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Poly(isoprenecarboxylates) from Glucose via Anhydromevalonolactone

Nicolas R. Ball-Jones, Grant W. Fahnhorst, and Thomas R. Hoyer*

Department of Chemistry, 207 Pleasant St., SE, University of Minnesota, Minneapolis, MN 55455

Abstract

A short and efficient synthesis of a series of isoprenecarboxylic acid esters (ICAEs) and their corresponding polymers is presented. The base-catalyzed eliminative ring-opening of anhydromevalonolactone (**3**) provides isoprenecarboxylic acid (**6-H**), which was further transformed to the ICAEs. Reversible addition-fragmentation chain-transfer (RAFT) polymerization was used to synthesize high molecular weight ($>100 \text{ kg mol}^{-1}$) poly(isoprenecarboxylates) with dispersities (M_w/M_n) of ca. 1.5. The glass transition temperatures (T_g) and entanglement molecular weights (M_e) of the poly(isoprenecarboxylates) were determined and showed similar trends to the T_g and M_e values for analogous poly(acrylate esters). These new glucose-derived materials could provide a sustainable alternative to poly(acrylates).

Graphical Abstract

The synthesis of polymers from renewable feedstocks is of growing importance to a sustainable society. We sought to capitalize on the ready availability of mevalonate (**1**), for which an efficient bioengineered preparation via fermentation of glucose has recently been developed in the Zhang laboratory.¹ The carboxylate **1** can be readily converted (Scheme 1) through acidification to mevalonolactone (**2**) and, in turn, anhydromevalonolactone (**3**). Simple hydrogenation then gives β -methyl- δ -valerolactone (β M δ VL, **4**). This saturated lactone has been demonstrated by investigators in the Hillmyer, Bates, and Macosko

*Corresponding Author hoye@umn.edu.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge on the ACS Publications website a DOI: ###.

Experimental procedures for preparation and structural characterization and copies of ¹H and ¹³C NMR spectra of monomers **6** and the derived poly(isoprenecarboxylate esters).

The authors are inventors on a provisional patent application.

laboratories to be an effective monomer for ring-opening transesterification polymerization (ROTEP) enroute to valuable polyesters containing P β M δ VL.^{1,2}

We have been exploring various alternative strategies that capitalize on the ready availability of **2-4** in ways that might lead to additional novel monomers and/or polymers. (*Z*)-3-Methylpenta-2,4-dienoic acid (or isoprenecarboxylic acid, **6-H**, Figure 1) has been prepared from anhydromevalonolactone (**3**).^{3,4} However, we can find no reports of the polymerization of **6-H** or any of its esters (**6-R**). In contrast, 4-methylpenta-2,4-dienoate (**7**),⁵ sorbic acid esters (**8**),⁶ pentadienoates (**9**),⁷ and 3-methylene-4-pentenoates⁸ have all been polymerized under one or more of radical, anionic, or cationic conditions. Light-induced topochemical polymerizations of the related dienoate salts **11a-d** have also been described.⁹ All of these unsymmetrical dienic monomers can, in principle, give rise to a variety of regioisomeric relationships in the derived polymeric backbones. For example, methyl penta-2,4-dienoate (**9** or β -vinylacrylate) has been radically polymerized to give a homopolymer comprising an 85:15 mixture of backbone repeat units arising from competitive 1,4- vs. 1,2-addition.⁷ Finally, we also note the recent work of Boday and coworkers, who polymerized “methylidenelactide”¹⁰ and pointed out that this compound was one of only a few examples of acrylate-like monomers in which all atoms are bio-derived (the others arising from itaconic or levulinic acid or via bioengineered routes to acrylic acid from sugars).¹¹

We report here the preparation of a series of esters derived from **6-H** and their radical polymerization to poly(isoprenecarboxylates). Cornforth first demonstrated³ the eliminative opening of lactone **3**, most likely via **5** and an E1cB mechanism, under the action of potassium tert-butoxide (Scheme 2). Acidification gives the acid **6-H**. We have routinely prepared and isolated the potassium salt **6-K** on multi-ten-gram scales. The non-nucleophilic bases NaO*t*Pr or 1,8-diazabicyclo[5.4.0]undec-7-ene (DBU) also effect this transformation, although not as cleanly as KO*t*Bu. Other known methods for accessing this penta-2,4-dienoic acid are less attractive from a preparative point of view: e.g. cross-coupling of alkenylstannanes,¹² multi-step sequences,¹³ or generation as a mixture of 3- and 4-methylpentadienoic acids from isoprene.¹⁴ Fischer esterification of **6-H** with any of the alcohols MeOH, EtOH, or *n*-BuOH gave, following distillation, each of the esters **6-Me**, **6-Et**, and **6-*n*Bu**, respectively, in the yield indicated in Scheme 2. Alternatively, the *tert*-butyl ester **6-*t*Bu** was prepared by suspension of **6-H** in isobutylene and treatment with H₂SO₄ as a Brønsted acid catalyst.

We first used azobisisobutyronitrile (AIBN) to initiate a polymerization of methyl isoprenecarboxylate (**6-Me**) (Scheme 3) to provide poly(methyl isoprenecarboxylate) (**PMIC**). This reaction was examined both in the bulk and in methanol at varying initial monomer concentrations. This demonstrated that **6-Me** behaves in a similar fashion to other conjugated dienoates (Figure 1). ¹H and ¹³C NMR analysis of the **PMIC** suggested that the polymerization occurs via competing 1,4- and 1,2-addition modes in a ratio of ca. 1.5:1. Additionally, the broad nature of nearly all resonances were indicative of the likely formation of multiple diastereomeric relationships among the new stereogenic alkene (*E/Z*) and sp³ carbon atoms (*R/S*) that arise from the addition of each monomer.

We carried out a competition experiment in which the two diene monomers **6-Me** and ethyl sorbate (ethyl hexa-2,4-dienoate) were copolymerized to partial (ca. 50%) conversion under AIBN initiation in order to gain some insight about the relative reactivity of the two. Although overlap of resonances from each of the unreactive monomers and the copolymer product made it difficult to obtain precise quantitative assessment, we conclude that the **6-Me** was consumed ca. 4 times faster than the ethyl sorbate. This is consistent with an expected easier approach of any propagating radical to the unsubstituted methylene carbon (C5) of the monomer **6-Me** compared to attack at C5 of ethyl sorbate.

To gain additional control over M_n and lower the dispersities of the polymer products, especially when made via bulk polymerization,¹⁵ we explored several reversible deactivation radical polymerization strategies.¹⁶ Nitroxide mediated radical polymerization of **6-Me** in the bulk initiated by TIPNO-St¹⁷ behaved in a manner characteristic of a living polymerization; the M_n increased linearly with conversion (see Figure S1 in the Supporting Information). This product showed a substantially lower dispersity ($\text{MWD} = 1.45$) than that of the polymer prepared from the AIBN bulk polymerization (cf. Scheme 3).

Because of the somewhat exotic nature of the TIPNO-St initiator, we also explored reversible addition-fragmentation chain-transfer (RAFT) polymerization of the esters **6-R** (Figure 2a). When **6-Me** (1 equiv) was polymerized in the presence of AIBN (8×10^{-5} equiv) and the trithiocarbonate **12** (DDMAT¹⁸, 1×10^{-3} equiv) as the RAFT agent, the resulting **PMIC** showed an M_n of $150 \text{ kg} \cdot \text{mol}^{-1}$ and a dispersity of 1.5 (SEC vs. PS). The T_g of the sample was 34°C and its entanglement molecular weight ($M_e = 4\rho RT/5G_n^\circ$) was $17 \text{ kg} \cdot \text{mol}^{-1}$. The RAFT polymerization of **6-Me** again appeared to be living (Figure 2b). As has been reported with, for example, methyl methacrylate, this RAFT polymerization also proceeded in the absence of a radical initiator.^{19,20} It is also worth noting that neither of these controlled polymerization methods altered the ratio of 1,4- vs. 1,2-addition modes of polymerization (i.e., the ratio remained ca. 1.5:1).

With the goal of establishing the effect of the ester alkyl moiety on T_g and M_e , we also prepared high molecular weight polymer samples from the series of esters **6-Et**, **6-nBu**, and **6-tBu**. Samples of each of **PEIC**, **PnBIC**, and **PtBIC** having $M_n > 100 \text{ kg} \cdot \text{mol}^{-1}$ were prepared using AIBN and **12**. The T_g s and M_e s of these poly(isoprenecarboxylates) are given in Table 1a. The T_g s decrease as the ester alkyl moiety grows in size until the *t*-butyl analogue is reached, in which case there is a substantial increase in the T_g . This is quite analogous to the trend seen for simple poly(acrylate) esters (cf. Table 1b). Similarly, the M_e s for the poly(isoprenecarboxylates) parallel those for the analogous poly(acrylates). The former tend to be higher than the latter for most of the same ester alkyl groups, perhaps reflecting the contribution from the larger side chain moieties arising from the 1,2-mode of polymerization of the isoprenecarboxylate monomers **6**.

In summary, we have prepared a series of four esters of isoprenecarboxylic acid (**6-H**) that differ in the size of the ester alkyl moiety. This parent acid was made by an eliminative opening of anhydromevalonolactone (**3**), a commodity efficiently available in large quantities from glucose.¹ Each ester was polymerized under RAFT conditions to provide a series of high molecular weight polymers. The glass transition temperature and

entanglement molecular weight of each was determined. The ester alkyl group in these polymers affected the T_g and M_e in a very similar fashion as is known for simple poly(acrylates). This work establishes the feasibility of using glucose as a source of polymers with acrylate-like properties.

Supplementary Material

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Scheme 1.

The facile chemical conversion of mevalonate (1) to β-methyl-δ-valerolactone (βMδVL, 4) via mevalonolactone (2) and anhydromevalonolactone (3)

Figure 1. Isoprenecarboxylic acid (**6-H**) and its esters (**6-R**) described here and related dienoates (**7-11**) whose polymerizations have been previously described.

Scheme 2.

Elimination reaction to form the dienolate potassium salt 6-K and subsequent Fischer esterification of the conjugate acid 6-H to provide isoprenecarboxylate esters 6-R

Solvent	[6-Me] ₀ mol·L ⁻¹	Conversion	<i>M</i> _n	<i>M</i> _w	Đ
none	8.0	98	54 k	300 k	5.6
MeOH	3.0	99	14 k	32 k	2.3
MeOH	1.8	84	6.8 k	12 k	1.7
MeOH	0.7	78	1 k	1.4 k	1.4

Scheme 3.

Free radical polymerization of 6-Me, initiated by AIBN as both a neat sample and in MeOH solution

Figure 2.

RAFT polymerization of isoprenecarboxylates **6-R**. **(a)** Conditions used for the polymerization of bulk samples of each of **6-Me**, **6-Et**, **6-*n*Bu**, and **6-*t*Bu**. **(b)** SEC of aliquots vs. time for polymerization of **6-Me** (in the presence of 0.01 equiv of **12**) showing linear increase in molecular weight with % conversion.

Table 1
Glass transition temperature (T_g) and M_e of poly(isoprenecarboxylates) vs. poly(acrylates)

(a) Comparison of glass transition temperatures (T_g) and entanglement molecular weights (M_e) for the four PICA esters; all five samples had $M_n > 100$ kg·mol⁻¹. (b) T_g and M_e for poly(methyl acrylate) (**PMA**), poly(ethyl acrylate) (**PEA**), poly(*n*-butyl acrylate) (**PⁿBA**), and poly(*t*-butyl acrylate) (**P^tBA**).

a Poly(isoprenecarboxylates)				
	<i>PMIC</i>	<i>PEIC</i>	<i>PⁿBIC</i>	<i>P^tBIC</i>
T_g (°C)	34	10	-19	55
M_e (kg/mol)	17	22	41	39

b Poly(acrylates)				
	<i>PMA</i>	<i>PEA</i>	<i>PⁿBA</i>	<i>P^tBA</i>
T_g (°C)	22 ^a	-8 ^a	-43 ^a	55 ^a
M_e (kg/mol)	9 ^b	12 ^c	29 ^d	NA

^aRef. 21a-d.

^bRef. 21a-d.

^cRef. 21a-d.

^dRef. 21a-d.