. J. *J. Mater. Sci.* **2006**, *41*, 8152-8159. (l) Xiao, X. F.; Liu, R. F. *Mater. Lett.* **2006**, *60*, 2627-2632.

(25) (a) Hench, L. L.; Splinter, R. J.; Allen, W. C.; Greenlee, T. K. *J. Biomed. Mater. Res.*, **1971**, *2*, 117-141. (b) Hench, L. L. *J. Am. Ceram. Soc.*, **1998**, *81*, 1705-1728. (c) Hench, L. L. *J. Eur.*

Ceram. Soc., **2009**, *29*, 1257-1265. (d) Misra, S. K.; Nazhat, S. N.; Valappil, S. P.; Torbati, M. M.; Wood, R. J. K.; Roy, I.; Boccaccini, A. R. *Biomacromolecules* **2007**, *8*, 2112-2119.

(26) Oonishi, H.; Hench, L. L.; Wilson, J.; Sugihara, F.; Tsuji, E.; Matsuura, M.; Kin, S.; Yamamoto, T.; Mizokawa, S. *J. Biomed. Mater. Res.* **2000**, *51*, 37-46.

(27) Xu, K.; Angell, C. A. *J. Electrochem. Soc.* **1998**, *145*, 70-72.

(28) Allcock, H. R.; Olmeijer, D. L. *Macromolecules*, **1998**, *31*, 8036-8046.

(29) Kumar, A.; Pandey, P. S. *Org. Lett.* **2008**, *10*, 165-168.

(30) Ohno, H.; Ito, K. *Chem. Lett.* **1998**, 751.

(31) Mecerreyes, D. *Prog. Polym. Sci.* **2011**, *36*, 1629.

(32) (a) Grady, B. P. *Polym. Eng. Sci.* **2008**, *48*, 1029. (b) Lin, B.; Qiu, L.; Lu, J.; Yan, F. *Chem. Mater.* **2010**, *22*, 6718. (c) Green, M. D.; Long, T. E. *Polym. Rev.* **2009**, *49*, 291.

Chapter 1

“Click Polyester”: Synthesis of Polyesters Containing Triazole Units in the Main Chain via Safe and Rapid “Click” Chemistry and Their Properties

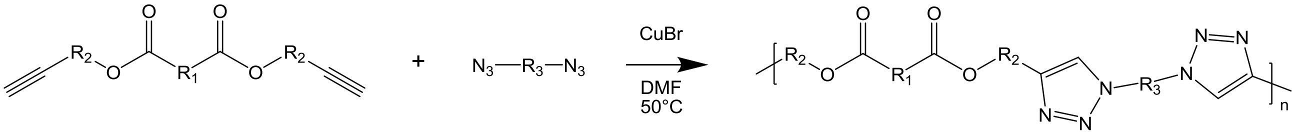
Abstract

We performed click Cu(I)-catalyzed polymerizations of diynes that contained ester linkages and diazides to produce polyesters (click polyesters) of large molecular weights **[**(~1.0–7.0**)** × 10^4**]**, that contained main-chain 1,4-disubstitued triazoles in excellent yields. We found that the incorporated triazole rings improved the thermal properties of the polymers and magnified the even-odd effect of the methylene chain length on the thermal properties of the click polyesters. We also found that, by changing the positions of the triazole rings, the thermal properties of the polyesters could be controlled. We also introduced the use of *in situ* azidation to produce click polyesters. *In situ* azidation is a safe reaction, as explosive diazides are not used as reactants. Additionally, microwave-assisted, Cu(I)-catalyzed cycloadditions were found to accelerate the *in situ* polymerization rates. This is the first study that has applied click chemistry for the synthesis of a series of polyesters**.**

1-1 Introduction

Even though many different kinds of polymers have been synthesized, their properties characterized, and used in commercial applications, polyesters still constitute a useful class of polymers. Specifically, aliphatic polyesters are expected to soon replace conventional plastics, because they are biodegradable and are mechanically strong.[1] However, the syntheses of high molecular weight ($M_n > 1.0 \times 10^4$) aliphatic polyesters obtained via polycondensations of dicarboxylic acids and diols require severe conditions (>250 ˚C and a greatly reduced pressure).[2] Recently, we published reports concerning the "room-temperature" polycondensations of dicarboxylic acids with diols that were catalyzed by the Lewis acids, scandium trifluoromethanesulfonate [$Sc(OTf)_3$][3a] and scandium trifluoromethanesulfonimide [$Sc(NTf_2)_3$].[3b] These polycondensations directly afforded aliphatic polyesters with M_ns $> 1.0 \times 10^4$. Although identifying new Lewis acids has been a difficult task,[4] we focused on scandium catalysts, because they are insensitive to protic compounds.[5] After the polycondensations, the catalysts could be recovered and then subsequently reused.[3a,3b,3e] Another way to simplify the recovery process, is to covalently couple the scandium catalyst to a polystyrene resin support.[3c] These so-called "room-temperature polycondensations" not only save energy by not requiring high temperatures, but increase the types of monomers that can be used. We have published reports concerning room-temperature polycondensations of diols with dicarboxylic acids that contained a C=C double bond,[3c] bromo substituents,[3c] hydroxyl groups (chemoselective dehydration polycondensation),[3f,3g] or chirality.[3h] Using atom-transfer radical polymerization (ATRP) in combination with poly(butylene bromoadipate) as the macroinitiator, it was possible to synthesize polyesters that had poly(methyl methacrylate) side chains.[3c]

Scheme 1-1. Synthesis of Click Polyesters.



It is still unusual to find examples of work that report new synthetic strategies and catalysts[3i] for the synthesis of aliphatic polyesters under environmentally benign conditions. Click chemistry, introduced by Sharpless and his colleagues,[6] is used to efficiently prepare many different types of organic compounds. The Cu(I)-catalyzed click 1,3-dipolar cycloadditions between azides and alkynes[7a] proceed readily under mild conditions, without producing by-products, and with great chemoselectivities. Additionally, these Cu(I)-catalyzed azide-alkyne cycloadditions (CuAAC) are usually highly regioselective, e.g., the formation of 1,4-disubstituted 1,2,3-triazoles. Although there have been many reports concerning the improvement of reaction conditions for click-type syntheses,[7b] and click reactions have been used to synthesize biologically active substances,[8] its application to polymer synthesis (click polymerization) has been limited.[9] Polyesters are a major class of polymeric materials, nevertheless click chemistry has not been used to synthesize polyesters.

For industrial processes and applications, control of the thermal properties of polymeric materials is necessary. Polymer blends have been used to achieve the desired thermal properties, however, for the production of nano-materials, the micro-scale molecular design must be considered. Therefore, we need to be able to control the physical and chemical properties of the targeted polymer by changing the type(s) of monomer(s) incorporated and/or the type(s) of synthetic reaction(s). Click polymerization should enable the synthesis of polyesters from diyne monomers containing ester linkages and diazido monomers. Click polymerizations are polyaddition reactions, by which we can design a large number of different molecular architectures by changing the type(s) of monomer(s) incorporated. Additionally, the polymerization may be accompanied by the formation of main-chain 1,4-disubstituted triazoles. Therefore, production of main-chain 1,4,-disubstitured triazole polyesters will substantially increase the types of “next-generation” polyesters available.

On the other hand, the small molecular weight, organic azides that are used for CuAAC are dangerous compounds. A small azide molecule is considered to have less than six carbon and one oxygen atoms per azide functionality. This definition is an empirically derived rule and does not guarantee that a particular azide-containing compound is stable. Handling purified azides is not a safe practice, and they, therefore, should not be purified. To improve the safety of CuAACs for polyester, we developed a practical reaction that uses azide reactants that are generated *in situ* from their corresponding halides[10] and that then react immediately with Cu(I) acetylides, to form the corresponding 1,4-disubstituted-1,2,3-triazoles.

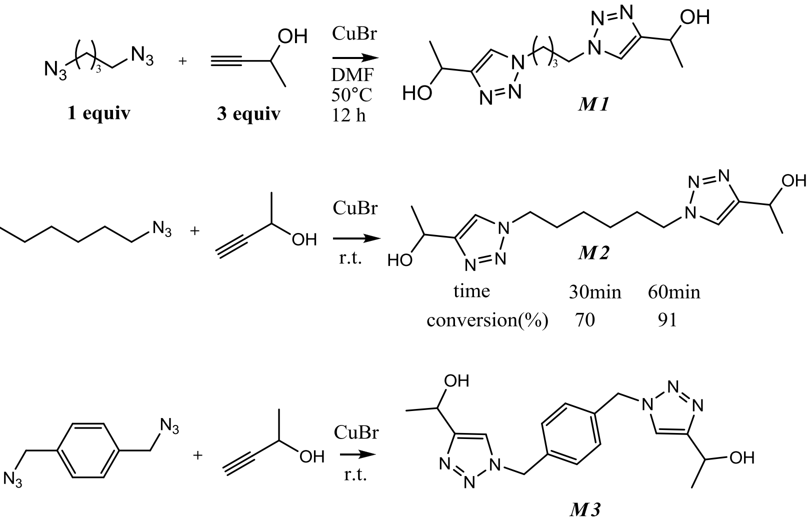
Rapid syntheses induced by microwave irradiation to control the temperature have attracted considerable attention recently, because such procedures are more convenient and economical than the corresponding traditional syntheses that use alternative heat sources e.g., an oil bath. Almost 4000 articles have been published concerning microwave-assisted organic synthesis since Gedye, Giguere, and colleagues first reported the use of microwave heating to accelerate organic chemical transformations.[11] Microwave heating reduces reaction times from hours to minutes, reduces the amounts of by-products produced, increase yields, and improves reproducibility.[11c] Therefore, many academic and industrial research groups are already using microwave-assisted reactions for the rapid optimization of reactions, for the efficient synthesis of new chemical entities, and for the discovery and characterization of new chemistries.[11c] Fokin and colleagues have developed a microwave-enhanced, fast, completely regioselective, and efficient three-component reaction that uses small compounds for the generation of 1,4-disubstituted-1,2,3-triazoles.[10b] Furthermore, as reported by Liskamp and colleagues, microwave-assisted CuAAC can be used to polymerize peptide-based polymers from amino acids derivatives.[12] To broaden the scope of microwave-assisted CuAAc reactions, we report herein the application of microwave heating to safely form polyesters via *in situ* azidation. With the use of microwave irradiation and *in situ* azidation, we reduced the reaction times needed and eliminated the danger incurred when handling small azide compounds.

Herein, I report the use of click chemistry to synthesize polyesters. These reactions were accompanied by the formation of main-chain 1,4-disubstituted triazoles. I found that the triazole backbone improved the thermal properties of the polyesters. I also found that, in conjunction with *in situ* azidation, microwave irradiation accelerated the polymerization rates. To the best of our knowledge this is the first time click chemistry has been used to synthesize a series of polyesters.[13]

1-2 Results and Discussion

Model Reactions. We first investigated a Cu(I)-catalyzed, Huigen-type, 1,3-dipolar cycloaddition that used 1,4-diazidobutane as the azide and 3-butyn-2-ol as the alkyne with Cu(I) (CuBr) as the catalyst. We heated a mixture of 1,4-diazidobutane (1.3 mmol) and 3-butyn-2-ol (3.9 mmol) to 50 ˚C, then added 10 mg CuBr in 1-mL volumes of DMF, and then stirred the mixture at 50 ˚C for 12 h (**Scheme 1-2**). The reaction proceeded smoothly and gave the expected product (*M1*), the 1,4-disubstituted 1,2,3-triazole isomer, in high yield (~100%), and its structure and yield were confirmed by characterization of the ^{1}H-NMR spectrum of the unpurified product.

Scheme 1-2. Model Click Reactions of Model Reaction that Used 1,4-Diazidobutane, 3-Butyn-2-ol, and Cu(I)Br as the Catalyst in DMF at 50 ˚C (*M1*). 1,6-Diazidohexane (*M2*) and *p*-Diazidoxylene (*M3*) with 3-Butyn-2-ol. (Solvent, DMF; Catalyst, Cu(I)Br, Room Temperature, 1 h Reaction Time).



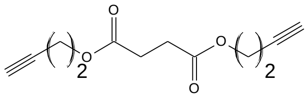
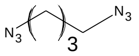
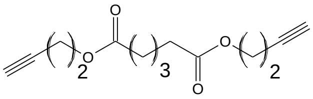
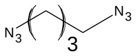
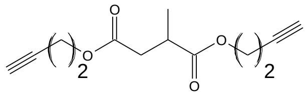
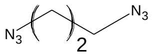
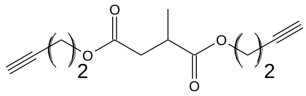
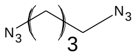
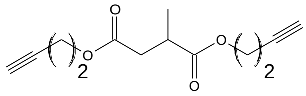
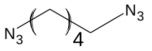
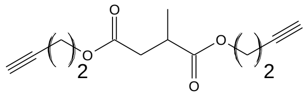
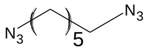
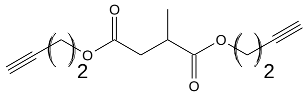
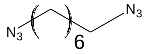
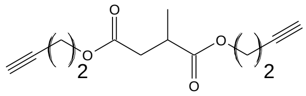
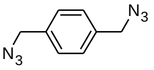
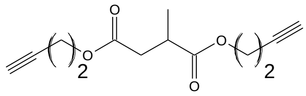
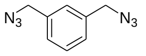
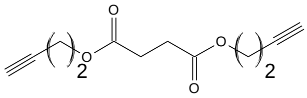
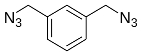
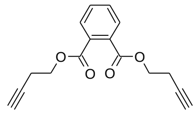
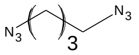
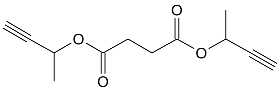
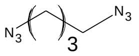
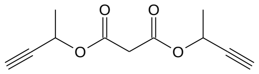
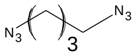
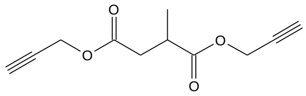
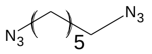
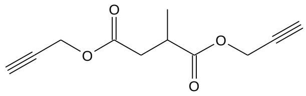
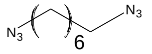
The model reaction to synthesize *M3* using the aromatic *p*-diazidoxylene and 3-butyn-2-ol was also carried out at 25 ˚C for 1 h with a yield of 81% (**Scheme 1-2**). However, under the same reaction conditions, with the substitution of 1,6-diazidohexane for *p*-diazidoxylene, 91% conversion to *M2* was achieved in the same amount of time. However, we couldn't confirm the higher conversion based on the reactive nature of benzyl azide and lower conversion compared to alkyl azide was obtained in the ^{1}H NMR spectra. This is ascribed to steric hindrance by the aromatic ring.

Polymer Syntheses. Because the model 1,3-dipolar cycloaddition reactions proved to be regioselective, it appeared possible to use the click reaction to synthesize polyesters (**Scheme 1-1**). The diyne monomers, bis(butynyl) succinate, bis(butynyl) adipate, bis(butynyl) methylsuccinate, bis(butynyl) phthalate, bis(isobutynyl) succinate, bis(isobutynyl) malonate, bis(propynyl) methylsuccinate, and the diazide monomers, 1,3-diazidopropane, 1,4-diazidobutane, 1,5-diazidopentane, 1,6-diazidohexane, 1,7-diazidoheptane, *p*-diazidoxylene, *m*-diazidoxylene, were prepared in our laboratory.[13]

The click polymerizations were catalyzed by Cu(I) (as CuBr) without an N-substituted Cu(I)-stabilizing ligand that might have reduced the product yield by base cleavage of the ester bonds.[14] The click polymerizations were run in DMF at 50 ˚C for 30 h, and the products were obtained in excellent yields (85-99%, **Table 1-1**). The number averaged molecular weights (M_n) and the molecular weight distributions (M_w/M_n) of the click polyesters were determined using SEC. The measurements were performed in the presence of 100 mM tetramethylethylenediamine to eliminate the possibility that Cu would promote the Cu(I)-mediated crosslinking of a newly formed triazole pair.[9d]

Using bis(butynyl) methylsuccinate as the diyne monomer and different alkane diazides (runs 3-7), the click polymerizations proceeded smoothly to give the corresponding polyesters with M_ns between ~1.0×10^4 and 5.0×10^4. For each of their size exclusion chromatograms, only a single, symmetrical peak was recorded. The click polymerizations that used a diazide derivative of *p*-xylene in conjunction with bis(butynyl) methylsuccinate also proceeded smoothly to give the corresponding polyesters. When *p*-diazidoxylene was used as the monomer, a high molecular weight polyester ($M_n = 5.9 \times 10^4$) was obtained. It is seems that the high molecular weight was ascribed to the conformation of the obtain “click polyester” not to reactivity of benzylic azide (see model reaction), as *m*-diazidoxylene as the monomer did not afford much higher molecular weight polyester ($M_n = 0.9 \times 10^4$, run 9).

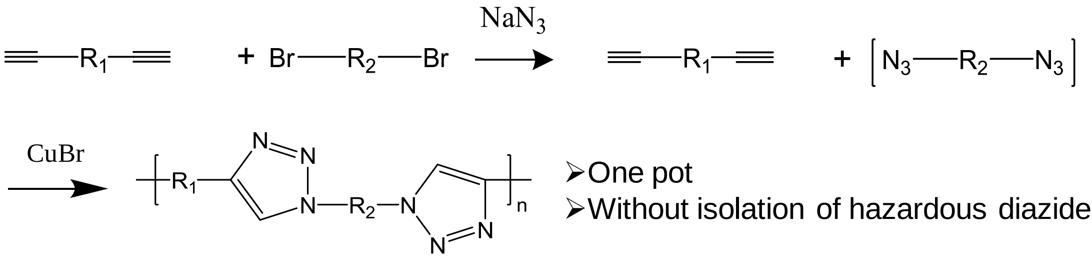
Table 1-1. Click Polymerizations of Dialkynes and Diazides[a]

run	diyne	diazide	yield[b] (%)	M_n[c] x10^{-4}	M_w/M_n[c]	T_g[d] (°C)	T_m[d] (°C)
1			-[e]	insoluble	insoluble	-[e]	-[e]
2			-[e]	insoluble	insoluble	-[e]	-[e]
3			99	0.88	2.0_8	17	76
4			89	1.37	2.4_9	14	125
5			99	1.36	2.8_5	-4	52
6			99	5.08	2.4_6	6	76
7			84	1.13	2.9_0	-3	72
8			64	5.93	2.2_6	51	137
9			70	0.84	1.7_0	29	not detected
10			53	6.69	2.5_3	50	78
11			95	0.19	1.4_0	-[e]	-[e]
12			99	0.89	3.2_4	-[e]	-[e]
13			85	0.59	5.8_3	-[e]	-[e]
14			99	1.33	2.7_2	14	84
15			73	1.14	2.5_2	1	68

[a] All runs were performed on a 1 mmol scale in 0.5 mL (DMF), at 50˚C, for 30 h, with 10 mg CuBr as the catalyst. [b] After reprecipitation from DMF with diethyl ether. [c] Determined by SEC with DMF as the eluent and relative to poly(stylene) standards. [d] T_m was determined from the first heating DSC scan and T_g from the second scan (heating and cooling rates: 10 ˚C/min). [e] Not measured.

Safe Synthesis of Click Polyesters via *in Situ* Azidation. We performed click polymerizations of diynes and dibromo compounds in the presence of sodium azide to synthesize click polyesters via *in situ* azidation. These reactions were benign, as purified diazide compounds, which might explode, were not involved (**Scheme1- 3**).

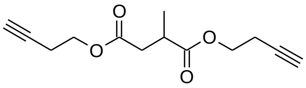
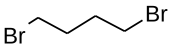
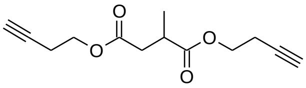
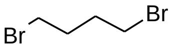
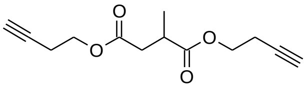
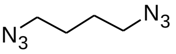
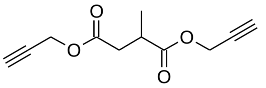
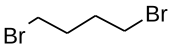
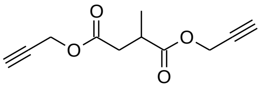
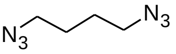
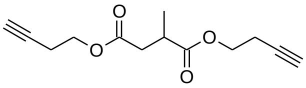
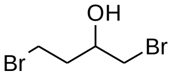
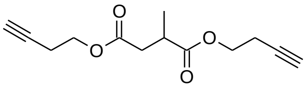
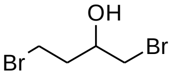
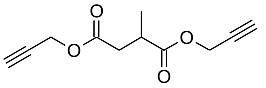
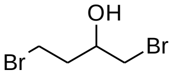
Scheme 1-3. One Pot *in Situ* Click Polymerization.



- One pot
- Without isolation of hazardous diazides

We first investigated Cu(I)-mediated safe click reactions with the reaction temperatures controlled by an oil-bath (**Table 1-2**). The reactions were performed at 50 ˚C for 24 h. For all synthesizes, the polyesters obtained via *in situ* azidation had M_n values molecular weights (0.59×10^4, run 2; 0.33×10^4, run 4; **Table 1-2**) that were smaller than the corresponding click polyesters that had been synthesized using ioslated diazido monomers (3.79×10^4, run 3; 0.68×10^4, run 5; **Table 1-2**). We also performed click polymerizations with the hydroxyldibromide, 1,4-dibromo-2-butanol, in the presence of sodium azide, to synthesize click polyesters containing pendent hydroxyl groups (runs 6-8). However, only polyesters of relatively low molecular weight were recovered [$M_n = (0.1–0.3) \times 10^4$].

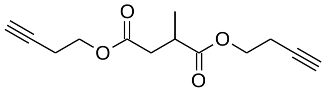
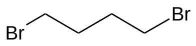
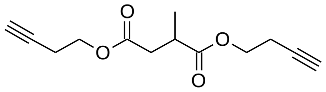
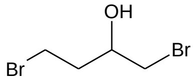
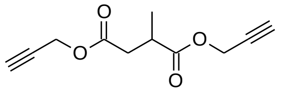
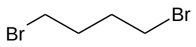
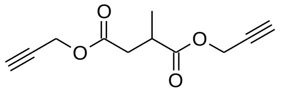
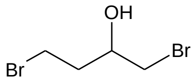
Table 1-2. Safe Syntheses of Click Polyesters via *in Situ* Azidation that Used an Oil Bath for Temperature Control[a]

run	diyne	dibromo or diazide compound		DMF (mL)	yield[b] (%)	M_n^cx10^{-4}	M_w/M_n^c
1			NaN_3	0.5	99	0.3	1.9
2			NaN_3	1	98	0.6	3.1
3				1	99	3.7	2.8
4			NaN_3	1	98	0.3	2.2
5				1	99	0.7	2.4
6			NaN_3	0.5	98	0.1	2.1
7			NaN_3	1	99	0.3	2.2
8			NaN_3	1	99	0.2	2.3

[a]All runs are performed on a 1 mmol scale in DMF at 50˚C, for 24h, with 30 mg of CuBr as the catalyst, and 1.0 equiv each of sodium azide and the halide. [b]After reprecipitation from DMF using diethyl ether. [c]Determined by SEC measurement in DMF relative to poly(stylene) standards.

Next, we attempted click polymerizations, with the temperature (50 ˚C) controlled by modulating the power of the microwave irradiation between 0 and 50 W and reaction times of 24 h (**Table 1-3**). In contrast to the results obtained when the temperature was controlled by an oil bath ($M_n = 0.59 \times 10^4$, run 2; 0.33×10^4, run 4; **Table 1-2**), controlling the temperature using microwave irradiation produced higher molecular weight click polyesters ($M_n = 0.94 \times 10^4$, run 1; 0.42×10^4, run 3; **Table 1-3**). The polymerizations were completed in shorter periods of time when microwave irradiation was used than when an oil bath was used and that microwave radiation provides the effective driving force for the click polymerizations.[9c, 10b, 12, 16] However, microwave irradiation did not improve the incorporation of monomers that contained hydroxyl groups (runs 3 and 4). This lack of improvement might be ascribed to absorbance of microwave by the pendent hydroxyls during the polyaddtion.

Table 1-3. Safe Synthesis of Click Polyesters via *in Situ* Azidation that Used Microwave Irradiation for Temperature Control[a]

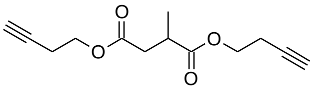
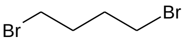
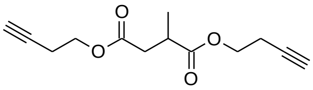
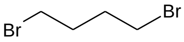
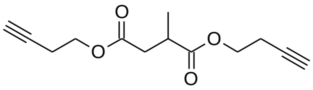
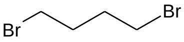
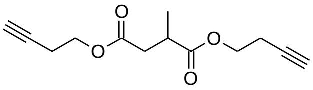
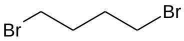
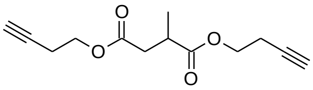
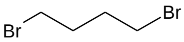
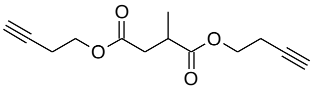
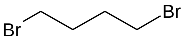
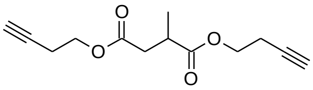
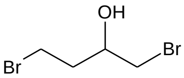
run	diyne	dibromo compound	yield[b] (%)	$M_n{}^c$x10^{-4}	$M_w/M_n{}^c$
1			99	0.9	2.4
2			99	0.2	1.9
3			98	0.4	2.4
4			99	0.2	2.1

[a] All runs are performed on a 1 mmol scale in 1 mL DMF, for 24 h, at 50 ˚C that was maintained by modulating the irradiation power between 0 and 50 W; with 30 mg CuBr as the catalyst; and 1.0 equiv of sodium azide and 1.0 equiv. of the halide. [b] After reprecipitation from DMF using diethyl ether. [c] Determined by SEC with DMF as the eluent relative to poly(stylene) standards.

Finally, the irradiation power was set to 50 W (**Table 1-4**). Remarkable increases in the molecular weights of the polyesters were achieved to attain a more effective microwave-assisted polymerization. For example, the polyester of run 1 ($M_n = 2.5 \times 10^4$) was prepared in only 30 min and that of run 2 in 15 min (M_n=1.8×10^4). We also found that the molecular weight of the polyester that incorporated 1,4-dibromo-2-butanol increased (run 7). As expected, the molecular weights of the polyesters tended to decrease with increasing monomer concentration, perhaps because transesterification was favored at the high temperature used, which was the boiling point of DMF.

This microwave-assisted polymerization is a simple technique, requiring only the mixing of reagents and microwave irradiation. It avoids the need to isolate and handle potentially unstable small organic azides and shortens the reaction time from hours to minutes.

Table 1-4. Instant "Click Polymerization" via *in Situ* Azidation using Microwave Irradiation for Temperature Control[a]

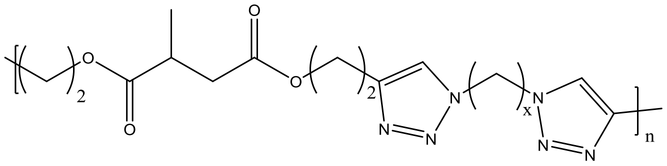
run	diyne	dibromo compound	DMF	time (min)	yield[b] (%)	M_n^cx10^{-4}	M_w/M_n^c
1			2	30	99	2.5	4.8
2			2	15	99	1.8	3.7
3			1.5	30	99	1.3	4.5
4			1.5	15	99	1.1	4.0
5			1	30	99	0.8	2.3
6			1	15	99	0.7	2.7
7			1	15	99	0.5	2.4

[a] All runs are performed with 50 W irradiation power, with 30 mg CuBr as the catalyst, 2.0 equiv of sodium azide and 2.0 equiv of the halide. [b] After reprecipitation from DMF using diethyl ether. [c] Determined by SEC with DMF as the eluent and relative to poly(stylene) standards.

Themal Properties of "Click Polyester"s

Polymerization shown in this study was accompanied by the formation of main-chain 1,4-disustituted triazoles. We found that the presence of main-chain triazole rings improved the thermal properties of the polyesters *per se* and magnified the even-odd effect of the methylene chain length on the thermal properties. For example, the polyester synthesized from bis(butynyl) methylsuccinate and 1,4-diazidobutane (x = 4, where x as the number of methylene groups) had higher T_g and T_m values ($M_n = 1.37 \times 10^4$, $T_g = 14$ ˚C, $T_m = 125$ ˚C, run 4, in **Table 1-1**) compared with poly(octamethylene methylsuccinate), which did not have a main-chain triazole ring ($M_n = 2.2 \times 10^4$, $T_g = -53$ ˚C, T_m was not observable). In contrast, the polyester synthesized from 1,5-diazidopentane (x = 5, run 5 in **Table 1-1**) had values for its thermal properties that were much smaller ($T_g = -4$˚C, $T_m = 52$˚C).

The differences for ΔT_g (18 ˚C) and ΔT_m (73 ˚C) (runs 4 and 5), were greater than those usually effected by the even-odd effect for T_gs [e.g., for poly(nonamethylene methylsuccinate), T_g=-61˚C, ΔT_g (8˚C)].[15] The click polyester synthesized from 1,6-diazidohexane (x = 6, run 6) had larger T_g (6 ˚C) and T_m (76 ˚C) values than did that synthesized from 1,5-diazidopentane (x = 5). Zigzag curves with zigzag shapes were observed for plots of T_g and T_m vs. the methylene chain length of the diazides (**Figure 1-2**). Although an even–odd effect is usually observed for the thermal properties of polyesters[2,15] the height difference between the highest and lowest points is usually small for the zigzag plots of aliphatic polyesters. Therefore, the introduction of main-chain triazole rings enhanced the even–odd effect.



x = 3, 4, 5, 6, or 7

sample	T_g[a]	T_m[a]
x=3	17	76
x=4	14	125
x=5	-4	52
x=6	6	76
x=7	-3	72

[a] T_m is measured by the first DSC scan at heating rate of 10˚C/min. T_g by the second scan.

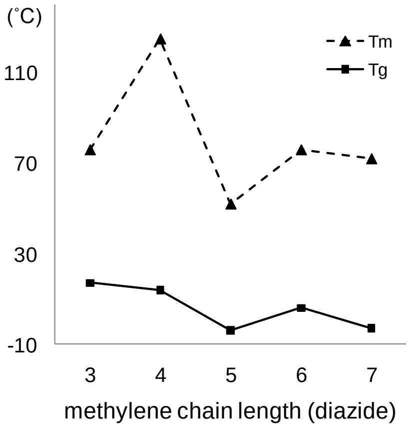


Figure 1-2. Plots of the T_m and T_g values of click polyesters as a function of the main-chain number of methylene units.

Energy minimizations were performed for the repeat units of the click polyesters, i.e., Me-[OCOCH(CH_3)CH_2COO(CH_2)$_2$-triazole-(CH_2)$_4$-trialzole-(CH_2)$_2$]$_2$-Me and Me-[OCOCH(CH_3)CH_2COO(CH_2)$_2$-triazole-(CH_2)$_5$-trialzole-(CH_2)$_2$]$_2$-Me using semiempirical molecular orbital calculations[16] to model the conformations of the corresponding click polyesters (runs 4 and 5). The three-dimensional structures of the energy-minimized models (**Figure 1-3**), indicate that the value of the main-chain torsion angle is larger for the click polyester synthesized from 1,5-diazidopentane (run 5), which produces a larger overall free volume and inhibits intramolecular stacking.

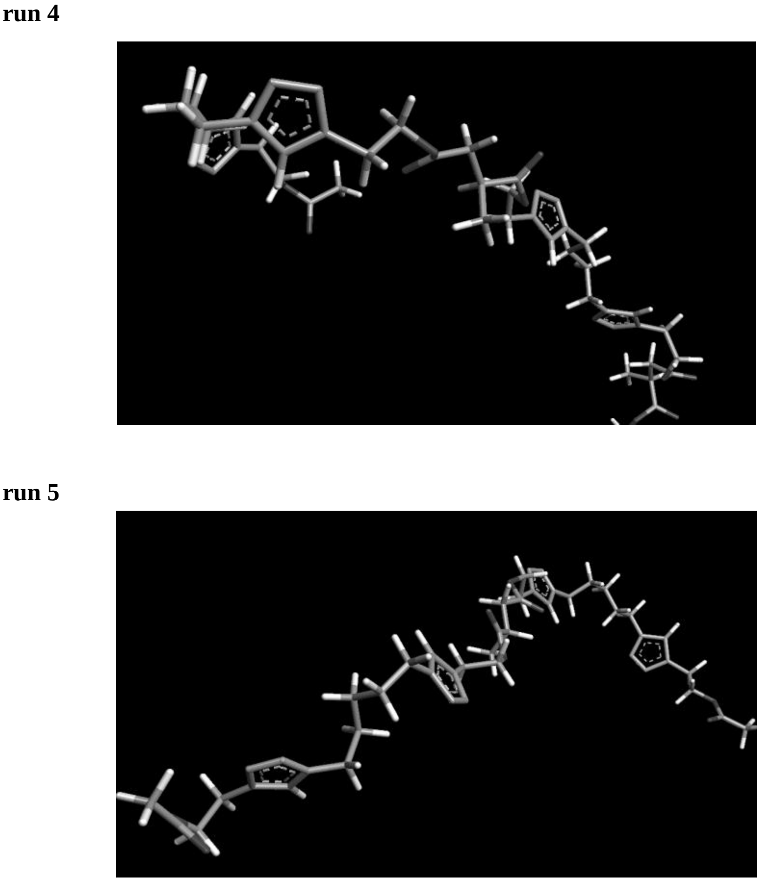


Figure 1-3. Semiempirical molecular orbital calculations to model the conformations of the corresponding click polyesters (runs 4 and 5 in **Table 1**).

Interestingly, when the number of intervening methylenes between the triazole rings was an even value, e.g., run 4 (number of intervening methylenes: 4) and 14 (number of intervening methylenes: 6) (**Table 1-1**), a decrease in the T_m value was found ($\Delta T_{m\ (run\ 14\text{-}run\ 4)}$ = -41˚C) with increase of the methylene number; whereas, when the number of intervening methylenes was an odd value, e.g., runs 5 (number of intervening methylenes: 5) and 15 (number of intervening methylenes: 7), an increase in the T_m value was found ($\Delta T_{m\,(\text{run 15-run 5})}$ = 16 ˚C); although the corresponding T_g values were not affected (see **Figure 1-4**). Therefore, it is revealed that we can control the thermal properties of the click polyesters by changing the methylene chain length of the monomer and/or the positioning of the triazole rings, which should allow us to control their thermal properties.

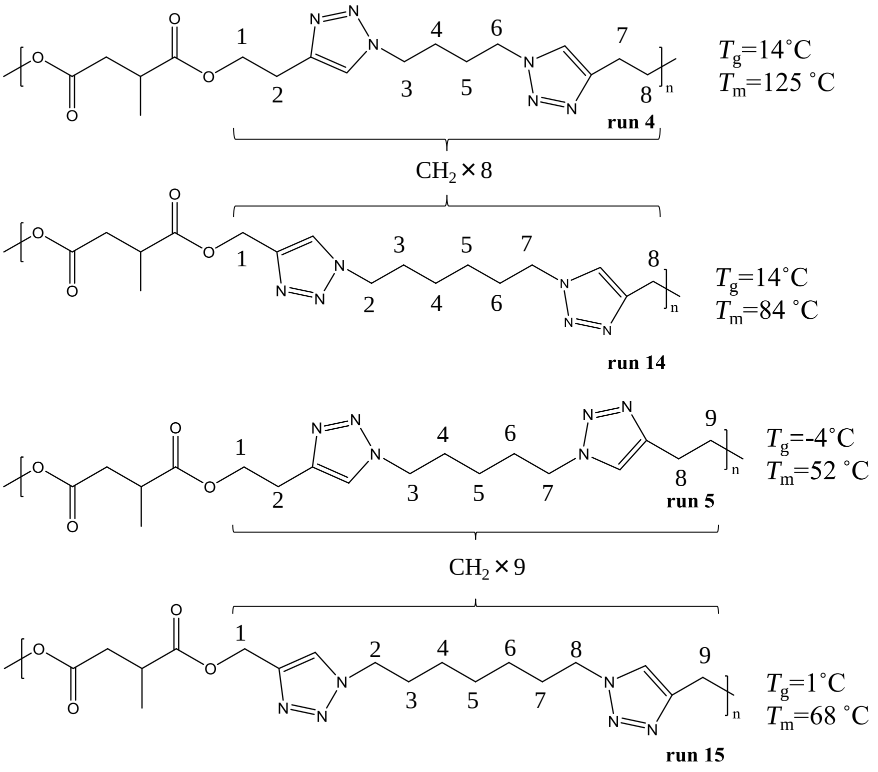


Figure 1-4. Changes in the Positioning of the Triazole Rings.

Thermal Degradability. For the thermal gravimetric measurements of the click polyesters (runs 4 and 5 in **Table 1-1**) produced by oil bath heating, although the thermal stabilities of the click polyesters are slight improved compared with poly(nonamethylene methylsuccinate), remarkable even-odd effect were not confirmed (**Figure 1- 5**).

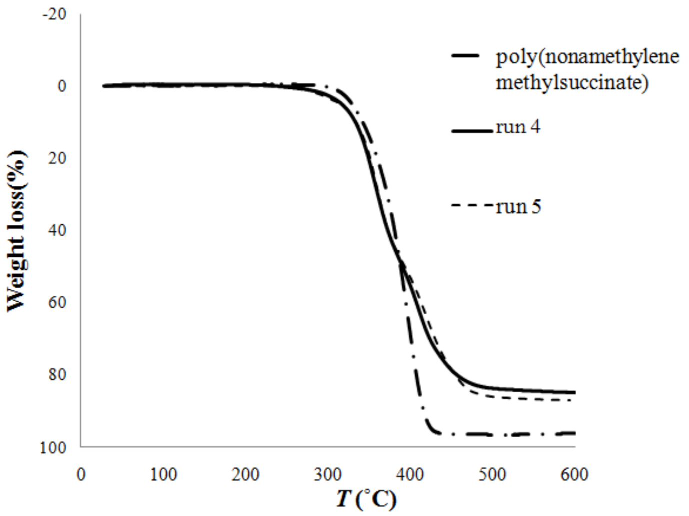


Figure 1-5. Thermogravimetric analysis under nitrogen flow, with a heating rate of 10 °C min^{-1}.

Biodegradability. Biodegradation of the click polyesters of runs 4 and 5 (**Table 1-1**) and poly(nonamethylene methylsuccinate), that had been mixed with activated sludge (pH 7.4, 25°C) was monitored using a BOD tester. The amount of a polymer degraded was calculated from its BOD value and the theoretical oxygen demand (TOD) value, and reported as a percentage (**Figure 1-6**), as defined in the Experimental Section. All three BOD values were reproducible. The click polyesters were not biodegraded within 40 days as shown their BOD/TOD values of ~2–4%; whereas the value for poly(nonamethylene methylsuccinate) was 14% by day 40. Therefore, the main-chain triazoles of the click polyesters suppressed biodegradation.

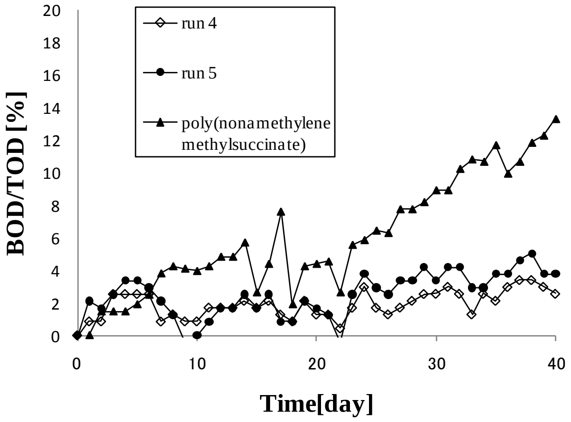


Figure 1-6. BOD curves for of poly(nonamethylene methylsuccinate), and the polyesters of runs 4 and 5, each mixed with activated sludge (pH, 7.5, 25°C).

In this chapter, I used dialkynes containing ester linkages and diazides to synthesize, via click polymerization catalyzed by Cu(I), polyesters with high M_ns [$(1.0–7.0) \times 10^4$] in an excellent yields. These polymers contained main-chain 1,4-disubtituted triazoles. I found that the presence of the main-chain triazoles improved the thermal properties of the polyesters and magnified the even-odd effect caused by the of methylene chain length on the thermal properties of the polyesters. Additionally, I could fine tune the thermal properties of the polyesters by changing the positions of triazoles. I also demonstrated that it is possible produce the click polymers via microwave irradiation and that, when used in conjunction with *in situ* azidation, the synthesis of a click polyester is a safe and effective procedure that should find industrial use. My work is the first example that click chemistry has been used to synthesize polyesters and our results should provide the foundation for the syntheses of novel polyester-based materials.

1-3 Experimental Section

Materials and Methods. Chemicals were obtained from commercial sources and were used without further purification. A MWO-1000S synthesizer (EYELA, Tokyo, Japan) was used for microwave irradiation. ^{1}H-NMR spectra were acquired at 27 ˚C using Bruker Analytik DPX200 and DPX600 spectrometers (200 MHz and 600 MHz, respectively). The chemical shift of tetramethylsilane (TMS) was taken as zero ppm. Number average molecular weights (M_n) and the polydispersity indexes (PDI; M_w/M_n) of the polyesters were estimated using a size exclusion chromatography (SEC) system consisting of a Tosoh DP8020 pump system, a Tosoh RI-8020 differential refractometer, and Tosoh TSK-gel α-3000 and α-5000 columns (Tosoh, Tokyo, Japan). The eluent was 0.05% LiBr, 100 mM of tetramethylethylenediamine in DMF. The flow rate was 0.5 mL/min, and the temperature was 40 ˚C. Differential scanning calorimetry (DSC), using a DSC6220S calorimeter (Seiko Instruments Inc., Chiba, Japan) was performed from −80 to 180 ˚C, with the temperature increased or decreased at a rate of 10 ˚C/min. The instrument was calibrated using indium and tin samples. For all experimental samples, a complete temperature, heating cycle from −80 ˚C to 180 ˚C and back to −80 ˚C, was obtained. Each sample weighted between 4 and 6 mg and was placed into an aluminum pan that was covered with a lid within the calorimeter. The glass transition temperature (T_g) was taken as the inflection point of the corresponding heat capacity jump of the DSC trace. The melting temperature (T_m) was defined as the minimum point of the endothermic trough. Thermogravimetric analyses (TGA) were performed under nitrogen, at rates of 10 ˚C/min between 20 ˚C and 600 ˚C (TG/DTA 220U; Seiko Instruments Inc., Chiba, Japan).

Preparation of diazido monomers. As an example, the preparation of 1,4-diazidobutane is described. Into a 20 mL round-bottom flask were added 1,4-dibromobutane (1.51 g, 7.0 mmol) and sodium azide (1.24 g, 19.0 mmol) both of which had been dissolved in 10 mL of DMF. After stirring the mixture at room temperature for 24 h, 5 mL of water was added to quench the reaction. After having been cooled to room temperature, the solution was extracted with 30 mL of diethyl ether. The organic phases were combined, washed twice with 10-mL volumes of 50% $NaHCO_{3(aq)}$, and then dried over $MgSO_4$. After filtration and solvent evaporation, 1,4-diazidobutane was obtained in 90% yield (881 mg) as a white liquid. The other diazidoalkanes, 1,5-diazidopentane (91% yield), 1,6-diazidohexane (82% yield), 1,7-diazidoheptane (50% yield), and 1,3-diazidopropane (32% yield), were prepared using similar procedures and were isolated as syrups. *m*-Diazidoxylene (79% yield) and *p*-diazidoxylene (64% yield), which were used as aromatic, monomeric diazido reactants, were prepared using similar procedures and were obtained as white liquids. The diazides used for this report were not purified and were stored in ethyl acetate.

1,3-diazidopropane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.42 (t, 4H, 6.5Hz), 1.84 (2H, quintet, 6.5 Hz).

1,4-diazidobutane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.33 (t, 4H, 6.2Hz), 1.71-1.65 (m, 4H).

1,5-diazidopentane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.39 (t, 4H, 6.6 Hz), 1.70-1.57 (m, 4H), 1.54-1.40 (m, 2H).

1,6-diazidohexane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.28 (t, 4H, 6.6 Hz), 1.69-1.58 (m, 4H), 1.48-1.35 (m, 4H).

1,7-diazidoheptane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.27 (t, 4H, 6.7 Hz), 1.68-1.58 (m, 4H,), 1.46-1.33 (br, 6H).

***m*-diazidoxylene**; ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.42 (t, 1H, 6.6Hz), 7.30 (d, 2H, 3.2 Hz), 7.26 (s, 1H), 4.38 (s, 4H).

***p*-diazidoxylene**; ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.34 (s, 4H), 4.36 (s, 4H).

Preparation of diyne monomers. As an example, the preparation of bis(butynyl) methylsuccinate is described. Into a 50 mL round-bottom flask were added methylsuccinic acid (633 mg, 4.80 mmol), $Sc(OTf)_3$ (49 mg, 9.95 mmol), and 3-butyn-1-ol (1.36 g, 19.4 mmol). The reaction mixture was stirred at 60 ˚C for 6 h under reduced pressure (25 mmHg). After the reaction mixture had been diluted with 30 mL chloroform, the solution was washed with 10 mL of water saturated with $NaHCO_3$ and then dried over $MgSO_4$. After filtration and solvent evaporation, bis(butynyl) methylsuccinate was obtained as an auburn liquid in 71% yield (803 mg). Bis(butynyl) succinate (62% yield, white solid), bis(butynyl) adipate (87% yield, white solid), bis(isobutynyl) succinate

(43% yield, auburn liquid), bis(isobutynyl) malonate (15% yield, auburn liquid), bis(butynyl) phthalate (10% yield, white solid), and bis(propynyl) methylsuccinate (92% yield, auburn liquid) were prepared using similar procedures.

bis(butynyl) succinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.21 (t, 4H, 6.8 Hz), 2.67 (s, 4H), 2.54 (dt, 4H, 2.7 and 6.8 Hz), 2.01 (t, 2H, 2.7 Hz).

bis(butynyl) methylsuccinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.19 (t, 4H, 6.7 Hz), 2.93 (quintet,1H, 6.6 Hz), 2.78 (dd, 1H, 8.1 and 16 Hz), 2.57-2.50 (m, 4H), 2.45 (dd, 1H, 6.0 and 16 Hz), 2.00 (t, 2H, 2.5Hz), 1.24 (d, 3H, 7.1Hz).

bis(butynyl) adipate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.19 (t, 4H, 6.8 Hz), 2.57-2.49 (m, 4H), 2.36 (t, 4H, 6.4 Hz), 2.01 (t, 2H, 2.6 Hz), 1.71-1.65 (m, 4H).

bis(isobutynyl) succinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 5.45 and 5.44 (2H, 2xq, 6.7Hz), 2.67 (s, 4H), 2.45 and 2.44 (2×s, 2H), 1.51 (d, 6H, 2.9 Hz).

bis(isobutynyl) malonate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 5.50 and 5.49 (2H, 2xq, 6.7Hz), 3.43 (s, 2H), 2.49 and 2.48 (2×s, 2H), 1.54 (d, 6H, 3.5 Hz).

bis(butynyl) phthalate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.78-7.71 (m, 2H), 7.60-7.53 (m, 2H), 4.43 (t, 4H, 6.8 Hz), 2.70-2.62 (m, 4H), 2.03 (t, 2H, 2.6 Hz).

bis(propynyl) methylsuccinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.70 (s, 2H), 2.98 (m, 1H), 2.82 (dd, 1H, 4.0 and 16Hz), 2.48 (t,2H, 2.2 Hz), 2.49 (dd, 1H, 3.0 and 16 Hz), 1.26 (d, 3H, 3.6 Hz).

Model Reactions. The model compounds ***M1***, ***M2***, and ***M3*** (**Scheme 1-2**) were prepared by click reactions of 1,6-diazidohexane or *p*-diazidoxylene, respectively, with 3-butyn-2-ol. As an example of the procedure used, into a 10 mL round-bottom flask were added 1,6-diazidohexane (137 mg, 0.8 mmol) and three equivalents of 3-butyn-2-ol both dissolved in 0.5 mL of DMF. The mixture was stirred at room temperature for 1 hour. The products were characterized using ^{1}H-NMR spectroscopy and were not purified so that the extent of conversion could be determined.

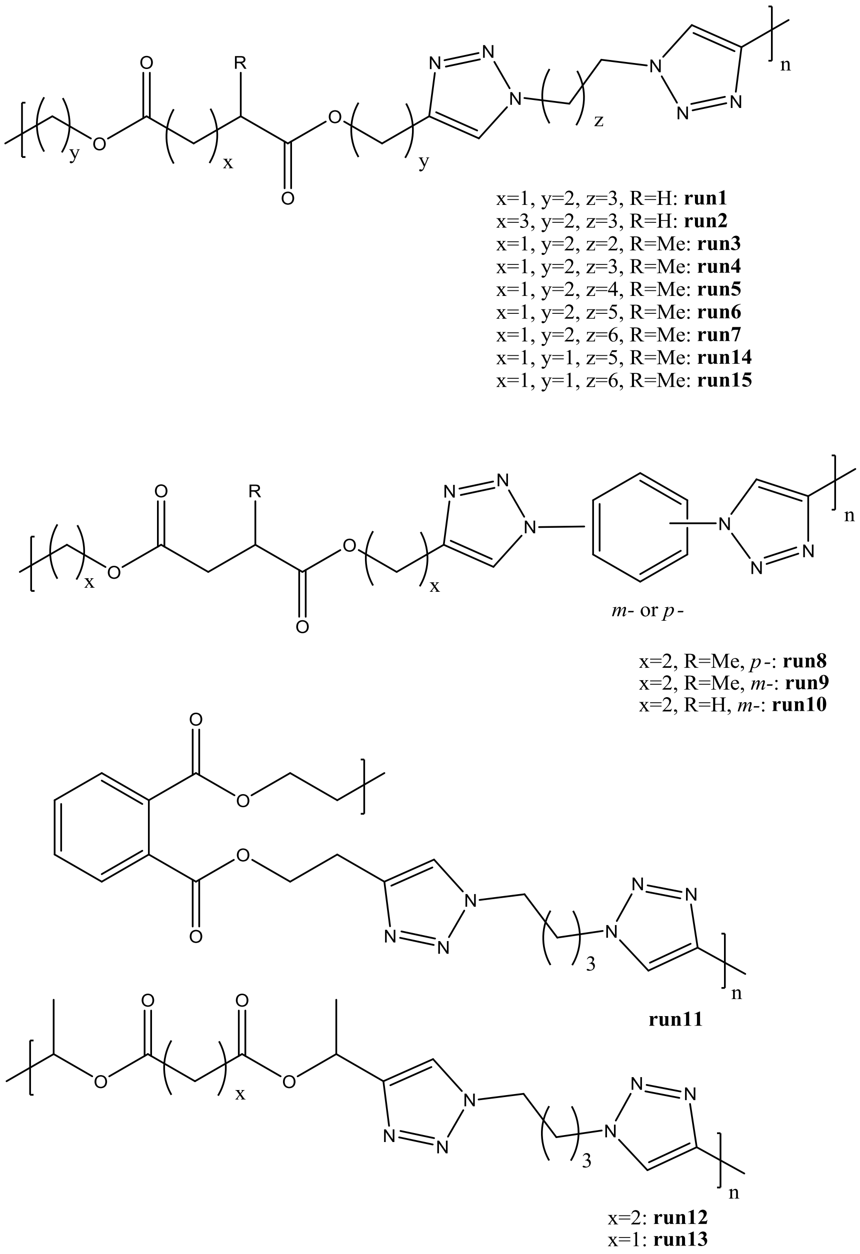


Figure 1-7. The Click Polyesters Synthesized in **Table 1-1**.

Polymer Syntheses: Polymerization of Click Polyesters Synthesized Using an Oil Bath for Temperature Control. The structures and chracterizations of all click polyesters synthesized for this report are summarized in **Figure 1-7** and **Table 1-1**. As an example of the procedure used (run 4, **Table 1-1**), bis(butynyl) methylsuccinate, which served as the diyne (236 mg, 1.0 mmol), and 1,4-diazidobutane (140 mg, 1.0 mmol), which served as the diazide were added into a 10 mL round-bottom flask that contained 0.5 mL DMF. Next, with the contents of the flask contained under a nitrogen atmosphere, 10 mg of CuBr was added. After stirring the mixture at 50 ˚C for 30 h, it was diluted with 5-mL volumes of DMF. A green solid was obtained in 99% yield after twice being precipitated from the DMF solution with 90 mL volumes of diethyl ether.

For **runs 1** and **2** the yields could not be calculated, and their ^{1}H-NMR spectra could not be acquired, because the products were insoluble in all organic solvents tested.

run 3 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.93 (2H, brs), 4.34 (4H, t, 6.9Hz), 4.20 (4H, brs), 2.95-2.89 (5H, br), 2.74 (1H, dd, 6.6 and 15Hz), 2.38 (1H, dd, 7.3 and 15Hz), 2.36-2.29 (2H, br), 1.02 (3H, d, 6.8Hz).

run 4 (yield: 89%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.50 (2H, brs), 4.37 (8H, br), 3.05 (4H, brs), 2.91-2.81 (1H, m), 2.68 (1H, dd, 8.8 and 16Hz), 2.38 (1H, dd, 5.1 and 16Hz), 1.92 (4H, brs), 1.17 (3H, d, 7.1Hz).

run 5 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.44 (1H, s), 7.43 (1H, s), 4.32 (4H, t, 6.4Hz), 3.05 (4H, brs), 2.91-2.85 (1H, m), 2.69 (1H, dd, 8.6 and 16Hz)), 2.40 (1H, dd, 5.4 and 16Hz), 1.94 (4H, brs), 1.34 (2H, brs), 1.17(3H, d, 7.2Hz).

run 6 (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.89 (2H, s), 4.30-4.17 (8H, br), 2.94-2.87 (5H, br), 2.73 (1H, dd, 6.8 and 14Hz), 2.39 (1H, dd, 6.0 and 17 Hz), 1.74 (4H, brs), 1.21 (4H, brs), 1.02 (3H, d, 7.0 Hz).

run 7 (yield: 84%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.87 (2H, s), 4.30-4.22 (4H, br), 4.22-4.17 (4H, br), 2.93-2.87 (5H, br), 2.74 (1H, dd, 7.1 and 14Hz), 2.40 (1H, dd, 6.0 and 17Hz), 1.81-1.67 (4H, br, 5.9Hz), 1.29-1.13 (4H, br), 1.02 (3H, d, 7.0 Hz).

run 8 (yield: 64%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.93 (1H, s), 7.92 (1H, s) 7.25 (4H, s), 5.51 (4H, brs), 4.19 (4H, brt, 6.4Hz), 2.89 (4H, brt, 6.9Hz), 2.73 (1H, m), 2.70 (1H, dd, 6.7 and 13Hz), 2.34 (1H, dd, 6.0 and 16 Hz), 0.96 (3H, brd, 7.0Hz).

run 9 (yield: 70%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.94 (1H, s), 7.93 (1H, s), 7.35-7.16 (4H, br), 5.52 (4H, brs), 4.20 (4H, t, 6.4Hz), 2.90 (4H, t, 6.4Hz), 2.73 (1H, m), 2.70 (1H, dd, 6.7 and 16Hz), 2.37 (1H, dd, 5.9 and 17 Hz), 0.98 (3H, brd, 7.1Hz).

run 10 (yield: 53%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.96 (2H, s), 7.34-7.17 (4H, br), 5.53 (4H, s), 4.21 (4H, t, 6.4 Hz), 2.94-2.90 (4H, br), 2.82 (4H, d, 32Hz).

run 11 (yield: 95%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 8.02 (2H, s), 7.66 (2H, brs), 7.52 (2H, brs), 4.51-4.40 (4H, br), 4.37-4.30 (4H, br), 3.18-3.10 (4H, br), 2.05-1.50 (6H, br).

run 12 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.57 (2H, brs), 6.05-6.00 (2H, br), 4.37 (4H, brs), 2.63 (4H, brs), 1.92 (4H, brs), 1.64 (6H, brs).

run 13 (yield: 85%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.10 (2H, brs), 5.95 (2H, brs), 4.36 (4H, brs), 3.49 (2H, brs), 1.77 (4H, brs), 1.51 (6H, brs).

run 14 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.63 (2H, brs), 5.19 (4H, brs), 4.35 (4H, brs), 2.93-2.79 (1H, m), 2.72 (1H, dd, 7.7 and 17Hz), 2.44 (1H, dd, 4.6 and 16Hz), 1.90 (4H, brs), 1.36 (4H, brs), 1.19 (3H, d, 6.5 Hz).

run 15 (yield: 73%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.60 (1H,s), 7.58 (1H. s), 5.19 (4H, d, 5.6Hz), 4.34 (4H, t, 7.2Hz), 2.98-2.86 (1H, m), 2.73 (1H, dd, 8.4 and 17Hz), 2.45 (1H, dd, 5.8 and 17Hz), 1.89 (4H, brt, 6.4Hz), 1.38-1.28 (6H, br), 1.30 (3H, d, 7.0Hz).

Safe Syntheses of Click Polyesters via *in Situ* Azidation Using an Oil Bath for Temperature Control. The reactants and the properties of the products for the click polyester syntheses via *in situ* azidation, using an oil bath for temperature control, are given in **Scheme 1-3** and **Table 1-2**. As an example of the experimental procedure (run 2, **Table 1-2**), bis(butynyl) methyl succinate, which served as the diyne (236 mg, 1.0 mmol), 1,4-dibromobutane (216 mg, 1.0 mmol), and sodium azide (130 mg, 2.0 mmol) were added into a 10 mL round-bottom flask that contained 1.0 mL of DMF. Then, with the contents of the flask under nitrogen, 30 mg (0.20 mmol) of CuBr was added. After stirring at 50 ˚C for 24 h, the reaction mixture was diluted with 5-mL volumes of DMF and the product was precipitated from the DMF solution with two 90-mL volumes of diethyl ether, washed with water, and dried in vacuum. A brown solid was obtained in a 99% yield.

runs 1–3; ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.88 (2H, brs), 4.32 (4H, brs), 4.21 (4H, brt, 6.4Hz), 2.93-2.87 (5H, br), 2.72 (1H, dd, 7.1 and 15Hz), 2.40 (1H, dd, 6.1 and 16Hz), 1.74 (4H, brs), 1.02 (3H, brd, 7.0Hz).

runs 4–5; ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.10 (1H, brs), 8.03 (1H, brs), 5.38-5.34 (1H, m), 5.09 (4H, brs), 4.39-4.31 (4H, br), 3.82 (1H, brs), 2.88-2,68 (2H, m), 2.60-2.50 (1H, m), 2.16-1.78 (2H, m), 1.08 (3H, d, 6.9Hz).

runs 6–7; ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.88 (1H, brs), 7.82 (1H, brs), 5.35-5.33 (1H, m), 4.44-4.19 (6H, m), 3.80 (brs, 1H), 2.94-2.85 (5H, m), 2.81-2.64 (1H, m), 2.55-2.36 (1H, m), 1.92-1.74 (2H, m), 1.05 (3H, d, 6.8Hz).

run 8; ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.12 (1H, s), 8.04 (1H, s), 5.39 (1H, m), 5.10 (4H, brs), 4.48-4.31 (4H, m), 3.80 (brs, 1H), 2.85-2.69 (2H, m), 2.61-2.56 (1H, m), 2.04-1.79 (2H, m), 1.05 (3H, d, 6.8 Hz).

Safe Syntheses of Click Polyesters via *in Situ* Azidation Using Microwave Irradiation for Temperature Control. The reactants and properties of the polyester products are given in **Table 3**. As an example of the experimental procedure (run 1), bis(butynyl) methyl succinate as the diyne (236 mg, 1.0 mmol), 1,4-dibromobutane (216 mg, 1.0 mmol), and sodium azide (130 mg, 2.0 mmol) were added into a test tube that contained 1.0 mL of DMF. Next, with the contents of the tube under a nitrogen atmosphere 30 mg of CuBr was added. After stirring for 24 h in the microwave synthesizer (with the microwave power varied between 0 and 50 W, so that the temperature remained at 50 ˚C), the reaction mixture was diluted with 5-mL volumes of DMF, precipitated from the DMF solution with two 90 mL volumes of diethyl ether**,** washed with water, and dried in vacuum. A brown solid was obtained in 99% yield.

Instant Click Polymerization via *In Situ* Azidation. The reactants and properties of the polyester products are given in **Table 1-4**. As an example of the experimental procedure (run 1), bis(butynyl) methylsuccinate as the diyne (236 mg, 1.0 mmol), 1,4-dibromobutane (216 mg, 1.0 mmol), and sodium azide (130 mg, 2.0 mmol) were added into a test tube containing 2.0 mL of DMF. Next, with the contents of the tube under a nitrogen atmosphere, 30 mg of CuBr was added. After stirring the reaction mixture for 30 min in the microwave synthesizer (irradiation power at 50 W, 153 ˚C, which is the boiling point for DMF), the reaction mixture was diluted with 5-mL volumes of DMF, precipitated from the DMF solution with two 90-mL volumes of diethyl ether, washed with water, and dried in vacuum. A brown solid was obtained in 99% yield.

Semiempirical Molecular Orbital Calculation. The repeat units of the click polyesters, i.e., Me-[OCOCH(CH_3)CH_2COO(CH_2)$_2$-triazole-(CH_2)$_4$-trialzole-(CH_2)$_2$]$_2$-Me and Me-[OCOCH(CH_3)CH_2COO(CH_2)$_2$-triazole-(CH_2)$_5$-trialzole-(CH_2)$_2$]$_2$-Me using semiempirical molecular orbital calculations by AM1 molecular orbital (MO) method[16] in MOPAC 2000 (MOPAC 2000 version 1.0, Fujitsu Ltd., Tokyo, Japan, 1999) in order to investigate the conformations of the corresponding click polyesters (runs 4 and 5 in **Table 1-1**), in which planar zigzag structure of the polyester main chain is programmed for the starting conformation.

Biodegradation Test. Using a biodegradation (BOD) tester (Model 200F; Taitec Co., Koshigaya-shi, Japan) in accordance with the ISO standard guidelines (ISO 14851), BOD was assessed as the amount of oxygen consumed at 25 ˚C during a 40-day period. The biodegradability was calculated as the percentage of the amount of consumed oxygen and normalized to that of a blank test sample to the theoretical amount of oxygen required for complete oxidation of the sample. The BOD values are reported as the means of three measurements. Activated sludge was obtained from a sewage plant in Showa-ku, Nagoya, Aichi Prefecture, Japan. After filtration of the sludge samples, the supernatants (15 mL) were added to the incubation medium (150 mL) that contained (mg/L): K_2HPO_4, 217; KH_2PO_4, 85; Na_2HPO_4, 447; NH_4Cl, 5; $CaCl_2$, 27; $MgSO_4\cdot 7H_2O$, 23; and $FeCl_3\cdot 6H_2O$, 0.25. The sample (10 mg/L) was coated onto the bottle, and $NaOH_{(aq)}$ (11 mol/L) was placed within to absorb the CO_2 produced.

1-4 References and Notes

(1) [a] Lenz, R. W.; *Adv. Polym. Sci.* **1993**, *107*, 1-40. [b] Koeshak, V. V.; Vinogradora, S. V. “Polyester”, Pergamon Press, New York, N. Y., 1995.

(2) [a] Carothers, W. H.; Dorough, G. L. *J. Am. Chem. Soc.* **1930**, *52*, 711-721. [b] Takiyama, E.; Niikura, I.; Hatano, Y. *Japan Patent* 1992, 189823. [c] Miura, M.; Watanabe, H.; Fujiwara, M. *Japan Patent* 1995, 53695.

(3) [a] Takasu, A.; Oishi, Y.; Iio, Y.; Inai, Y.; Hirabayashi, T. *Macromolecules* **2003**, *36*, 1772–1774. [b] Takasu, A.; Iio, Y.; Oishi, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2005**, *38*, 1048–1050. [c] Takasu, A.; Iio, Y.; Mimura, T.; Hirabayashi, T. *Polym. J.* **2005**, *37*, 946–953. [d] Takasu, A.; Takemoto, A.; Hirabayashi, T. *Biomacromolecules* **2006**, *7*, 6–9. [e] Takasu, A.; Narukawa, Y.; Hirabayashi, T. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 5247–5253. [f] Takasu, A.; Shibata, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2007**, *40*, 151–153. [g] Shibata, Y.; Takasu, A. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47*, 5747–5759. [h] Takasu, A.; Narukawa, Y.; Hirabayashi, T. *J. Polym. Sci., Part A: Polym. Chem.* **2006**, *44*, 5247–5253. [i] Takasu, A.; Makino, T.; Yamada, S. *Macromolecules* **2010**, *43*, 144-149.

(4) [a] Ajioka, M.; Enomoto, K.; Suzuki, K.; Yamaguchi, A. *Bull. Chem. Soc. Jpn*, **1995**, 68, 2125-2131. [b] Ni: Mochizuki, M.; Mukai, K.; Yamada, K.; Ichise, N.; Murase, S.; Iwaya, Y. *Macromolecules* **1997**, *30*, 7403-7407. [c] $HfCl_4(THF_2)$: Ishihara, K.; Ohara, S.; Yamamoto, H.*Science* **2000**, *290*, 1140-1142. [d] Sn distannoxane: Ishii, M.; Okazaki, M.; Shibasaki, Y.; Ueda, M. *Biomacromolecules* **2001**, *2*, 1267-1270.

(5) [a] Kobayashi, S.; Hachiya, I.; Yamanoi, Y. *Bull. Chem. Soc. Jpn.* **1994**, *67*, 2342-2344. [b] Kobayashi, S.; Nagayama, S.; Busujima, T. *J. Am. Chem. Soc.* **1998**, *120*, 8287. [c] Kobayashi, S. *Eur. J. Org. Chem.* **1999**, *15*, 33.

(6) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, 40, 2004-2021.

(7) [a] Rostovtsev, V. V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2002**, *41*, 2596-2599. [b] Chan, T. R.; Hilgraf, R.; Sharpless, K. B.; Fokin, V. V. *Org. Lett.* **2004**, *17*, 2853.

(8) [a] review: Pieteres, R. J.; Rijkers, D. T. S.; Liskamp, R. M. J. *QSAR Comb. Sci.* **2007**, *26*, 1181. [b] review: Tron, G. C.; Pirali, T.; Billington, R. A.; Canonico, P. L.; Sorba, G.; Genazzani, A. A. *Med. Res. Rev.* **2008**, *28*, 278.

(9) [a] adhesive polymer : Diaz, D. D.; Punna, S.; Holzer, P.; Mcpherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. G. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4392. [b] polyketone: Tang, B. Z.; Qin, A.; Jim, C. K. W.; Lu, W.; Lam, J. W. Y.; Häussler, M.; Dong, Y.; Sung, H. H. Y.; Williams, I. D.; Wong, G. K. L. *Macromolecules* **2007**, *40*, 2308-2317. [c] helical polymer: Kobayashi, S.; Itomi, K.; Morino, K.; Iida, H.; Yashima, E. *Chem. Comm.* **2008**, 3019-3021. [d] poly(ethylene glycol): Liu, X.-M.; Thakur, A.; Wang, D. *Biomacromolecules* **2007**, *8*, 2653-2658. [e] biomass-based polymer: Michinobu, T.; Inazawa, Y.; Hiraki, K.; Katayama, Y.; Masai, E.; Nakamura, M.; Ohara, S.; Shigehara, K. *Chem. Lett.* **2008**, 154-155. [f] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2007**, *28*, 15-54. [g] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2008**, *29*, 952-981. [h] review: Johnson, J. A.; Finn, M. G.; Koberstein, J. T.; Turro, N. J. *Macromol. Rapid Commun.* **2008**, *29*, 1052-1072. [h] new "click" chemistry: Koyama, Y.; Yonekawa, M.; Takata, T. *Chem. Lett.* **2008**, *37*, 918-919. [i] Lee, Y. G.; Koyama, Y.; Yonekawa, M.; Takata, T. *Macromolecules* **2009**, *42*, 7709-7717. [j] α-azide-ω-alkyne monomers: Binauld, S.; Damiron, D.; Hamaide, T.; Pascault, J. P.; Fleury, E.; Drockenmuller, E. *Chem. Comm.* **2008**, 4138-4140.

(10) [a] Feldman, A. K.; Colasson, B.; Fokin, V. V. *Org. Lett.* **2004**, *22*, 3897-3899. [b] Appukkuttan, P.; Dehaen, W.; Fokin, V. V.; Eycken, E. V. *Org. Lett.* **2004**, *23*, 4223-4225.

(11) [a] Gedye, R.; Smith, F.; Westaway, K.; Ali, H.; Baldisera, L.; Laberge, L.; Rousell, J. *Tetrahedron Lett.* **1986**, *27*, 279-282. [b] Giguere, R. J.; Bray, T. L.; Duncan, S. M.; Majetich,

G. *Tetrahedron Lett.* **1986**, *27*, 4945-4958. [c] Kappe, C. O. *Angew. Chem. Int. Ed.* **2004**, *43*, 6250 –6284.

(12) Dijk, M. D.; Nollet, M. L.; Weijers, P.; Dechesne, A. C.; Nostrum, C. F.; Hennink, W. E.; Rijkers, D. T. S.; Liskamp, R. M. J. *Biomacromolecules* **2008**, *9*, 2834-2843.

(13) Preliminary results: Nagao, Y.; Takasu, A. *Macromol. Rapid Commun.* **2009**, *30*, 199-203.

(14) Urbani, C. N.; Bell, C. A.; Whittaker, M. R.; Monteiro, M. J. *Macromolecules* **2008**, *41*, 1057-1060.

(15) [a] Koyama, E.; Sanda, F.; Endo, T.; *J. Polym. Sci., Part A; Polym. Chem.* **1997**, *35*, 2925-2934. [b] Ge, J. J.; Honigfort, P. S.; Ho, R.-M.; Wang, S.-Y.; Harris, F. W.; Cheng, S. Z. D. *Macromol. Chem. Phys.* **1999**, *200*, 31-43.

(16) Dewar, M. J. S.; Zoebisch, E. G.; Healy, E. F.; Stewart, J. J. P. *J. Am. Chem. Soc.* **1985**, *107*, 3902-3909. **2000**, *41*, 3875–3881.

(17) [a] Munteanu, M.; Choi, S.; Ritter, H. *Macromolecules* **2008**, *41*, 9619-9623. [b] Velmathi, S.; Nagahata, R.; Takeuchi, K. *Polym. J.* **2007**, *39*, 841-844. [c] Iwamura, T.; Ashizawa, K.; Sakaguchi, M. *Macromolecules* **2009**, *42*, 5001-5006.

Chapter 2

Anode-Selective Electrophoretic Deposition of a Bioactive Glass/Sulfone-Containing Click Polyester Composite

Abstract

A room temperature thiol−ene click polymerization afforded a poly(ester-sulfide) (M_n = 1.4–6.9 × 10^4), which represents the first in a new class of click polyesters. Subsequent Oxone oxidation of the poly(ester-sulfide) led to the corresponding poly(ester-sulfone), which had improved thermal stability in comparison with the parent poly(ester-sulfide). A bioactive glass/poly(ester-sulfone) composite could be deposited on a stainless-steel anode by electrophoretic deposition (EPD). Hydroxyapatite was found on the surface of electrophoretically deposited bioactive glass/poly(ester-sulfone) composites that had been immersed in simulated body fluid (SBF) for 2 weeks. This bioactive glass/poly(ester-sulfone) composite might therefore find use as a surface coating for implantable medical devices on which a hydroxyapatite layer can form post implantation to strengthen the interface between the implant and host bone.

2-1 Introduction

The design of high performance polyesters and their composites with inorganic phases for biomedical applications is an expanding field.[1] Although polyesters are usually produced by condensation of a diol and a dicarboxylic acid or a hydroxylcarboxylic acid,[2] or by ring-opening polymerization of a lactone,[3] the former method requires severe reaction conditions even when a customized catalyst is used,[4] and the latter uses highly strained cyclic monomers, which makes it difficult to synthesize polyesters with specific functionalities and/or properties. We have reported on low-temperature polycondensations of diols and dicarboxylic acids,[5] which allowed us to use thermally labile monomers that contained functional groups.[6]

Conversely, click chemistry, introduced by Sharpless and co-workers,[7] is an efficient tool for the preparation of a wide range of organic compounds. Cu(I)-catalyzed click chemistry involves an efficient 1,3-dipolar cycloaddition between an azide and an alkyne under mild conditions, without formation of by-products, with high chemoselectivity,[8] and shows promise for preparation of macromolecules and biomacromolecules.[9] We have also reported on the syntheses of polyesters that contain main-chain triazole units by Cu(I)-catalyzed click polymerization of dialkynes and diazides.[10] Because the azides used for this method are prepared *in situ*, the danger of an explosion is minimized.[10b]

Because Cu in high concentration is toxic, its use may be limited;[11] therefore, development of metal-free click reactions is desirable.[12] The thiol–ene click reaction is an efficient method for the production of many types of polymers.[13] Thiol–ene click polymerizations proceed via a thiyl-radical-mediated, mechanism, involving alternating propagation and chain-transfer steps (**Figure 2-1**). The reactions are highly efficient, proceed rapidly, even in the presence of oxygen, and do not use metal catalysts. One round of polymerization involves the addition of a thiyl radical to a vinyl, followed by abstraction of a hydrogen from a second thiol to give a thioether, and regenerate the thiyl radical (**Figure 2-1b**). Click thiol–ene polymerization can be used in conjunction with many different thiol- and vinyl-containing compounds, which should allow for orthogonal and site-selective functionalization of polymers.

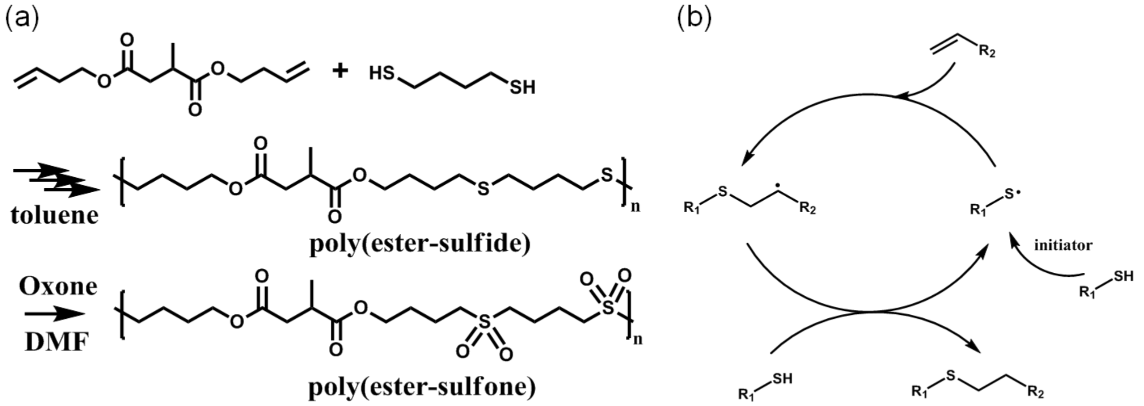


Figure 2-1. (a) Schematic of a the thiol−ene polymerization reported herein and subsequent Oxone oxidation of the poly(ester-sulfide) to produce the poly(ester-sulfone). (b) Reaction cycle for one round of a thiol−ene click reaction.

Thiol−ene click polymerization might be an attractive route to synthesize polymers that can be used in applications that require materials with specific physical and/or chemical properties.[14] Sulfur-containing polymers have excellent optical properties and biocompatibility.[15] Introduction of sulfurs into a polyester should increase their refractive index, thermal stability, and affinity towards metals in comparison with the analogous non-sulfur-containing polyesters.[15c,15f]

In the field of biomedical materials, new bioactive materials that can effectively coat a targeted metal substrate at nano- to micrometer scales are needed.[16] Electrophoretic deposition (EPD) is a promising technique for the fabrication of inorganic and organic films.[16a,17] EPD is based in the controlled electric–field-induced deposition of charged particles or molecules in an orderly manner onto an electrode. Nano- to micrometer films can be made, including those formed by organic/inorganic composites.[16a, 17h, 17i]

45S5Bioglass® was the first silicate material found to bind directly to bone.[18] This glass contains SiO_2, P_2O_5, CaO and Na_2O. When in contact with a biological fluid, a thin layer of carbonate hydroxyapatite—a substance similar to carbonated calcium-deficient hydroxyapatite, the main mineral found in bone, dental enamel, and dentine—can form on the surface of Bioglass®.[18d] In addition, metal surfaces of orthopedic implants are usually coated with bioactive ceramics and bioactive glasses to prevent the release of harmful metal ions and to form a native-like bond between the implant and the bone surfaces. However, the mechanical strength of Bioglass® is poor, which precludes its incorporation into load-bearing prostheses. Therefore, attempts have been made to improve the mechanical strength of Bioglass® by developing composites based on Bioglass® and biopolymers.[17b,18e] As an alternative, polymer-bioceramic composite coatings for orthopedic applications have been suggested.[17d] These coatings should provide an improved connection to host tissue given that they are softer than pure ceramic or Bioglass® coatings and thus a lower mismatch of mechanical properties exists between the implant and host bone tissue. Moreover, the polymer causes the bioactive glass particles to adhere to the metallic substrate at low temperatures, which avoids the need for high temperature sintering of monolithic bioceramic or Bioglass® coatings.[16a,17c,17d,17h,17i] Bioglass®/polymer films deposited on different substrates have been prepared by low temperature EPD, including polyetheretherketone/Bioglass®[17j] and chitosan/ Bioglass®[17d]. In addition, hydroxyapatite/polycaprolactone (PCL) composite has been prepared by EPD,[19] which suggests that appropriately designed click polyesters might also be used in combination with bioactive inorganic particles to produce an evolutional polyester-based bone-regenerating coating materials by EPD.

In this chapter, I describe a thiol-ene click polymerization for the synthesis of a sulfide-containing polyester that was then converted to a sulfone-containing polyester via Oxone oxidation (**Figure 2-1**). Given the electrical characteristics of sulfones, i.e., electrochemical stability, oxidation potential, and ionic conductivity, we were able to selectively deposit a Bioglass®/poly(ester-sulfone) soft film onto a stainless steel anode by EPD. Finally, I found that a thin layer of hydroxyapatite formed on the surface of the Bioglass®/poly(ester-sulfone) film when it was exposed to a simulated body fluid (SBF) confirming the bioactivity of the new soft composite coatings developed here.

2-2 Results and Discussion

Synthesis of the Poly(ester-sulfone)

I first attempted to prepare the sulfide-containing polyester by thiol-ene thermal radical polymerization that used bis(butenyl) methylsuccinate and 1,4-butanedithiol with azobisisobutyronitrile as the thermal initiator at 70˚C. Polymerization proceeded gradually and was complete within several hours (**Figure 2-2**). ^{1}H NMR spectrum of the poly(ester-sulfide) (thermal polymerization for 2 h) before reprecipitation showed existence both of terminal double bond (5.10 ppm) and thiol (1.31 ppm), indicating that the thiol moieties was not consumed by undesired oxidative coupling. Because the reaction did not produce a polymer of relatively high M_n, photo-polymerization was next attempted.

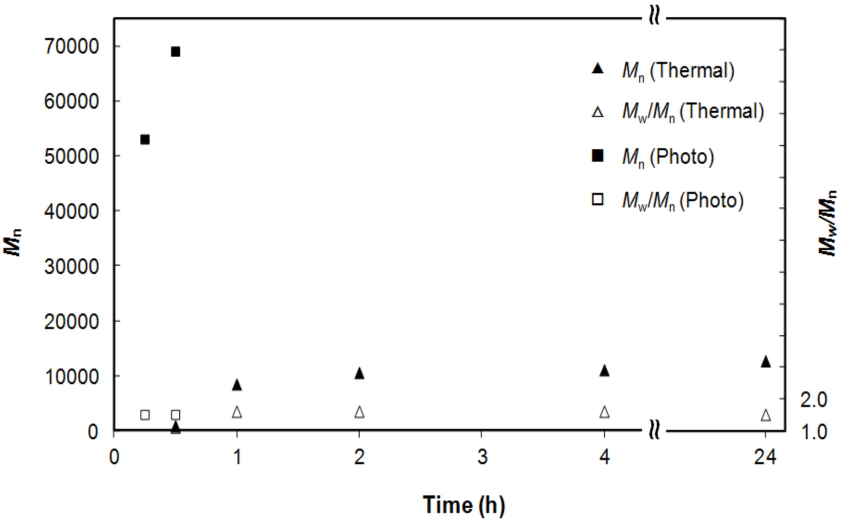


Figure 2-2. Thermal and photo thiol-ene click polymerizations of bis(butenyl) methylsuccinate and 1,4-butanedithiol. $[M]_0/[cat] = 50$, M_n and M_w/M_n were determined by SEC with DMF as the solvent. Poly(styrene) served as the standard.

Thiol-ene photo-polymerization was then conducted with Irgacure 184 as the photo-initiator under UV irradiation at room temperature. Polymerizations using this photo-initiator proceeded rapidly even in an air atmosphere (**Table 2-1**, entries 3 and 6). Within short time periods (15–30 min), the photo-polymerizations gave poly(ester-sulfide)s of greater M_ns than did the thermal polymerization (**Figure 2-2**, **Table 2-1**) and in excellent yields (89%–94%, **Table 2-1**). The SEC data demonstrated that the poly(ester-sulfide)s have a M_w/M_n range (M_w/M_n = 1.5–1.7), which is commonly found for ordinary A-A- and B-B-type step-growth polymerizations.[20] The M_n of the polyester could be controlled by the amount of photo-initiator used without substantial loss of yield (compare entries 1 and 4, 2 and 5, and 3 and 6 in **Table 2-1**). The poly(ester-sulfide) (entry 6, **Table 2-1**; M_n = 29000) had a T_g of –64˚C, which is much lower than room temperature, and its T_m was not observed.

Additionally, we conducted photo-initiated thiol-ene polymerization using two other types of dithiol monomers (**Figure 2-3**). When the ether-type dithiol monomer was used, we readily obtained a poly(ester-sulfide) with a large M_n. However, the M_n for the 1,4-benzenedimethanethiol-containing polyester was substantially smaller. 1,4-Benzenedimethanethiol has a planar aromatic structure whereas 3,6-dioxa-1,8-octanedithiol represents a linear and flexible chain. Steric hindrance and rigidity of the thiol-monomer seems to inhibit to produce a high molecular weight polyester.[21]

Table 2-1. Photo-Initiated Thiol-ene Click Polymerizations of Bis(Butenyl) Methylsuccinate 1,4-Butanedithiol using Irgacure 184 as the Catalyst.

Entry	Time (min)	$[M]_0/[cat]$	$M_n{}^a$	$M_w/M_n{}^a$	Yield (%)	Atmosphere
1	15	100	35000	1.6	94	N_2
2	30	100	49000	1.5	92	N_2
3	30	100	14000	1.6	89	Air
4	15	50	53000	1.5	89	N_2
5	30	50	69000	1.5	90	N_2
6	30	50	29000	1.7	90	Air

[a] M_n and M_w/M_n were determined by SEC with DMF as the solvent. Poly(styrene) served as the standard.

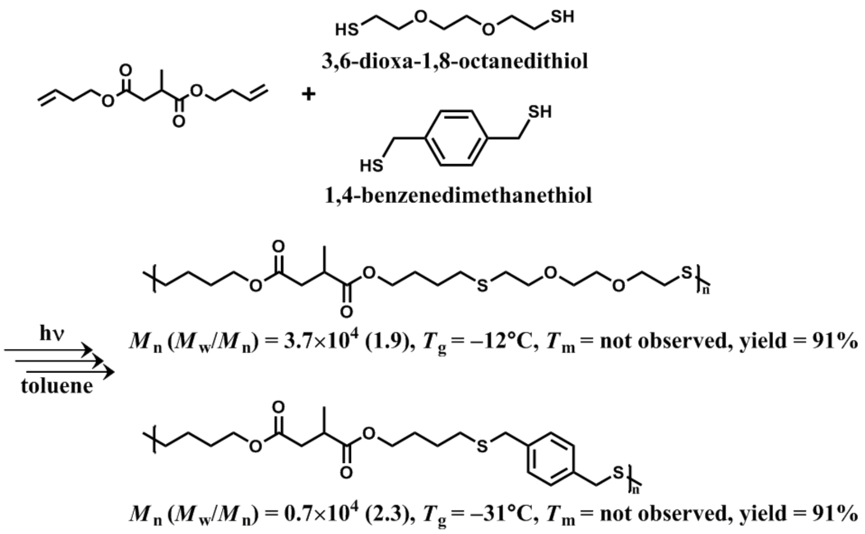


Figure 2-3. Thiol-ene click polymerization of bis(butenyl) methylsuccinate with 3,6-dioxa-1,8-octanedithiol and 1,4-benzenedimethanethiol. Conditions: 1 mmol scale, 1 mL toluene as the solvent, room temperature, 30 min, $[M]_0/[cat] = 50$, UV irradiation.

Next, we investigated the Oxone oxidation of the poly(ester-sulfide) ($M_n = 5600$ and $M_w/M_n = 1.7$) to produce the corresponding poly(ester-sulfone) (**Figure 2-1**). Initially, we examined the influence of the Oxone concentration and the reaction time (**Table 2-2**). Only when 2 equiv. of Oxone per sulfide were used did quantitative conversion to sulfones occur. IR absorbance bands (1070–1030 cm^{-1}) ascribable to sulfoxide (the reaction intermediate) were not observed (**Figure 2-4a**) nor were any ^{1}H-NMR resonances that would be influenced by the presence of a sulfoxide. However, the presence of sulfone was confirmed by their IR absorbencies at 1271 cm^{-1} and 1124 cm^{-1}.

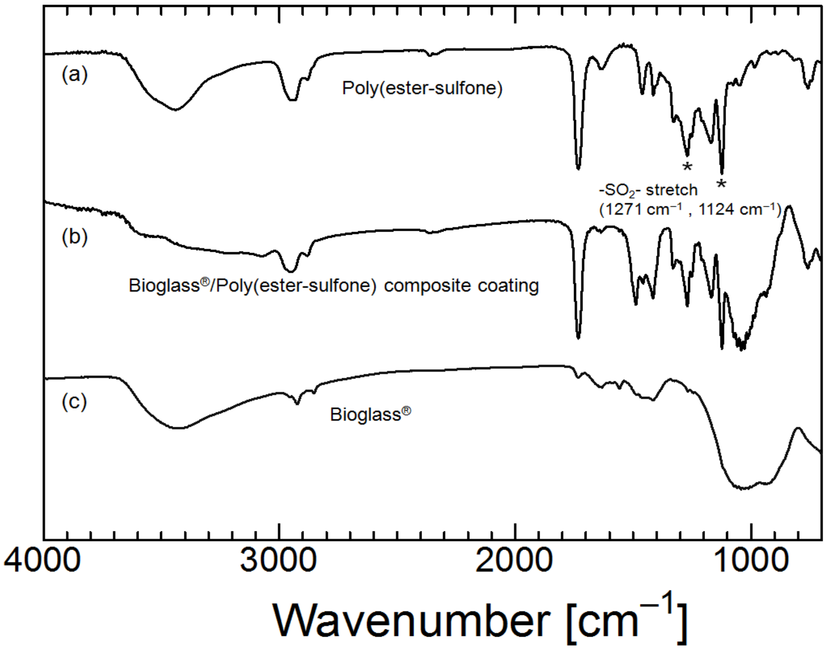


Figure 2-4. FTIR spectra of (a) poly(ester-sulfone), (b) Bioglass®/poly(ester-sulfone) composite film, and (c) pure Bioglass®.

Table 2-2. Oxidation of Poly(ester-sulfide) to Poly(ester-sulfone).

Entry	Oxone[a] (equiv.)	Time (h)	Conversion[b] (%)	Yield[c] (%)
1	1	6	53	0
2	2	1	90	88
3	2	1.5	91	89
4	2	3	98	87
5	2	6	100	80

[a] Equivalent to one sulfide per poly(ester-sulfide) repeat unit.
[b] Determined *in situ* by ^{1}H NMR spectroscopy. [c] After reprecipitation.

The M_n (~12000) of the poly(ester-sulfone) (sulfonation conversion = 100%) was similar to that of its parent poly(ester-sulfide) (M_n = 11000). Moreover, the M_w/M_ns for the two polyesters were similar, indicating that neither degradation nor side reactions occurred during the oxidation

(**Figure 2-5**). DSC heating traces for the poly(ester-sulfide) and the poly(ester-sulfone) are shown in **Figure 2-6**. The poly(ester-sulfide) had a higher T_g than did the parent polyester, probably because of the restricted molecular rotation neighboring the sulfone units and its high polarity inducing significant intermolecular interaction. For the poly(ester-sulfone), T_m was 116˚C. The degradation temperatures associated with a 5% weight loss [T_d(5%)] were 363˚C for the poly(ester-sulfone) and 288˚C for the poly(ester-sulfide) (**Figure 2-7**). Obviously the presence of the sulfones improved the thermal stability of the polyester.

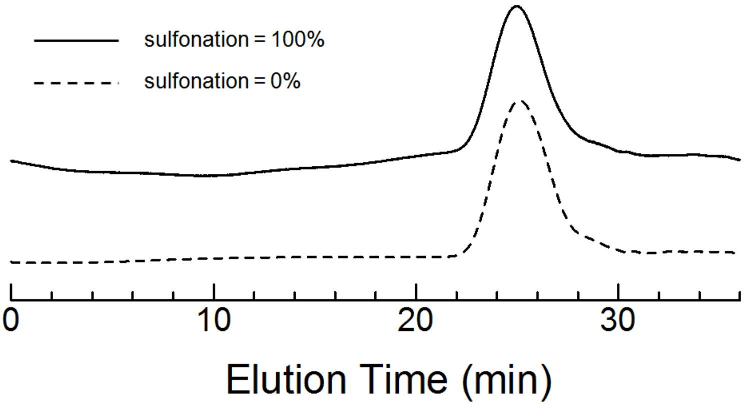


Figure 2-5. Size exclusion chromatograms of poly(ester-sulfide) and poly(ester-sulfone). The poly(ester-sulfone) was prepared from the poly(ester-sulfide) used for the chromatography.

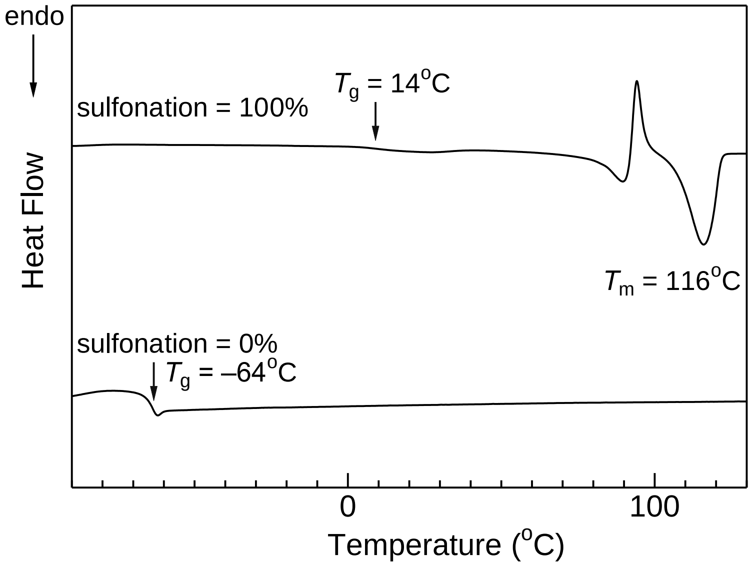


Figure 2-6. DSC traces for the poly(ester-sulfide) (M_n = 11000) and the poly(ester-sulfone) (M_n = 12000).

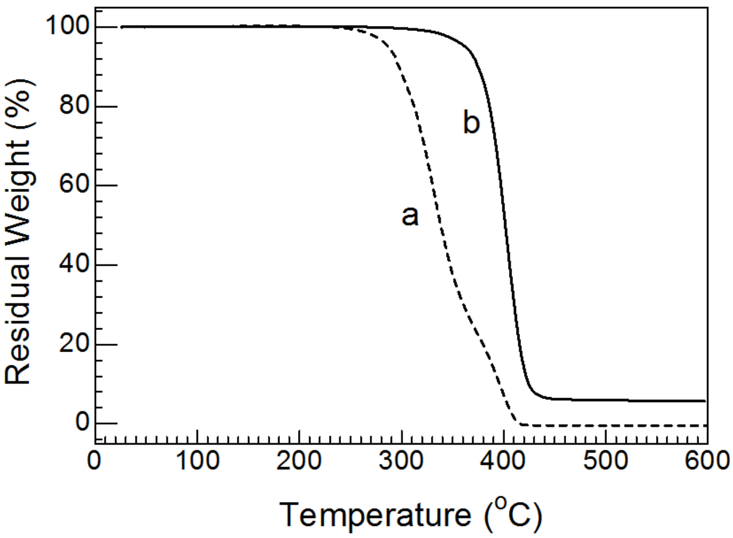


Figure 2-7. Thermogravimetric curves for (a) the poly(ester-sulfide) (M_n = 11000) and (b) the poly(ester-sulfone) (M_n = 12000).

Electrophoretic Deposition of Bioglass®/Poly(ester-sulfone) Coatings

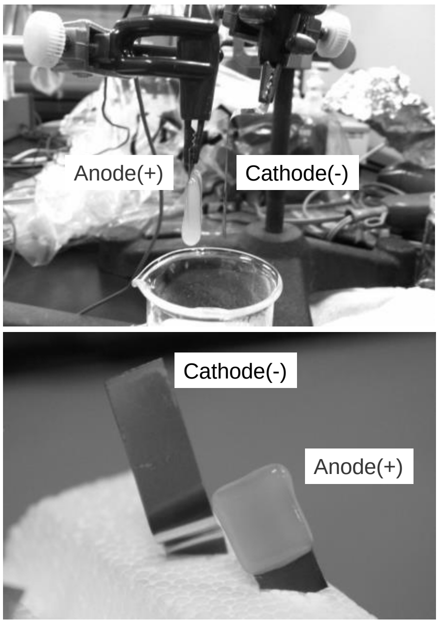


Figure 2-8. Anode selective electrophoretic deposition of poly(ester-sulfone) from the suspension.

Mixtures of Bioglass® and poly(ester-sulfone) (M_n = 12000) formed colloidal suspensions in mixed solvents of DMF and ethanol or *n*-butanol and could be deposited onto a stainless-steel anode by EPD. The results are summarized in **Table 2-3**. Notably, isolated Bioglass® particles moved towards the cathode in the same system (entry 4) because the surface of these Bioglass® particles were covered with Ca^{2+} and Na^{+}.[17d] Conversely, we found an interesting phenomenon that the deposition of pure poly(ester-sulfone) is achieved via electrophoretic motion of polar sulfone to the anode in suspension ("swimming polyester", entries 1 and 2 and **Figure 2-8**). It is suggested that the polarized sulfones must dominate the surface charge of the composite (**Figure 2-9a**). The ^{1}H-NMR spectra (**Figure 2-10**) of the poly(ester-sulfone) before and after deposition on the electrode (**Table 2-3**, entry 1) indicate that EPD did not alter the structure/composition of the poly(ester-sulfone). Ordinary aliphatic polyesters, e.g., polycaprolactone or polylactic acid, are not charged, and, when they are part of composites, are deposited onto the cathode by EPD,[18] which makes the deposition of the Bioglass®/poly(ester-sulfone) onto the anode an unusual phenomenon. Therefore, control of the electrophoretic behavior of a Bioglass®/polyester composite can probably be controlled by the choice of the polyester.

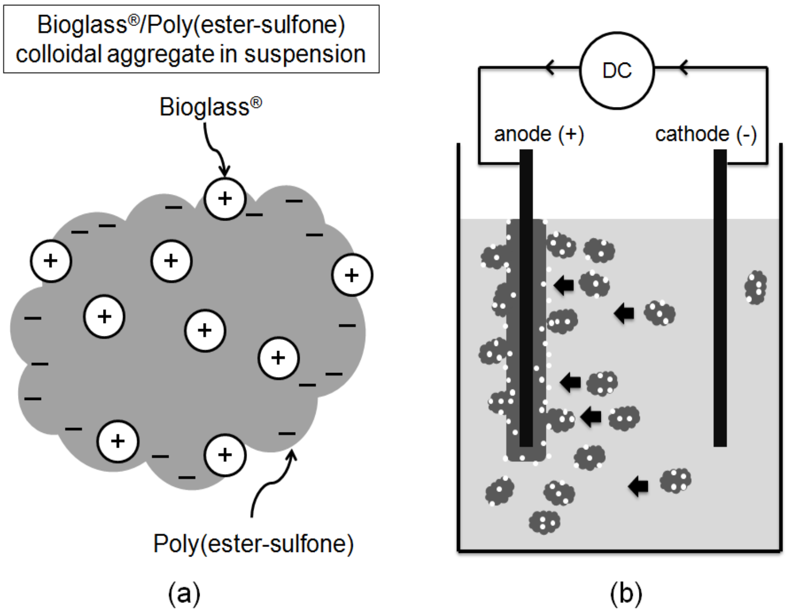


Figure 2-9. (a) Schematic of a charged Bioglass®/poly(ester-sulfone) colloidal suspension in organic solution. (b) Schematic of the electrophoretically controlled deposition of the Bioglass®/poly(ester-sulfone) colloid.

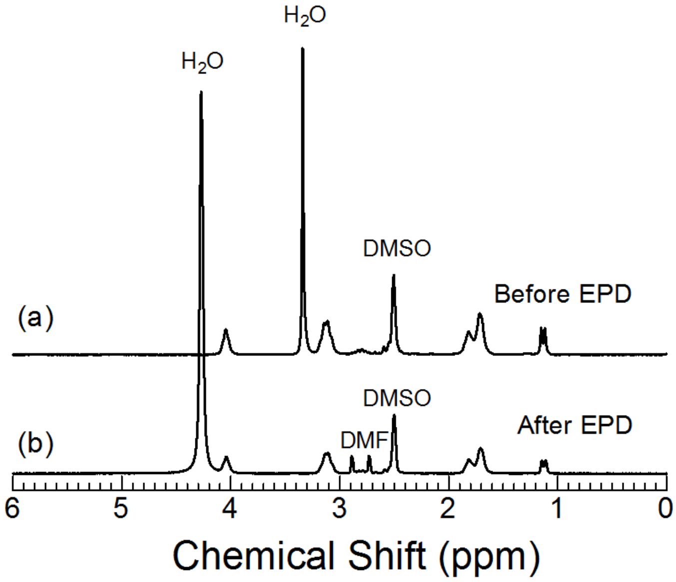
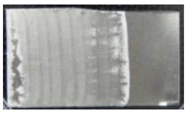


Figure 2-10. ^{1}H NMR spectra of the poly(ester-sulfone) (a) before EPD and (b) after EPD.

There were cracks in the films prepared from a pure poly(ester-sulfone) suspension (6 g/L; **Table 2-3**, entry 1) and in Bioglass®/poly(ester-sulfone) films prepared from colloidal suspension that contained twice the concentration of the poly(ester-sulfone) (12 g/L; **Table 2-3**, entry 7). To deposit a smooth pure poly(ester-sulfone) film on the anode, a smaller concentration (4 g/L) of the poly(ester-sulfone) was used (compare entry 2 in **Table 2-3**). In general, *n*-butanol, rather than ethanol, more effectively controlled the stability of the Bioglass® suspension (compare entries 3 and 4 in **Table 2-3**).[17k] However, as a consequence of the lower electric permittivity of *n*-butanol, the films were thinner when *n*-butanol, rather than ethanol, was the cosolvent (compare entries 5 and 6 in **Table 2-3**). Therefore, we selected a film prepared with DMF/ethanol as the solvent (**Table 2-3**, entry 5) for the experiments shown in **Table 2-3**.

Table 2-3. Films formed on the stainless steel electrodes by EPD.

Entry	Matrix	Concentration	Solvent (v/v)	Suspension	Coating[a]	
		Polymer/Bioglass® (g/L)			Electrode selectivity	States
1	Poly(ester-sulfone)	6/0	DMF/Ethanol (1/1)	Stable	Anode	 (Clacked)
2	Poly(ester-sulfone)	4/0	DMF/Ethanol (1/1)	Stable	Anode	 (Thin)
3	none	0/20	DMF/Ethanol (1/1)	Unstable	N.D.	
4	none	0/20	DMF/*n* -Butanol (1/1)	Stable	Cathode	 (Thin)
5	Poly(ester-sulfone)	6/20	DMF/Ethanol (1/1)	Stable	Anode	 (Thick)
6	Poly(ester-sulfone)	6/20	DMF/*n* -Butanol (1/1)	Stable	Anode	 (Thin)
7	Poly(ester-sulfone)	12/20	DMF/Ethanol (1/1)	Stable	Anode	 (Cracked)

[a] After deposition, the coatings were dried in air at 50°C for 6 h and then under reduced pressure for 6h.

We assessed the surface and cross-section morphology of the Bioglass®/poly(ester-sulfone) film by SEM and EDX. The SEM images of the film show that Bioglass® particles are well dispersed in a matrix formed by the poly(ester-sulfone) (**Figures 2-11a, b**). **Figures 2-11c** and **11d** show a SEM image and an EDX map for a cross-section of the film, respectively. The colors in the EDX map identify silicon (red), carbon (green), and sulfur (blue) and indicate that the Bioglass®

particles were homogeneously dispersed, i.e., the poly(ester-sulfone) surrounds and is in close contact with the Bioglass® particles. Additionally, the nearer to the surface of the electrode, the greater is the sulfur density (The bottom of the micrograph in **Figure 2-11d** is the region closest to the electrode.). Our results strongly indicate that a Bioglass®/poly(ester-sulfone) colloidal diphasic suspension has formed (see **Figure 2-9**) and that the sulfone moieties were responsible for anode-selective deposition. The composite thickness was 38 μm on average (**Figure 2-11e**).

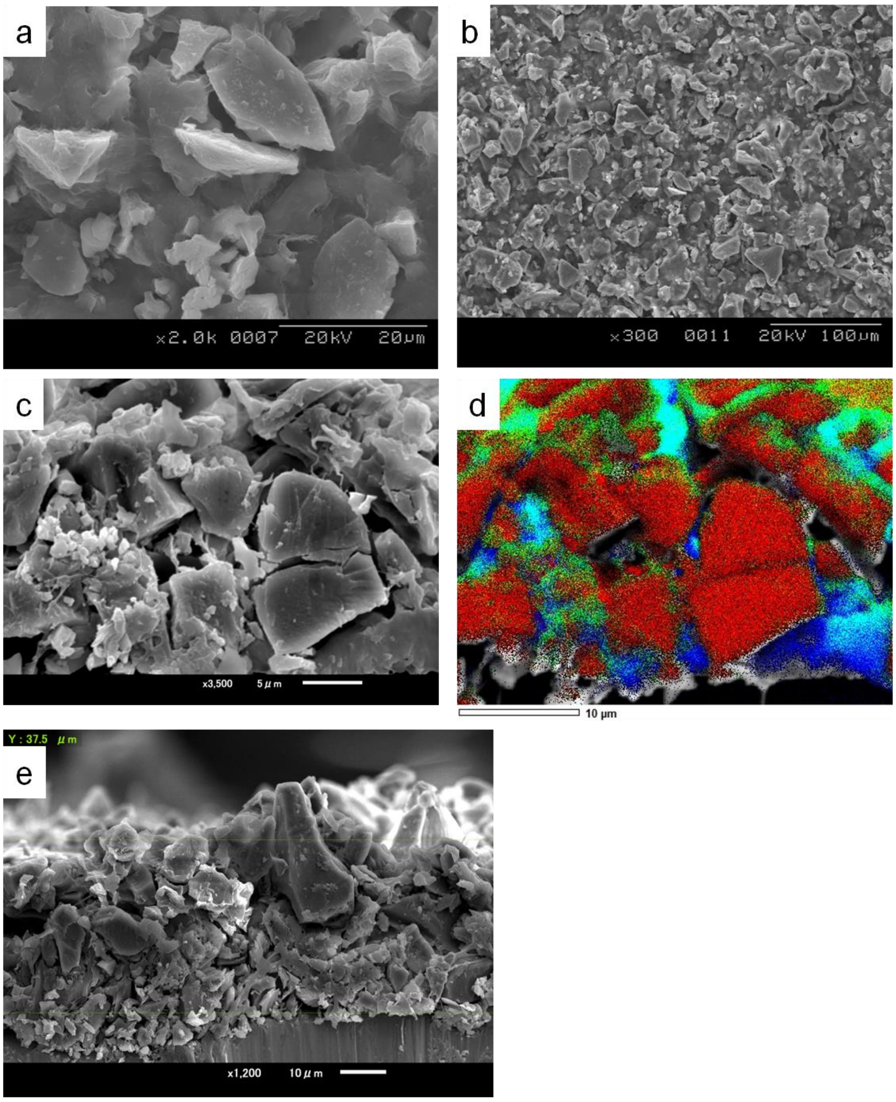


Figure 2-11. Scanning electron micrographs of Bioglass®/Poly(ester-sulfone) films. Surfaces of the composite a) at high magnification (×1000) and b) at low magnification (×300). c) A cross section of the composite (×3500 magnification). d) A cross section of an EDX map showing the distribution of silicon (red), carbon (green), and sulfur (blue) (×3500 magnification). e) Thickness of the composite (×1200 magnification).

After a 1-week immersion in SBF, SEM images of the Bioglass®/poly(ester-sulfone) film revealed a dense deposit covering the film (**Figure 2-12a, b**). Such deposits were absent prior to soaking the film in SBF (**Figure 2-11a, b**). At the higher magnification, many spherical particles are seen on the surface of the film (**Figure 2-12a**). For the film soaked for 2 weeks in SBF, more densely packed spherical particles were seen (**Figure 2-12c**). The morphology of these deposits is very similar to that of hydroxyapatite deposited on titanium or a bioactive glass/ceramic composite by biomimetic methods, i.e. upon exposure to SBF.[17b,17j,19,23] As a control experiment, the pure poly(ester-sulfone) film on the stainless steel electrode (**Table 2-3**, entry 2) was also immersed in SBF for 1 week at 37°C. No new deposit, similar in appearance to hydroxyapatite crystals, formed on the surface of the film (**Figures 2-12e, f**). The substances deposited on the surface of the Bioglass®/poly(ester-sulfone) film were identified by XRD as dicalcium phosphate dihydrate (DCPD) and hydroxyapatite, which is a hydrolysis product of DCPD[22] (**Figure 2-13**). Phase analysis by XRD also indicated that the amount of hydroxyapatite had increased, and the amount of DCPD had decreased after the 2-week immersion in SBF. The extent to which DCPD was hydrolyzed to hydroxyapatite was therefore dependent on immersion time.

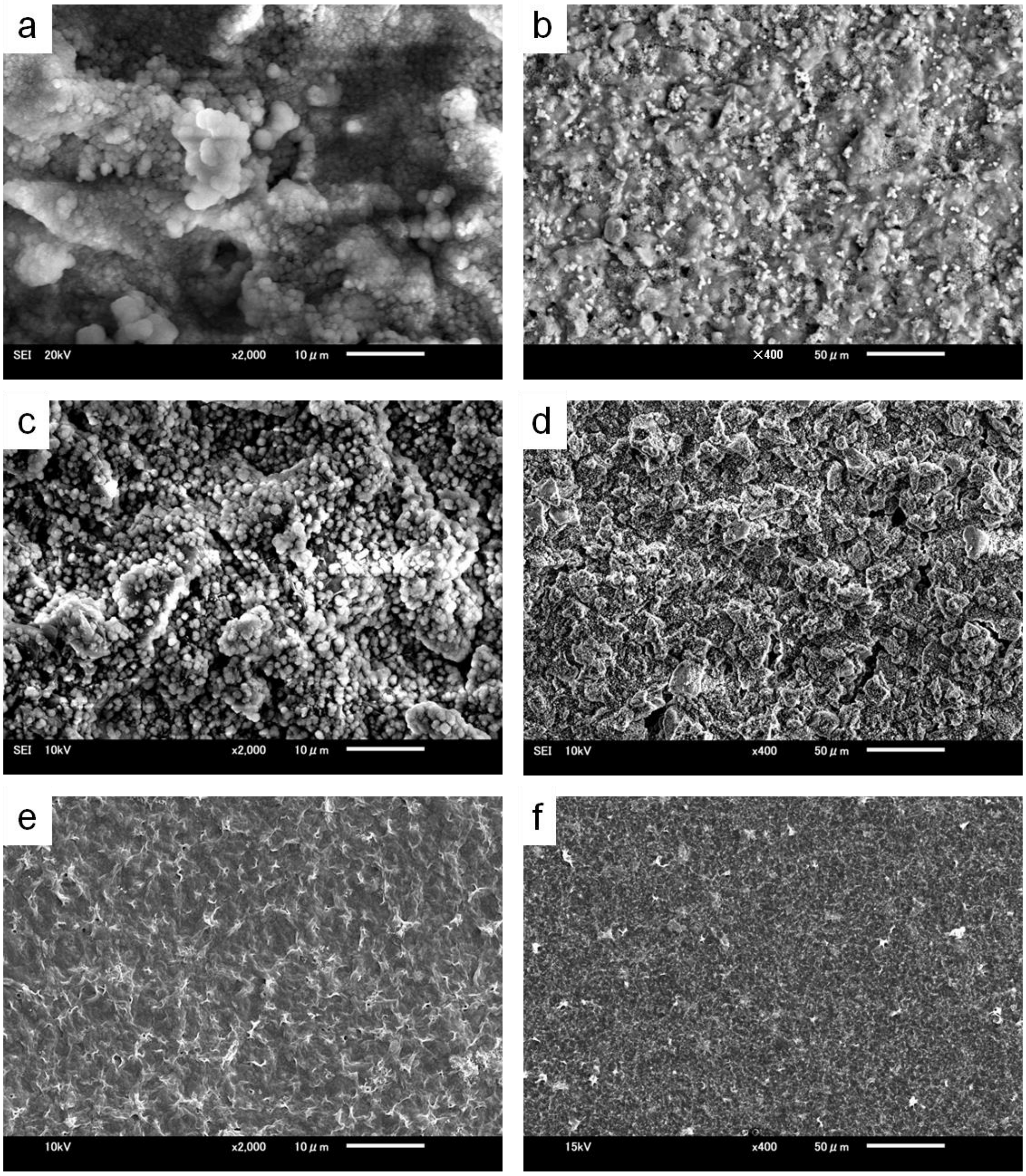


Figure 2-12. Scanning electron micrographs of Bioglass®/Poly(ester-sulfone) films that had been immersed in SBF. (a, b) 1-week immersion (magnification ×2000, ×400, respectively) and (c, d) 2-week immersion (magnification ×2000, ×400, respectively) at 37°C. (e, f) Control experiment using a pure poly(ester-sulfone) film (magnification ×2000, ×400, respectively).

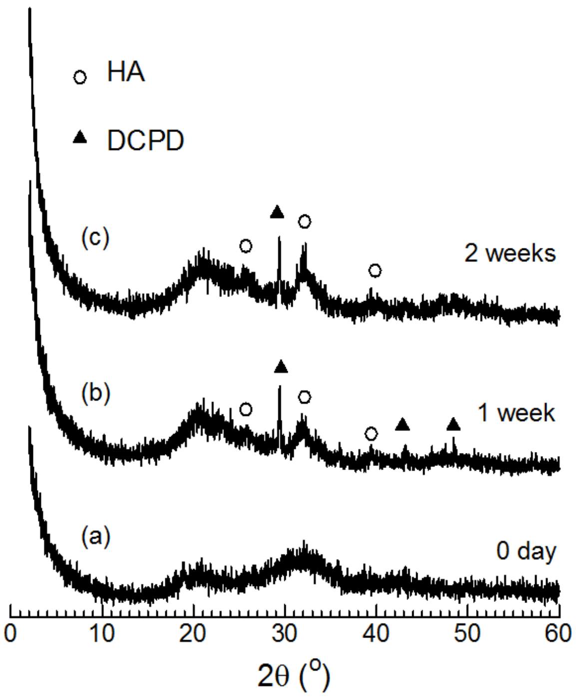


Figure 2-13. XRD patterns for (a) the Bioglass®/poly(ester-sulfone) film before immersion in SBF and after immersion in SBF for (b) 1 and (c) 2 weeks. DCPD, dicalcium phosphate dihydrate. HA, hydroxyapatite.

The demand for implantable medical devices is steadily increasing, especially the demand for spinal and orthobiologic implants, and improved technologies and biomaterials are therefore required. In this chapter 2, we prepared a Bioglass®/click poly(ester-sulfone) colloid, which could be deposited onto a stainless steel surface by EPD to form a soft composite coating. The Bioglass®/click poly(ester-sulfone) film developed a surface layer of hydroxyapatite when immersed in SBF confirming the bioactive behavior of the new composite coating. The easy deposition and the ability to produce surface hydroxyapatite layers are properties required for bone-related implants, e.g. bioactive coatings on metallic substrates. The synthesis of the poly(ester-sulfone) was facile, and the poly(ester-sulfone) was stable in the EPD cell, e.g. under electric fields. The results reported herein therefore provide a foundation upon which new bioactive composite materials may be developed as soft coatings for bone-related implants.

2-3 Experimental Section

Materials and Methods. Chemicals were obtained from commercial sources and used without further purification. ^{1}H NMR spectra were acquired at 27°C using a Bruker Analytik DPX200 spectrometer (200 MHz). Tetramethylsilane was the internal standard (0 ppm). FT-IR spectra of the polyesters in KBr disks were obtained using a JASCO/IR-430 spectrometer. Number average molecular weight (M_n) and polydispersity indexes (M_w/M_n) for the polyesters were estimated using a size exclusion chromatography (SEC) system consisting of a Tosoh DP8020 pump system, a Tosoh RI-8020 differential refractometer, and Tosoh TSK-gel α-3000 and α-5000 columns (Tosoh, Tokyo, Japan). The eluent was 0.05% (w/v) LiBr, 100 mM tetramethylethylenediamine in *N,N*-dimethylformamide (DMF). The flow rate was 0.5 mL/min, and the temperature was 40°C. Differential scanning calorimetry (DSC), which used a DSC6220S calorimeter (Seiko Instruments Inc., Chiba, Japan), was performed from –90 to 180°C to –90°C, at 10°C/min. The instrument was calibrated with indium and tin. Each polyester sample weighted between 5 and 7 mg and was contained in an aluminum pan that was covered with a lid within the calorimeter. The glass-transition temperature (T_g) was taken as the inflection point of the DSC heat-capacity jump. The melting temperature (T_m) was defined as the minimum point in the endothermic trough. Thermogravimetric analyses (TGA) were performed under nitrogen at 10°C/min between 20 and 600°C (TG/DTA 220U; Seiko Instruments Inc., Chiba, Japan).

Preparation of Bis(butenyl) Methylsuccinate. Methylsuccinic acid (2.0 g, 15 mmol), $Sc(OTf)_3$ (74 mg, 0.15 mmol), and 3-buten-1-ol (4.3 g, 60 mmol) were added into a 50-mL round-bottom flask. The mixture was stirred at 60°C for 12 h under reduced pressure (90 mmHg) then diluted with 30 mL chloroform, washed with 10 mL of saturated $NaHCO_{3(aq)}$, and dried over $MgSO_4$. After filtration and solvent evaporation, bis(butenyl) methylsuccinate was obtained as a white liquid in 91% yield (3.3 g). ^{1}H-NMR (200 MHz, $CDCl_3$, δ): 5.89–5.68 (m, $C{=}C\mathit{H}CH_2$, 2H), 5.16–5.05 (m, $C\mathit{H}_2{=}C$, 4H), 4.19–4.10 (m, $CH_2C\mathit{H}_2OC{=}O$, 4H), 2.89 (quin, $O{=}CC\mathit{H}(CH_3)CH_2$, 1H, 6.8 Hz), 2.73 (dd, O=CCH_2CH(CH_3), 1H, 8.0 and 16 Hz), 2.45–2.34 (m, O=CCH_2CH(CH_3) and C=CHC$H_2$$CH_2$, 5H), 1.21 (d, 3H, C(C$H_3$), 7.1Hz).

Synthesis of the Poly(ester-sulfide) by Thermal Polymerization. To examine reaction variables, a series of 10 mL round-bottom flasks were prepared that contained bis(butenyl) methylsuccinate (1.0 mmol), the thermal initiator azobisisobutyronitrile (2.0×10^{-2} mmol), and 1,4-butanedithiol (1.0 mmol) in 1 mL of distilled toluene. The mixtures were stirred at 70˚C under a nitrogen atmosphere for various times and then diluted with $CHCl_3$. The poly(ester-sulfide) preparations were individually precipitated twice from $CHCl_3$ by addition of *n*-hexane, and dried under vacuum. White syrups were obtained. The polymer preparations were physically characterized by NMR and SEC and thermally characterized by DSC (data not shown).

Synthesis of the Poly(ester-sulfide) by Photo-Polymerization. To examine reaction variables, a series of 10 mL round-bottom flasks were prepared that contained bis(butenyl) methylsuccinate (1.0 mmol), 1-hydroxycyclohexyl phenyl ketone (Irgacure 184) (1.0×10^{-2} or 2.0×10^{-2} mmol), and 1,4-butanedithiol (1.0 mmol) in 1 mL of distilled toluene. The mixtures were stirred at room temperature under nitrogen and UV-irradiated using a Toshiba H-400P high-pressure mercury lamp (400 W and 250−400 nm) for various times. Then the mixtures were individually diluted with $CHCl_3$. The poly(ester-sulfide)s were individually precipitated twice from $CHCl_3$ by addition of *n*-hexane and dried under vacuum. White syrups were obtained. Details for the syntheses are summarized in **Table 2-1**. The polymer preparations were characterized by ^{1}H-NMR and IR spectroscopy, and SEC. The thermal properties were determined by DSC and TGA. ^{1}H-NMR (200 MHz, $CDCl_3$, δ): 4.13–4.06 (brm, CH_2CH_2OC=O, 4H), 2.89 (quin, O=CCH(CH_3)CH_2, 1H, 6.8 Hz), 2.73 (dd, O=CCH(H)CH(CH_3), 1H, 8.0 and 16 Hz), 2.57–2.50 (brm, C=CHC$H_2$$CH_2$, 4H), 2.40 (dd, O=CC$H$(H)CH($CH_3$), 1H, 6.0 and 16 Hz), 1.78-1.62 (brm, SCH_2CH_2, 16H), 1.21 (d, 3H, C(CH_3), 7.0Hz). IR (KBr) cm^{-1}: 2939 ($\nu_{C\text{-}H}$), 1732 [$\nu_{C=O}$(ester)], 1275 and 1163 [$\nu_{C\text{-}O}$(ester)].

Oxone Oxidation of the Poly(ester-sulfide) to the Poly(ester-sulfone). A variety of conditions were examined, an example (**Table 2-2**, entry 5) follows. The poly(ester-sulfide) (402 mg, 1.1 mmol repeat unit) and Oxone (1.36 g, 2.2 mmol) in DMF (8 mL) were added into a 30 mL round-bottom flask. After stirring at 30˚C for 6 h, the mixture was filtered, and the solvent was evaporated under reduced pressure to give a white solid that was then dissolved in 5 mL of DMF and precipitated by addition of 90 mL of H_2O/CH_3OH (9/1, v/v). A total of 427 mg of the poly(ester-sulfone) was obtained as a white solid. The product was characterized by ^{1}H-NMR and FTIR spectroscopy, and by SEC. The conversion of sulfide into sulfone was calculated by ^{1}H NMR intensity ratio of signals at 1.21 and 3.13 ppm. Its thermal properties were determined using DSC and TGA. ^{1}H-NMR (200 MHz, DMSO-d_6, δ): 4.05 (brs, $CH_2CH_2OC{=}O$, 4H), 3.18–3.07 (brm, $CH_2CH_2SO_2$, 8H), 2.80 (quin, $O{=}CCH(CH_3)CH_2$, 1H, 6.4 Hz), 2.62 (dd, $O{=}CCH(H)CH(CH_3)$, 1H, 7.9 and 17 Hz), 2.55–2.43 (brm, $O{=}CCH(H)CH(CH_3)$ and $C{=}CHCH_2CH_2$, 5H), 1.83 (brs, $SO_2CH_2CH_2CH_2CH_2SO_2$, 4H), 1.72 (brs, $SO_2CH_2CH_2CH_2CH_2$, 8H), 1.21 (d, 3H, $C(CH_3)$, 7.1Hz). IR(KBr) cm^{-1}: 2938 ($\nu_{C\text{-}H}$), 1732 [$\nu_{C=O}$(ester)], 1330 and 1123 ($\nu_{S=O2}$), 1269 and 1169 [$\nu_{C\text{-}O}$(ester)].

Preparation of Stainless Steel Electrodes Coated with Bioglass®/Poly(ester-sulfone) Composites. Bioglass® powder of composition 45S5 (45 wt% SiO_2, 24.5 wt% Na_2O, 24.5 wt% CaO, and 6 wt% P_2O_5) of mean particle size < 7μm was used. A suspension of Bioglass® powder in 15 mL of ethanol or *n*-butanol was agitated in an ultrasonicator for 15 min and then stirred for 5 min. The poly(ester-sulfone) was stirred in 15 mL of DMF for 15 min at 50˚C to obtain a homogeneous solution. Then the Bioglass® and poly(ester-sulfone) solutions were mixed, ultrasonically agitated for 15 minutes and then stirred for 5 min. To deposit Bioglass®/poly(ester-sulfone) composites onto stainless steel electrodes by EPD, the distance between the electrodes was 7.5 mm, and the deposition time was 90 s at a voltage of 30 V. The depositions were carried out on 0.2 × 15 × 25 mm of stainless steel SUS 301 electrodes obtained from The Nilaco Corporation (Tokyo, Japan). Pure poly(ester-sulfone), prior to EPD and recovered from the electrode after EPD, was characterized by

^{1}H-NMR and FTIR spectroscopy. Pure Bioglass® and poly(ester-sulfone) preparations were also subjected to EPD at similar EPD conditions.

Biomineralization of Bioglass®/Poly(ester-sulfone) Composite Films. The surface composition of the Bioglass®/poly(ester-sulfone) composite coating deposited on the anode was investigated after immersion of samples in SBF. The composition of SBF, which was buffered with tri(hydroxymethyl)aminomethane and hydrochloric acid to maintain a pH of 7.4, has been described in the literature.[23] After holding the samples in SBF 30 mL for 1 or 2 weeks at 37°C, the composites were removed and washed with distilled water. The microstructures of the Bioglass®/poly(ester-sulfone) composite and of pure poly(ester-sulfone) films were visualized by scanning electron microscopy (SEM) (dual-stage JSM-6010LA; JEOL Ltd., Tokyo, Japan). Elemental composition was determined by energy-dispersive X-ray spectroscopy (EDX). The elemental distribution was determined using Smart Map, which simultaneously acquired X-ray data from each pixel in an image (JEOL Ltd., Tokyo, Japan). X-ray diffraction (XRD) was used to determine the crystalline composition of the film surfaces and was performed with an automated diffractometer (RINT2000/PC; Rigaku, Tokyo, JAPAN) at a scan rate of 2° min^{-1}, between 0° and 60°.

2-4 References and Notes

(1) [a] Vert, M. *Biomacromolecules*, **2005**, *6*, 538-546. [b] Takwa, M.; Xiao, Y.; Simpson, N.; Malmström, E.; Hult, K.; Koning, C. E.; Heise, A.; Martinelle, M. *Biomacromolecules*, **2008**, *9*, 704-710. [c] Misra, S. K.; Valappil, S. P.; Roy, I.; Boccaccini, A. R. *Biomacromolecules*, **2006**, *7*, 2249-2258. [d] Seyednejad, H.; Vermonden, T.; Fedorovich, N. E.; Eijik, R.; Steenbergen, M. J.; Dhert, W. J. A.; Nostrum, C. F.; Hennink, W. E. *Biomacromolecules*, **2009**, *10*, 3048-3054. [e] Naolou, T.; Busse, K.; Kressler, J. *Biomacromolecules*, **2010**, *11*, 3660-3667. [f] Zhang, P.; Wu, H.; Wu, H.; Lu, Z.; Deng, C.; Hong, Z.; Jing, X.; Chen, X. *Biomacromolecules*, **2011**, *12*, 2667-2680. [g] Moglia, R. S.; Holm, J. L.; Sears, N. A.; Wilson, C. J.; Harrison, D. M.; Cosgriff-Hernandez, E. *Biomacromolecules*, **2011**, *12*, 3621-3628.

(2) [a] Carothers, W. H.; Dorough, G. L. *J. Am. Chem. Soc.* **1930**, *52*, 711-721. [b] Takiyama, E.; Niikura, I.; Hatano, Y. Japan Patent 189,823, 1995. [c] Miura, M.; Watanabe, H.; Fujiwara, M. Japan Patent 53, 695, 1995. [d] Buzin, P.; Lahcini, M.; Schwarz, G.; Kricheldord, H. R. *Macromolecules*, **2008**, *41*, 8491-8495. [e] Garaleh, M.; Lahcini, M.; Kricheldorf, H. R.; Weidner, S. M. *J. Polym. Sci.; Part A: Polym. Chem.* **2009**, *47*, 170–177.

(3) [a] Kricheldorf, H. R.; Kreiser-Saunders, I. *Macromol. Chem. Phys.* **1990**, *191*, 1057-1066. [b] Lofgren, A.; Albertsson, A. C.; Dubois, P.; Jerome, R. *J. Macromol. Sci.; Rev. Macromol. Chem. Phys.* **1995**, *35*, 379-418. [c] Kim, S.; Han, Y. K.; Kim, Y. H.; Hong, S. I. *Macromol. Chem. Phys.* **1992**, *193*, 1623-1631.

(4) [a] Ajioka, M.; Enomoto, K.; Suzuki, K.; Yamaguchi, A. *Bull. Chem. Soc. Jpn*, **1995**, 68, 2125-2131. [b] Ni: Mochizuki, M.; Mukai, K.; Yamada, K.; Ichise, N.; Murase, S.; Iwaya, Y. *Macromolecules* **1997**, *30*, 7403-7407. [c] $HfCl_4(THF_2)$: Ishihara, K.; Ohara, S.; Yamamoto, H. *Science* **2000**, *290*, 1140-1142. [d] Sn distannoxane: Ishii, M.; Okazaki, M.; Shibasaki, Y.; Ueda, M. *Biomacromolecules* **2001**, *2*, 1267-1270.

(5) [a] Takasu, A.; Oishi, Y.; Iio, Y.; Inai, Y.; Hirabayashi, T. *Macromolecules* **2003**, *36*, 1772-1774. [b] Takasu, A.; Iio, Y.; Oishi, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2005**, *38*, 1048-1050. [c] Takasu, A.; Iio, Y.; Mimura, T.; Hirabayashi, T. *Polym. J.* **2005**, *37*, 946-953. [d] in water: Takasu, A.; Takemoto, A.; Hirabayashi, T. *Biomacromolecules* **2006**, *7*, 6–9. [e] PLA: Takasu, A.; Narukawa, Y.; Hirabayashi, T. *J. Polym. Sci.; Part A: Polym. Chem.* 2006, 44, 5247–5253. [f] combination with ROP: Takasu, A.; Tsuruta, H.; Narukawa, Y.; Shibata, Y.; Oshimura, M.; Hirabayashi, T. *Macromolecules.* **2008,** *41*, 4688-4693. [g] customized catalyst: Takasu, A.; Makino, T.; Yamada, S. *Macromolecules.* **2010**, *43*, 144-149. [h] microwave-assisted: Yamada, S.; Takasu, A. *Polym. J.* **2011**, *43*, 1003-1007.

(6) [a] hydroxyl: Takasu, A.; Shibata, Y.; Narukawa, Y.; Hirabayashi, T. *Macromolecules* **2007**, *40*, 151–153. [b] hydroxyl: Shibata, Y.; Takasu, A. *J. Polym. Sci.; Part A: Polym. Chem.* **2009**, *47*, 5747-5759. [c] mercapto: Yamamoto, K.; Takasu, A. *Macromolecules* **2010**, *43*, 8519-8523. [d] disulfide: Sato, Y.; Takasu, A. *Polym. J.* **2010**, *42*, 956-959.

(7) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, *40*, 2004-2021.

(8) [a] Rostovtsev, V. V.; Green, L. G.; Fokin, V. V.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2002**, *41*, 2596-2599. [b] Chan, T. R.; Hilgraf, R.; Sharpless, K. B.; Fokin, V. V. *Org. Lett.* **2004**, *17*, 2853.

(9) [a] adhesive polymer : Diaz, D. D.; Punna, S.; Holzer, P.; Mcpherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. G. *J. Polym. Sci.; Part A: Polym. Chem.* **2004**, *42*, 4392. [b] polyketone: Tang, B. Z.; Qin, A.; Jim, C. K. W.; Lu, W.; Lam, J. W. Y.; Häussler, M.; Dong, Y.; Sung, H. H. Y.; Williams, I. D.; Wong, G. K. L. *Macromolecules* **2007**, *40*, 2308-2317. [c] helical polymer: Kobayashi, S.; Itomi, K.; Morino, K.; Iida, H.; Yashima, E. *Chem. Comm.* **2008**, 3019-3021. [d] poly(ethylene glycol): Liu, X. M.; Thakur, A.; Wang, D. *Biomacromolecules* **2007,** *8*, 2653-2658. [e] biomass-based polymer: Michinobu, T.; Inazawa, Y.; Hiraki, K.; Katayama, Y.; Masai, E.; Nakamura, M.; Ohara, S.; Shigehara, K.

Chem. Lett. **2008**, 154-155. Michinobu, T.; Hirai, K.; Inazawa, Y.; Katayama, Y.; Masai, E.; Nakayama, M.; Ohara, S.; Shigehara, K. *Polymer J.* **2011**, *43*, 648-653. [f] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2007**, *28*, 15-54. [g] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2008**, *29*, 952-981. [h] review: Johnson, J. A.; Finn, M. G.; Koberstein, J. T.; Turro, N. J. *Macromol. Rapid Commun.* **2008**, *29*, 1052-1072. [i] new "click" chemistry: Koyama, Y.; Yonekawa, M.; Takata, T. *Chem. Lett.* **2008**, *37*, 918-919. [j] Lee, Y. G.; Koyama, Y.; Yonekawa, M.; Takata, T. *Macromolecules* **2009**, *42*, 7709-7717. [k] α-azide-ω-alkyne monomers: Binauld, S.; Damiron, D.; Hamaide, T.; Pascault, J. P.; Fleury, E.; Drockenmuller, E. *Chem. Comm.* **2008**, 4138-4140. Binauld, D; Fleury, E.; Drockenmuller, E.; Huang, F. *J. Polym. Sci.; Part A: Polym. Chem.* **2010**, *48*, 2470-2476. [l] functional polymer: Schwartz E.; Breitenkamp, K.; Fokin, V. V. *Macromolecules* **2011**, *44*, 4735-4741. [m] polytriazoleimide: Zhou, X.; Wan, L.; Hu, Y.; E, Y.; Huang, F.; Du, L. *Polymer J.* **2010**, *42*, 216-222.

(10) [a] Nagao, Y.; Takasu, A. *Macromol. Rapid Commun.* **2009**, *30*, 199-203. [b] Nagao, Y.; Takasu, A. *J. Polym. Sci.; Part A: Polym. Chem.* **2011**, *48*, 4207–4218.

(11) [a] Sletten E. M.; Bertozzi, C. R. *Org. Lett.* **2008**, *10*, 3097-3099. [b] Codelli, J. A.; Baskin, J. M.; Agrad, N. J.; Bertozzi, C. R. *J. Am. Chem. Soc.* **2008**, *130*, 11486-11493. [c] Jewett, J. C.; Sletten, E. M.; Bertozzi, C. R. *J. Am. Chem. Soc.* **2010**, *132*, 3688-3690.

(12) Koyama, Y.; Yonekawa, M.; Takata, T. *Chem. Lett.* **2008**, *37*, 918-919.

(13) [a] Jacobine, A. F. In radiation Curing in Polymer Science and Technology III; Fouassier, J. D.; Rabek, J. F., Eds.; Elsevier: London, **1993**, *7*, 219-268. [b] Hoyle, C. E.; Lee, T. Y.; Roper, T. *J. Polym. Sci.; Part A: Polym. Chem.* **2004**, *42*, 5301–5338.

(14) [a] Wilderbeek, H. T. A.; Goossens, J. G. P.; Bastiaansen, C. W. M.; Broer, D. J. *Macromolecules* **2002**, *35*, 8962-8968. [b] Wilderbeek, H. T. A.; Meer, M. G. M.; Bastiaansen, C. W. M.; Broer, D. J. *J. Phs. Chem. B* **2002**, *106*, 12874-12883. [c] Killops,

K. L.; Campos, L. M.; Hawker, C. J. *J. Am. Chem. Soc.* **2008**, *130*, 5062-5064. [d] Kwinsnek, L.; Nazarenko, S.; Hoyle, C.E. *Macromolecules* **2009**, *42*, 7031-7041. [e] Kloxin, C. J.; Scott, T. F.; Bowman, C. N. *Macromolecules* **2009**, *42*, 2551-2556. [f] Shin, J.; Matsushima, H.; Chan, J. W.; Hoyle, C. E. *Macromolcules* **2009**, *42*, 3294-3301. [g] Lluch, C.; Ronda, J. C.; Galia, M.; Lligadas, G.; Cádiz, V. *Biomacromolecules* **2010**, *11*, 1646-1653.

(15) [a] Santerre, J. P.; Brash, J. L. *Macromolecules* **1991**, *24*, 5497-5503. [b] Marianucci, E.; Berti, F.; Pilati, F.; Manaresi, P. *Polymer* **1994**, *35*, 1564-1566. [c] Lu, C.; Cui, Z.; Wang, Y.; Li, Z.; Guan, C.; Yang, B.; Shen, J. *J. Mater. Chem.* **2003**, *13*, 2189-2195. [d] Rydholm, A. E.; Bowman, C. N.; Anseth, K. S. *Biomaterials* **2005**, *26*, 4495-4506. [e] Rydholm, A. E.; Reddy, S. K.; Anseth, K. S.; Bowman, C. N. *Biomacromolecules* **2006**, *7*, 2827-2836. [f] Huang, Y.; Paul, D. R. *Macromolecules* **2006**, *39*, 1554-1559.

(16) [a] Boccaccini, A. R.; Keim, S.; Ma, R.; Zhitmirsky, L. I. *J. R. Soc. Interface* **2010**, *7*, 581-613. [b] Gastillo, J.; Dimaki, M.; Svendsen, W. E. *Integr. Biol.* **2009**, *1*, 30–42. [c] Lee, S. W.; Belcher, A. M. *Nano Lett.* **2004**, *4*, 387-390. [d] Guo, L. J. *Adv. Mater.* **2007**, *19*, 495–513.

(17) [a] Sarker, P.; Nicholson, P. S. *J. Am. Ceram. Soc.* **1996**, *79*, 1987-2002. [b] Roether, J. A.; Boccaccini, A. R.; Hench, L. L.; Maquet, V.; Gautier, S.; Jérôme, R. *Biomaterials*, **2002**, *23*, 3871-3878. [c] Corni, I.; Neumann, N.; Novak, S.; König, K.; Veronesi, P.; Chen, Q.; Ryan, M. P.; Boccaccini, A. R. *Surf. Coat. Technol.* **2009**, *203*, 1349-1359. [d] Pishbin, F.; Simchi, A.; Ryan, M. P.; Boccaccini, A. R. *Surf. Coat. Technol.* **2011**, *205*, 5260-5268. [e] Rodriguez, H. H.; Vargas, G.; Cortés D. A. *Ceram. Int.* **2008**, *34*, 1303-1130. [f] Van der Biest, O. O.; Vandeperre, L. J. *Annu. Rev. Mater. Sci.* **1999**, *29*, 327-352. [g] Boccaccini, A. R.; Zhitomirsky, I. *Curr. Opin. Solid State Mater. Sci.* **2002**, *6*, 251-260. [h] Ma, R.; Zhitomirsky, I. *J. Alloy Compd*. **2011**, *509*, S510-S513. [i] Wang, Y.; Deen, I.; Zhitomirsky, I. *J. Colloid Interface Sci.* **2011**, *362*, 367-374. [j] Boccaccini, A. R.; Peters, C.; Roether, J.

A.; Eifler, D.; Misra S. K.; Minay, E. J. *J. Mater. Sci*. **2006**, *41*, 8152-8159. [k] Xiao, X. F.; Liu, R. F. *Mater. Lett*. **2006**, *60,* 2627-2632.

(18) [a] Hench, L. L.; Splinter, R. J.; Allen, W. C.; Greenlee, T. K. *J. Biomed. Mater. Res.*, **1971**, *2*, 117-141. [b] Hench, L. L. *J. Am. Ceram. Soc.*, **1998**, *81*, 1705-1728. [c] Hench, L. L. *J. Eur. Ceram. Soc.*, **2009**, *29*, 1257-1265. [d] Oonishi, H.; Hench, L. L.; Wilson, J.; Sugihara, F.; Tsuji, E.; Matsuura, M.; Kin, S.; Yamamoto, T.; Mizokawa, S. *J. Biomed. Mater. Res.* **2000**, *51*, 37-46. [e] Misra, S. K.; Nazhat, S. N.; Valappil, S. P.; Torbati, M. M.; Wood, R. J. K.; Roy, I.; Boccaccini, A. R. *Biomacromolecules* **2007**, *8*, 2112-2119

(19) Xiao. X.; Liu, R.; Tang, X. *J. Mater. Sci.: Mater. Med.* **2009**, *20*, 691-697.

(20) [a] Carothers, C. H. *Trans. Faraday Soc.* **1936**, *32*, 39. [b] Flory, P. J. *Chem. Rev.* **1946**, *39*, 137.

(21) Wutticharoenwong, K.; Soucek, M. D. *Macromol. Mater. Eng.* **2008**, *293*, 45-46.

(22) Fulmer, M. T.; Brown, P. W. *J. Mater. Sci.: Mater. Med.* **1998**, *9*, 197-202.

(23) Kokubo, T.; Kushitani, H.; Sakka, S. *J. Biomed. Mater. Res.*, **1990**, *24*, 721-734.

Chapter 3

Electrophoretic Behavior of Polyester-Gel Containing Sulfone Units

3-1 Introduction

Current portable electronic devices such as cellular phones and laptop computers have always relied on battery power, and while rechargeable batteries have attained significant advances, from the old nickel cadmium to today's lithium polyelectrolyte, they still have their drawbacks.[1] Therefore, it is still significant interest to overcome the limited amount of battery capacity.[2] However, so a liquid electrolyte is used in normal cells that it is necessary to solidify battery container in order to prevent leakage and spoiling, which also causes an increase in battery weight.[3] In addition, we have to care that organic liquid electrolyte is hazardous because of ignition when it is heated, so has also become a serious problem in the development of huge cell in power production using natural power such as wind and solar energy.[4] In 1990s, the majority of commercial lithium batteries were fabricated with Li^+-salt solution as electrolytes immobilized in a variety of polymer matrices.[5] This has ultimately led to the development of polymer Li-ion batteries consisting of a polymer matrix swollen with Li^+-salt solution. Meanwhile, lithium-ion cells are extending their new uses such for large scale storage batteries having higher voltage cells such as 5–6 V discharge as well as larger charge–discharge capacity and higher energy density.[6] To develop advanced electrolyte with high voltage stability, combined with high ion conductivity, high thermal stability, non-flammability, and confident safe, we focused on sulfone-based solid electrolyte because of tetramethylene sulfone and ethylmethyl sulfone showing a high ionic conductivity and good oxidation potentials.[7] Sulfones are investigated for high-voltage cells due to their lower volatility and high resistance to electrochemical oxidation.[8] Sulfones with different length of oligo ethylene glycol segments have been also synthesized and tested for use in rechargeable lithium batteries.[9] Moreover, it was reported that sulfone-ester mixed solvent showed good anodic stability and could be used for high-voltage lithium cells.[10]

Recently, we reported the facile synthesis of poly(ester-sulfone) via thiol−ene click polymerization and oxone oxidation.[11] Additionally, we found the poly(ester-sulfone) was stable even under electrical field and showed unique electophoretic behavior. In this chapter, I examine sulfone units as novel electrolyte building block to prepare poly(ester-sulfone) gel for solid electrolyte via double thiol−yne (DTY) click polymerization (**Figure 3-1**).[12] This polymer consisted of sulfone, ethylene glycol, and ester in the main-chain. I also investigated elctrophoretic behavior of the poly(ester-sulfone) gel even in the heterogeneous state, and the deposits onto electrode are characterized.

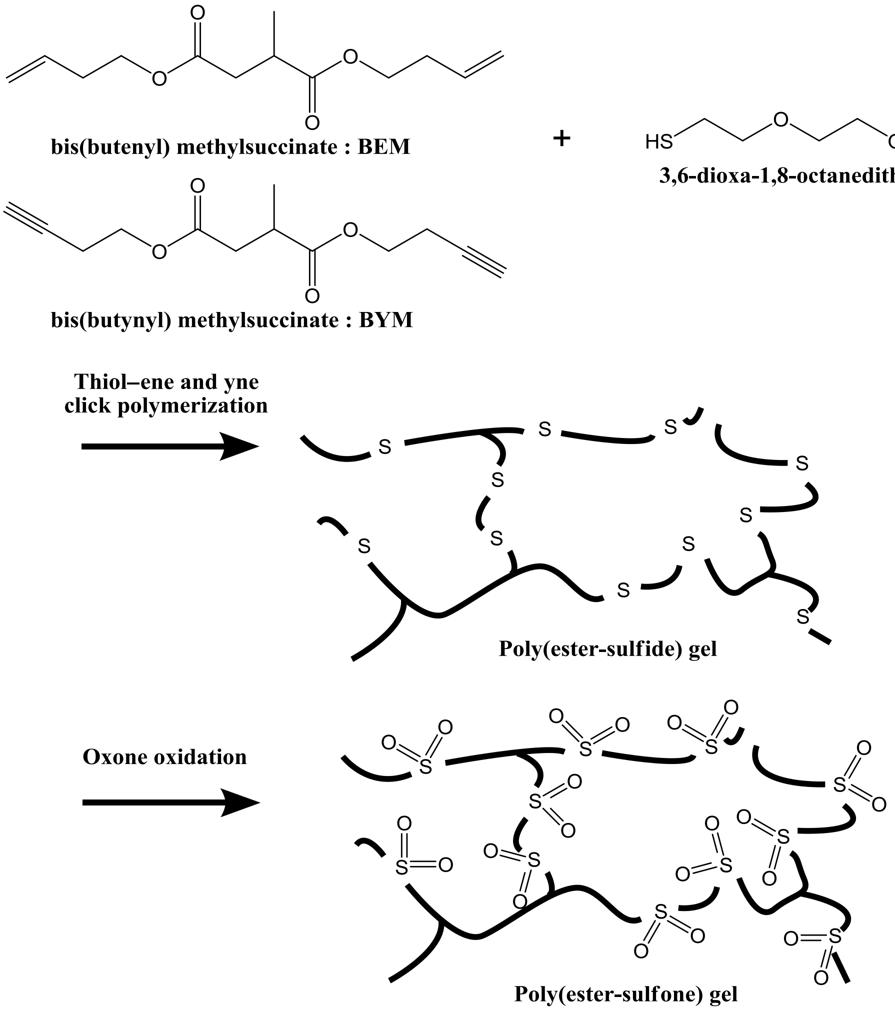


Figure 3-1. Double thiol−yne (DTY) click polymerization and subsequent oxidation to poly(ester-sulfone) gel.

3-2 Results and Discussion

Preparation of Poly(ester-sulfone) Gel

The samples of poly(ester-sulfide) gel were prepared by DTY click polymerization of bis(butenyl) methylsuccinate (BEM), bis(butynyl) methylsuccinate (BYM) and 3,6-dioxa-1,8-octanedithiol (TEGDT) monomer mixtures under standard conditions. BEM, BYM and TEGDT in a molar ration of 1:1:3, 1:1:4 and 11:10:40 were reacted in toluene with azobisisobutyronitrile as initiator at 70°C for 45 min to give a soft, colorless organogel. However, in the rests of those conditions the desired gelation did not occurred even after 2 hours reaction. These results indicated that, first of all, the gelation could be accomplished in excess amount of TEGDT as dithiol monomer for BYM as diyne monomer (run1-3 in **Table 3-1**). Conversely, in excess feed ratio of TEGDT we could not obtain poly(ester-sulfide) gel (run 5-8 in **Table 3-1**). This is because excess TEGDT did not play as the cross-linker but formed blanching units during the DTY polymerization. This result was strongly supported by ^{1}H NMR analysis indicating remaining double bond units in the main chain (run6-8 in **Table 3-1**). Remaining double bond ratio of run 6-8 indicated each alkyne functional group has been consumed with two thiols to generate thioethers completely, although, didn't reach to network structure.

Table 3-1. Preparation of poly(ester-sulfide) gel.

run	BEM/BYM/TEGDT (mmol)	remaining double bond[a] (%)	gelation
1	0.50/0.50/1.0	49	–
2	0.50/0.50/1.5	N.A.	+
3	0.50/0.50/2.0	N.A.	+
4	0.55/0.50/1.0	63	–
5	0.55/0.50/2.0	N.A.	+
6	0.60/0.40/2.0	0	–
7	0.80/0.20/2.0	0	–
8	1.0/0.10/2.0	0	–

[c] Determined by ^{1}H NMR spectroscopy.

Remaining monomer ratio of BYM, BEM monomers were determined by ^{1}H NMR spectroscopy during the DTY polymerization with a stoichiometric BYM and BEM mixture in which dithiol monomer is in excess, 1:1:3 respectively (run 2 shown in **Figure 3-2**) because DTY reacted twice in the mechanism. Rapid consumption of both the BYM and BEM is observed in the first several minutes of the reaction. As the reaction proceeds, the consumption of BYM exceeds that of BEM. This result indicated that the reaction rate of BYM was faster than BEM, and also showed the reaction process that reactive double bonds were introduced into the main-chain by the addition of a thiyl radical to an alkyne in the early stage of DTY polymerization. These double bonds in the main-chain are capable of undergoing further reaction through addition of a second thiyl radical. Thus we could not obtain the network structure gel in the presence of excess thiols (run 6-8, **Table 3-1**).

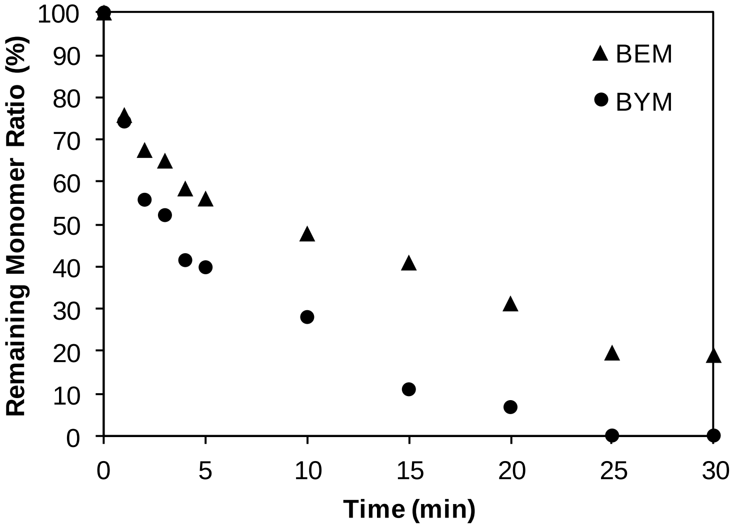


Figure 3-2. Remaining monomer ratio in the reaction mixture of BEM (▲) and BYM (●) during curing of a stoichiometrically ratio of reactive monomer 1:1 BEM:BYM (excess thiol).

Oxone oxidation of the poly(ester-sulfide) (run 2, **Table 3-1**) to produce the corresponding poly(ester-sulfone) gel was also investigated by immersion of the dried and fractured gel in *N*,*N*-dimethylformamide (DMF) solution containing 2 equiv. of oxone per sulfide monomer feed at 40°C for 12 h. The white stiff gel could be obtained after extraction with distilled water in a

Soxhlet apparatus. The presence of sulfone was confirmed by their IR absorbencies at 1290 cm^{-1} and 1126 cm^{-1} (**Figure 3-3**). The thermal transitions of gels were observed by DSC. None of the gels showed evidence of crystallinity and the melting temperature. However, a significant increase of glass transition temperature (T_g) was recognized after the oxidation of the poly(ester-sulfide) gel to poly(ester-sulfone) gel, increased from −35°C to 13°C. The high polarity of sulfone functional groups causes electrostatic association.[13] This lowers flexibility of the main chain resulted in an increased T_g. However improved the thermal stability of the gel was not recognized after sulfonation (**Table 3-2**).

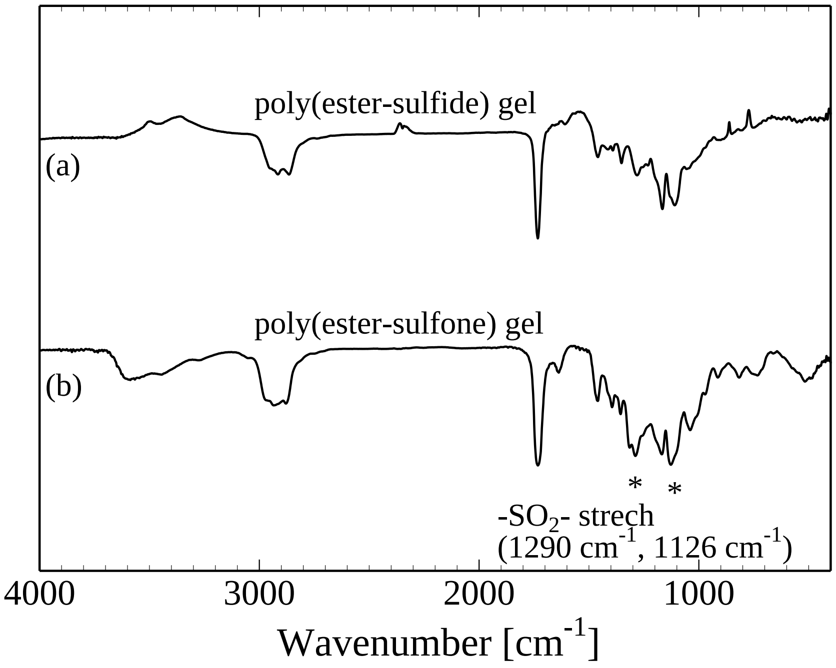


Figure 3-3. FTIR spectra of (a) poly(ester-sulfide) gel, (b) poly(ester-sulfone) gel.

Table 3-2. Thermal property of the poly(ester-sulfide) gel and poly(ester-sulfone) gel.

	T_g [b] (°C)	T_m [b] (°C)	T_{d5} [c] (°C)
poly(ester-sulfide) gel[a]	-35	N.A.	288
poly(ester-sulfone) gel	13	N.A.	281

[a] run 2 in **Table 3-1**. [b] T_m was determined from the first heating DSC scan and T_g from the second scan (heating rates: 10 ˚C/min). [c] T_{d5} associated with a 5% weight loss was determined from TGA scan (heating rates: 10 ˚C/min).

Electrophoretic Deposition (EPD) of Poly(ester-sulfone) Gel in the Heterogeneous State

To directly deposit the poly(ester-sulfone) gel onto stainless steel substrates, we tested the possibility of using a EPD procedure as shown **Figure 3-4**. The results are summarized in **Table 3-3.** We found that the poly(ester-sulfone) gel deposited onto stainless steel substrate just stirred in the heterogeneous state with *n*-butanol/DMF solution. When using poly(ester-sulfide) gel before sulfonation we could not observe the deposits on substrates. We also found this sulfonated-gel deposited onto anode selectively when we conducted EPD procedure. The adhesive ability of the poly(ester-sulfone) gel onto the substrates was improved under electric field, and selective deposition was achieved via electrophoretic motion of polar sulfone in the heterogeneous state. It is suggested that the polarized sulfones must dominate the surface of the gel.

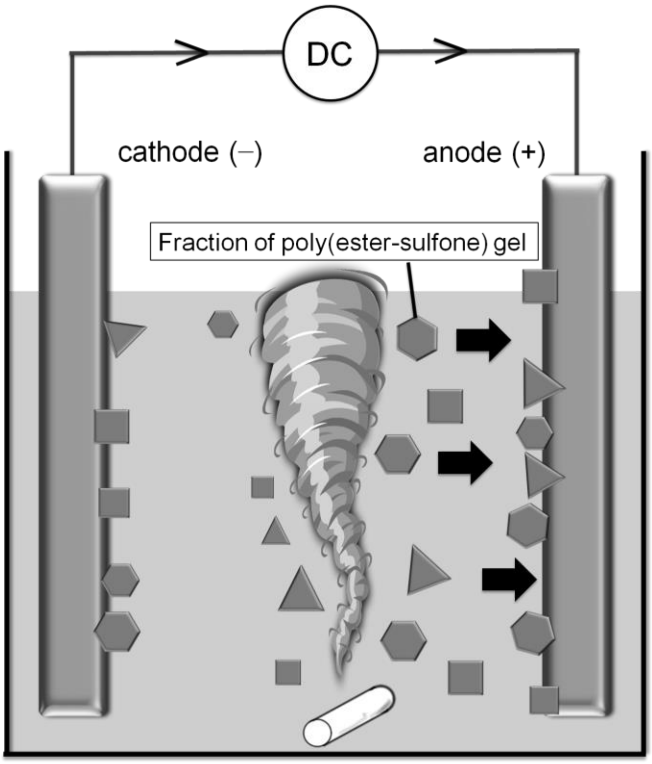


Figure 3-4. Schematic of the electrophoretically controlled deposition of the poly(ester-sulfone) gel fraction.

Table 3-3. Adhesive capacity and selectivity of the poly(ester-sulfone) gel onto electrode by EPD.

	only stirring		EPD with stirring	
	anode	cathode	anode	cathode
deposits weight[a] on electrode (mg/cm^2)	0.825	0.865	2.42	1.73

[a] Calculated from the average of three datum.

Sulfone compounds have excellent electrical properties, so low molecular weight sulfones such as tetramthylene sulfone and ethylmethyl sulfone are used as solvent for electrochemical device, e.g. liquid electrolyte. It is well-known that thiol–ene "click" reaction is efficient synthetic method for some functional polymers. In this chapter 3, I performed DTY copolymerization of BEM, BYM, and TEGDT to synthesize poly(ester-sulfide) gel in which bis(butenyl) methyl succinate acted as the cross-linker, and the subsequent oxidation using Oxone to give poly(ester-sufone) gel. The synthesized poly(ester-sulfone) gel was deposited on a stainless-steel electrode by electrophoretic deposition (EPD) although the parent poly(ester-sulfide) gel was not. The advantages and characteristics of employing this gel indicate the potential of the materials for use as solid electrolyte.

3-3 Experimental Section

Materials and Methods. Chemicals were obtained from commercial sources and used without further purification. ^{1}H NMR spectra were acquired at 27˚C using a Bruker Analytik DPX200 spectrometer (200 MHz). Tetramethylsilane was the internal standard (0 ppm). FT-IR spectra of the polyesters in KBr disks were obtained using a JASCO/IR-430 spectrometer. The flow rate was 0.5 mL/min, and the temperature was 40˚C. Differential scanning calorimetry (DSC), which used a DSC6220S calorimeter (Seiko Instruments Inc., Chiba, Japan), was performed from –90 to 180˚C to –90˚C, at 10˚C/min. The instrument was calibrated with indium and tin. Each sample weighted between 7 and 9 mg and was contained in an aluminum pan that was covered with a lid within the calorimeter. The glass-transition temperature (T_g) was taken as the inflection point of the DSC heat-capacity jump. The melting temperature (T_m) was defined as the minimum point in the endothermic trough. Thermogravimetric analyses (TGA) were performed under nitrogen at 10˚C/min between 20 and 600˚C (TG/DTA 220U; Seiko Instruments Inc., Chiba, Japan).

Preparation of Bis(butenyl) Methylsuccinate (BEM). Methylsuccinic acid (2.0 g, 15 mmol), $Sc(OTf)_3$ (74 mg, 0.15 mmol), and 3-buten-1-ol (4.3 g, 60 mmol) were added into a 50-mL round-bottom flask. The mixture was stirred at 60˚C for 12 h under reduced pressure (90 mmHg) then diluted with 30 mL chloroform, washed with 10 mL of saturated $NaHCO_{3(aq)}$, and dried over $MgSO_4$. After filtration and solvent evaporation, BEM was obtained as a white liquid in 91% yield (3.3 g).

^{1}H-NMR (200 MHz, $CDCl_3$, δ): 5.89–5.68 (m, $C{=}C\mathit{H}CH_2$, 2H), 5.16–5.05 (m, $C\mathit{H}_2{=}C$, 4H), 4.19–4.10 (m, $CH_2C\mathit{H}_2OC{=}O$, 4H), 2.89 (quin, $O{=}CC\mathit{H}(CH_3)CH_2$, 1H, 6.8 Hz), 2.73 (dd, $O{=}CC\mathit{H}_2CH(CH_3)$, 1H, 8.0 and 16 Hz), 2.45–2.34 (m, $O{=}CC\mathit{H}_2CH(CH_3)$ and $C{=}CHC\mathit{H}_2CH_2$, 5H), 1.21 (d, 3H, $C(C\mathit{H}_3)$, 7.1Hz).

Preparation of Bis(butynyl) Methylsuccinate (BYM). Into a 50 mL round-bottom flask were added methylsuccinic acid (2.5 g, 19 mmol), $Sc(OTf)_3$ (93 mg, 0.19 mmol), and 3-butyn-1-ol (5.4 g, 77 mmol). The reaction mixture was stirred at 60 ˚C for 12 h under reduced pressure (25 mmHg). After the reaction mixture had been diluted with 30 mL chloroform, the solution was washed with 10 mL of water saturated with $NaHCO_3$ and then dried over $MgSO_4$. After filtration and solvent evaporation, BYM was obtained as an auburn liquid in 84% yield (3.76 g).

^1H-NMR ($CDCl_3$) δ (ppm): 4.19 (t, $CH_2CH_2OC{=}O$, 4H, 6.7 Hz), 2.93 (quin, $O{=}CCH(CH_3)CH_2$, 1H, 6.6 Hz), 2.78 (dd, $O{=}CCH_2CH(CH_3)$, 1H, 8.1 and 16 Hz), 2.57-2.50 (m, $CH_2C{\equiv}C$, 4H), 2.45 (dd, $O{=}CCH_2CH(CH_3)$, 1H, 6.0 and 16 Hz), 2.00 (t, $C{\equiv}CH$, 2H, 2.5Hz), 1.24 (d, $C(CH_3)$, 3H, 7.1Hz).

Synthesis of the Poly(ester-sulfide) Gel. A variety of conditions were examined, an example (**Table 3-1**, run 2) follows. BEM (0.5 mmol), BYM (0.5 mmol), 3,6-dioxa-1,8-octanedithiol (TEGDT) (1.5 mmol), and azobisisobutyronitrile (0.03 mmol) were mixed together in 1 mL of distilled toluene, and the mixture was added to 10 mL round-bottom flask. After stirring the mixture at 70˚C for 40 min under a nitrogen atmosphere, we obtained colorless organogel. The gel preparations were dried under vacuum. The product was characterized by FTIR spectroscopy. Its thermal properties were determined using DSC and TGA.

Oxone Oxidation of the Poly(ester-sulfide) Gel to the Poly(ester-sulfone) Gel. The fractured poly(ester-sulfide) gel (930 mg) which was prepared from run 2 in **Table3-1**, and Oxone (2.71 g, 4.4 mmol) in DMF (17.6 mL) were added into a 30 mL round-bottom flask. After stirring at 40°C for 12h, the mixture was washed with distilled water in a Soxhlet apparatus for 24h. After drying, the poly(ester-sulfide) gel was obtained as a white and stiff solid in 43% yield (395 mg). The product was characterized by FTIR spectroscopy. Its thermal properties were determined using DSC and TGA.

Preparation of Stainless Steel Electrodes Coated with Poly(ester-sulfone) Gel. Poly(ester-sulfone) gel (75 mg) was agitated by stirring in 15 mL of DMF for 15 min at 80°C to obtain well dispersed heterogeneous solution. Then 15 mL of *n*-butanol and poly(ester-sulfone) heterogeneous solutions were mixed, stirred for 5 min. To deposit poly(ester-sulfone) gel fractions onto stainless steel electrodes by EPD, the distance between the electrodes was 7.5 mm, and the deposition time was 90 s at a voltage of 30 V. The depositions were carried out on 0.2 × 15 × 25 mm of stainless steel SUS 301 electrodes obtained from The Japan Metal Service SA (Saitama, Japan).

3-4 References and Notes

(1) [a]Yoshino, N *J. Power Sources* **2001**, *100*, 101-106. [b] Liu, S.; Dougal, R. A.; Weidner, J. W.; Gao, L. *J. Power Sources* **2005**, *141*, 326-339.

(2) Winter, M.; Besenhard, J. O. ; Spahr, M. E.; Novak, P. *Adv. Mater.* **1998**, *10*, 725-763.

(3) Ue, M. ; Ida, K. ; Mori, S. *J. Electrochem. Soc.* **1994**, *141*, 2989-2996.

(4) [a] O'Regan, B. O.; Grätzel, M. *Nature* **1991**, *353*, 737-740. [b] Kay, A.; Grätzel, M. *Sol. Energy Mater. Sol. Cells* **1996**, *40*, 99-117.

(5) [a] Glenis S.; Horowitz, G.; Tourillon, G.; Garnier, F. *Thin Solid Film* **1984**, *111*, 93-103. [b] Marks, R. N.; Halls, J. J. M.; Bradley, D. D. D. C.; Frield, R. H.; Holms, A. B. *J. Phys. Condens. Matter* **1994**, *6*, 1379-1394. [c] Halls, J. J. M.; Walsh, C. A.; Greenham, N. C.; Marseglia, E. A.; Friend, R. H.; Moratti, S. C.; Holmes, A. B. *Nature* **1995**, *376*, 498-500. [d] Yu, G.; Gao, J.; Hummelen, J. C.; Wudl, F.; Heeger, A. J. *Science* **1995**, *270*, 1789-1791. [e] Matsumoto, K.; Sogabe, S.; Endo, T. *J. Polym. Sci.; Part A: Polym. Chem.* **2012**, *50*, 1317-1324.

(6) [a] Molenda, J.; Marzec, J.; Swierczek, K.; Ojczuk, W.; Ziemnicki, M.; Molenda, M.; Drozdek, M.; Dziembau, R. *Solid State Ionics* **2004**, *171*, 215-227. [b] Ohzuku, T.; Ariyoshi, K.; Takeda, S.; Sakai, Y. *Electrochimica Acta* **2001**, *46*, 2327-2336. [c] Terada, Y.; Yasaka, K.; Nishikawa, F.; Konishi, T.; Yoshio, M.; Nakai, I. *J. Solid State Chem.* **2001**, *156*, 286-291.

(7) [a] Allcock, H. R.; Olmeijer, D. L. *Macromolecules* **1998**, *31*, 8036-8046. [b] Sun, X.; Angell, C. A. *Solid State Ionics* **2004**, *175*, 257-260. [c] Xing, L.; Vatamanu, J.; Borodin, O.; Smith, G. D.; Bedrov, D. *J. Phys. Chem. C* **2012**, *116*, 23871-23881.

(8) [a] Schuster, M.; Araujo, C. C.; Atanasov, V.; Andersen, H. T.; Kreuer, K.; Maier, J. *Macromolecules* **2009**, *42*, 3129-3137. [b] Shao, N.; Sun, X.; Dai, S.; Jiang, D. *J. Phys. Chem. B* **2012**, *116*, 3235-3238.

(9) Sun, X.; Angell, C. A. *Electrochem. Commun.* **2005**, *7*, 261-266.

(10) Watanabe, Y.; Kinoshita, S.; Wada, S.; Hoshino, K.; Morimoto, H.; Tobishima, S. *J. Power Sources* **2008**, *179*, 770-779.

(11) Nagao, Y.; Takasu, A.; Boccaccini, A. R. *Macromolecules* **2012**, *45*, 3326-3334.

(12) Fairbanks, B. D.; Scott, T. F.; Kloxin, C. J.; Anseth, K. S.; Bowman, C. N. *Macromolecules* **2009**, *42*, 211-217.

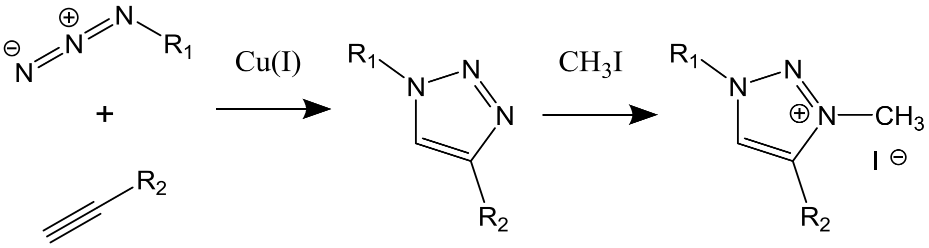
(13) *Handbook of Chemistry and Physics*, 66th ed.; Weast, R. C., Ed.; CRC Press: Boca Raton, FL, 1985.

Chapter 4

Synthesis of “Click Polyester” Based Ionomer Containing 1,2,3-Triazolium Ring

4-1 Introduction

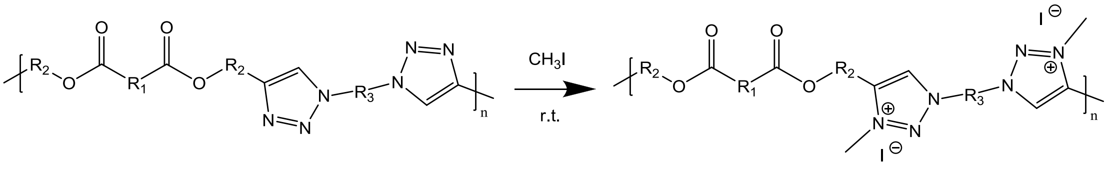
Even though many polymer materials have been studied, synthesized and developed, polyesters still constitute an important class of polymers as future materials.[1] The design of high performance polyesters and their development are expanding field in biomedical applications[2] and electrochemical devices,[3] such as artificial tissues, medical implant, actuators, solid electrolyte and composite with inorganic materials, because polyesters are biodegradable and biocompatible nevertheless possess heat–stability and mechanical strength. But now polyesters are usually produced by polycondensation[4] or by ring-opening polymerization of lactones.[5] The former method requires severe reaction conditions and the latter uses highly strained cyclic monomers, which makes it difficult to synthesize polyesters with variable molecular design. So it is still important subject to find new synthetic strategies for polyesters with desired functionalities and properties under environmentally benign conditions.[6] Previous our studies have focused on click chemistry to develop the new synthesis route of polyesters that combined the mild reaction condition and a wide range of molecular design. Click chemistry, introduced by Sharpless and coworkers,[7] is an efficient tool for the preparation of variable organic compounds[8] including polymers.[9] We have reported the use of click chemistry to synthesize "click polyesters".[10] These reactions, Cu-catalyzed cycloaddition of azides to alkynes, were accompanied by the formation of main-chain 1,4-disubstituted triazoles. We found that the triazole segment improved the thermal properties of the polyesters.[10a] We also reported that it is possible to produce the click polymers via microwave irradiation and that, when used in conjunction with *in situ* azidation, the synthesis of click polyesters is safe and effective procedure.[10b]



Scheme 4-1. Transformation of 1,2,3-triazole to 1,2,3-triazolium ring.

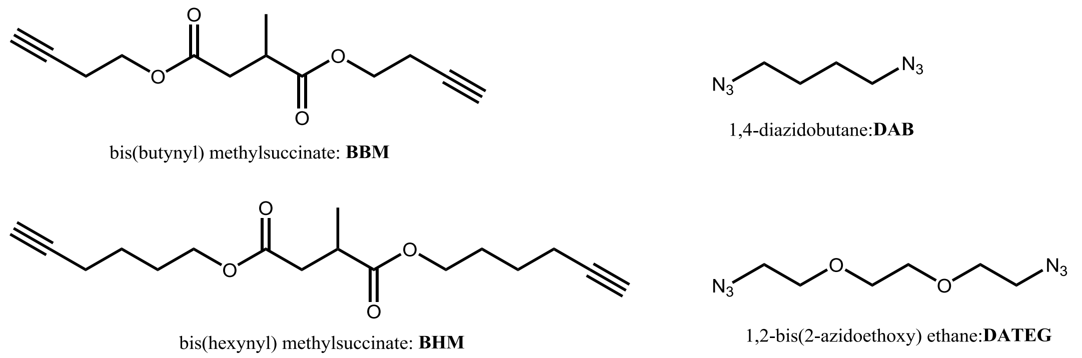
It is known that 1,2,3-triazole formed by azide−alkyne click reaction can be easily quaternized with methyl iodide to 1,2,3-triazolium ring.[11] *N*-alkylation as the second step in the synthesis of 1,2,3-triazolium salts can produce a 2-alkylated or 3-alkylated 1,4-disubstituted triazolium salt so that we have to care the regioselectivity. However, when 1,4-disubstituted 1,2,3-triazoles are methylated by methyl iodide only 1,3,4-trisubstituted 1,2,3-triazolium salt products are obtained (**Scheme 4-1**).[12] As compared to 1,2,3-triazole, the 1,2,3-triazolium ring have expected to be a stronger hydrogen bond donor for anion recognition. And also the triazolium salts have been developed as potential ionic liquids (ILs).[13] Among many kinds of ILs, those containing *N*-heterocyclic salts are the most widely used,[14] in which imidazolium salts represent the most popular derivation in ILs and the most classes are commercially available.[15] However they have limitation that they could not behave as inactive solvents under strongly basic conditions, where they suffer from deprotonation of the 1,3-dialkylimidazolium cation leading to the formation of a stable carbene.[16] Conversely, 1,2,3-triazolium ring lacks an acidic carbon localized between two *N*-atoms, consequently they have advantages from this viewpoints.

Polymerized ionic liquids (PILs) were first reported by Ohno and his coworker to synthesize them from IL monomer.[17] PILs possess excellent ionic conductivity compared to non-ionized polymer, nevertheless they are solid, of course show lower conductivity than ILs. However, PILs retain other characteristic such as thermal, mechanical, and chemical stability. For these reasons, PILs have been investigated by many polymer chemists as well as material scientists.[18] Utilizing these fascinating properties, the applications to ion conducting membranes, electrical device, biomimetic sensors, actuator and artificial muscle as ion exchange polymers are easily expected.[19] In this chapter, I describe the use of click chemistry to synthesize click polyester ionomer containing 1,2,3-triazolium salts (**Scheme 4-2**).



Scheme 4-2. Synthesis of “click polyester” ionomer containing 1,2,3-triazolium ring.

4-2 Results and Discussion



bis(butynyl) methylsuccinate: **BBM**

1,4-diazidobutane:**DAB**

bis(hexynyl) methylsuccinate: **BHM**

1,2-bis(2-azidoethoxy) ethane:**DATEG**

Figure 4-1. Chemical structures of compounds used for synthesis of the poly(ester-triazole).

Table 4-1. Summary of Synthesis of Poly(ester-triazole).

entry	diyne	diazido	yield[a] (%)	M_n[b] × 10^{-4}	M_w/M_n[b]	T_g[c] (°C)	T_m[c] (°C)	T_d[d] (°C)
1	BBM	DAB	99	3.6	2.8	14	127	316
2	BBM	DATEG	99	4.5	3.1	−6	N.A.	326
3	BHM	DAB	99	5.2	2.2	−3	102	274
4	BHM	DATEG	99	7.1	3.5	−16	N.A.	

[a]After reprecipitation with diethyl ether and wash with water. [b]Determined by SEC with DMF as the eluent and relative to poly(stylene) standards. [c]T_m was determined from the first heating DSC scan and T_g from the second scan. [d]T_d was evaluated by TGA.

We first investigated the synthesis of poly(ester-triazole) by Cu(I)-catalyzed, Huigen-type, 1,3-dipolar cycloadditon that used diyne monomers and diazido monomers with CuBr as catalyst. These monomers were prepared according to reported methods.[10a] We used bis(butynyl) methylsuccinate (BBM), bis(hexynyl) methylsuccinate (BHM) as the diyne monomer and 1,4-diazidobutane (DAB), 1,2-bis(2-azidoethoxy) ethane (DATEG) as the diazidomonomer (**Figure 4-1**). The click polymerizations were catalyzed by Cu(I) as CuBr without base ligand to avoid the cleavage of the monomer's ester bonds.[10b] The result summarized in **Table 4-1**. The polymerization proceeded smoothly to give the corresponding poly(ester-triazole)s (**Figure 4-2**) with molecular weights (M_n)s between 36000 and 71000 in excellent yield. When BYM was used as the monomer, higher molecular weight polyesters were obtained. It seems that the higher M_n was ascribed to the more extensive space between the ester unit and the triple bond. We also found that when DATEG reacted with diyne click polyester had high M_n (**Table 4-1**, entry **2**: M_n 45000; **4**: M_n 71000), while entry **1** and **3** had lower M_n (36000; 52000). The difference in M_n was probably due to the flexibility of DATEG and stabilization of Cu(I) induced by $NCH_2CH_2OCH_2CH_2OCH_2CH_2N$ units.[19]

The thermal properties of poly(ester-triazole)s were evaluated by DSC and TGA. The glass transition temperature (T_g) appeared in the range from −16 to 14°C, clearly depending on flexibility of the diazidomonomers and the spacer structures of the diyne monomers. The thermal weight loss temperatures (T_d) of poly(ester-triazole)s were observed in the range 274−326°C. The T_d of entry **2** (326°C) were higher than the corresponding poly(ester-triazole)s of entry **1** (316°C). The result suggested the increased thermal stability owing to the ether units. Also introduced longer space between the ester unit and the triple bond remarkably decreased T_d of the click polyester.

Table 4-2. Thermal Property of Poly(ester-triazolium) Ionomers.

entry	T_g^a (°C)	T_m^a (°C)	T_d^b (°C)
1a	49	N.A.	215
2a	20	N.A.	237
3a	27	N.A.	231
4a	23	N.A.	213

[a]T_m was determined from the first heating DSC scan and T_g from the second scan. [b]T_d was evaluated by TGA.

Next, we conducted ionization of poly(esters-triazole) to poly(ester-triazolium). Poly(ester-triazolium) ionomers were obtained as orange glassy solid by methylation of poly(ester-triazole) with methyl iodide in DMF (1/3, v/v) at room temperature for 24 h. Obtained ionomers were well soluble in water and acetonitrile. The structure of ionomers, all triazole units quaternized to triazolium moiety with the appearance of single signalas for the triazolium and methyl protons with matching 1:3 integrations at 8.87 and 4.26 respectively (entry **1**), was confirmed by ^1H NMR spectra. We couldn't characterize these ionomers using GPC because they were retained in the chromatography column due to their ionic character. However, ^1H NMR spectra of the poly(ester-triazolium) ionomers indicated that degradation reaction didn't occur during ionization.

So we assumed the M_n of poly(ester-triazolium) ionomers increased by mass ascribed to 2 methyl iodide per repeating unit of parent poly(ester-triazole) and molecular weight dispersity was not changed. In addition, thermal properties of poly(ester-triazolium) ionomers clearly changed compared to corresponding poly(ester-triazole). Whereas entry **1** and **3** are semicrystalline polymers (entry **1**: T_g 14°C, T_m 127°C; **3**: T_g −3°C, T_m 102°C), entry **1a** and **3a** are high T_g amorphous materials (entry **1a**: T_g 49°C; **3a**: T_g 27°C). The T_d of ionomers was observed in the range from 213−237°C. Obviously, ionization of triazoles afforded a decrease in thermal stability. Although, this moderate thermal stability of triazolium has been published recently[20], anion exchange with more bulky and/or hydrophobic organic anions should provide significantly higher thermal stability.

The applications of ionic polymer composite such as actuators, sensors, and artificial muscle need to fabricate ion exchange polymers, i.e. ionomer. In this chapter, I synthesized triazolium based ionomers by chemical modification of a click poly(ester-triazole) precursor obtained via Cu-catalyzed azide-alkyne cycloaddition. Considering the simple synthetic strategy and variable molecular design of polymer structures ascribed to triazole units and their interesting converted to triazolium ionic derivatives, this click poly(ester-triazolium)s provide new guideline to develop new class of polymerized ionic liquids.

4-3 Experimental Section

Materials and Methods. Chemicals were obtained from commercial sources and used without further purification. ^{1}H NMR spectra were acquired at 27˚C using a Bruker Analytik DPX200 spectrometer (200 MHz). Tetramethylsilane was the internal standard (0 ppm). The flow rate was 0.5 mL/min, and the temperature was 40˚C. Differential scanning calorimetry (DSC), which used a DSC6220S calorimeter (Seiko Instruments Inc., Chiba, Japan), was performed from –90 to 180˚C to –90˚C, at 10˚C/min. The instrument was calibrated with indium and tin. Each sample weighted between 7 and 9 mg and was contained in an aluminum pan that was covered with a lid within the calorimeter. The glass-transition temperature (T_g) was taken as the inflection point of the DSC heat-capacity jump. The melting temperature (T_m) was defined as the minimum point in the endothermic trough. Thermogravimetric analyses (TGA) were performed under nitrogen at 10˚C/min between 20 and 600˚C (TG/DTA 220U; Seiko Instruments Inc., Chiba, Japan).

Preparation of diazido monomers. As an example, the preparation of 1,2-bis(2-azidoethoxy) ethane is described. Into a 20 mL round-bottom flask were added 1,2-bis(2-chloroethoxy) ethane (2.00 g, 10.7 mmol) and sodium azide (2.08 g, 32.1 mmol) both of which had been dissolved in 15 mL of DMF. After stirring the mixture at 60°C for 12 h, 5 mL of distilled water was added to quench the reaction. After having been cooled to room temperature, the solution was extracted with 30 mL of diethyl ether. The organic phases were combined, washed twice with 10-mL volumes of 50% $NaHCO_{3(aq)}$, and then dried over $MgSO_4$. After filtration and solvent evaporation, 1,2-bis(2-azidoethoxy) ethane was obtained in 90% yield (1.915 g) as a white liquid. 1,4-Diazidobutane (90% yield) was reacted at room temperature for 12 h, and obtained as white liquid. The diazides used for this report were stored in ethyl acetate until using polymerization.

1,2-bis(2-azidoethoxy) ethane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.70 (t, N_3CCH_2, 4H, 4.8 Hz), 3.68 (s, OCH_2CH_2O, 4H), 3.39 (t, N_3CH_2C, 4H, 5.2 Hz).

1,4-diazidobutane; ^{1}H-NMR ($CDCl_3$) δ (ppm): 3.33 (t, N_3CH_2, 4H, 6.2Hz), 1.71-1.65 (m, CCH_2, 4H).

Preparation of diyne monomers. As an example, the preparation of bis(butynyl) methylsuccinate is described. Into a 50 mL round-bottom flask were added methylsuccinic acid (633 mg, 4.80 mmol), $Sc(OTf)_3$ (49 mg, 9.95 mmol), and 3-butyn-1-ol (1.36 g, 19.4 mmol). The reaction mixture was stirred at 60 ˚C for 6 h under reduced pressure (25 mmHg). After the reaction mixture had been diluted with 30 mL chloroform, the solution was washed with 10 mL of water saturated with $NaHCO_3$ and then dried over $MgSO_4$. After filtration and solvent evaporation, bis(butynyl) methylsuccinate was obtained as an auburn liquid in 71% yield (803 mg). Bis(hexynyl) methylsuccinate (89% yield, white liquid) was prepared using similar procedures.

bis(butynyl) methylsuccinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.19 (t, $CCH_2OC=O$, 4H, 6.7 Hz), 2.93 (quin, $O=CCH(CH_3)C$, 1H, 6.6 Hz), 2.78 (dd, $O=CCH_2C$ (CH_3), 1H, 8.1 and 16 Hz), 2.57-2.50 (m, $CH_2C{\equiv}C$, 4H), 2.45 (dd, $O=CCH_2C$ (CH_3), 1H, 6.0 and 16 Hz), 2.00 (t, $C{\equiv}CH$, 2H, 2.5Hz), 1.24 (d, CCH_3, 3H, 7.1Hz).

bis(hexynyl) methylsuccinate; ^{1}H-NMR ($CDCl_3$) δ (ppm): 4.11 (dt, $CCH_2OC=O$, 4H, 2.5 and 6.5 Hz), 2.90 (quin, $O=CCH(CH_3)C$, 1H, 6.9 Hz), 2.74 (dd, $O=CCH_2C$ (CH_3), 1H, 8.2 and 16 Hz), 2.24 (dt, $CH_2C{\equiv}C$, 4H, 2.4 and 7.0 Hz), 1.96 (t, $C{\equiv}CH$, 2H, 2.5 Hz), 1.74 (m, $OCCH_2$, 4H), 1.60 (m, $OCCCH_2$, 4H), 1.22 (d, CCH_3, 3H, 7.1 Hz).

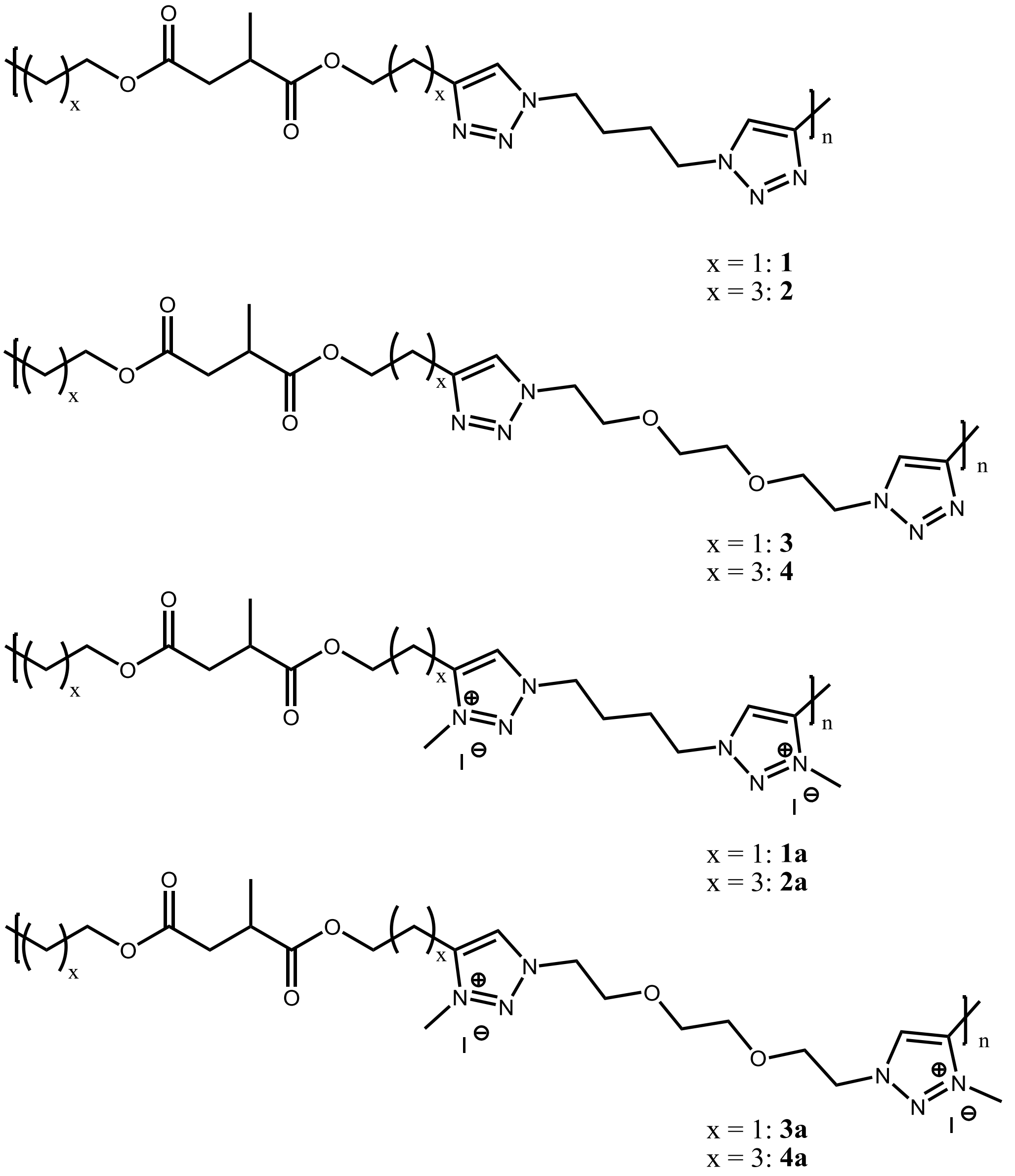


Figure 4-2. The poly(ester-triazole) and poly(ester-triazolium).

Polymerization of Click Poly(ester-triazole). The structures and chracterizations of all click polyesters synthesized for this report are summarized in **Figure 4-2** and **Table 4-1**. As an example of the procedure used (**1**, **Table 4-2**), bis(butynyl) methylsuccinate, which served as the diyne (236 mg, 1.0 mmol), and 1,4-diazidobutane (140 mg, 1.0 mmol), which served as the diazide were added into a 10 mL round-bottom flask that contained 0.5 mL *N*,*N*-dimethylformamide (DMF). Next, with the contents of the flask contained under a nitrogen atmosphere, CuBr (7.2 mg, 5.0×10^{-2} mmol) was added. After stirring the mixture at 50 ˚C for 24 h under a nitrogen atmosphere, it was diluted with 5 mL volumes of chloroform. A green solid was obtained after twice being precipitated from the chloroform solution with 90 mL volumes of diethyl ether. And then the green solid had been diluted with 10 mL chloroform, the solution was washed with 90 mL of distilled water and then dried over $MgSO_4$. After filtration and solvent evaporation, **1** was obtained in 99% yield (372 mg) as auburn solid. **2** was synthesized using similar procedures. **3** and **4** were synthesized 2.0 mL of DMF as solvent for 4 h at 50°C, because these polyester mixtures were solidified during the polymerization.

1 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.50 (brs, C=C*H*N), 4.37 (br, NCH_2CH$_2$ and CH_2OC=O), 3.05 (br, CH_2C=C), 2.87 (brm, CH$_2$C*H*(CH$_3$)), 2.69 (dd, CH(*H*)CH(CH$_3$), 8.8 and 16Hz), 2.39 (dd, C*H*(H)CH(CH$_3$), 5.1 and 16Hz), 1.93 (brs, NCH$_2$CH_2), 1.17 (d, CCH_3, 6.9 Hz).

2 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.54 (brs, C=C*H*N), 4.50 (t, CH_2OC=O, 5.2 Hz), 4.34 (m, NCH_2CH$_2$), 3.83 (t, NCH$_2$CH_2O, 5.1 Hz), 3.56 (brs, OCH_2CH_2O), 3.04 (t, CH_2C=C, 5.8 Hz), 2.86 (m, CH$_2$C*H*(CH$_3$)), 2.70 (dd, CH(*H*)CH(CH$_3$), 8.4 and 16 Hz), 2.38 (dd, C*H*(H)CH(CH$_3$), 5.6 and 16 Hz), 1.17 (d, CCH_3, 7.0 Hz).

3 (yield: 99%); ^{1}H-NMR ($CDCl_3$) δ (ppm): 7.35 (brs, C=C*H*N), 4.36 (brs, NCH_2CH$_2$), 4.09 (brs, CH_2OC=O), 2.88 (m, CH$_2$C*H*(CH$_3$)), 2.77-2.70 (brm, CH_2C=C), 2.76-2.65 (brm, CH(*H*)CH(CH$_3$)), 2.39 (dd, C*H*(H)CH(CH$_3$), 5.7 and 16 Hz), 1.92 (brs, NCH$_2$CH_2), 1.17 (br, OCH$_2$CH_2CH_2), 1.21 (d, CCH_3, 7.1 Hz).

4 (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 7.80 (brs, C=C*H*N), 4.43 (t, NCH_2CH$_2$, 5.0 Hz), 3.99 (brs, CH_2OC=O), 3.74 (t, NCH$_2$CH_2O, 5.0 Hz), 3.46 (s, OCH_2CH_2O), 2.78 (brm, CH$_2$C*H*(CH$_3$)), 2.60 (brm, CH_2C=C), 2.55-2.37 (brm, CH_2CH(CH$_3$)), 1.58 (brs, OCH$_2$CH_2CH_2), 1.09 (d, CCH_3, 7.0 Hz).

Ionization of Click Poly(esters-triazole) to Poly(ester-triazolium). A solution of click poly(ester-triazole) **1** (376 mg, 1.0 mmol repeat unit) and CH_3I (3 mL) in DMF (15 mL) was stirred for 24 h at room temperature. Crude poly(ester-triazolium) **1a** was recovered from the mixture after being precipitated with 90 mL volumes of diethyl ether, dried under vacuum at 65°C for 12h to yield pure **1a** as an orange glassy solid (660 mg, 99%).

1a (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.87 (brs, C=CHN$^+$), 4.69 (brs, NCH_2CH$_2$), 4.35 (brm, CH_2OC=O), 4.26 (s, NCH_3), 3.27 (brm, CH_2C=C), 2.85 (brm, CH$_2$CH(CH$_3$)), 2.73-2.55 (brm, CH_2CH(CH$_3$)), 2.00 (brm, NCH$_2$CH_2), 1.14 (d, CCH_3, 6.9 Hz).

2a (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.79 (brs, C=CHN$^+$), 4.81 (brm, NCH_2CH$_2$), 4.34 (brm, CH_2OC=O), 4.28 (s, NCH_3), 3.89 (brm, NCH$_2$CH_2), 3.55 (s, OCH_2CH_2O), 3.28 (brm, CH_2C=C), 2.82 (brm, CH$_2$CH(CH$_3$)), 2.58-2.51 (brm, CH_2CH(CH$_3$)), 1.11 (d, CCH_3, 6.9 Hz).

3a (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.87 (brs, C=CHN$^+$), 4.67 (brs, NCH_2CH$_2$), 4.24 (s, NCH_3), 4.10 (brs, CH_2OC=O), 2.92 (brs, CH_2C=C), 2.88 (brm, CH$_2$CH(CH$_3$)), 2.76-2.59 (brm, CH_2CH(CH$_3$)), 2.01 (brs, NCH$_2$CH_2), 1.74 (brs, OCH$_2$CH_2CH_2), 1.17 (d, CCH_3, 6.9 Hz).

4a (yield: 99%); ^{1}H-NMR (DMSO-d_6) δ (ppm): 8.78 (brs, C=CHN$^+$), 4.75 (t, NCH_2CH$_2$, 4.8 Hz), 4.22 (s, NCH_3), 4.06 (brm, CH_2OC=O), 3.89 (t, NCH$_2$CH_2, 4.4 Hz), 3.54 (s, OCH_2CH_2O), 2.90 (brs, CH_2C=C), 2.83 (brm, CH$_2$CH(CH$_3$)), 2,69-2.55 (brm, CH_2CH(CH$_3$)), 1.70 (brs, OCH$_2$CH_2CH_2), 1.13 (d, CCH_3, 7.0 Hz).

4-4 References and Notes

(1) [a] Lenz, R. W.; *Adv. Polym. Sci.* **1993**, *107*, 1-40. [b] Koeshak, V. V.; Vinogradora, S. V. “Polyester”, Pergamon Press, New York, N. Y., 1995.

(2) [a] Vert, M. *Biomacromolecules* **2005**, *6*, 538-546. [b] Takwa, M.; Xiao, Y.; Simpson, N.; Malmström, E.; Hult, K.; Koning, C. E.; Heise, A.; Martinelle, M. *Biomacromolecules* **2008**, *9*, 704-710. [c] Misra, S. K.; Valappil, S. P.; Roy, I.; Boccaccini, A. R. *Biomacromolecules* **2006**, *7*, 2249-2258. [d] Seyednejad, H.; Vermonden, T.; Fedorovich, N. E.; Eijik, R.; Steenbergen, M. J.; Dhert, W. J. A.; Nostrum, C. F.; Hennink, W. E. *Biomacromolecules* **2009**, *10*, 3048-3054. [e] Naolou, T.; Busse, K.; Kressler, J. *Biomacromolecules* **2010**, *11*, 3660-3667. [f] Zhang, P.; Wu, H.; Wu, H.; Lu, Z.; Deng, C.; Hong, Z.; Jing, X.; Chen, X. *Biomacromolecules* **2011**, *12*, 2667-2680. [g] Moglia, R. S.; Holm, J. L.; Sears, N. A.; Wilson, C. J.; Harrison, D. M.; Cosgriff-Hernandez, E. *Biomacromolecules* **2011**, *12*, 3621-3628.

(3) [a] Jimènez, M. M. D.; Elizalde, M. P.; González, M.; Silva, R. *Electrochem. Acta* **2000**, *45*, 4187-4193. [b] Sato, M.; Tada, Y.; Nakashima, S.; Ishikura, K.; Handa, M.; Kasuga, K. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *43*, 1511-1525. [c] Guimard, N. K. E.; Sessler, J. L.; Schmidt, C. E. *Macromolecules* **2009**, *42*, 502-511. [d] Gorur, M.; Yilmaz, F.; Kilic, A.; Demirci, A.; Ozdemir, Y.; Kosemen, A.; San, S. E. *J. Polym. Sci., Part A: Polym. Chem.* **2010**, *48*, 3668-3682.

(4) [a] Carothers, W. H.; Dorough, G. L. *J. Am. Chem. Soc.* **1930**, *52*, 711-721. [b] Takiyama, E.; Niikura, I.; Hatano, Y. Japan Patent 189,823, 1995. [c] Miura, M.; Watanabe, H.; Fujiwara, M. Japan Patent 53, 695, 1995. [d] Buzin, P.; Lahcini, M.; Schwarz, G.; Kricheldord, H. R. *Macromolecules*, **2008**, *41*, 8491-8495. [e] Garaleh, M.; Lahcini, M.; Kricheldorf, H. R.; Weidner, S. M. *J. Polym. Sci.; Part A: Polym. Chem.* **2009**, *47*, 170–177.

(5) [a] Kricheldorf, H. R.; Kreiser-Saunders, I. *Macromol. Chem. Phys.* **1990**, *191*, 1057-1066. [b] Lofgren, A.; Albertsson, A. C.; Dubois, P.; Jerome, R. *J. Macromol. Sci.; Rev. Macromol. Chem. Phys.* **1995**, *35*, 379-418. [c] Kim, S.; Han, Y. K.; Kim, Y. H.; Hong, S. I. *Macromol. Chem. Phys.* **1992**, *193*, 1623-1631.

(6) [a] Shibata, Y.; Takasu, A. *J. Polym. Sci., Part A: Polym. Chem.* **2009**, *47*, 5747–5759. [b] Takasu, A.; Makino, T.; Yamada, S. *Macromolecules* **2010**, *43*, 144-149.Takasu, A.; Takemoto, A.; Hirabayashi, T. *Biomacromolecules* **2006**, *7,* 6–9.

(7) Kolb, H. C.; Finn, M. G.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2001**, 40, 2004-2021.

(8) [a] review: Pieteres, R. J.; Rijkers, D. T. S.; Liskamp, R. M. J. *QSAR Comb. Sci.* **2007**, *26*, 1181. [b] review: Tron, G. C.; Pirali, T.; Billington, R. A.; Canonico, P. L.; Sorba, G.; Genazzani, A. A. *Med. Res. Rev.* **2008**, *28*, 278.

(9) [a] adhesive polymer : Diaz, D. D.; Punna, S.; Holzer, P.; Mcpherson, A. K.; Sharpless, K. B.; Fokin, V. V.; Finn, M. G. *J. Polym. Sci., Part A: Polym. Chem.* **2004**, *42*, 4392. [b] polyketone: Tang, B. Z.; Qin, A.; Jim, C. K. W.; Lu, W.; Lam, J. W. Y.; Häussler, M.; Dong, Y.; Sung, H. H. Y.; Williams, I. D.; Wong, G. K. L. *Macromolecules* **2007**, *40*, 2308-2317. [c] helical polymer: Kobayashi, S.; Itomi, K.; Morino, K.; Iida, H.; Yashima, E. *Chem. Comm.* **2008**, 3019-3021. [d] poly(ethylene glycol): Liu, X.-M.; Thakur, A.; Wang, D. *Biomacromolecules* **2007**, *8*, 2653-2658. [e] biomass-based polymer: Michinobu, T.; Inazawa, Y.; Hiraki, K.; Katayama, Y.; Masai, E.; Nakamura, M.; Ohara, S.; Shigehara, K. *Chem. Lett.* **2008**, 154-155. [f] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2007**, *28*, 15-54. [g] review: Binder, W. H.; Sachsenhofer, R. *Macromol. Rapid Commun.* **2008**, *29*, 952-981. [h] review: Johnson, J. A.; Finn, M. G.; Koberstein, J. T.; Turro, N. J. *Macromol. Rapid Commun.* **2008**, *29*, 1052-1072. [h] new "click" chemistry: Koyama, Y.; Yonekawa, M.; Takata, T. *Chem. Lett.* **2008**, *37*, 918-919. [i] Lee, Y. G.; Koyama, Y.; Yonekawa, M.; Takata, T. *Macromolecules* **2009**, *42*, 7709-7717. [j] α-azide-ω-alkyne monomers: Binauld, S.; Damiron, D.; Hamaide, T.; Pascault, J. P.; Fleury, E.; Drockenmuller, E. *Chem. Comm.* **2008**, 4138-4140.

(10) [a] Nagao, Y.; Takasu, A. *Macromol. Rapid. Commun.* **2009**, *30*, 199-203. [b] Nagao, Y.; Takasu, A. *J. Polym. Sci., Part A: Polym. Chem.* **2010**, *48*, 4207-4218. [c] Nagao, Y.; Takasu. A.; Boccaccini, A. R. *Macromolecules* **2012**, *45*, 3326-3334.

(11) Kumar, A.; Pandey, P. S. *Org. Lett.* **2008**, *10*, 165-168.

(12) Begtrup, M. *Acta Chem. Scand.* **1971**, *25*, 249-259.

(13) [a] Zekarias Yacob and Ju¨rgen Liebscher (2011). 1,2,3-Triazolium Salts as a Versatile New Class of Ionic Liquids, Ionic Liquids - Classes and Properties, Prof. Scott Handy (Ed.), ISBN: 978-953-307-634-8, InTech, Available from: http://www.intechopen.com/books/ionic-liquids-classes-and-properties/1-2-3-triazolium-salts-as-aversatile-new-class-of-ionic-liquids. [b] Aizpurua, J. M.; Sagartzazu-Aizpurua, M.; Monasterio, Z.; Azcune, I.; Mendicute, C.; Miranda, J. I.; Garcia-Lecina, E.; Altube, A.; Fratila, R. M. *Org. Lett.* **2012**, *14*, 1866-1868. [c] Yoshida, Y.; Takizawa, S.; Sasai, H. *Tetrahedron Lett.* **2011**, 52, 6877–6879. [d] Caumes, C.; Roy, O.; Faure, S.; Taillefumier, C. *J. Am. Chem. Soc.* **2012**, *134*, 9553-9556.

(14) Sowmiah, S.; Srinivasadesikan, V.; Tseng, M.; Chu, Y. *Molecules* **2009**, *14*, 3780-3813.

(15) [a] Welton, T. *Chem. Rev.* **1999**, *99,* 2071-2084. [b] Wasserscheid, P.; Keim, W. *Angew. Chem. Int. Ed.* **2000**, *39,* 3772-3789. [c] Dupont, J.; de Souza, R.F.; Suarez, P.A.Z. *Chem. Rev.* **2002**, *102,* 3667-3692.

(16) Canal, J. P.; Ramnial, T.; Dickie, D. A.; Clyburne, J. A. C. *Chem. Commun.* **2006**, 1809-1818.

(17) Ohno, H.; Ito, K. *Chem. Lett.* **1998**, 751-752.

(18) [a] Nomula, S.; Cooper, S. L. *Macromolecules* **2001**, *34*, 2653-2659. [b] Matsumi, N.; Sugai, K.; Miyake, M.; Ohno. H. *Macromolecules* **2006**, *39*, 6924-6927. [c] Nakamura, K.; Saiwaki, T.; Fukao, K. *Macromolecules* **2010**, *43*, 6092-6098. [d] Aitken, B. S.; Buitrago, C. F.; Heffley, J. D.; Lee, M.; Gibson, H. W.; Winey, K. I.; Wagener, K. B. *Macromolecules* **2012**, *45*, 681-687. [e] Nakamura, K.; Fukao, K.; Inoue, T. *Macromolecules*, **2012**, *45*, 3850-3858. [f] Matsumoto, K.; Sogabe, S.; Endo, T. *J. Polym. Sci., Part A: Polym. Chem.* **2012**, *50*, 1317-1324. [g] Kim, H. K.; Zhang, M.; Yuan, X.; Lvov, S. N.; Chung, T. C. M. *Macromolecules* **2012**, *45*, 2460-2470.

(19) [a] Alvarez, E. J.; Wu, H-F.; Liou, C-C.; Brodbelt, J. *J. Am. Chem. Soc.* **1996,** *118,* 9131-9138. [b] Kim, K. J.; Shahinpoor, M. *Smart Mater. Struct.* **2003**, *12*, 65–79.

(20) Sanghi, S.; Willett, E.; Versek, C.; Tuominen, M.; Coughlin, E. B. *RSC ADV.* **2012**, *2*, 848-853.

Conclusions

Moreover, we performed further applications of click polyesters in chapter 3 and 4. Each digest is as follows.

This thesis focused on two different synthetic approaches to fine-tuning designer polyesters (“Click Polyester”) via Cu(I)-catalyzed click 1,3-dipolar cycloadditions and thiol−ene click reaction, and also further applications of click polyesters. The experimental results are summarized as follows.

Chapter 1. “Click Polyester”: Synthesis of Polyesters Containing Triazole Units in the Main Chain via Safe and Rapid “Click” Chemistry and Their Properties

In this chapter, I used dialkynes containing ester linkages and diazides to synthesize, via click polymerization catalyzed by Cu(I), polyesters with high M_ns [(1.0–7.0) × 10^4] in an excellent yields. These polymers contained main-chain 1,4-disubtituted triazoles. I found that the presence of the main-chain triazoles improved the thermal properties of the polyesters and magnified the even-odd effect caused by the of methylene chain length on the thermal properties of the polyesters. Additionally, I could fine tune the thermal properties of the polyesters by changing the positions of triazoles. I also demonstrated that it is possible produce the click polymers via microwave irradiation and that, when used in conjunction with *in situ* azidation, the synthesis of a click polyester is a safe and effective procedure that should find industrial use. This work is the first time that click chemistry has been used to synthesize polyesters and our results should provide the foundation for the synthesize of novel polyester-based materials.

Chapter 2. Anode-Selective Electrophoretic Deposition of a Bioactive Glass/Sulfone-Containing Click Polyester Composite

The demand for implantable medical devices is steadily increasing, especially the demand for spinal and orthobiologic implants, and improved technologies and biomaterials are therefore required. In this chapter 2, I prepared a Bioglass®/click poly(ester-sulfone) colloid, which could be deposited onto a stainless steel surface by EPD to form a soft composite coating. The Bioglass®/click poly(ester-sulfone) film developed a surface layer of hydroxyapatite when immersed in SBF confirming the bioactive behavior of the new composite coating. The easy deposition and the ability to produce surface hydroxyapatite layers are properties required for bone-related implants, e.g. bioactive coatings on metallic substrates. The synthesis of the poly(ester-sulfone) was facile, and the poly(ester-sulfone) was stable in the EPD cell, e.g. under electric fields. The results reported herein therefore provide a foundation upon which new bioactive composite materials may be developed as soft coatings for bone-related implants.

Chapter 3. Electrophoretic Behavior of Polyester-Gel Containing Sulfone Units

In this chapter 3, I performed DTY copolymerization of BEM, BYM, and TEGDT to synthesize poly(ester-sulfide) gel in which bis(butenyl) methyl succinate acted as the cross-linker, and the subsequent oxidation using Oxone to give poly(ester-sufone) gel. The synthesized poly(ester-sulfone) gel was deposited on a stainless-steel electrode by electrophoretic deposition (EPD) although the parent poly(ester-sulfide) gel was not. The advantages and characteristics of employing this gel indicate the potential of the materials for use as solid electrolyte.

Chapter 4. Synthesis of “Click Polyester” Ionomer Containing 1,2,3-Triazolium Ring in the Main Chian

The applications of ionic polymer composite such as actuators, sensors, and artificial muscle need to fabricate ion exchange polymers, i.e. ionomer. In this chapter, I synthesized triazolium based ionomers by chemical modification of a click poly(ester-triazole) precursor obtained via Cu-catalyzed azide-alkyne cycloaddition. Considering the simple synthetic strategy and variable molecular design of polymer structures ascribed to triazole units and their interesting converted to triazolium ionic derivatives, this click poly(ester-triazolium)s provide new guideline to develop new class of polymerized ionic liquids.

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Yu Nagao

List of Publications

1. Nagao, Y.; Takasu, A.

Synthesis of Polyesters Containing Triazole Units in the Main Chain by Click Chemistry and Improved Thermal Property

Macromolecular Rapid Communication, **2009**, *30*, 199–203.

2. Nagao, Y.; Takasu, A.

"Click Polyester": Synthesis of Polyesters Containing Triazole Units in the Main Chain via Safe and Rapid "Click" Chemistry and Their Properties

Journal of Polymer Science Part A: Polymer Chemistry, **2010**, *48*, 4207-4218.

3. Nagao, Y.; Takasu, A.; Boccaccini A. R.

Anode-Selective Electrophoretic Deposition of a Bioactive Glass/Sulfone-Containing Click Polyester Composite

Macromolecules, **2012**, *45(8)*, 3326–3334.