Synthesis of Photocleavable Poly(methyl methacrylate-*block*-D-lactide) via Atom-Transfer Radical Polymerization and Ring-Opening Polymerization

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ABSTRACT: The synthesis and characterization of a photocleavable block copolymer containing an *ortho*-nitrobenzyl (ONB) linker between poly(methyl methacrylate) and poly(D-lactide) blocks is presented here. The block copolymers were synthesized via atom transfer radical polymerization (ATRP) of MMA followed by ring-opening polymerization (ROP) of D-Lactide and ROP of D-lactide followed by ATRP of MMA from a difunctional photoresponsive ONB initiator, respectively. The challenges and limitations during synthesis of the photocleavable block copolymers using the difunctional photoresponsive ONB initiator are discussed. The photocleavage of the copolymers occurs under mild conditions by simple irradiation with 302 nm wavelength UV light (Relative intensity at 7.6 cm: 1500 μW/cm^2) for several hours. © 2013 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2013**, *51*, 4309–4316

KEYWORDS: atom transfer radical polymerization (ATRP); block copolymers; D-lactide; photochemistry; photocleavable; photoreactive effects; ring-opening polymerization

INTRODUCTION Photolabile groups, such as *ortho*-nitrobenzyl (ONB) alcohol derivatives,[1–3] ketoester derivatives,[4,5] and benzophenone esters,[6] have been used extensively in synthetic organic chemistry and have found numerous applications in academia and industry. Among the many photolabile groups that have been studied, ONB alcohol derivatives have gained tremendous attention and have become one of the most popular photolabile protecting groups.[7,8] ONB structures have been used as crosslinkers for photodegradable hydrogels,[9–14] as photocleavable linkers in block copolymers,[15–22] in photocleavable bioconjugates,[23–25] and for side-chain functionalization in copolymers.[26–28] These cleavable materials are particularly useful as precursors for the production of highly ordered nanoporous templates by facilitating the removal of the minor block of phase-separated block copolymer films, and producing light-sensitive block copolymer micelles. Many block polymers, for example, polystyrene-*b*-poly(methyl methacrylate) (PS-*b*-PMMA),[19] polystyrene-*b*-poly(ethylene oxide) (PS-*b*-PEO),[19,20] poly(γ-methyl-ε-caprolactone)-*b*-poly(acrylic acid) (P*m*CL-*b*-PAA),[21] polystyrene-*b*-poly(ε-caprolactone) (PS-*b*-PCL),[22] and polyurethane-*b*-poly(ethylene oxide) (polyurethane-*b*-PEO) have been synthesized with photocleavable ONB junctions.[29]

Herein, poly(D-lactide)-*b*-poly(methyl methacrylate) and poly(methyl methacrylate)-*b*-poly(D-lactide) containing a photocleavable ONB group as a linker (abbreviated: PDLA-ONB-PMMA/PMMA-ONB-PDLA) were successfully synthesized by combining atom transfer radical polymerization (ATRP) and ring-opening polymerization (ROP) for the first time. The challenge and limitation during synthesis of the block copolymers using the ONB initiator including nitrobenzene for ATRP and the basic condition for ROP were highlighted. We use a biocompatible and biodegradable PDLA sacrificial block, which is also suitable for bio-related applications.[30,31] In addition, it is well recognized that ultraviolet (UV) irradiation induces important physico-chemical changes in PLA polymers involving a reduction of molecular weights, which will benefit facile removal of the sacrificial block (PDLA) after cleavage.[32–37]

EXPERIMENTAL

Materials

All commercially obtained solvents and reagents were used without further purification except as noted below. D-Lactide was kindly provided by Purac Biochem BV (Gorinchem, The Netherlands), and recrystallized three times from dry toluene. Methyl methacrylate (MMA) was washed with

Additional Supporting Information may be found in the online version of this article.

5 wt % sodium hydroxide (NaOH) aqueous solution to remove the inhibitor and washed with water several times. The collected organic layers were dried with anhydrous magnesium sulfate ($MgSO_4$) overnight and vacuum distilled before use. Tin (II) 2-ethylhexanoate [$Sn(Oct)_2$] was dried under high vacuum at 80 °C overnight before use. 1,8-Diazabicyclo [5.4.0] undec-7-ene (DBU) was vacuum distilled from calcium hydride (CaH_2) before use. Toluene and tetrahydrofuran (THF) were distilled from sodium (Na)/benzophenone. Dry dichloromethane (CH_2Cl_2) was obtained by distilling from CaH_2.

Synthesis of Difunctional Photocleavable Initiator ONB

5-Hydroxy-2-nitrobenzyl Alcohol

In a round-bottom dry flask, 5-hydroxy-2-nitrobenzaldehyde (10.1 g, 0.06 mol) was dissolved in anhydrous methanol (MeOH) (150 mL). Sodium borohydride ($NaBH_4$) (6 g, 0.16 mol) was slowly added under stirring and nitrogen flow at 0 °C. Then, the resulting mixture was warmed to room temperature and stirred for 3 h. The reaction was cautiously quenched by the addition of a 10% HCl (aq.) solution, and extracted with ethyl acetate (EtOAc) (200 mL × 3). The combined organic layers were washed with brine, dried with anhydrous $MgSO_4$, and concentrated in vacuum. The yellow solid residue was purified by flash column chromatography with hexane/EtOAc (1:1 v:v) to give 5-hydroxy-2-nitrobenzyl alcohol as a yellow solid (yield, 94%).

^{1}H NMR (300 MHz, DMSO-d_6, δ ppm): 10.89 (s, 1H), 8.07 (d, 1H), 7.29 (s, 1H), 6.81 (d, 1H), 5.52 (s, 1H), 4.85 (s, 1H).

5-Bromoisobutyrate-2-nitrobenzyl Alcohol

In a round-bottom flask, 5-hydroxy-2-nitrobenzyl alcohol (4 g, 0.024 mol) was dissolved in anhydrous THF (20 mL). A sodium hydride (NaH) slurry in dry THF (20 mL, 0.024 mol NaH) was added slowly under stirring and nitrogen flow. α-Bromoisobutyryl bromide (6 g, 0.026 mmol) was added dropwise via a constant pressure funnel at 0 °C. Then, the reaction mixture was warmed to room temperature and stirred overnight. The solution was diluted with twice its volume in EtOAc. The organic phase was washed with 1 M of NaOH (aq) (2 × 100 mL), brine (2 × 100 mL), and water (3 × 100 mL), then dried over $MgSO_4$ and the solvent was evaporated under reduced pressure. The crude product was purified by chromatography with hexane/EtOAc (1:2 v:v) to yield compound ONB as a clear yellow oil. The yield of ONB is 65%, covering both the installation of the ATRP initiating site and the sodium borohydride reduction.

^{1}H NMR ($CDCl_3$, 300 MHz) δ (ppm): 2.12 (6H, s, 2× CH_3), 5.08 (2H, d, CH_2), 7.25 (1H, dd, aromatic), 7.61 (1H, d, aromatic), 8.22 (1H, d, aromatic); ^{13}C NMR (300 MHz, MeOH-d_4): δ 171.14 (C═O), 156.32 (C_{Ar}—NO_2), 145.97 (C_{Ar}—O), 142.62 (C_{Ar}—CH_2), 128.08 (C_{Ar}), 122.20 (C_{Ar}), 61.80 (C_{Ar}), 56.77 (CH_2—OH), 31.88 (C— $(CH_3)_2$), 30.76 (CH_3). FTIR (ATR, cm^{-1}): 3546 (b, OH), 1756 (s, C═O), 1584 (m, NO_2), 1521 (s, NO_2), 1215 (s, C—Br), 1128 (s, Ar—O—C—).

General Procedures for the Synthesis of Block Copolymers PDLA-ONB-PMMA (Route A, ROP Followed by ATRP)

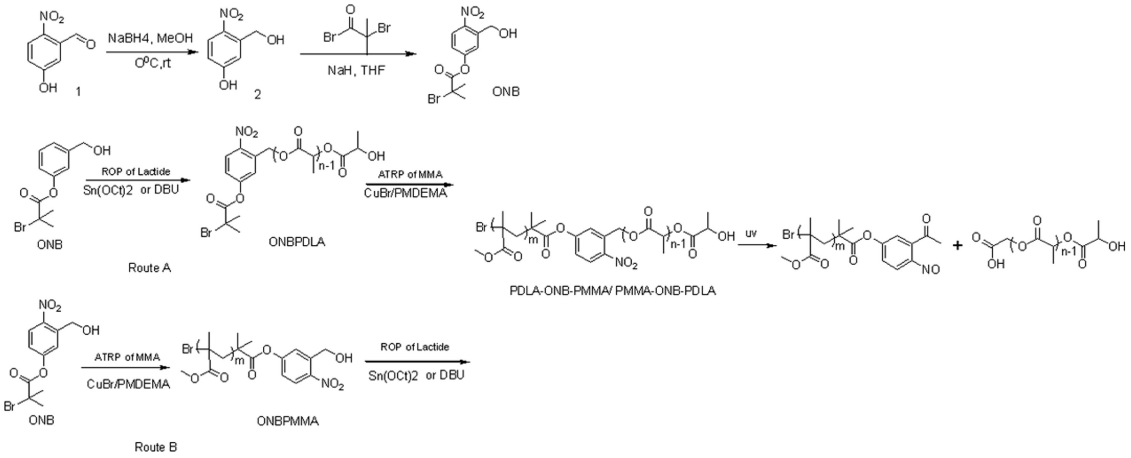
ROP was performed under inert atmosphere and water-free conditions. D-Lactide (0.5 g, 3.47 mmol), ONB (0.1 g, 0.314 mmol), and freshly distilled toluene (5 mL) were added to a flame-dried two-neck, round-bottom flask equipped with a gas inlet and a septum under dry N_2 flow. A solution of $Sn(Oct)_2$ (0.01 g) in toluene (∼0.1 mL) was added via gas-purged syringe. The solution was allowed to react for 3 days at 80 °C. The resulting polymer was precipitated from 150 mL of hexane, and washed with cold methanol. The polymer was dried over night at 50 °C under high vacuum.

For the ATRP of MMA under oxygen-free conditions, macroinitiator ONB-PDLA (0.2 g, 0.11 mmol, $M_{n,NMR} = 1760$ g/mol, $Đ = 1.20$), MMA (0.51 g, 5.1 mmol), CuBr (0.016 g, 0.11 mmol), and freshly distilled toluene (2.5 mL) were added to a double-neck, round-bottom flask equipped with a gas inlet and a septum. The solution was degassed with three freeze/pump/thaw cycles. *N,N,N′,N″,N″*-pentamethyldiethylenetriamine (PMDETA) (0.029 mL, 0.11 mmol) was added via gas-purged syringe to the reaction flask. The flask was then placed in an oil bath at 80 °C. After a given reaction time, the resulting polymer solution was cooled, exposed to air, and diluted with THF. The polymer solution was passed through a neutral alumina column. After concentration, the polymer was precipitated into 100 mL of cold methanol and dried under high vacuum.

General Procedures for the Synthesis of the Block Copolymers PMMA-ONB-PDLA (Route B, ATRP Followed by ROP)

For the ATRP of MMA under oxygen-free conditions, ONB initiator (0.34 g, 1.1 mmol), MMA (5.7 g, 57 mmol), CuBr (158 mg, 1.1 mmol), and freshly distilled toluene (30 mL) were added to a two-neck, round-bottom flask equipped with a gas inlet and a septum. The solution was degassed with three freeze/pump/thaw cycles. PMDETA (0.23 mL, 1.1 mmol) was added via gas-purged syringe to the reaction flask. The flask was then placed in an oil bath at 80 °C. After 5 h resulting polymer solution was cooled, exposed to air and diluted with THF. The polymer solution was passed through a neutral alumina column. After concentration, the polymer was precipitated from 100 mL of cold methanol and dried under high vacuum.

ROP of D-lactide was performed under inert atmosphere and water-free conditions. D-Lactide (0.25 g, 1.73 mmol), macroinitiator ONB-PMMA (0.208g, $M_{n,nmr} = 15{,}300$ g/mol, $Đ = 1.19$) and freshly distilled toluene (4 mL)were added to a flame dried two-neck, round-bottom flask equipped with a gas inlet and a septum under N_2 flow. A solution of $Sn(Oct)_2$ (0.007 g) in toluene was added via gas-purged syringe. The solution was allowed to react for 3 days at 80 °C. The resulting polymer solution was



SCHEME 1 Synthesis of photocleavable poly(methyl methacrylate-*b*-D-lactide).

precipitated from 150 mL of hexane and washed with cold methanol. The polymer was dried overnight at 50 °C under high vacuum.

In the case of DBU as catalyst, D-lactide (0.25 g, 1.73 mmol), macroinitiator ONB-PMMA (0.208 g, $M_{n,nmr} = 15{,}300$ g/mol, $Đ = 1.19$) and freshly distilled CH_2Cl_2 (2 mL)were added to a flame dried two-neck, round-bottom flask equipped with a gas inlet and a septum under N_2 flow. DBU (4 μL, 0.0268 mmol) was added via gas-purged micro syringe. The solution was allowed to react at 25 °C for 4 h and then quenched by injecting 1 mL of methanol. The resulting polymer solution was precipitated from 150 mL of hexane and washed with cold methanol. The polymer was dried overnight at 50 °C under high vacuum.

Characterization

^{1}H NMR spectra were recorded on a Bruker DPX-300 NMR Spectrometer in chloroform-*d* ($CDCl_3$), except where otherwise noted. Molecular weight and dispersity ($Đ$) were measured on an Agilent Technologies 1200 gel permeation chromatograph (GPC) in $CHCl_3$ at 40 °C with a flow rate of 1 mL/min on systems equipped with three-column sets (Polymer Laboratories, 300 mm × 7.5 mm, 5 μm, 10^{-5}, 10^{-4}, and 10^{-3} Å pore sizes) and refractive index detectors (HP 1047A) at 40 °C. Linear polystyrene standards were used for molecular weight calibration. A UVM-57 handheld UV lamp (302 nm, 6 W, 0.16 Å, Relative intensity at 7.6 cm: 1500 μW/cm^2) was used for photocleavge. UV–Vis spectra were acquired on a Perkin-Elmer Lambda 35 instrument at room temperature.

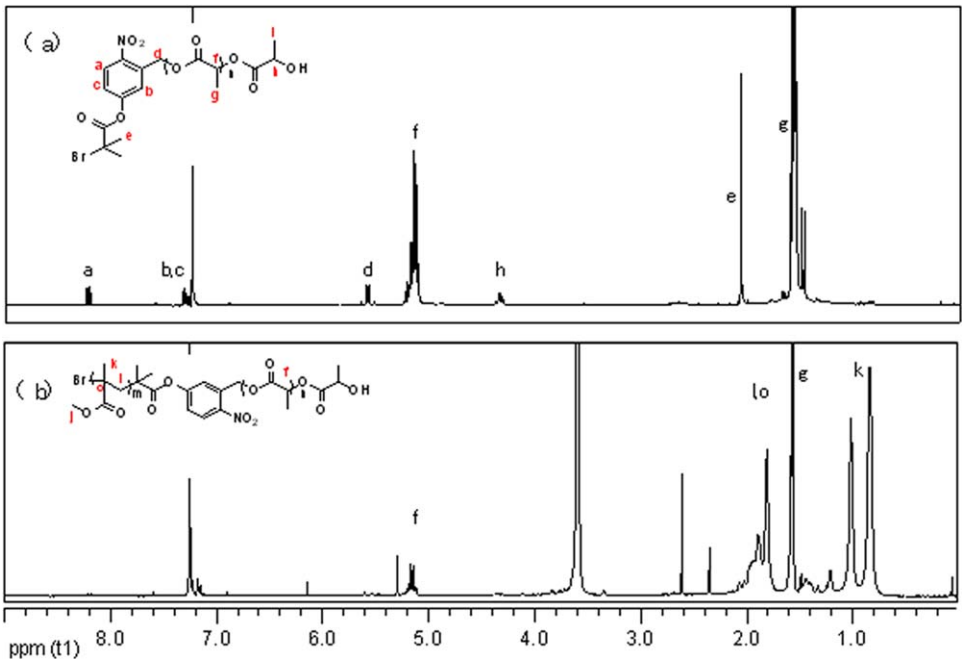


FIGURE 1 $_1$H NMR spectra of ONB-PDLA$_{20}$ (a) and PDLA$_{20}$-ONB-PMMA$_{93}$ (b) in $CDCl_3$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

TABLE 1 Molecular Weights and Compositions of the ONB Macroinitiators and Synthesized Block Copolymers

	$M_{n,NMR}$ (kg/mol)	$M_{n,GPC}$ (kg/mol)	$Đ$
ONB-PDLA$_{20}$	1.76	1.7	1.20
ONB-PDLA$_{40}$	3.20	3.3	1.25
PDLA$_{20}$-ONB-PMMA$_{93}$	11.4	19	1.23
PDLA$_{40}$-ONB-PMMA$_{79}$	11.8	12	1.19
ONB-PMMA$_{188}$	19.1	15	1.18
ONB-PMMA$_{150}$	15.3	14	1.19
PMMA$_{188}$-ONB-PDLA$_{183}$-Sn[a]	32.6	20	1.55
PMMA$_{188}$-ONB-PDLA$_{33}$-Sn[a]	21.8	16	1.34
PMMA$_{188}$-ONB-PDLA$_{138}$-DBU[b]	23.3	20	1.24
PMMA$_{188}$-ONB-PDLA$_{32}$-DBU[b]	21.4	18	1.23

[a] The block copolymer was synthesized using Sn(Oct)$_2$ as catalyst and ONB-PMMA$_{188}$ as macroinitiator.
[b] The block copolymer was synthesized using DBU as catalyst and ONB-PMMA$_{188}$ as macroinitiator.

RESULTS AND DISCUSSION

The bifunctional ONB initiator, 5-bromoisobutyrate-2-nitrobenzyl alcohol, bearing a hydroxyl group and a α-bromoester group was prepared in two steps. The first is that 5-hydroxy-2-nitrobenzaldehyde (**1**) was reduced with $NaBH_4$ to give 5-hydroxy-2-nitrobenzyl alcohol (**2**). Then, 5-hydroxy-2-nitrobenzyl alcohol was esterified with α-bromoisobutyryl bromide. As the phenol of 5-hydroxy-2-nitrobenzyl alcohol is several orders of magnitude more reactive for nucleophilic substitution than the benzyl alcohol, particularly as there is the nitro group para to the phenol. With proper stoichiometric control of the deprotonating agent, and slow addition of a slight excess of the 2-bromoisobutyryl bromide, a very high degree of functionalization only at the phenol can be achieved. Considering the bifunctional initiator ONB used for the synthesis of the targeted block copolymers, two different synthetic routes appeared to be possible and both are shown in Scheme 1: (A) synthesis of an ONB-poly(D-lactide) (ONB-PDLA) macroinitiator by ROP of D-lactide and followed by chain extension of ONB-PDLA by ATRP of MMA; or (B) preparation in the reverse manner, that is, ATRP of MMA with subsequent chain extension by ROP of D-lactide.

Route A: ROP of D-Lactide and Followed by Chain Extension of ONB-PDLA by ATRP of MMA

For ROP of D-lactide, solution or bulk polymerization methods can be used. The former can be performed at relatively low temperatures but require longer reaction times, wheras the latter need higher temperatures with shorter reaction times. Here, to protect the α-bromoester functional group of the bifunctional initiator ONB from dissociation at high temperatures, the solution polymerization method was applied. ROP of D-lactide was performed at 80 °C using tin (II) *bis*(2-ethylhexanoate) [Sn(Oct)$_2$] as catalyst and toluene as solvent. Figure 1(a) shows the ^{1}H NMR spectrum of the obtained polymer ONB-PDLA. We calculated the degree of polymerization by comparing the integral of the nitrobenzyl protons (d) with the methine protons (f) of the ONB-PDLA. This calculated value is in good agreement with the theoretical values calculated from the monomer to initiator molar ratio. The molecular weights from GPC and ^{1}H NMR and the $Đ$ of ONBPDLA are listed in Table 1.

ROP of D-lactide was also attempted by organo-base catalysis with 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU), which has been demonstrated to work well for lactide ring opening with superb end group-fidelity, good polymerization control, and fast kinetics at room temperature.[38] However, in our system, no ONB-PDLA polymer was obtained using DBU as catalyst and ONB as initiator at 25 °C after 4 h. The ^{1}H NMR spectrum of the mixture of ONB and DBU shows that ONB is not stable in the presence of DBU (Supporting Information Fig. S1). The complex nature of the NMR spectrum indicates the presence of several species owing to the occurrence of side reactions. As no polymer was obtained, our hypothesis is that transesterification at the ATRP initiating site occurred, and thus destroying it.

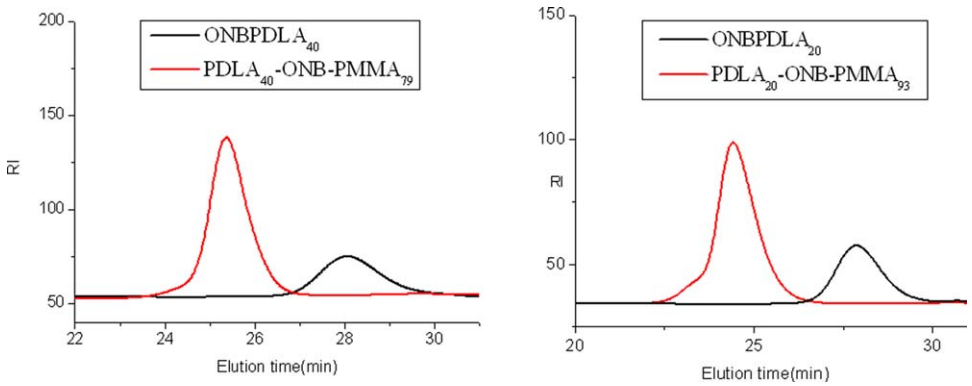


FIGURE 2 GPC traces of ONB-PDLA macroinitiator and the corresponding diblock copolymer PDLA-ONB-PMMA. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

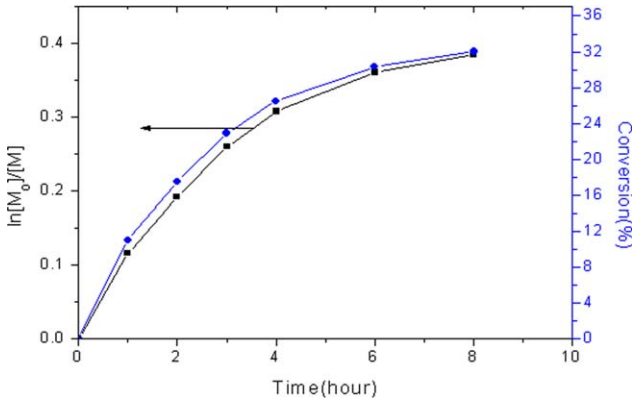


FIGURE 3 Kinetics study for ATRP of MMA using ONB as initiator. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

The completion of the ATRP of MMA initiated by ONB-PDLA is confirmed via ^{1}H NMR with the appearance of characteristic resonances belonging to the methoxy (j) and methyl groups (k) of the PMMA side chain, and methylene (l) and methine (o) groups of the PMMA backbone [Fig. 1(b)]. The GPC curves of the copolymer PDLA-ONB-PMMA (Fig. 2, red lines) reveal a clear shift toward higher MW when compared to the ONB-PDLA macroinitiator trace (Fig. 2, black lines). Moreover, the diblock copolymer traces are unimodal and symmetrical, no tailing in the low-molecular-weight region is observed, and the molecular weight distributions are quite narrow. The molecular weights from GPC and ^{1}H NMR and the $Đ$ of the PDLA-ONB-PMMA are listed in Table 1. The repeat units of both blocks were calculated from the $M_{n,NMR}$.

Route B: ATRP of MMA with Subsequent Chain Extension by ROP of D-Lactide

ATRP of MMA initiated by ONB was conducted at 80 °C using distilled toluene as solvent. Figure 3 shows the results of the kinetic studies on ATRP of MMA using ONB as the initiator. Compared to the kinetics curve of ATRP of MMA using α-bromoisobutyrate as initiator,[39] we found that when using ONB as initiator, the polymerization rate is slower and monomer conversion is much lower. The nonlinear plot of ln[M]/[M$_0$] versus time (Fig. 3) indicates that some side reaction and/or termination occurred in the system. In fact, the nitrobenzene group of the initiator has been shown to perturb radical polymerization.[40] Although the molecular weight cannot be controlled well, the obtained ONB-PMMA has a fairly narrow $Đ$ (Table 1). In the kinetics study, low MMA initial concentration (0.13 g/mL) was used owing to easy to withdraw the samples from the flask and the evaluated sample reached a conversion of only 32% after 8 h. Increasing the monomer concentration could possibly improve the polymerization rate and monomer conversion. With increasing monomer concentration to 0.19 g/mL, the conversion of MMA after 8 h can rise to 78.5%. ONB-PMMA$_{188}$ with narrow dispersity is synthesized under this condition. However, its molecule weight ($M_{n,GPC}$) is much higher than theory one. The initiating efficiency calculated from $M_{n,GPC}/M_{n,theory}$ is about 30%, which indicates that the polymerization is not well controlled and nitrobenzene group in ONB initiator perturbs ATRP.

Figure 4(a) shows the ^{1}H NMR spectrum of ONB-PMMA. In addition to the characteristic protons of the methoxy, methylene, and methine groups in PMMA, the protons from the nitrobenzene group are apparent. The molecular weight of

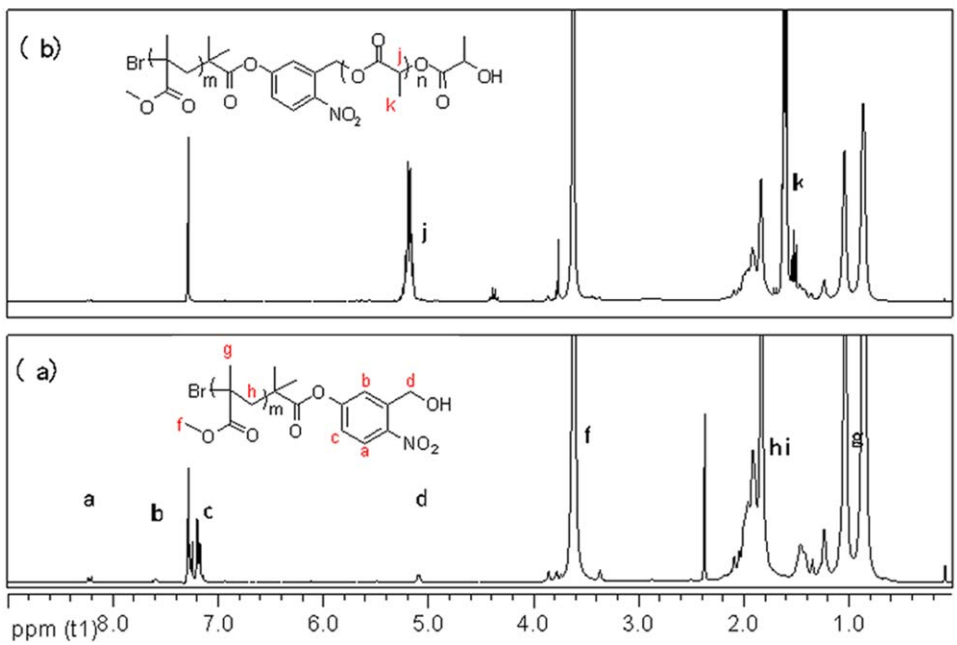


FIGURE 4 ^{1}H NMR spectra of ONB-PMMA$_{188}$ (a) and PMMA$_{188}$-ONB-PDLA$_{138}$-DBU (b) in $CDCl_3$. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

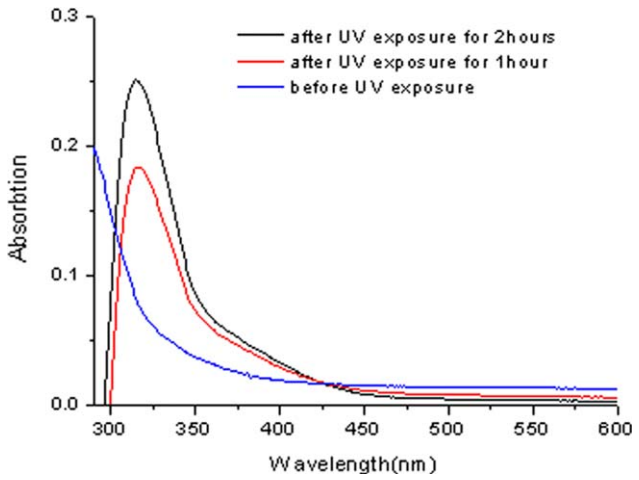


FIGURE 5 Time-dependent UV–Vis spectra changes of $PMMA_{188}$-ONB-$PDLA_{138}$-DBU in THF (0.86 mg/mL). [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

ONB-PMMA was calculated according to the integration of the aromatic proton near the nitro group and the methoxy protons in the PMMA. This value agrees with the molecular weight obtained by GPC.

Chain extension of ONB-PMMA was performed by ROP of D-lactide. Here, both $Sn(Oct)_2$ and DBU catalysts were used, as either catalyst system worked well. The obtained copolymers were characterized by ^1H NMR [Fig. 4(b)] and GPC (Table 1). Compared with the ^1H NMR spectrum of ONB-PMMA, two new resonances (at 5.2 and 1.7 ppm) appeared in the ^1H NMR spectrum of PMMA-ONB-PDLA. These corresponded to the methine proton and methyl protons of PDLA, respectively. The copolymers obtained from $Sn(Oct)_2$ ($PMMA_{188}$-ONB-$PDLA_{183}$-Sn and $PMMA_{188}$-ONB-$PDLA_{33}$-Sn) have broader $Đ$ than those of the copolymers obtained with the DBU catalyst ($PMMA_{188}$-ONB-$PDLA_{138}$-DBU and $PMMA_{188}$-ONB-$PDLA_{32}$-DBU), which may be owing to the occurrence of transesterification reactions when the $Sn(Oct)_2$ catalyst is used. Although ONB cannot initiate ROP of D-lactide using DBU as catalyst, ONB-PMMA can act as macroinitiator for ROP of D-lactide using the same catalyst. This may be owing to the PMMA macromolecular chain sterically protecting the ONB ester from transesterification or other side reactions.

Photocleavage of the Block Copolymers

The block copolymers $PMMA_{188}$-ONB-$PDLA_{138}$-DBU and $PMMA_{188}$-ONB-$PDLA_{183}$-Sn were dissolved in THF to prepare 1 mg/mL solutions, and the solutions were exposed to 365 nm UV light (UVL-56, 1350 $\mu W/cm^2$ at 7.6 cm, 583 J/cm^2) for 12 h. The cleaved polymer was isolated by simply removing the solvent in vacuum. GPC analysis of the polymer after UV exposure shows that the elution time of the sample is almost same as that before UV exposure and no drop in molecular weight occurred, which means that photocleavage reaction did not occur under these conditions. In addition, a low-molecular-weight (M_n = 300 g/mol) peak appeared near the toluene flow marker. The UV–Vis spectrum of ONB initiator is shown in Supporting Information Figure S3. The maximum absorption of ONB occurred at about 300 nm. According to the UV–Vis spectra of the copolymer $PMMA_{188}$-ONB-$PDLA_{138}$-DBU (Fig. 5), the maximum absorption of the copolymer occurred at about 290–300 nm and there is very little absorption at 365 nm. Therefore, a UV lamp with its maximum emission at 302 nm and relative intensity at 7.3 cm of 1500 $\mu W/cm^2$ was used instead for the photocleavage reaction. The evolution of the UV absorption spectrum with exposure time is shown in Figure 5. A red-shifted absorption is observed for the diblock copolymer after UV exposure, indicating that the ONB linker is cleaved and transforms from a nitrobenzyl linker to the nitrosobenzaldehyde coproduct (Scheme 1). The THF solution of the copolymer after UV exposure was evaporated and washed with MeOH. GPC analysis of the copolymers before, and after, UV irradiation is shown in Figure 6. After irradiation, the peak associated with the block copolymer is no longer observed, and one new peak is visible on the chromatogram, corresponding to the dissociated PMMA block. Meanwhile, the expected PDLA block is not observed in the GPC curve. When the polymer after UV exposure was not washed by MeOH, the

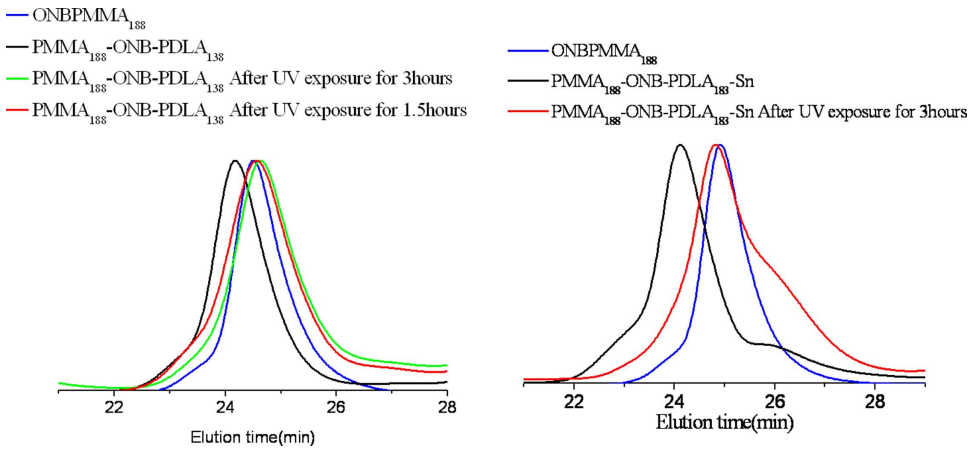


FIGURE 6 GPC traces of $PMMA_{188}$-ONB-$PDLA_{138}$-DBU (left) and $PMMA_{188}$-ONB-$PDLA_{183}$-Sn (right) before and after UV exposure (302 nm) for several hours. [Color figure can be viewed in the online issue, which is available at wileyonlinelibrary.com.]

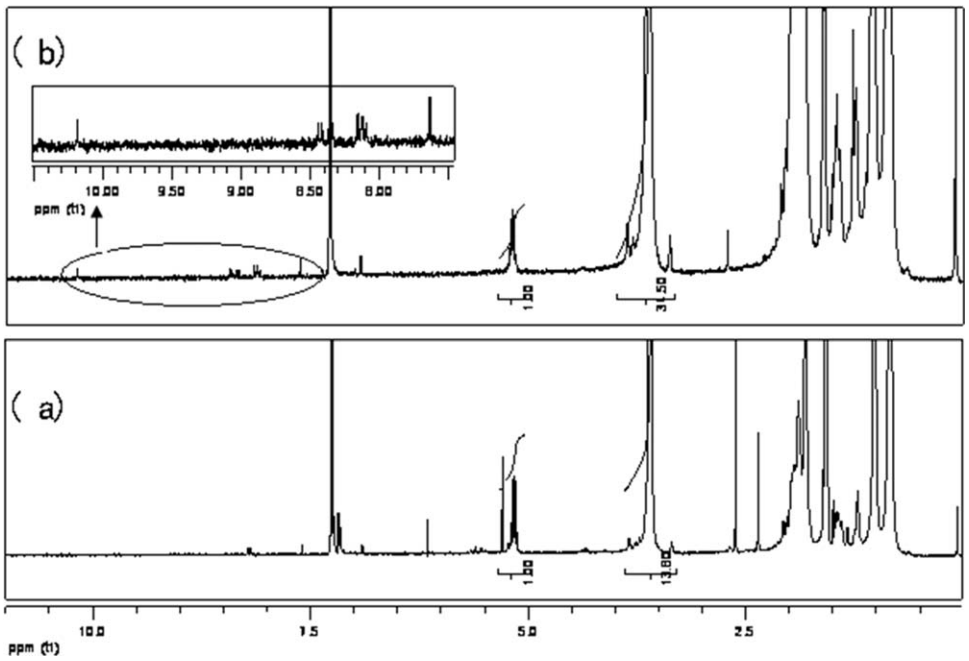


FIGURE 7 ^{1}H NMR spectra of $PDLA_{20}$-ONB-$PMMA_{93}$ before (a) and after (b) UV exposure.

peak corresponding to PMMA block is accompanied by one more peak at about 300 g/mol (Supporting Information Fig. 2*S*). This peak might arise from the photodegradation of the PDLA block. The photodegradation of PLA is reported to proceed via the Norrish II mechanism at ester group and ethylidene group adjacent to the ester oxygen.[32] This general mechanism of photodegradation has been expanded by Bocchini et al.[37] to include the formation of anhydride groups when the radiation source used is closer to a natural outdoor exposure. In the proposed mechanism, anhydride groups are formed via initial tertiary radicals that react with oxygen and extract hydrogen-forming hydroperoxide groups. The hydroperoxide further undergoes photolysis with the formation of the anhydride group by β-scission.

Additionally, the photocleavage was followed by ^{1}H NMR. In Figure 7, significant changes in the spectrum are observed after photocleavage. The benzyl CH_2 protons from the nitrobenzyl group at δ 5.5 ppm disappear and a resonance corresponding to the coproduct benzaldehyde proton appears at δ 10.2 ppm, indicating that the photolysis took place. At the same time, the aromatic signals are also affected owing to the transition from a nitrobenzene to a nitrosobenzene structure, and thus confirming the cleavage. Furthermore, comparison of the integral ratio of the methoxy protons in the PMMA block and the methine proton in the PDLA block before and after UV irradiation shows a reduction of PDLA content.

CONCLUSIONS

In this study, we have successfully synthesized photocleavable PDLA-ONB-PMMA and PMMA-ONB-PDLA block copolymers with good control of molecular weight and dispersity by combining ATRP and ROP through the use of a bifunctional initiator (ONB) by two different synthetic routes. For the first route, it was found that DBU could not be successfully applied as a catalyst for ROP of lactide. However, $Sn(Oct)_2$ catalyst works well in this system, resulting in the ONB-PDLA macroinitiator. The well-defined block copolymer PDLA-ONB-PMMA was synthesized via chain extension of ONB-PDLA by ATRP of MMA. For the second route, although the nitrobenzene group of ONB perturbs ATRP of MMA, the obtained ONB-PMMA macroinitiators with narrow $Đ$ effectively initiate ROP of lactide using $Sn(Oct)_2$ or DBU catalysts, resulting in the formation of PMMA-ONB-PDLA block copolymers. The photocleavage of the copolymers occurs under mild conditions by simple irradiation with UV light (302 nm, relative intensity at 7.6 cm: 1500 $\mu W/cm^2$) for several hours. Moreover, it is found that PDLA blocks also photodegraded with a corresponding reduction of molecular weight observed by GPC and NMR which is a further benefit for the facile removal of the sacrificial block.

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