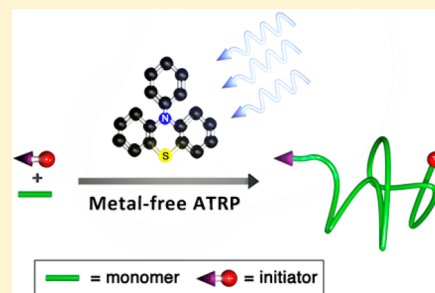


Metal-Free Atom Transfer Radical Polymerization

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Supporting Information

ABSTRACT: Overcoming the challenge of metal contamination in traditional ATRP systems, a metal-free ATRP process, mediated by light and catalyzed by an organic-based photoredox catalyst, is reported. Polymerization of vinyl monomers are efficiently activated and deactivated with light leading to excellent control over the molecular weight, polydispersity, and chain ends of the resulting polymers. Significantly, block copolymer formation was facile and could be combined with other controlled radical processes leading to structural and synthetic versatility. We believe that these new organic-based photoredox catalysts will enable new applications for controlled radical polymerizations and also be of further value in both small molecule and polymer chemistry.



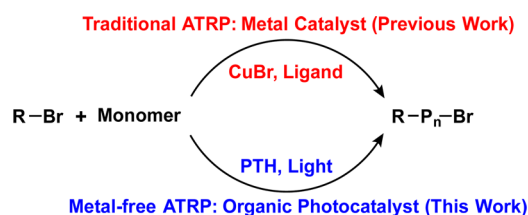
INTRODUCTION

Controlled free radical polymerizations (CRPs) represent one of the most far reaching developments in polymer synthesis, allowing nonexperts facile access to functionalized polymers with well-defined structure and architecture.^{1–6} Of the CRP techniques, atom transfer radical polymerization (ATRP) is arguably the most utilized and operates via a redox equilibrium process mediated by a ligated metal catalyst [i.e., Cu(I), Ru(II), Fe(II)].¹ For a variety of applications, such as microelectronics, biomaterials, etc., a key limiting factor in using ATRP is metal contamination.^{7–9} A significant focus for the ATRP field since the initial discovery^{10–12} has therefore been directed toward lowering catalyst loadings^{13–15} and/or removal of residual metals.^{16–18} Although catalyst loadings can be decreased to parts per million (ppm), we envisaged that a much more viable and ambitious solution to this grand challenge would be the development of a metal-free catalyst system for atom transfer radical polymerization.

In recent years our group has disclosed the photomediated ATRP of methacrylates and acrylates using Ir-based photoredox catalysts.^{19–21} This system provides for excellent spatial and temporal control over the chain-growth process, enabling the formation of complex 3-dimensional nanostructures in a single step.^{19,22} However, as in ATRP, the use of ppm levels of metal catalyst limited the practicality of this system. Although the emergent field of photoredox catalysis has primarily utilized transition metals (i.e., iridium and ruthenium),²³ organic catalysts have recently attracted significant attention²⁴ and, in some cases, have been shown to be more efficient than metal-based systems.²⁵ We saw this as an opportunity to establish a metal-free ATRP process by developing an organic-based catalyst that could replace Ir(ppy)₃ in photomediated,

controlled radical polymerizations. The ultimate aim is an organic photoredox system that is reducing in the excited state and effectively catalyzes controlled radical polymerization processes in an analogous manner to traditional ATRP systems (Scheme 1).

Scheme 1. Previous ATRP Systems Rely on Metal Catalysts (i.e., CuBr) with Ligands for Control; Metal-Free ATRP Relies on an Organic Photoredox Catalyst (i.e., PTH) To Produce Identical Polymers



An immediate challenge in developing a metal-free ATRP is designing an organic catalyst that is highly reducing in the excited state. The majority of organic-based dyes, currently used as photoredox catalysts, are oxidizing in the excited state and would not possess the desired reduction potentials required to reduce the alkyl bromide initiator or subsequent polymer chain ends to a propagating radical. We therefore reasoned that an organic catalyst is needed that has an excited state reduction potential on par with Ir(ppy)₃, as well as a stable radical cation species, which is formed after reduction of the alkyl bromide

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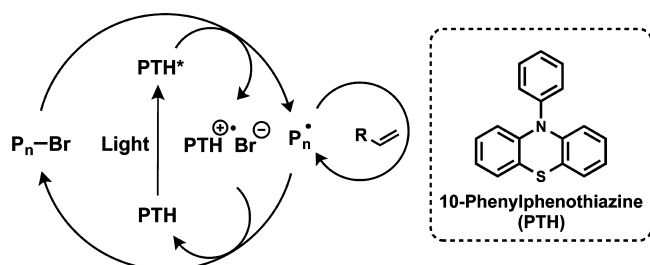


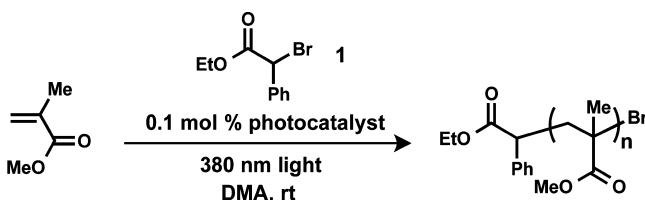
Figure 1. Proposed mechanism of metal-free photomediated ATRP with 10-phenylphenothiazine as the catalyst (P_n = polymer chain).

(Figure 1). After surveying a range of possible organic dyes, phenothiazine derivatives were chosen as candidates for our initial studies due to the desired photophysical properties (*vide supra*), low cost, ready availability, and facile modification chemistry.²⁶

DISCUSSION

Initially, we examined the use of commercially available 10-methylphenothiazine (Me-PTH) for the polymerization of methyl methacrylate (MMA) under 380 nm irradiation at room temperature. Encouragingly, polymerization was observed with good agreement between theoretical and experimental molecular weight, albeit with poor control over the molecular weight distribution (Table 1, entry 1). We postulated that tuning the nitrogen substituent on the phenothiazine ring would reduce catalyst decomposition, allowing for greater

Table 1. Optimization of a Light-Mediated Polymerization of Methyl Methacrylate Using Organic Photoredox Catalysts^a



entry	catalyst	M_n (exp) [g/mol]	M_n (theo) [g/mol]	M_w/M_n
1	Me-PTH	8300	7400	1.74
2 ^b	PTH	15 400	14 000	1.32
3 ^b	PTH	12 000	11 000	1.25
4	PTH	6200	7200	1.30
5	PTH	2400	2600	1.18
6	PTH	1300	1800	1.20
7 ^c	PTH	—	—	—
8 ^d	PTH	42 300	—	2.00
9 ^e	—	—	—	—
10 ^f	eosin Y	—	—	—
11 ^f	methylene blue	—	—	—

^aReaction conditions: MMA (1 equiv), photocatalyst (0.001 equiv), **1** (0.008–0.01 equiv), DMA (2.7 M of MMA) at room temperature with irradiation from 380 nm LEDs for 4 h (M_n = number-average molecular weight; M_w = weight-average molecular weight). M_n and M_w/M_n determined using size exclusion chromatography (SEC) or ¹H NMR. ^bReaction run with benzyl methacrylate (1 equiv) for 7 h. ^cReaction run in the dark. ^dReaction run in the absence of **1**. ^eReaction run in the absence of catalyst. ^fIrradiated with visible light (50 W fluorescent bulbs).

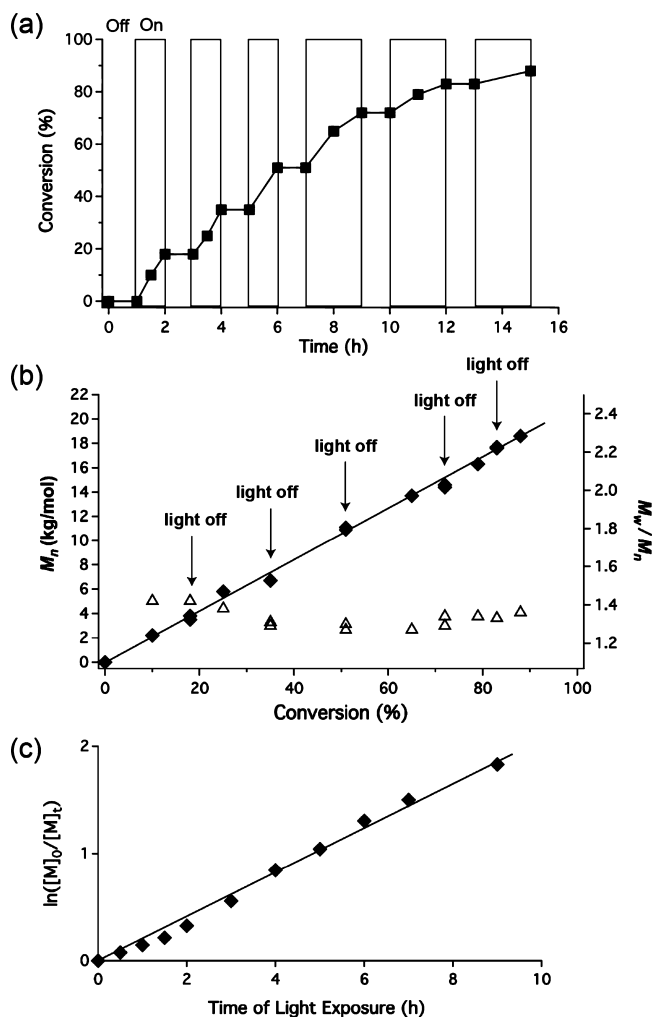


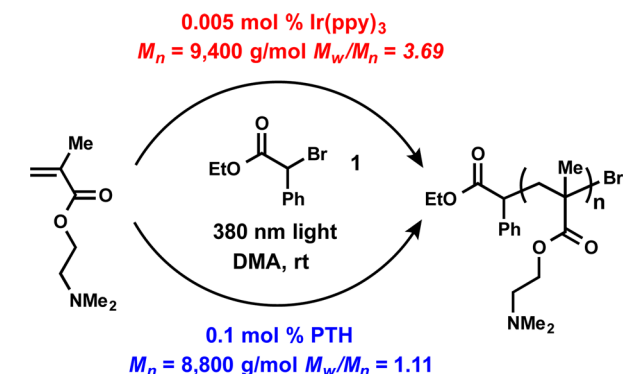
Figure 2. Polymerization of BnMA using PTH with repeated “on–off” cycling of the reaction to light.

control over the polymerization process. To this end, we synthesized 10-phenylphenothiazine, PTH, from commercially available phenothiazine and chlorobenzene using C–N cross-coupling chemistry followed by repeated purification to obtain highly pure PTH²⁷ (see Supporting Information, $E_{red}(PTH^{*+}/PTH^{*}) = -2.1$ V vs SCE²⁸). Significantly, we found that the controlled polymerization of MMA could be achieved in the presence of a traditional ATRP initiator, **1**, and PTH. Of even greater encouragement was the observation of conventional CRP behavior with the molecular weight being determined by the initial monomer/initiator ratio and low polydispersities being obtained in each case (Table 1, entries 2–6). These experiments establish that, for the first time, an atom transfer radical polymerization (ATRP) process could occur with a metal-free catalyst system.

To further support the controlled nature of this polymerization, a range of experimental conditions were examined. When the polymerization was conducted in the absence of light, initiator, or catalyst, either no or uncontrolled polymerization was observed (Table 1, entries 7–9), demonstrating that this is indeed a photomediated process that is initiated by **1** and catalyzed by PTH. Moreover, when other organic-based photoredox catalysts were employed (eosin Y and methylene blue), which are oxidizing in the excited state, no reaction occurred (Table 1, entries 8 and 9). This further corroborates

that a catalyst that is highly reducing in the excited state is needed to activate the alkyl bromide chain-end.

Scheme 2. Dimethylaminoethyl Methacrylate (DMAEMA) Gives Uncontrolled Polymerization with Ir-Based System and Controlled Polymerization with PTH, Demonstrating the Broad Scope of Photomediated ATRP



The lack of reaction in the dark suggested that the polymerization could be activated/deactivated by light leading to controlled regulation of the polymerization process. To investigate this responsive nature, PTH was combined with the initiator, **1**, and benzyl methacrylate (BnMA). Upon observing no conversion after 1 h in the dark, the reaction was exposed to 380 nm light, reaching 18% conversion in 1 h (Figure 2a). After removal of the light source, no further conversion was observed during the course of 1 h; however, re-exposure to 380 nm light led to further reaction progress. This cycle could be repeated several times up to high conversions (~90%) indicating very efficient activation and deactivation of the polymerization process. Significantly, a linear increase in molecular weight versus conversion is obtained even with multiple “on–off” light switching cycles (Figure 2b), and the observation of first order kinetics through the course of the reaction demonstrated a controlled polymerization process (Figure 2c). In analogy with traditional ATRP processes, these data indicate that when light is removed from the system the chain-ends are oxidized to the stable and dormant alkyl bromides, and upon re-exposure to light in the presence of PTH, the chain-ends are efficiently and reversibly converting to propagating radicals.

In contrast to Ir(ppy)₃ and traditional metal-catalyzed ATRP processes, a unique feature of PTH is its highly reducing excited state, which may allow a wider selection of functional groups to be tolerated during the polymerization. We sought to take advantage of this feature by polymerizing monomer types that were inaccessible with the Ir-based system. The test vehicle chosen was 2-(dimethylamino)ethyl methacrylate (DMAEMA), a monomer utilized ubiquitously for its stimuli-responsive properties.^{29–32} In the presence of Ir(ppy)₃ under the previously optimized conditions, very broad polydispersities were observed (Supporting Information Table S1, $M_w/M_n > 3$). We surmised that the uncontrolled polymerization was a result of radical formation through oxidation of the amine; this is a well-known reaction pathway for photoredox catalysts.³³ In direct contrast, for the less oxidizing PTH ($E_{1/2}^{ox} = 0.68$ V vs SCE, see Supporting Information), irradiation resulted in a well-defined polymerization process with accurate control over molecular weight and low polydispersities (~1.1) (Scheme 2). Moreover, this system allows precise control over the M_n of

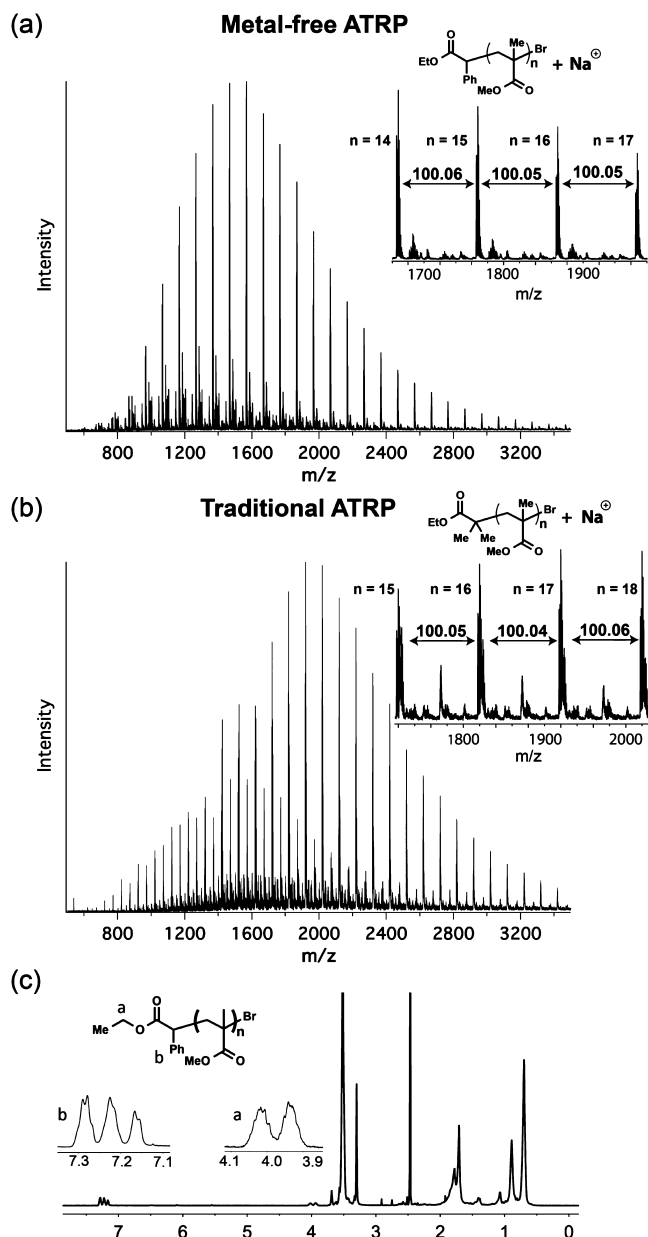


Figure 3. (a) ESI-MS of PMMA produced under optimized metal-free ATRP conditions with major peaks separated by molecular weight of the monomer; (b) ESI-MS of PMMA produced using reported conditions of traditional ATRP; (c) ¹H NMR of PMMA sample showing initiator-derived protons.

these polymers by varying the initiator to monomer ratio, as well as enabling the synthesis of functional materials (block copolymers), both of which could not be achieved using the Ir-based catalyst system (see Supporting Information). Therefore, this system not only avoids metal contamination, but extends the scope of the photomediated ATRP in general.

A fundamental key to the success of any controlled radical process, such as ATRP, is chain-end fidelity. Achieving high chain-end fidelity allows for effective block copolymer formation, chain end functionalization, and the successful synthesis of a wide variety of well-defined macromolecules. It was therefore critical to determine chain-end fidelity in these reactions. Initially, a low molecular weight PMMA ($M_n = 1400$ g/mol, $M_w/M_n = 1.08$) was synthesized by PTH-mediated, metal-free ATRP under the optimized conditions described

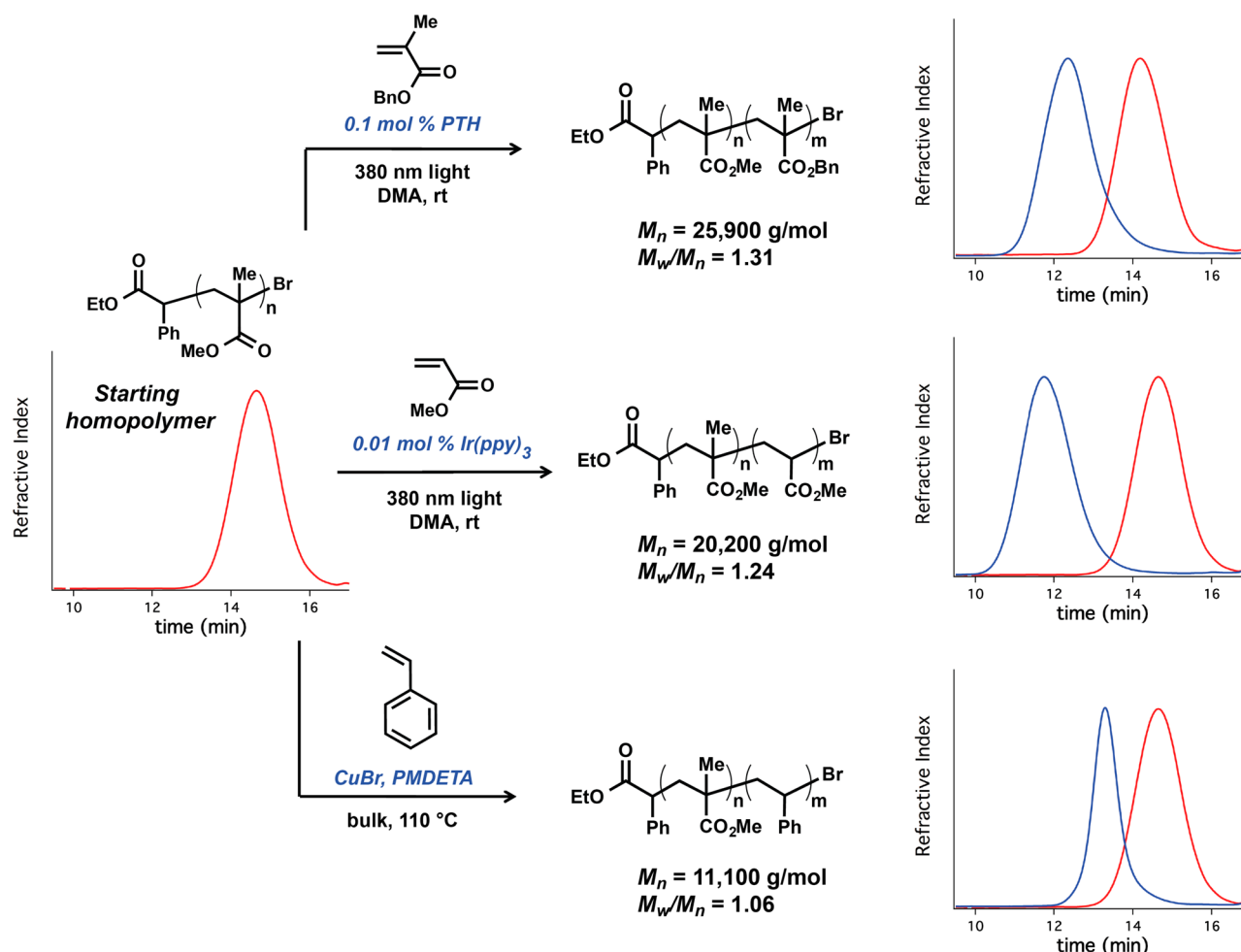


Figure 4. Synthesis of block copolymers starting from a PMMA macroinitiator prepared by metal-free ATRP conditions and accompanying SEC traces of various blocks produced using different combinations of catalyst systems (red trace = starting PMMA macroinitiator, blue trace = block copolymer).

above and analyzed using electrospray ionization mass spectrometry (ESI-MS) (Figure 3a). Of particular note is the correlation of observed molecular weight with the expected values for the individual PMMA oligomers based on the presence of the initiating unit at one chain end and a bromine atom at the propagating chain end with each peak separated by the mass of one monomer unit (100 amu). Further evidence for chain-end fidelity is supplied by the isotopic splitting for the respective molecular ions, clearly indicating the presence of a single Br atom at one chain end (Supporting Information Figure S4).

To illustrate the similarity of polymers obtained from this new process and traditional ATRP procedures, a low molecular weight PMMA derivative was prepared using CuBr as catalyst and 4,4'-dinonyl-2,2'-dipyridyl as ligand at 90 °C ($M_n = 1100$ g/mol, $M_w/M_n = 1.20$). Analysis by ESI-MS again showed the expected oligomer distribution and chain ends with a very similar peak distribution and profile (Figure 3b).

¹H NMR was used to further confirm the level of incorporation and fidelity of the chain ends with resonances for the initiating ethyl 2-phenylacetate group being observed at ~4.0 and 7.2 ppm. Integration of these resonances and comparison with resonances for the backbone allowed molecular weights to be calculated that were in full agreement with values obtained by both MS and GPC analysis (Figure 3c).

These data firmly establish that PTH-mediated, metal-free ATRP procedures give a degree of control over chain ends similar to that observed for traditional ATRP systems with the polymers obtained from both processes being analogous.

Although ESI-MS and NMR give evidence for α and ω chain ends, successful block copolymerization provides definitive proof that a controlled polymerization system has been achieved. To examine the utility of this metal-free process, the polymerization of **1** and MMA with 0.1 mol % PTH was conducted to give a starting PMMA homopolymer ($M_n = 5100$ g/mol, $M_w/M_n = 1.12$). After standard purification and storage, the stable homopolymer was examined as a macroinitiator for the polymerization of benzyl methacrylate under metal-free ATRP conditions (0.1 mol % PTH, 380 nm irradiation for 4 h) leading to a well-defined PMMA-*b*-PBnMA block copolymer (Figure 4, $M_n = 25\,900$ g/mol, $M_w/M_n = 1.31$). The size exclusion chromatogram (SEC) clearly shows a shift to higher molecular weight species with little tailing in the homopolymer regime, indicating excellent alkyl bromide chain-end fidelity in the PMMA macroinitiator and a high reinitiation efficiency. To further explore the scope of this process, a PMMA-*b*-PBnMA copolymer could also be prepared (Supporting Information Figure S5, $M_n = 27\,900$ g/mol, $M_w/M_n = 1.28$) starting from ethyl 2-bromoisobutyrate as initiator, illustrating the versatility of this process.

Block and random copolymerizations with other monomer families were then conducted to demonstrate the broad scope of this system. The presence of bromo chain-ends suggests potential orthogonality for combining metal-free ATRP with other controlled radical processes, increasing the range of block copolymers that can be prepared. To demonstrate the ability of metal-free ATRP to be combined with other catalyst systems, the starting PMMA homopolymer ($M_n = 3600$ g/mol, $M_w/M_n = 1.19$) was used to polymerize methyl acrylate under $\text{Ir}(\text{ppy})_3$ catalyst conditions.²⁰ Significantly, a well-defined block copolymer (Figure 4, $M_n = 20\,200$ g/mol, $M_w/M_n = 1.24$) with virtually no tailing in the homopolymer regime of the SEC trace was obtained. Taking this concept even further, the same PTH-derived PMMA macroinitiator could be used for the polymerization of styrene under traditional ATRP conditions employing CuBr as the catalyst. The resulting block copolymer (Figure 4, $M_n = 11\,100$ g/mol, $M_w/M_n = 1.06$) again revealed a monomodal shift in retention time of the chromatogram. Finally, the reverse CRP order, Cu-based ATRP to produce a PMMA macroinitiator followed by chain extension with BnMA using PTH as catalyst, was also shown to be a facile process leading to well-defined diblock copolymers (Supporting Information Figure S6). Under our standard conditions several random copolymers were also synthesized with varying incorporations of styrene, as well as methyl acrylate, while maintaining good agreement between theoretical and experimental molecular weights (Supporting Information Tables S2 and S3).

CONCLUSION

We have demonstrated a successful metal-free atom transfer radical polymerization. Use of an affordable, easily prepared organic catalyst, PTH, leads to a controlled, photomediated process that bears many characteristics of traditional ATRP procedures including accurate control over molecular weight, low polydispersity, and high retention of chain end groups. This allows a variety of block copolymers to be prepared in a sequential manner as well as in combination with other ATRP processes (traditional Cu-catalyzed and photomediated Ir-based systems). This organic-based catalyst system circumvents issues of metal contamination in polymers made using ATRP and allows for the production of a variety of functional materials, pushing the field of CRP into new areas and applications. We further anticipate that the unique properties of this new class of organic-based photoredox catalysts, specifically their highly reducing nature, will find applications in both small molecule and polymer functionalization chemistry.

ASSOCIATED CONTENT

Supporting Information

Experimental procedures for preparation of all compounds and characterization data for all compounds. This material is available free of charge via the Internet at <http://pubs.acs.org>.

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Notes

The authors declare no competing financial interest.

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