Photoredox Catalyst-Mediated Atom Transfer Radical Addition for Polymer Functionalization under Visible Light †

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COMMUNICATION

Photoredox Catalyst-Mediated Atom Transfer Radical Addition for Polymer Functionalization under Visible Light †

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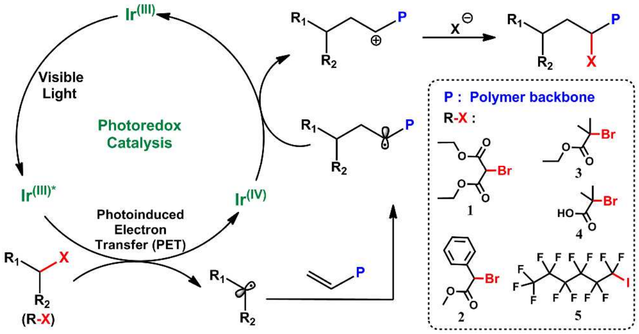
A facile method for post-functionalization of polymers with side olefin groups was developed by visible light-mediated atom transfer radical addition (ATRA) employing a photoredox catalyst, *fac*-Ir(ppy)$_3$. In this work, various haloalkanes and *α*-halocarbonyls were introduced via post-modification into the polymer chains. This communication reports the first example of successful post-modification of polymers using photoredox catalyst.

In 1912, Ciamician realized that “light” is an abundant and renewable energy source, and used it to perform green chemical reactions.[1] Since the 1910s, the use of UV light as a way to initiate organic reactions has been intensively investigated in organic chemistry.[2-6] In recent years, there has been growing interests in the development of organic reactions using visible light as the energy source due specifically to the emergence of photocatalysts which mediate the desired organic reactions. The inability of organic compounds to absorb visible light is a significant advantage as it avoids the side reactions that usually occur when using high energy UV lights.[7,8] In 2011, visible light-mediated atom transfer radical addition (ATRA) process was introduced by Stephenson *et al.* as a powerful tool for organic transformations with attractive features, including simple reaction setup, mild reaction conditions, minimal side reactions, and straightforward purification.[9,10] Stephenson *et al.*,[7,9-11] MacMillan *et al.*,[8,12] Yoon *et al.*[13,14] demonstrated the ability of photoredox catalysts, such as Ru(bpy)$_3$Cl$_2$ and *fac*-Ir(ppy)$_3$, to initiate organic transformations between haloalkanes and olefins with a variety of substrates and broad functional group tolerances under visible light. In these organic transformations, the photoredox catalysts under visible light produced excited species, which were able to reduce or oxidize a substrate. Recently, the application of visible light photoredox catalysis has been extended to polymer synthesis with Lalevée *et al.* reporting an epoxy cationic polymerization, photocatalyzed by Ru(bpy)$_3$Cl$_2$ hexahydrate in the presence of green light irradiation.[15-18] In 2012, Hawker *et al.* developed visible light-mediated controlled free radical polymerization of an array of methacrylates employing *fac*-Ir(ppy)$_3$ as a photoredox catalyst and an alkyl bromide compound as the initiator.[19-22]

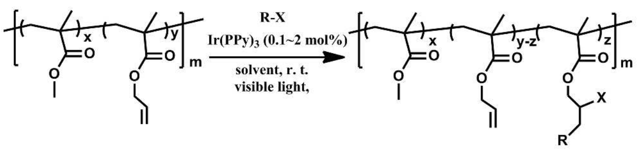
Boosted by a growing demand for functional polymers for different high-tech applications, the introduction of ‘clickable’ groups in the polymer chains has aroused a large interest. Polymer chemists have developed a broad portfolio of highly efficient post-modification reactions applicable to polymers, using for example: activated ester/amine,[23-25] nucleophile isocyanate,[26] alkyne-azide click chemistry,[27] enzymatic reaction,[28,29] Diels-Alder,[30] thiol-ene and -yne reactions.[31,32] These reactions were successfully employed for the synthesis of polymers with complex structures and functionalities,[33,34] such as dendrimer synthesis,[35] polymer side-chain or end group modification, and synthesis of block and graft copolymers.[36] Tao, Wei and coworkers[37-39] expended these post-modifications to multicomponent reactions to introduce several functional groups into the polymers.



Scheme 1 Proposed mechanism for the post-modification of polymers via visible light-mediated atom transfer radical addition (ATRA).

In this communication, we report the first successful use of a photoredox catalyst for the post-modification of polymers under visible light. In our approach, we employed an iridium based photoredox catalyst (*fac*-Ir(ppy)$_3$) for the post-functionalization of polymers *via* visible light-mediated atom transfer radical addition (ATRA) of haloalkanes and *α*-halocarbonyls to olefins under mild reaction conditions (**Scheme 1**). In the proposed mechanism initially proposed by Stephenson[6,7] for organic reactions, the photocatalyst, excited by visible light (Ir$^{(III)*}$), reduces the halogenated substrate (R-X) to produce an oxidized photocatalyst (Ir$^{(IV)}$) and an electrophilic radical that undergoes addition to aside olefin in the polymer chain. The addition produces a radical that can be oxidized to a carbocation by the catalyst to complete the catalytic cycle and subsequently generate the product by nucleophilic trapping of a halide to produce the ATRA product.

In the first step, we synthesized a model polymer, poly(allyl methacrylate-*r*-methyl methacrylate) (P(AM-*r*-MMA), M_n = 21 000 g/mol, PDI=1.16), *via* reversible addition-fragmentation chain transfer (RAFT) polymerization, with 4-cyanopentanoic acid dithiobenzoate (CPADB) as the chain transfer agent. The molar ratio of the allyl methacrylate (AM) to methyl methacrylate (MMA) were calculated by ^{1}H NMR, using the characteristic signal of the allyl group at δ 5.5-6.5 ppm and the methyl ester group at δ 3.5 ppm (**Figure S1 in ESI**). The final composition ([AM]/[MMA] = 20/80 mol%) determined by nuclear magnetic resonance (NMR) was close to the initial feed ratio. To avoid side reactions between the dithiobenzoate and the catalyst, we decided to remove the dithiobenzoate end-group via a combination of aminolysis and a thiol-ene Michael addition. First, the dithiobenzoate group was aminolysed using hexylamine to yield a thiol which was subsequently reacted with methyl acrylate via thiol-ene Michael addition to afford an inert thio-ester end-group, as previously published[36,40-42] (**Scheme S1 in ESI**). After purification by precipitation in methanol, the polymer was analyzed by NMR to confirm the absence of signals at δ 7.2-7.8 ppm characteristic of the dithiobenzoate group (**Figure S1A in ESI**). In addition, UV-vis confirmed the absence of signal at 305 nm after aminolysis reaction (**Figure S2B in ESI**). The polymer after aminolysis/thiol-ene Michael addition was analyzed by GPC (M_n ~ 22 800 g/mol, PDI 1.25). A small shoulder at high retention time was observed (**Figure 1B**), which indicates the formation of a small amount of coupling polymer due to the oxidation of the thiol into a disulphide.[40]



Scheme 2 Post-modification of P(AM-*r*-MMA) with variety of atom transfer agents in the presence of photocatalyst and visible light.

Following the removal of the dithiobenzoate group, the post-functionalization of P(AM-*r*-MMA) was investigated using five alkyl halide compounds (R-X), including diethyl bromomalonate (BrMal, **1**), methyl α-bromophenylacetate (MBPA, **2**), ethyl α-bromoisobutyrate (EBiB, **3**), bromoisobutyric acid (BiBA, **4**), and 1-iodoperfluorohexane (IPFHex, **5**) as described in **Scheme 1 and 2.** The degree of functionalization (*f*) was evaluated at varied catalyst ratios ([Ir(ppy)$_3$] /[olefin]) in a range of solvents by monitoring allyl signal at δ 5.5-6.5 ppm in ^{1}H NMR spectra.

The reaction solutions were prepared by simply mixing the reactants using various molar ratios [Ir(ppy)$_3$]/[olefin]/[BrMal] = (0.1%~2%)/1/5 in dimethyl sulfoxide (DMSO). After purging with nitrogen for 30 min, the reaction mixtures were exposed to visible light (48Watts, 6 household fluorescent tubes). Samples were withdrawn at varying intervals and purified for ^{1}H NMR measurements. **Figure 1A** shows the evolution of *f* versus exposure time, indicating the dependence on catalyst to olefin ratios. The highest catalyst ratio ([Ir(ppy)$_3$]/[olefin] = 2 mol%) resulted in the highest conversion (90% after 26 h irradiation), whereas the other ones showed 72.1%, 35.9%, 11.3% for 1, 0.5 and 0.1 mol% of catalyst, respectively. Although high catalyst ratio (>1 mol%) was required to obtain high conversion in the post-functionalization, the samples prepared with 2 mol% catalyst showed the formation of side products. GPC analysis revealed the presence of a shoulder at low retention time, which indicated the presence of more coupling products (**Figure S2 in ESI**), resulting in a significant increase of the PDI. In contrast, at a concentration of 1 mol%, the narrow polydispersity indicates less coupling products and thus the molar catalyst ratio was fixed at 1 mol% for all further experiments. To confirm the effect of the catalyst, control experiments were performed in the absence of catalyst and light. After 24h, in the absence of the photoredox catalyst and light (in the dark), no conversion of the allyl group was observed.

Subsequently, the effect of the polymer concentration on the functionalization efficiency was evaluated at 1mg/mL and 10 mg/mL Although the degree of functionalization appeared independent of the concentration, at high concentration (10 mg/mL), GPC analysis revealed a shoulder attributed to intermolecular cross-linking (blue, **Figure 1B**). Reducing the polymer concentration from 10 mg/mL to 1 mg/mL resulted in suppression (red, **Figure 1B**) of the shoulder. The solvent effects were investigated next using DMSO, *N,N*-dimethylformamide (DMF) and *N*-methyl-2-pyrrolidone (NMP). DMSO provided the highest reaction yield (*f* = 72.1%) over DMF (53.0%) and NMP (58.2%) at the ratio [Ir(ppy)$_3$]/[olefin]/[BrMal] of 1%/1/5 after 26 h of irradiation (**Table S1 in ESI**).

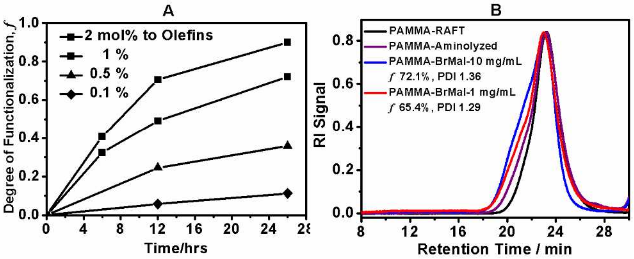


Figure 1 (A) Degree of functionalization (*f*) of aminolyzed P(AM-*r*-MMA) with diethyl bromomalonate (**1**) at varied catalyst ratios and (B) GPC curves for P(AM-*r*-MMA) before and after post-functionalization in DMSO.

Other initiators (**2**~**4**) were investigated to functionalize P(AM-*r*-MMA). Unfortunately, these alkyl bromide compounds **4** gave very low degree of functionalization (< 5%) after 26 h irradiation.

The post-modification of P(AM-*r*-MMA), using an iodoperfluoro-compound, **5**, was also investigated. The chemical modification of polymers using fluorinated compounds is an important process in industry for a wide range of high-tech applications due to the unique properties of perfluoro-compounds, such as superior hydrophobicity, thermal stability and solvent resistance.[43] Previous reports on the post-modification of preformed polymer using iodoperfluoro-compounds reported the use of high energy light source (UV and high wattage) or thermal radical initiators with ~60-70% yields.[43-48] To test our approach with these compounds, we decided to use 1-iodoperfluorohexane, IPFHex, **5**, as an example**.** Complete consumption of allyl group was demonstrated by ^{1}H NMR (**Figure S4 in ESI**) after 12 h of irradiation. Interestingly, the polymer precipitated during the reaction, which indicated a significant change in its solubility. This change is attributed to the successful attachment of perfluoroalky compounds onto the allyl groups.

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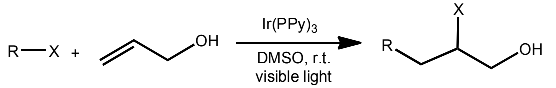
Table 1 Model reactions of visible light-mediated ATRA of haloalkanes to allyl alcohol



ENTRY	R-X	YIELD		
		R-X : AA =1.5:1	R-X : AA = 2:1	R-X : AA = 3:1
1	**1**	99%	--	--
2	**2**	75%	95%	--
3	**3**	30%	--	45%
4	**4**	8%	--	13%
5	**5**	86%	--	--

Notes: 1) "--" indicated no data; 2) The reaction was performed in DMSO in the presence of Ir(ppy)$_3$ as photocatalyst, allyl alcohol (AA) as model olefin and various halide compounds (R-X, described in **Scheme 1**) under 48 W visible light for 24 h.

To investigate the reaction behaviors of all alkyl halide compounds and confirm final structures of the products, model ATRA reactions (**Table 1**) between alkyl halide compounds and allyl alcohol (AA) were performed under the same conditions. The model reactions suggest that the reactions were strongly dependent on the structures of the alkyl halide compounds as shown in **Table 1**. The reactions were monitored by ^{1}H NMR using deuterated DMSO. NMR confirmed the absence of side reactions (**Figures S5**, **6**, **7**, **8**, and **9 in ESI**). The reaction yields varied from 75% to ~100% for **1** (99%), **2** (75%) and **5** (86%) after 24 h of irradiation, even at the lowest molar ratio of R-X:AA to 1.5:1. Entry 1 was purified by column chromatography using hexane/ethyl acetate (4/1, v/v) as eluent (R_f = 0.15). ^{1}H NMR and H-H COSY measurements confirmed the successful synthesis of the expected structure, described in **Table 1** (**Figures S10** and **11 in ESI**).

However, alkyl halide compounds **3** and **4** showed low yields (30% and 8%, respectively), possibly due to the slow activation of R-X by the photoredox catalyst. It is worthy to note that MBPA (**2**) gave an interesting result due to the presence of radical chiral carbon center. The ^{1}H NMR spectrum of the starting material (black curve, **Figure S6 in ESI**) showed that the proton on the chiral carbon center possesses both R and S structures with two different chemical environments, resulting in two chemical shifts at δ 5.95 and 5.18 ppm. Moreover, it causes the split of the methyl group by long distance coupling at δ 3.72 and 3.60 ppm. With the ratio of R-X:AA = 1.5:1 (entry 2, **Table 1**), the reaction reached a conversion of 75% after 24 h. However, this conversion plateaus at 75%, despite running the reaction for 72 h. When the molar ratio of R-X:AA was increased to 2:1, the yield was increased to 95%. Intriguingly, the peaks (δ 5.95 ppm and δ 3.72 ppm) at down field (red curve, **Figure S6 in ESI**) completely disappeared; indicating only one of the enantiomers of MBPA underwent reaction with the AA, while the rest remained unreacted. It is supposed that the Br present on the chiral carbon (enantiomer S) is not activated by the catalyst, due to possible steric hindrance of the phenyl group and demonstrates that this reaction can be stereospecific.

Further investigation of this technique for the post-functionalization of a polymer with side olefins was explored using a commercially available polyolefin, polybutadiene (1,2-vinyl PB). The molar ratio of [Ir(ppy)$_3$]/[olefin]/[R-X] was fixed at 1%/1/1, which yielded a conversion of 34.1% after 24h exposure to visible light in NMP (Note: the possible cyclization of 2 butadiene pendant groups to generate six- or five-member rings was not taken into account to calculate the degree of functionalization).[49] To reduce of the likelihood of intermolecular cross-linking, we employed a low concentration of polymer for the post-functionalization (**Figure 2**). The use of low concentration (1 mg/mL) resulted in the PDI remaining unchanged with respect to the original PB. Attempts to use other solvents for PB functionalization were not successful. Polar solvents such as DMF and DMSO displayed poor solubility of PB, whilst less polar solvents such as tetrahydrofuran (THF) and ethyl acetate (EtOAc) resulted in side products with dark brown colors, even in the absence of photocatalyst. The post-modification of IPFHex, **5**, was also investigated using PB. After 4 h, the polymers precipitated in DMSO and were not soluble in most common organic solvents (such as DMAc and THF).

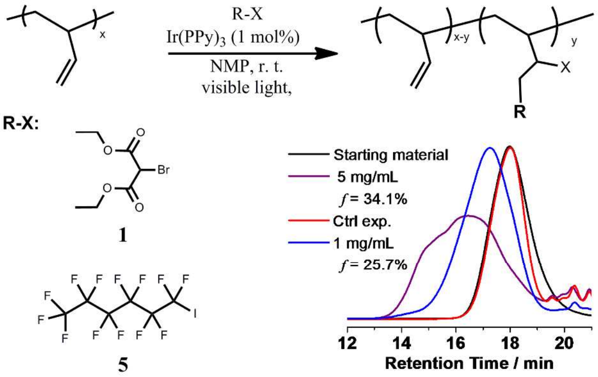


Figure 2 Schematic reaction of atom transfer radical addition of haloalkyl compounds (**1** and **5**) with polybutadiene. GPC curves before and after post-functionalization of polybutadiene.

In summary, we have described an easy reaction setup procedure utilizing mild conditions for the post-functionalization of polymers with side olefins by visible light-mediated atom transfer radical addition (ATRA) of haloalkane or α-halocarbonyls. The photocatalyst efficiency (Ir(ppy)$_3$) and solvent effects were investigated in detail to provide the optimal reaction conditions. Model reactions were also performed to evaluate the reaction efficiency and confirm the chemical structures of the final products. This methodology has been demonstrated to be suitable for the post-modification of the commercially available polyolefins such as polybutadiene. Finally, this approach was successfully employed for the introduction of perfluoro-compounds with high yields compared to previous approaches reported in the literature.

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† *Electronic Supplementary Information (ESI): Experimental details and further characterization data are available. See DOI: 10.1039/b000000x*

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