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Poly(alkylene itaconate)s – An interesting class of polyesters with periodically located *exo*-chain double bonds susceptible to Michael addition

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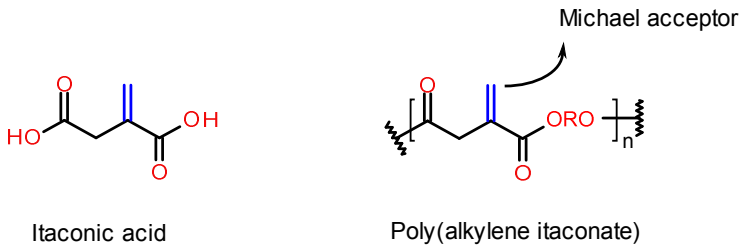
ABSTRACT

Itaconic acid is a bio-sourced dicarboxylic acid that carries a double bond; although several reports have dealt with the radical-initiated chain polymerization of dialkyl itaconates, only a few studies have utilized it as a di-acid monomer to prepare polyesters. In this study, we demonstrate that dibutyl itaconate can be melt-condensed with aliphatic diols to generate unsaturated polyesters; importantly, we show that the double bonds remain unaffected during the melt polymerization. A particularly useful attribute of these polyesters is that the *exo*-chain double bonds are conjugated to the ester carbonyl and, therefore, can serve as excellent Michael acceptors. A variety of organic thiols, such as alkane thiols, MPEG thiol, thio-glycerol, derivatized cysteine etc., were shown to quantitatively Michael-add to the *exo*-chain double bonds and generate interesting functionalized polyesters. Similarly, organic amines, such as N-methylbenzylamine, diallyl amine and proline, also add across the double bond; thus, these poly(alkylene itaconate)s could serve as potentially bio-benign polyesters that could be quantitatively transformed into a variety of interesting and potentially useful functionalized polymers.

INTRODUCTION

Bio-sourced monomers for the preparation of polymers have drawn a great deal of attention in recent times.[1] Itaconic acid is an inexpensive bio-sourced molecule which is produced industrially by the fermentation of glucose and has been listed as one of the "top value-added chemicals from biomass" by the US Department of Energy.[2] Itaconic acid, apart from being a 1,1-disubstituted olefin that can be polymerized via a radical-initiated chain polymerization, is also a aliphatic dicarboxylic acid that could be used to prepare condensation polymers, such as polyesters. Majority of the previous studies, however, have focused on the radical-initiated chain (co)polymerization of dialkyl itaconates that utilizes the double bond to form polymers that carry two pendant ester moieties;[3] relatively fewer studies, however, have explored its utility as a di-acid for the preparation of linear polyesters.[4-7] Barrett et al.[5] prepared polyesters by direct condensation of itaconic acid with diols, either thermally or enzymatically, and utilized the *exo*-chain double bond to crosslink the polyesters in an effort to develop polymeric biomaterials. Recently, Tang et al.[6] condensed itaconic anhydride with diols to generate unsaturated polyesters using an organo-catalyzed solution-polymerization process; the *exo*-chain double bonds were then shown to undergo photo-crosslinking, which provided them a means to prepare potentially bio-benign gels. On careful examination of the structure of the polyester based on itaconic acid, it becomes evident that the *exo*-chain double bond is a part of an α,β-unsaturated ester unit and, therefore, could serve as a Michael acceptor (Scheme 1); this in turn would provide an excellent opportunity to place a variety of functional units at periodic intervals using simple Michael addition.



Scheme 1. Itaconic acid and poly(alkylene itaconate)s

In an effort to explore the potentially interesting post-polymerization functionalization feature of these poly(alkylene itaconate)s, we present here a scalable melt-condensation approach under standard trans-esterification conditions using dibutyl itaconate and a diol; several diols, namely 1,12-dodecane diol, 1,20-icosanediol, 1,4-cyclohexane dimethanol (CDM) and polyethylene glycol (PEG-300), were used to prepare the polyesters bearing the *exo*-chain double bonds at different periodic intervals.

The first objective of the study was to demonstrate that the *exo*-chain double bonds remain intact even during the high temperature melt polymerization, and the second, and more important objective, was to demonstrate their amenability to post-polymerization functionalization using Michael addition – an aspect that had not been examined until very recently. In a very recent report, Lv et al.[7] prepared itaconate-based polyesters using ADMET; they demonstrated that the *exo*-chain double bonds can indeed be utilized as Michael acceptors. In a related study, Ji et al.[8] had earlier prepared a similar polyester bearing *exo*-chain double bonds using the Baylis-Hillman reaction and demonstrated the possibility of functionalization via Michael addition. Michael addition reaction has also been used extensively to prepare linear, hyperbranched and cross-linked polymers because of its mild and high yielding nature;[9] in addition, several recent studies have also used it effectively for post-functionalization of polymers by suitable inclusion of Michael acceptor sites, such as acrylates, as pendant groups.[10] The unique feature of the our study is that the Michael acceptor site is present directly as an *exo*-chain double bond solely by virtue of using itaconic acid as one of the monomers; this makes this class of polymers particularly attractive from the viewpoint of potential biological applications.

EXPERIMENTAL SECTION

Materials and methods. Itaconic acid, dodecanediol, 1,4,-cyclohexane dimethanol, PEG 300, tosyl chloride, MPEG 750 monomethyl ether, diallyl amine, N-benzylmethylamine and dibutyltin dilaurate (DBTDL) were purchased from Sigma-Aldrich Chemical Co. and used directly. L-Proline was purchased from Thomas Baker, eicosane-1,20-dioic acid from Tokyo Chemical Industry Co. Ltd (Japan), thioglycerol from Alfa Aesar and thiophenol from Merck and were used without further purification. Solvents used for synthesis were distilled prior to use and, if necessary, were dried following the standard procedures.[11] NMR spectra were recorded using a Bruker AV 400 MHz spectrometer in suitable deuterated solvents using tetramethylsilane (TMS) as internal reference. GPC studies were carried out using Shimadzu GPC system with UV-PDA detector. The separation of the polymers was achieved using PLgel 5 µm MIXED-C (Mixed gel, Varian) column operated at 27^{o}C and $CHCl_3$ as the eluent. Molecular weights were calculated using standard calibration curve based on the data from UV-PDA detector using narrow polystyrene standards. Thermal characterization was carried out using a Perkin Elmer DSC instrument at a heating/cooling rate of 10°C/min under dry nitrogen atmosphere. Typically, 4-5 mg of the sample was taken and two heating (excluding the first heating) and cooling runs were performed to ensure reproducibility.

Synthesis of the monomers

Dibutyl itaconate. 30 g (0.154 mol) of itaconic acid was taken along with 192 g (2.6 mol) of butanol and catalytic amount of sulphuric acid (~5 g) and refluxed for 6 h. The reaction mixture was then cooled to room temperature, concentrated to about half of its volume and poured into ice-water. The aqueous solution was extracted twice with chloroform; the combined organic extract was then washed with sodium bicarbonate, dried over anhydrous sodium sulphate and concentrated. The product (35 g) was distilled as a colourless, oily liquid using a short-path distillation set-up at 150°C (< 1 Torr) in 73 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 6.31 (s, 1H, -CH_2C(HC**H**)COO-), 5.68 (s, 1H, -CH_2C(**H**CH)COO-), 4.15 (t, 2H, -C(CH_2)COOC**H_2**-), 4.08 (t, 2H, -CH_2COOC**H_2**-), 3.32 (s, 2H, -C(CH_2)C**H_2**COO-), 1.66-1.56 (m, 4H, -$COOCH_2CH_2CH_2CH_3$), 1.42-1.33 (m, 4H, -$COOCH_2CH_2CH_2CH_3$) , 0.95-0.91 (m, 6H, -$COOCH_2CH_2CH_2CH_3$)

1,20-Eicosanediol. 10 g (29.24 mmol) of 1,20-eicosanedioic acid was dissolved in 150 ml of hot THF and dry-nitrogen was purged through the solution. 4.4 g (58.48 mmol) of borane-dimethyl sulfide was added drop-wise and the reaction mixture was stirred overnight. 4N HCl was added to the reaction mixture and THF was removed using a rotavapor. Distilled water was added to dissolve boric acid and the product was extracted in hot chloroform. Chloroform was completely removed using a rotovapor and the diol (8.6 g) was obtained as a white solid after distillation using the Kugelrohr at 215°C(< 1 Torr) in 94 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 3.64 (t, 4H, -C**H_2**OH), 1.58 (m, 4H, -C**H_2**CH_2OH), 1.25 (m, 32 H, -(C**H_2**)$_{16}$$CH_2CH_2$OH)

General polymerization procedure: Poly(dodecyl itaconate). 1 g (4.13 mmol) of dibutyl itaconate and 0.83 g (4.13 mmol) of 1,12-dodecanediol were taken in a test tube-shaped vessel and 52 mg (0.083 mmol) of dibutyltin dilaurate was added to it. 1.14 mg (0.010 mmol) of quinol was added as a radical quencher, to prevent crosslinking.[4] The polymerization was done under dry nitrogen-purge for 12 h at 160 °C and then in Kugelrohr at 165 °C under reduced pressure (< 1 torr) for about 3 h. The polymer was as a white solid after precipitation using chloroform as the solvent and methanol as the non-solvent in 77 % yield. Poly(icosyl itaconate) was prepared similarly, by using 1,20-icosanediol instead of dodecanediol in 75 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 6.36 (s, 1H, -CH_2C(HC**H**)COO-), 5.73 (s, 1H, -CH_2C(**H**CH)COO-), 4.19 (t, 2H, -C(CH_2)COOC**H_2**-), 4.12 (t, 2H, -CH_2COOC**H_2**-), 3.37 (s, 2H, -C(CH_2)C**H_2**COO-), 1.68 (m, 4H, -OCOCH_2C**H_2**(CH_2)$_{16}$C**H_2**CH_2OCO-), 1.29 (m, 16H, -OCOCH_2CH_2(C**H_2**)$_8$CH_2CH_2OCO-)

L-proline methyl ester. 3.5 g (30.97 mmol) of L-proline was added to a 100 mL round-bottom flask. 24 ml of dry methanol was added and nitrogen was flushed through the solution for 10 minutes. 3.25 ml of thionyl chloride (45.63 mmol) was added slowly via a dropping funnel to the solution in ice-cold condition. The mixture was then allowed to stir for 30 minutes at ambient temperature. The clear solution was then refluxed at 65°C for 4 hours. It was then cooled to room temperature and excess thionyl chloride and methanol were removed under reduced pressure to afford the hydrochloride form of L-proline methyl ester in the form of a sticky liquid. The liquid was dissolved in chloroform and 12.78 g of sodium bicarbonate (152.15 mmol) was added. The mixture was stirred for 4 h. It was then filtered and concentrated resulting in the title compound (2 g) in the form of a brownish liquid in 61 % yield.[12]

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 3.79 (dd, 1H, -CH_2(C**H**C$OOCH_3$)NH-), 3.72 (s, 3H, -CH_2(CHCOOC**H_3**)NH-), 3.11-3.05 (m, 1H, -CH_2C**H_2**NH-), 2.95-2.89 (m, 1H, -CH_2C**H_2**NH-), 2.17-2.09 (s, 1H, -C**H_2**(C$HCOOCH_3$)NH-), 1.89-1.81 (s, 1H, -C**H_2**(C$HCOOCH_3$)NH-), 1.79-1.72 (m, 2H, - CH_2C**H_2**CH_2NH-)

N-(tert-Butoxycarbonyl)-L-cysteine methyl ester. 200 mg (0.43 mmol) of N-(tert-Butoxycarbonyl)-L-cystine methyl ester and 184 mg (0.64 mmol) of tris(2-carboxyethyl)phosphine hydrochloride were dissolved in MeOH : H_2O (2 : 1) mixture. The reaction mixture was stirred under nitrogen atmosphere overnight. Methanol was then removed completely and ethyl acetate was used to extract the product from the aqueous layer. The organic layer was collected and washed with sodium bicarbonate solution and then passed through anhydrous sodium sulphate. It was concentrated to afford the product (200 mg) in the form of a light yellow liquid in 99 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 5.40 (s, 1H, -N**H**C$OOC(CH_3)_3$), 4.61 (s, 1H, -NH(C**H**C$OOCH_3$)CH_2SH), 3.82 (s, 3H, -NH(CHCOOC**H_3**)CH_2SH), 3.03-2.98 (m, 2H, -NH(CHC$OOCH_3$)C**H_2**SH), 1.45 (s, 9H, -NHCOOC(C**H_3**)$_3$)

MPEG 750 tosylate: 10 g (13.33 mmol) of PEG 750 monomethyl ether (MPEG 750) was dissolved in 50 ml of THF, and 1.6 g (40 mmol) of sodium hydroxide taken in 20 ml of water was added to it. The contents were placed in an ice-bath and 3.54 g (18.66 mmol) of tosyl chloride dissolved in 50 ml of THF was added drop-wise to it. The reaction mixture was allowed to warm up to ambient temperature and stirred overnight. The organic layer was collected and passed through anhydrous sodium sulphate. THF

was removed completely and the product was extracted in diethyl ether. The product (11 g) was obtained as a white semisolid after complete removal of diethyl ether in 91 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 7.8 (d, 2H, -OSO_2Ar**H**CH_3), 7.33 (d, 2H, -OSO_2Ar**H**CH_3), 4.14 (t, 2H, -C**H$_2$**OSO_2ArCH_3), 3.7-3.5 (m, 60H, -OC**H$_2$C H$_2$**O-), 3.36 (s, 3H, -OC**H$_3$**), 2.43 (s, 3H, -OSO_2ArC**H$_3$**)

MPEG 750 thiol. 12 g (13.27 mmol) of PEG 750 tosylate and 1.51 g (19.91 mmol) of thiourea were taken in absolute ethanol and refluxed for 24 h. Then, nitrogen was purged for 15 min and 1.06 g (26.54 mmol) of sodium hydroxide was added as a 2N solution and the reaction mixture was stirred under nitrogen atmosphere for 48 h. 2N HCl was then added and ethanol was removed completely using a rotovapor. Minimum quantity of water was added and then the contents were extracted with ethyl acetate. To remove sodium tosylate, ethyl acetate was completely removed and the product was further extracted in diethyl ether. The product (6 g) was obtained as a light yellow liquid in 59 % yield.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 3.7-3.5 (m, 60H, OC**H$_2$C H$_2$**O), 3.38 (s, 3H, -OC**H$_3$**), 2.71 (q, 2H, C**H$_2$**SH), 1.61 (t, 1H, CH_2S**H**)

Post-polymerization modification of poly(dodecylitaconate) by Michael addition with MPEG 750 thiol. 300 mg (1.01 mmol; wrt repeat unit) of poly(dodecylitaconate) was dissolved in dry chloroform and 1.16 g (1.51 mmol) of MPEG 750 thiol was added. N-propylamine (2 drops) was added in catalytic amount and nitrogen was purged through the reaction mixture for 10 minutes. The reaction mixture was stirred under nitrogen balloon for 3 days. The reaction mixture was then concentrated and precipitated by pouring into diethyl ether. The polymer was obtained as a light yellow solid after purification twice by precipitation using chloroform as the solvent and diethyl ether as the non-solvent in 71 % yield. PDI-ME and PDI-TG were also purified by the same method whereas in case of PDI-TP and PDI-CYS, methanol was used as the non-solvent.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 4.10-4.03 (m, 4H, C(CH_2)COOC**H$_2$**), 3.7-3.5 (m, 60H, OC**H$_2$C H$_2$**O), 3.38 (s, 3H, -OC**H$_3$**), 1.59 (m, 4H, $OCOCH_2$C**H$_2$**$(CH_2)_{16}$C**H$_2$**CH_2OCO), 1.25 (m, 16 H, $OCOCH_2CH_2$(C**H$_2$**)$_8CH_2CH_2OCO$)

Post-polymerization modification of poly(dodecylitaconate) by Michael addition with diallyl amine.

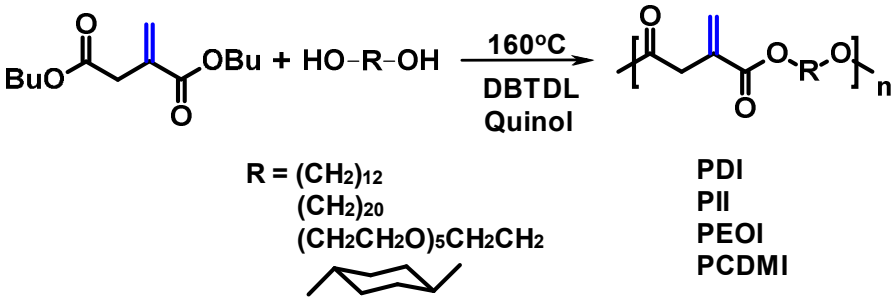
300 mg (1.01 mmol; wrt repeat unit) of poly(dodecylitaconate) was dissolved in dry chloroform and 176 mg (1.82 mmol) of diallyl amine and 107.43 mg (1.01 mmol) of lithium perchlorate were added to it. Nitrogen was purged through the reaction mixture for 10 minutes and the reaction mixture was stirred

under nitrogen atmosphere for 3 days. The reaction mixture was then concentrated and precipitated from methanol. The polymer was obtained as a light yellow solid by purification twice by precipitation using chloroform as the solvent and methanol as the non-solvent in 73 % yield. For PDI-MBA and PDI-PRO, the same procedure was followed except that in case of PDI-PRO, 3 equivalent of the amine was added.

^{1}H NMR (400 MHz, $CDCl_3$, δ ppm): 5.82-5.72 (m, 1H, -CH2C**H**=CH2), 5.16-5.10 (m, 2H, -CH2CH=C**H2**), 4.09-4.02 (m, 4H, C(CH_2)COOC**H_2**), 3.14-2-46 (m, 9H, -C**H_2**C**H**(COO-)C**H_2**N(C**H_2**CH=CH_2)C**H_2**CH=CH_2**),** 1.59 (m, 4H, OCOCH_2C**H_2**(CH_2)$_{16}$C**H_2**CH_2OCO), 1.25 (m, 16 H, OCOCH_2CH_2(C**H_2**)$_8$CH_2CH_2OCO)

RESULTS AND DISCUSSION

As stated earlier, our first objective was to develop a general scalable synthetic scheme for the preparation of periodically graftable polyesters based on itaconic acid – a bio-sourced and inexpensive monomer. For this purpose, initially dimethyl itaconate was prepared as one of the monomers but its relatively low boiling point made it difficult to carry out melt polycondensation effectively; hence, a higher boiling diester, namely, dibutyl itaconate, was prepared and used for the trans-esterification polymerization.



Scheme 2. Synthesis and structures of the parent linear polyesters based on itaconates.

The melt trans-esterification polymerization was carried out using several diols, namely 1,12-dodecanediol, 1,20-icosanediol, 1,4-cyclohexane dimethanol (CDM) and PEG-300, using dibutyltin dilaurate as the catalyst (Scheme 2). The polymerization was done in two steps – first, the melt containing the two monomers and the catalyst was stirred at 150°C under continuous nitrogen purge; during this period oligomerization occurred by the removal of butanol as a condensate. In the second step, the test tube-shaped reaction vessel was connected to a Kugelrohr apparatus and the contents were stirred by rotation at 160°C, under reduced pressure, to drive the equilibrium to the right and facilitate the formation of high molecular weight polymer. It was initially observed that some amount of

insoluble polymer was formed; however, upon carrying out the polymerization in the presence of a small amount of quinol, which acted as a radical quencher, gelation was largely inhibited.[5]

The parent polyesters, namely poly(dodecyl itaconate) (**PDI**) poly(icosyl itaconate) (**PII**), and poly(CDM-itaconate) (**PCDMI**) were isolated after two reprecipitations using chloroform as the solvent and methanol as a non-solvent; poly(oligoethyleneoxy itaconate) (**PEOI**), however, was obtained using chloroform as the solvent and diethyl ether as the non-solvent.

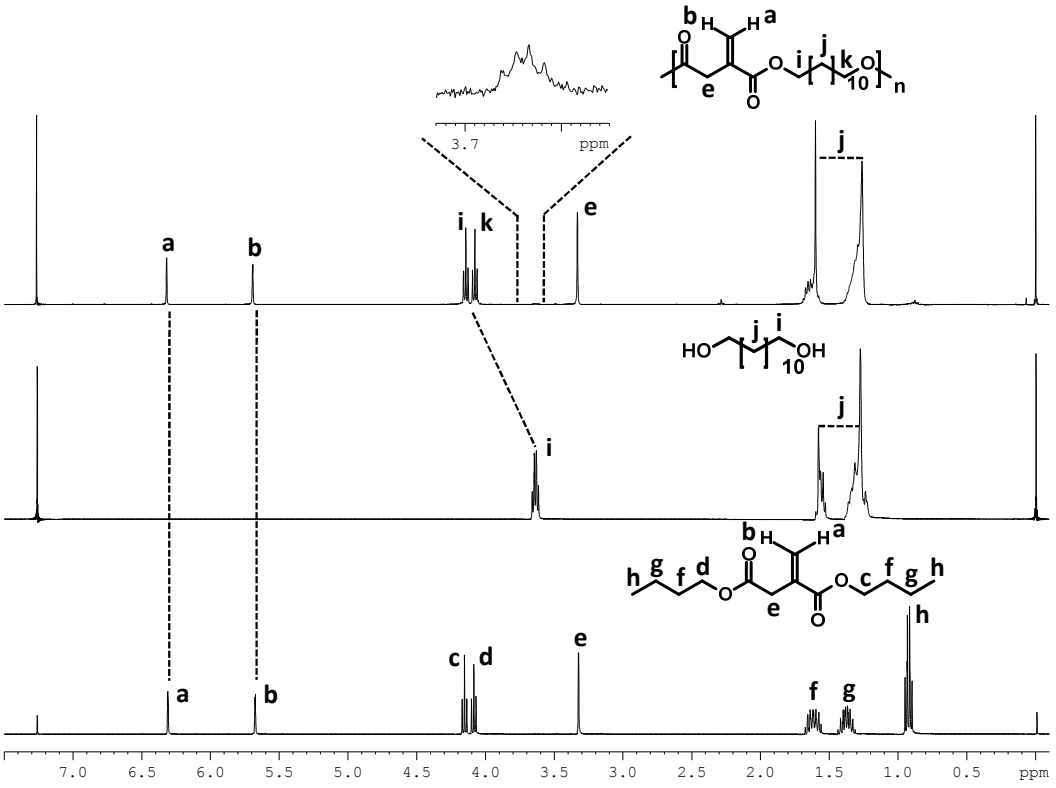
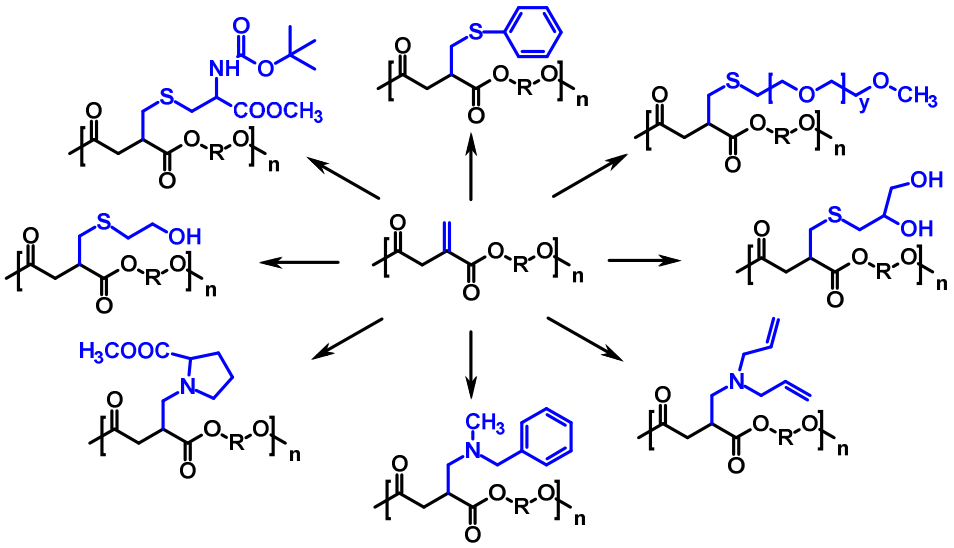


Figure 1. ^{1}H-NMR spectra of the monomer, dibutyl itaconate and one representative parent poly(alkyl itaconate), namely PDI. The expanded region shows the presence of end-groups arising from the alcohol termini, which was used to estimate the DP.

The proton NMR spectra of dibutyl itaconate and dodecanol, along with that of one parent polyester, are shown in Figure 1. The spectra clearly reveal the formation of the expected polyester; as an illustrative example, the spectrum of poly(dodecyl itaconate) is discussed here. The transformation of the dibutyl itaconate monomer to the long-chain polyester does not bring about large differences in the spectra, apart from the more intense peaks in the alkylene region (1.0 - 1.7 ppm). The methylene proton

(-C**H**$_2$OH) peak seen in the diol spectrum, however, almost completely disappears upon polyester formation; although, expansion of this region reveals the presence of very small residual peak that is ascribed to the chain ends. Using the relative intensity of this residual peak, and assuming that only one end (on average) is terminated by the diol, the lower limit for the degree of polymerization (DP) was estimated to be ~15. More importantly, the two peaks, at around 5.7 ppm and 6.3 ppm, in the polyester reveals that the itaconate double bond has remained intact during the high temperature melt condensation; this clearly underlines the value of this approach both in terms of its scalability and the unique opportunity it provides for further functionalization. One of the distinctive features of this approach is that the periodicity of the *exo*-chain double bonds along the polymer chain is governed by the choice of the diol used; here, we have examined two different linear alkylene chains, namely C12 and C20, in addition to two other aliphatic diols – one rigid CDM and the other a flexible PEG-300 diol, were also used. The ^{1}H-NMR spectra of the three other parent polyesters also reveal the formation of the expected structures wherein the *exo*-chain double bond remains unaffected (see Figure S1). It is important, however, to recognize that the polyesters formed would be regio-irregular and, therefore, the periodicity of the *exo*-chain double bonds would vary by ± 1 carbon atom. The GPC molecular weights (M_n) of the polyesters ranged from 15360 to 815800 (Figure S2); the molecular weights and PDI in some cases were unusually high suggesting the possible formation of microgels due to slight crosslinking.



Scheme 3. Structures of various derivatives prepared using Michael addition onto the parent polyester.

In order to examine the possibility of polymer modification via Michael addition, one representative poly(alkylene itaconate), namely **PDI**, was first treated with a variety of thiols, namely thiophenol (PDI-

TP), 2-mercaptoethanol (PDI-ME), thioglycerol (PDI-TG), derivatized cysteine (PDI-CYS) and MPEG-750 thiol (PDI-PEG750); in all cases n-propyl amine was used as a catalyst. The ^{1}H-NMR spectra (Figure 2) of the thiolated polyesters clearly reveal the complete disappearance of the olefinic protons suggesting that the Michael addition is nearly quantitative; the relative intensities of the additional peaks due to the added segment are in accordance with the expected structures (Figure S3). Upon Michael addition, a chiral center is generated along the polymer chain; this is clearly evident from several multiplets corresponding to the two methylene protons (**d** and **e**) adjacent to the chiral center; however, no stereo-selectivity would be expected and hence a racemic mixture of two chiral forms is formed.

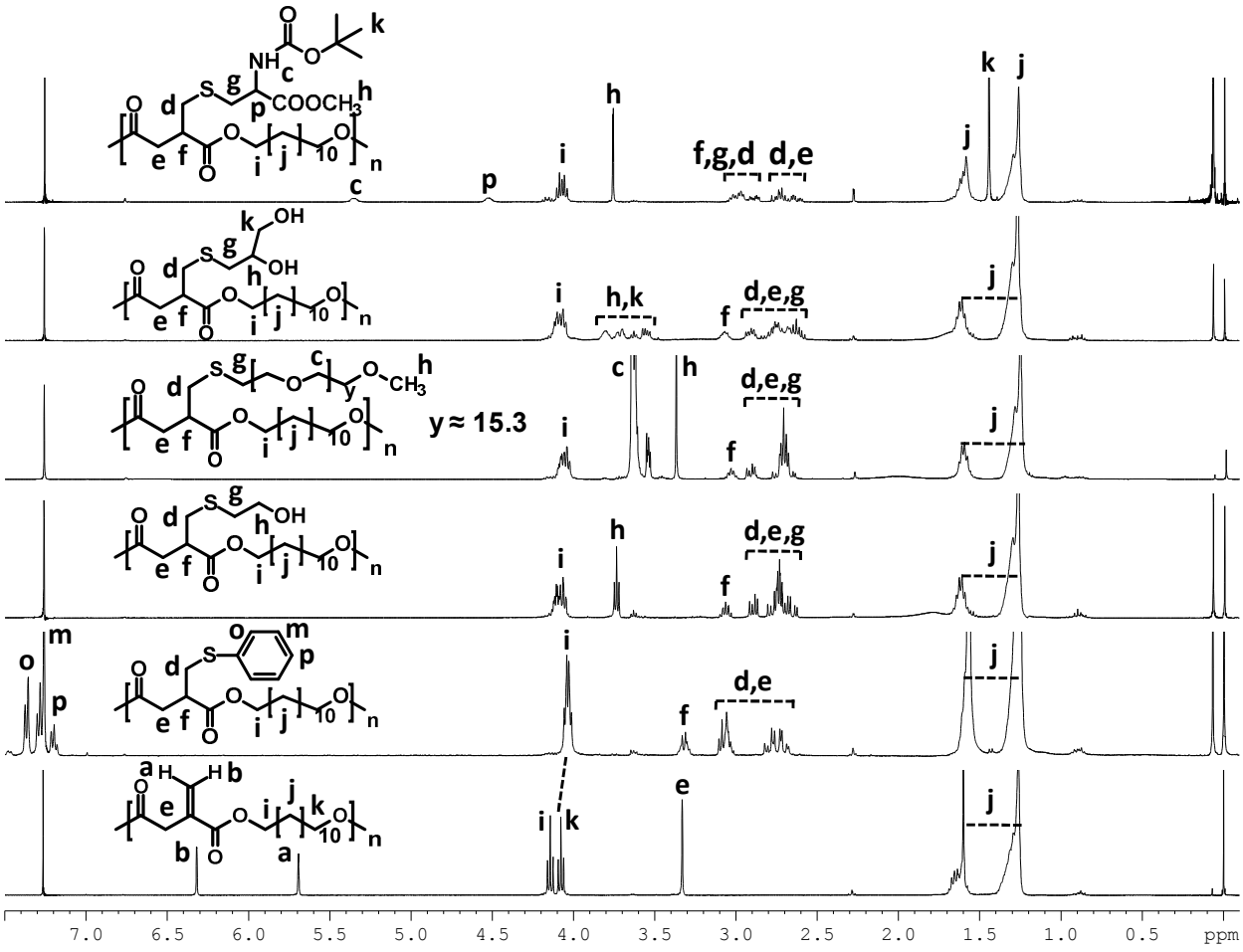


Figure 2. ^{1}H NMR spectra of the parent polyester **PDI** (a), and the different thiol-derivatized copolymers. All the spectra were recorded in $CDCl_3$. The expanded region (5.7 – 6.4 ppm) in the spectra of the grafted polymers clearly reveals the complete disappearance of the vinyl protons (Figure S3).

Similarly, Michael addition was also carried out using different amines, such as N-methylbenzyl amine (PDI-MBA), diallyl amine (PDI-DAA) and L-proline, methyl ester (PDI-PRO). Here again, disappearance of

the vinyl protons of the parent polyester confirms that the reaction is nearly quantitative (Figure 3); additionally, the relative intensities of the added fragment matches the expected values (Figure S4). It is interesting to note that, in the case of the polymer bearing the L-proline unit, the protons of the methyl ester appears as two distinct peaks of equal intensity (peak g); this is evidently due to the presence of two diastereomeric forms generated by the reaction with the L-proline derivative. It is interesting that, despite the fairly remote location of the methyl ester group with respect to the new sterogenic center that is formed, two distinct peaks are observed reflecting the two diastereomeric forms (Figure S4(c)). In the case of PDI-CYS also the methyl ester protons appear as two distinct peaks of equal intensity, although the two peaks were not as well separated (Figure S3(c)). Together, these experiments clearly reveal that poly(alkylene itaconate)s, generated by a fairly simple melt condensation process using dibutyl itaconate, yields an interesting class of unsaturated polyesters that can be readily functionalized by Michael addition using a variety of thiols and amines, including amino acid derivatives of cysteine and proline. The GPC molecular weights of the derivatized samples ranged from 4096 to 913466 (Figure S5); in some instances, derivatization appeared to lower the molecular weight of the sample. This apparent decrease in molecular weight is possibly due to the collapse of the amphiphilic chain into a compact folded form that has a smaller hydrodynamic volume than that of the parent polyester. Here again the unusually high molecular weights of some samples could be either due to aggregation or to the presence of microgels.

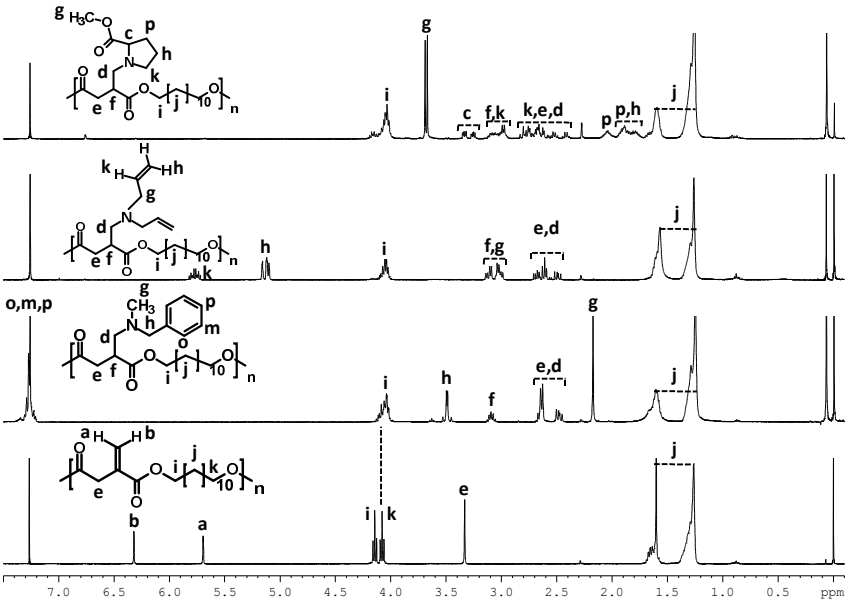


Figure 3. ^{1}H NMR spectra of the parent polyester **PDI** (a), and the different amine-derivatized copolymers. All the spectra were recorded in $CDCl_3$.

The DSC thermograms of the two parent linear polyesters, **PDI** and **PII** showed a clear melting transition, which is completely reversible, as evident from the crystallization peak during the cooling scan (Figure S6) and also completely reproducible (Figure S7). This melting peak, we ascribe to the backbone alkylene segments, and reflects the ability of these segments to collocate and crystallize.

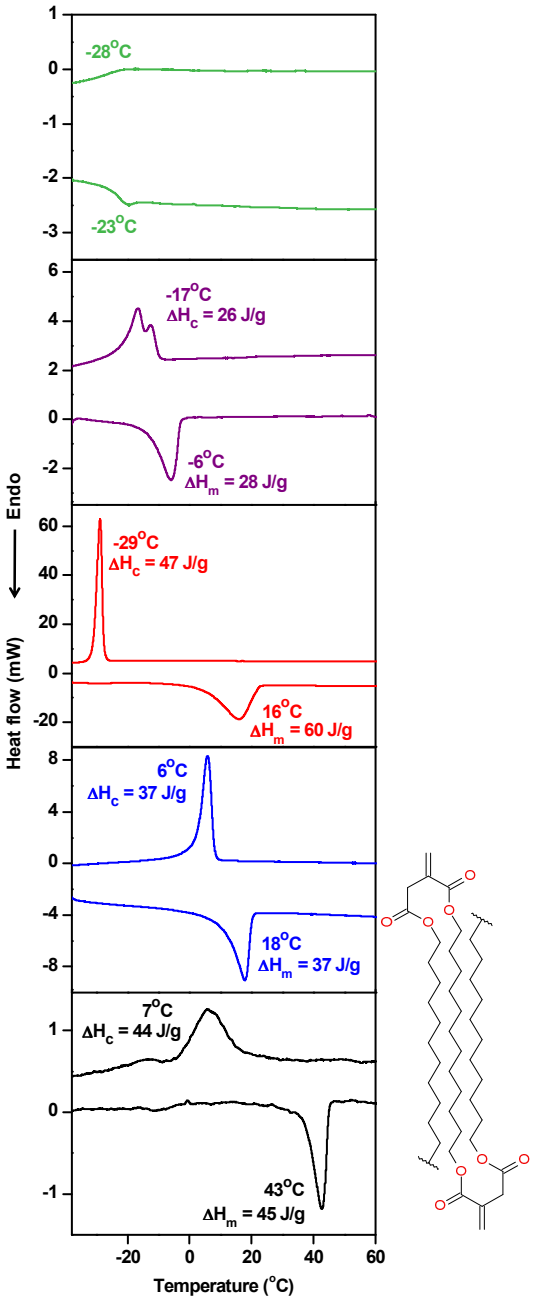


Figure 4. DSC thermograms of parent polyester PDI (black), PDI-TG (blue), PDI-PEG750 (red), PDI-ME (violet) and PDI-CYS (green); the scans were run at a heating rate of 10 deg/min and are completely reproducible; PDI sample was run at 2 deg/min due to its slow rate of crystallization. A simplified schematic depiction of the proposed folded zigzag conformation that could be adopted by the parent polyester is shown on the right.

Comparing the melting points of **PDI** and **PII** clearly reveals that the melting temperature of the polyester with the longer alkylene segment is significantly higher (43^{o}C to 58^{o}C), in accordance with what might be expected. It appears that the presence of an *exo*-chain double bond (sp^2 carbon) in the polyester appears to cause the backbone alkylene segments to fold back and possibly adopt a zigzag conformation that permits the alkylene segments to collocate and crystallize, as depicted in figure 4. On the other hand, PEOI which contains PEG300 in the backbone does not exhibit any transition whereas PCDMI displayed only a glass transition temperature at -8^{o}C which can be ascribed to the presence of the rigid cyclohexanedimethanol segment. However, only some of the derivatized samples exhibited a melting transition, while in the other cases no transition was visible in the expected temperature range (Figure 4). It appears that some of the substitutents appear to permit (or even assist) the formation of the folded conformation, while others appear to completely disrupt it; this is probably because of inter-chain interactions begin to dominate in the solid state and prevent the adoption of this folded conformation. Clearly, hydrophilic entities, such as in the cases of thioglycerol, mercaptoethanol or MPEG, appears to support the formation of the proposed structure, while the rest appear to disrupt it. This assumption is further strengthened if we compare the DSC thermograms of PDI-PRO and PII-PRO. In the case of PDI-PRO, no transition is visible whereas PII-PROLINE exhibits a melting transition at 43^{o}C (Figure S8). As the number of methylene groups in the backbone increases from 12 to 20, the tendency of the alkylene segments to collocate and thereby fold and subsequently crystallize increases; thus, intra-chain interactions gain prominence over inter-chain interactions.

In summary, we have demonstrated that dibutyl itaconate can be condensed with different diols under standard melt-transesterification polymerization conditions; the resulting polyesters carry periodically located *exo*-chain double bonds that serve as useful handles for further functionalization by Michael addition. A wide variety of thiols and amines were shown to readily react with these *exo*-chain double bonds to yield a range of interesting derivatives; NMR spectra of these derivatives clearly reveal that quantitative transformation can be achieved. When long chain diols are used, the resulting poly(alkenylene itaconate)s serve as excellent systems to locate desired functional groups at controlled intervals along the polymer chain; the ability to place amino acid derivatives, such as cystine and proline, clearly reveals the potential of these systems to prepare polymers that could have interesting biological applications.

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Supporting Information Available. All the original NMR spectra with the relative intensities and DSC thermograms. This material is available free of charge via the Internet at http://pubs.rsc.org.

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