Conjugated Polymers

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Click Functionalization of a Dibenzocyclooctyne-Containing Conjugated Polyimine

*Vladimir Kardelis, Ryan C. Chadwick, and Alex Adronov**

***Abstract:** A conjugated poly(phenyl-co-dibenzocyclooctyne) Schiff-base polymer, prepared through polycondensation of dibenzocyclooctyne bisamine (DIBO-(NH_2)$_2$) with bis(hexadecyloxy)phenyldialdehyde, is reported. The resulting polymer, which has a high molecular weight ($M_n > 30$ kDa, $M_w > 60$ kDa), undergoes efficient strain-promoted alkyne–azide cycloaddition reactions with a series of azides. This enables quantitative modification of each repeat unit within the polymer backbone and the rapid synthesis of a conjugated polymer library with widely different substituents but a consistent degree of polymerization (DP). Kinetic studies show a second-order reaction rate constant that is consistent with monomeric dibenzocyclooctynes. Grafting with azide-terminated polystyrene and polyethylene glycol monomethyl ether chains of varying molecular weight resulted in the efficient syntheses of a series of graft copolymers with a conjugated backbone and maximal graft density.*

Conjugated polymers have attracted tremendous attention in both academia and industry as a consequence of their unique properties.[1–3] A wide range of conjugated macromolecules have been investigated, including derivatives of polyacetylene,[4,5] polyphenylene,[6] polyarylenevinylene,[7,8] polypyrrole,[9] polythiophene,[10] and polyfluorene backbones,[11,12] as well as numerous more complex structures.[13] This structural variability, combined with post-polymerization modification (i.e., doping), allows manipulation of the optoelectronic and physical properties, including absorption/emission wavelengths, band gap, HOMO/LUMO levels, conjugation length, and solubility.[14–18] These parameters have made numerous commercial applications possible, including light-emitting diodes (LEDs),[19–23] field-effect transistors (FETs),[24] organic solar cells,[25] and chemical sensors.[26] Conjugated polymers have also been investigated as components in printed electronics.[1] A more recent and rapidly growing area of application involves the selective dispersion of single-walled carbon nanotubes.[27–30] In all of these cases, investigation of structure–activity relationships, where the backbone or side-chain structure of conjugated polymers is varied, requires de novo synthesis of each conjugated polymer. In addition, differences in monomer ratios within iterative syntheses can result in a range of molecular weights, polydispersities, and regiochemistries; all factors that have an effect on polymer properties.[31] In light of these limitations, a method for the generation of libraries of conjugated polymers with different backbone structures but identical degree of polymerization and polydispersity is desired. Such a method would require modification of the backbone structure after polymerization in order to maintain constant polymer length. This is challenging, since the post-polymerization modification of conjugated polymer backbones is uncommon and often suffers from incomplete functionalization.[32] Benzannulations have recently been demonstrated as an efficient method for post-polymerization modification, but they generally result in a very specific polymer structure.[33]

We have previously investigated the use of a dibromo derivative of dibenzoazacyclooctyne (DIBAC) for post-polymerization functionalization through strain-promoted azide–alkyne cycloaddition (SPAAC).[34] The strained cyclooctyne within the dibromo-DIBAC structure permitted rapid transformation of the alkynes into conjugated triazoles, thereby altering their electronic and physical properties. Unfortunately, we were unable to introduce the cyclooctyne moiety into the backbone of a polymer because the metal catalysts used in most cross-coupling polymerizations (Ni, Pd, Cu) rapidly underwent cycloaddition reactions with the strained alkyne of the monomer, rather than the desired oxidative addition at the carbon–halogen bond.[35–37] This led us to explore polymerization methods that do not involve the use of transition-metal catalysts, including reactions such as the Wittig, Horner–Wadsworth–Emmons,[38–40] Aza-Wittig,[41,42] and Knoevenagel condensation,[43] as well as Schiff-base formation.[44,45] Many of these methods have been demonstrated to yield high-molecular-weight polymers, and a wide variety of structural diversity has been explored. Amongst these, Schiff-base formation offers several advantages: it has been well-explored,[46–48] can produce high-molecular-weight polymers, and the installation of amine groups is straightforward to achieve by using Buchwald–Hartwig chemistry.[49]

The structurally most simple parent structure, dibenzocyclooctyne (DIBO),[50] is ideal as a monomer for conjugated polymer synthesis because it has a relatively planar, symmetrical structure.[50–54] In our hands, the synthetic approach based on a Wittig–Prévost homologation sequence was found to be compatible with initial introduction of aryl halides (in this case, iodides), which could subsequently be converted into the required amines in the target monomer **6** (DIBO-(NH_2)$_2$). As illustrated in Scheme 1, starting with dibenzosuberone, standard iodination conditions generated diiodosuberone **1** in modest yield.[55] No *ortho*/*para* selectivity was observed for the halogenation, and the *ortho*,*ortho*-, *para*,

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[*] V. Kardelis, R. C. Chadwick, A. Adronov
Department of Chemistry, McMaster University
1280 Main St. W., Hamilton, ON L8S 4M1 (Canada)
E-mail: adronov@mcmaster.ca

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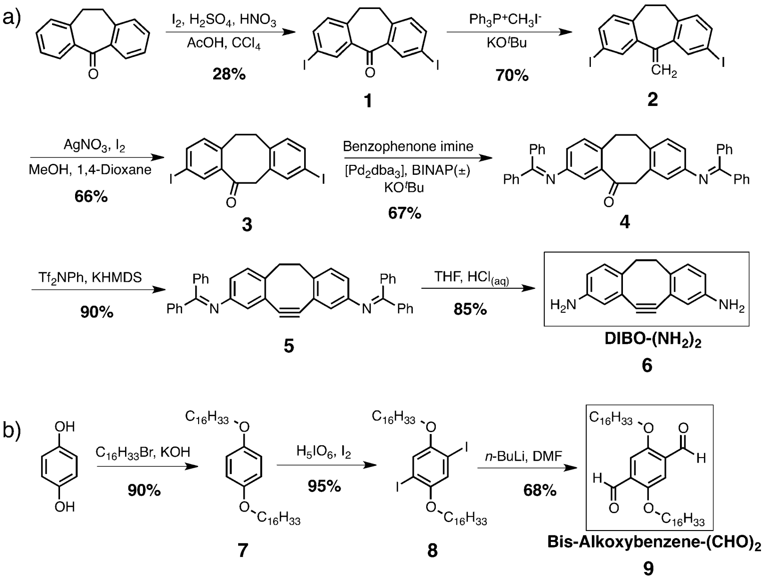


Scheme 1. Synthesis of the DIBO-$(NH_2)_2$ monomer **6** (a), and the bis(alkoxy)phenyl dialdehyde comonomer **9** (b).

para-, and *ortho*,*para*- derivatives were each isolated in approximately equal amounts. Ring expansion of **1** using the Wittig–Prévost homologation was carried out in good yield to generate the 8-membered cyclooctanone **3**.[56] Subsequently, standard Buchwald–Hartwig amination conditions using benzophenone imine generated the diimine-protected ketone **4** (Scheme 1).[49] In situ generation of the enol triflate followed by elimination using KHMDS formed the cyclooctyne **5**,[54,57] and finally deprotection under aqueous acidic conditions allowed the isolation of monomer **6**. The comonomer, an alkoxybenzene dialdehyde (**9**), was synthesized from bis(hexadecyloxy)diiodobenzene through a modified Bouveault aldehyde synthesis (Scheme 1 b).[58–60]

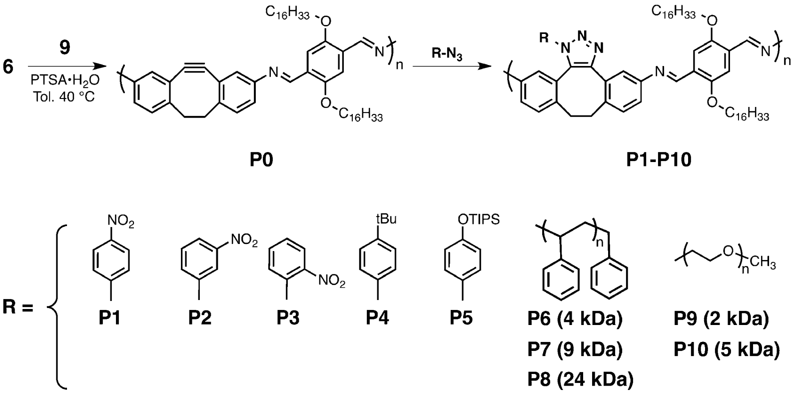
Polymerization was performed by heating monomers **6** and **9** in toluene with *p*-toluenesulfonic acid (PTSA) as a catalyst (Scheme 2). This polymerization proceeds rapidly until all of the amines either react or become protonated by the acid catalyst. After this point, the polymerization continues at a much slower rate, since the remaining ammonium ions must undergo deprotonation in order to react. Thus, a degree of molecular-weight control can be achieved by varying the catalyst amount and stopping the polymerization before oligomer coupling becomes significant. Addition of 2 mol% PTSA resulted in uniform polymerization, producing polymer with molecular weight on the order of 30 kDa within 3–4 hours (**P0**, Table 1). The product polymer **P0** was characterized by ^{1}H- and ^{13}C-NMR, Raman, UV/Vis, and fluorescence spectroscopy , as well as gel-permeation chromatography (GPC). The presence of alkyne moieties in **P0** was confirmed through observation of the alkyne stretch at 2160 cm^{-1} by Raman spectroscopy, and the position of the bridgehead signals in the ^{1}H-NMR spectra (Figure 1 a, b, respectively). Addition of larger quantities of PTSA resulted in higher polymerization rates, but initial formation of lower-molecular-weight oligomers. Over the course of several days, these oligomers undergo coupling reactions, thereby resulting in a polymer fraction with much higher molecular weight (> 100 kDa). However, a bimodal distribution containing a significant amount of the initially formed oligomers could not be avoided. The best results were thus achieved when low catalyst loadings were used.

Table 1: Physical and electronic properties of polyimine polymer **P0** and its clicked derivatives.

Polymer	$\lambda_{max,ab}$ [nm]	$\lambda_{max,em}$ [nm]	M_n [kg mol^{-1}]	M_w [kg mol^{-1}]	PDI[a]
P0	313, 412	545 (weak)	30.8	62.6	2.03
P1	300, 409	–	20.6	44.1	2.15
P2	297, 409	–	19.1	41.3	2.16
P3	298, 409	–	18.9	42.5	2.25
P4	295, 409	–	15.0	38.3	2.55
P5	288, 409	–	24.0	49.5	2.06

[a] PDI = Polydispersity index.

Polymer **P0** was then reacted with a series of aryl azides at room temperature in toluene at an alkyne concentration of approximately 35 mM by using a 1.5-fold excess of azide (Scheme 2). In all cases, complete functionalization was observed in 30 min, and the ^{1}H-NMR spectra showed no trace of unreacted cyclooctyne (see the Supporting Information). Varying the substituents on the aromatic ring from electron withdrawing (*p*-, *m*-, and *o*-nitro) to electron donating (*tert*-butyl and OTIPS) had no observable effect on the rate of cycloaddition. To our surprise, changing the electron-withdrawing/donating nature of the cycloadduct had little effect on the photophysical properties of the polymer backbone, as evidenced by UV/Vis absorption spectroscopy (see Table 1 and Figure S5 in the Supporting Information). Interestingly, whereas the alkyne-containing polymer was weakly fluorescent, none of the "clicked" derivatives **P1**–**P5** exhibited any fluorescence.



Scheme 2. Synthesis of cyclooctyne-containing polymer **P0** and its cycloadducts **P1**–**P5**.

GPC data for the clicked polymers (Table 1) suggested that a decrease in molec-

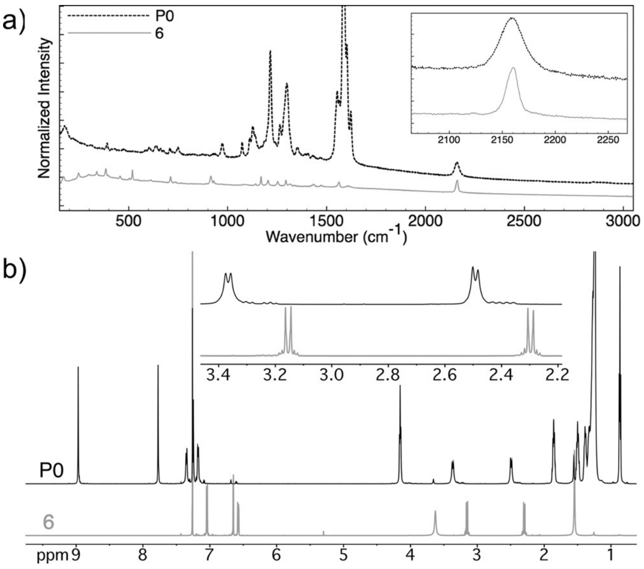


Figure 1. a) Raman spectrum of **P0** and **6** at 785 nm excitation. b) ^{1}H NMR spectra of **P0** and **6**. Note the preservation of ethylene bridge proton signals at 2.5 and 3.4 ppm.

ular weight occurred upon alkyne–azide cycloaddition. However, ^{1}H-NMR indicated no evidence of backbone degradation, since the amount of residual aldehyde, arising from the end groups, remained constant relative to backbone signals. We hypothesized that the change in apparent molecular weight could be due to a change in the conformation of the polymer in solution, rather than chain scission. To investigate this hypothesis, modeling studies using both density functional theory (DFT) and semi-empirical methods were used to determine any changes in conformation upon cycloaddition. Using DFT (M06 Functional, Pople's 6-31 basis set),[61,62] we modeled the structure of the DIBO unit before and after cycloaddition (see the Supporting Information). We then constructed oligomers (4 repeat units) using this structure and geometry-optimized them using semi-empirical methods (Parametric Method 3).[63] These studies suggest that cycloaddition results in an accordion-like contraction of the polymer chain, which is congruent with the decreased molecular volume exhibited by the "clicked" polymers as measured by GPC (Figure 2).

An NMR kinetics study to determine cyclooctyne reactivity within the polymer backbone indicated a second-order rate constant of 0.031 $\text{M}^{-1}\,\text{s}^{-1}$ in chloroform (for full details, see the Supporting Information).[64] This is slightly lower than the literature value for DIBO derivatives (0.057 $\text{M}^{-1}\,\text{s}^{-1}$),[65] but is unsurprising when taking into account the decreased availability and mobility of the cyclooctyne functionality within the polymer chain.

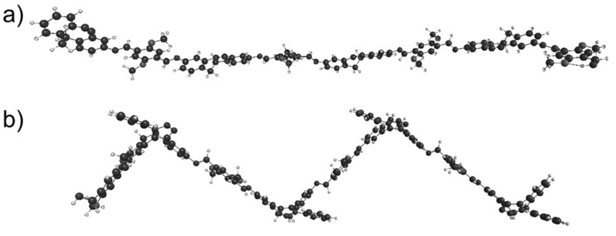


Figure 2. Optimized geometry of short polymer chain (PM3) before (a) and after (b) reaction with phenyl azide. Note the accordion-like contraction of the polymer backbone.

To further test the cycloaddition, we performed a series of reactions with azide-terminated polymers (Scheme 2, **P6**–**P10**). Initially we used polystyrene azides with molecular weights of 4, 9, and 24 kDa (Table 2).[66,67] Polymer **P0** was stirred with 1.5 equivalents of azide-terminated polymer (per alkyne) at 60 °C for 12 hours in deuterated toluene. Alkyne conversion was found to be quantitative, even when employing 24 kDa polystyrene grafts, as Raman and ^{1}H-NMR spectroscopy showed no evidence of residual alkyne in the high-molecular-weight products (Figure 3 a, b, and Table 2).

Table 2: Graft copolymer properties (**P6**--**P10**).

	Graft		Graft copolymer		
Graft Composition	M_n (GPC, kDa)	PDI (GPC)	M_n (GPC, kDa)	Theor. M_n (kDa)	Weight % Graft
N_3-PS-4k (**P6**)	3.9	1.12	140	182	83
N_3-PS-9k (**P7**)	8.7	1.09	270	330	91
N_3-PS-24k (**P8**)	24	1.13	790	980	97
N_3-PEG-OMe-2k (**P9**)	2.0	–	N/A[a]	106	71
N_3-PEG-OMe-5k (**P10**)	5.0 Da	–	N/A[a]	220	86

[a] Values not measured due to poor solubility in THF.

The quantitative grafting of polymer chains also provides a method for modifying the solution properties of the polyimine. By grafting with azide-terminated polyethylene glycol monomethyl ether (N_3-PEG-OMe), we were able to alter the solubility of this polymer. As expected, the starting polyimine and its small-molecule cycloadducts (**P0**–**P5**) are highly soluble in nonpolar solvents such as chloroform, toluene, and tetrahydrofuran. These structures show only slight solubility in *N*,*N*-dimethylformamide and dimethylsulfoxide, and essentially no solubility in other polar solvents. After grafting with 2 kDa N_3-PEG-OMe, the graft copolymer remained soluble in toluene but also exhibited high solubility in methanol. However, grafting with 5 kDa N_3-PEG-OMe resulted in a graft copolymer that exhibited marked solubility in water (Figure 4 d). As in the case of polystyrene, ^{1}H-NMR and Raman data show quantitative conversion of the backbone alkynes to the resulting triazole rings (Figure 4 a, b).

By using tapping-mode atomic force microscopy (AFM), we were able to image individual graft-copolymer structures (Figure 3 c and Figure 4 c). Samples for AFM measurements were prepared by spin-coating dilute solutions of the graft copolymers onto freshly cleaved mica. These AFM images show individual graft copolymers on the mica surface with sizes and aspect ratios that are consistent with the expected features of the graft copolymers. For example, polymer **P8**, which has 24 kDa PS grafts, exhibits a rigid, cylindrical shape with a width on the order of 30 nm, and a length on the order of 80 nm (Figure 3 c), while polymers **P9** and **P10**, which have

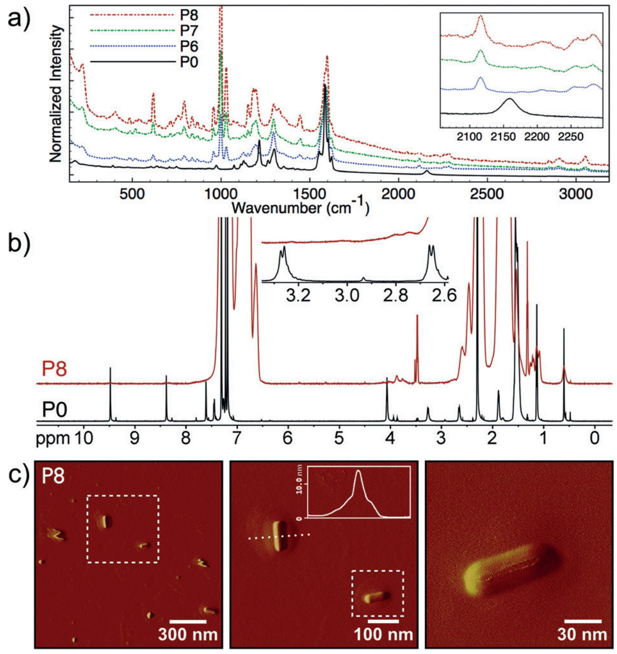


Figure 3. a) Raman spectra measured with 785 nm excitation confirm the complete reaction of all alkyne moieties (2160 cm^{-1}, see inset for magnification) of **P0** for each polystyrene graft (**P6**–**P8**). b) ^{1}H-NMR of **P0** and **P8** (24 kDa graft) in [D$_8$]toluene, showing complete disappearance of the ethylene bridge protons ($\delta = 3.27$ and 2.66 ppm, magnified in the inset). c) Amplitude mode AFM images showing individual graft copolymers for the polystyrene 24k graft (**P8**). Note: dashed boxes indicate the area of magnification in the subsequent image to the right; the inset shows the height profile along the indicated dotted line.

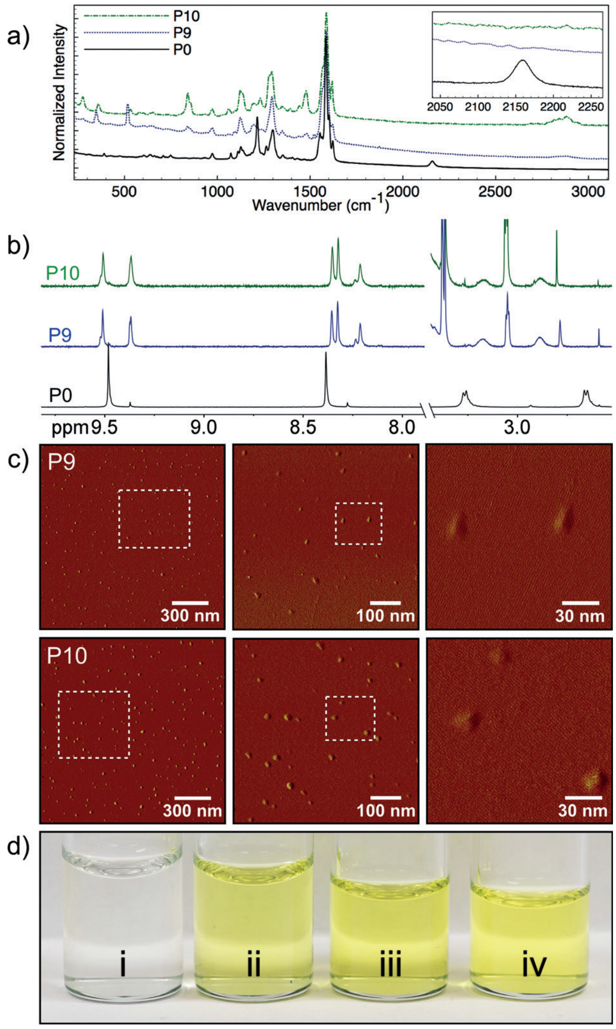


Figure 4. a) Raman spectra at 785 nm excitation confirm complete reaction of all of the alkyne groups (2160 cm^{-1}) of **P0** for each PEG-OMe graft (**P9** and **P10**). b) ^{1}H-NMR spectra for **P0**, **P9**, and **P10** in [D$_8$]toluene, showing complete disappearance of the ethylene bridge protons ($\delta = 3.27$ and 2.66 ppm). A shift in the imine protons is also observed ($\delta = 9.5$ ppm). c) Amplitude-mode AFM images showing individual PEG-OMe graft copolymers (**P9** and **P10**). Note: dashed boxes indicate the area of magnification in the subsequent image to the right. d) 2 kDa PEG-OMe graft copolymer exhibits no solubility in water (i), but shows solubility in methanol (ii); 5 kDa PEG-OMe graft copolymer exhibits solubility in both water (iii) and methanol (iv).

PEO grafts, exhibit a more spherical shape, with diameters on the order of 20–30 nm (Figure 4c). The greater flexibility and lower molecular weight of the PEO grafts allowed the polymer to adopt a more coiled, globular structure, rather than the extended cylindrical shape of **P8**.

In summary, we have demonstrated the synthesis of a high-molecular-weight (> 30 kDa) polymer containing strained dibenzocyclooctyne moieties. Each cyclooctyne within the polymer backbone reacts with aliphatic and aryl azides at a rate that is consistent with similar small-molecule cyclooctynes. We prepared a library of homologous triazole-containing polymers (**P1**–**P5**) from the single progenitor polyalkyne (**P0**) through SPAAC. We also demonstrated the high-efficiency of these reactions though coupling with azide-terminated polystyrene and polyethylene glycol monomethyl ether chains. These polymer grafting reactions were rapid and quantitative, producing samples with compositions containing up to 97% graft in under 12 hours at modest temperatures (60 °C). Further studies to investigate more diverse modification of these polymers and their applications are now in progress.

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