Organometallics **1999,** *18,* 5577−5583

Preparation, Characterization, and Application of Polymer-Supported Stannols and Distannoxanes†

Duncan H. Hunter* and Chantelle McRoberts

Department of Chemistry, University of Western Ontario, London, ON N6A 5B7, Canada

Received August 6, 1999

Novel organotin copolymers derived from poly-3- and poly-4-(2-di-*n*-butylchlorostannyl)-ethylstyrene-*co*-divinylbenzene-*co*-styrene have been prepared. The copolymers were prepared with various proportions of monomers and converted to organotin oxides and organotin carboxylates. Copolymer-bound organotin oxides, as a mixture of stannol and distannoxane, have been shown to catalyze the lactonization of hydroxycarboxylic acids.

Introduction

The synthetic versatility of organotin reagents is well documented, and several exhaustive reviews exist.[1] Common organotin reagents include trialkyltin halides, which can be converted to trialkylarylstannanes, silylstannanes, and distannanes as well as stannols and distannoxanes. These tin derivatives have been applied to numerous organic transformations. Of particular interest to this work is the application of organostannols and distannoxanes to esterfication reactions.[2]

Despite the versatility of organotin reagents, they are generally toxic and quantitative removal of organotin impurities from reaction mixtures is often difficult. To alleviate these pitfalls, an insoluble cross-linked polystyrene-supported trialkylchlorostannane has been prepared and applied to the Geise reaction[3] and Stille coupling reaction.[4] In addition, it has been reduced to form a tethered tin hydride.[5] This immobilized trialkylstannane was effective for free radical cyclizations with a reactivity similar to tri-*n*-butylstannane. However, unlike tri-*n*-butylstannane, tin impurities were removed by simple filtration. This polymer-supported tin hydride was applied to free radical dehalogenations,[6] deaminations,[6] dehydroxylations,[7] and ring enlargement reactions.[8] This insoluble polymer-supported tin system overcomes purification and toxicity concerns often associated with tin reagents.

In recent years, this laboratory has been developing an approach to radiopharmaceutical[9] and pharmaceutical preparation based on this same polymer-bound trialkylchlorostannane. Investigations have focused on a polymer-bound chlorostannane with the highest attainable loading capacity. This present study reports on the preparation and characterization of trialkylchlorostannane copolymers of varying loading capacity. These copolymers have been converted to distannoxane, stannol, and stannyl carboxylate derivatives. Their application as catalysts for esterfication reactions has been investigated.

Results and Discussion

Copolymer Preparation. As illustrated in Scheme 1, three copolymers, **2A**−**C**, have been prepared using different amounts of **1**, styrene, and divinylbenzene (Table 1). Neither **1** nor **2A**−**C** are commercially available but have been prepared by modification of a published procedure[9] as described in the Experimental Section. Each of these copolymers was a granular white solid, insoluble but swellable in both organic and alcoholic solvents, including chloroform and ethanol. The extent of cross-linking, as determined by the proportion of divinylbenzene employed, remained constant at 15 mol %. However, the mol % of **1** was decreased from 85% (**2A**) to 42% (**2B**) to 8.5% (**2C**). Technical grade divinylbenzene as a mixture of meta and para isomers was used for all preparations. In addition, the technical mixture contained 20 mol % ethylvinylbenzene. Because polymer yields were not quantitative (50−73 wt %) and the relative reactivity of each monomer is unknown, the actual proportions of the monomers in the resultant copolymers are unknown and ethylvinylbenzene might also have been incorporated. Consequently, the structure drawn in Scheme 1 for **2A**−**C** is not meant to suggest a block copolymer and the ethylvinylbenzene component has been omitted.

Solid-state MAS ^{119}Sn NMR spectroscopy of each copolymer showed only one signal at 148−150 ppm, which is consistent with a trialkylchlorostannane such

---

* To whom correspondence should be addressed. E-mail: dhunter@julian.uwo.ca.

† This work contains parts of the Ph.D. Thesis of C. McRoberts, 1999, University of Western Ontario.

[1] (a) Van Der Kerk, G. J. M. In *Organotin Compounds: New Chemistry and Applications* Zuckerman, J. J., Eds.; Advances in Chemistry Series; 1976; p 157. (b) Davies, A. G. *Organotin Chemistry:* VCH: Weinheim, 1997. (c) Smith, P. J. *Chemistry of Tin*; Blackie: London, 1998. (d) Pereyre, M.; Quintard, J. P.; Rahm, A. *Tin in Organic Synthesis*; Butterworths: London, 1986.

[2] Mascaretti, O. A.; Furlan, R. L. E. *Aldrichim. Acta* **1997**, *30*, 55, and references therein.

[3] Bokelman, C.; Neumann, W. P.; Peterseim, M. *J. Chem. Soc., Perkin Trans. 1* **1992**, 3165.

[4] Kuhn, H.; Neumann, W. P. *Synlett* **1994**, 123.

[5] Gerigk, U.; Gerlach, M.; Neumann, W. P.; Vieler, R.; Weintritt, V. *Synthesis* **1990**, 448.

[6] Gerlach, M.; Jordens, F.; Kuhn, H.; Neumann, W. P.; Peterseim, M. *J. Org. Chem.* **1991**, *56*, 5971.

[7] Neumann, W. P.; Peterseim, M. *Synlett* **1992**, 801.

[8] Dygutsch, D. P.; Neumann, W. P.; Peterseim, M. *Synlett* **1994**, 363.

[9] (a)Hunter, D. H.; Marinescu, A. M.; Loc'h, C.; Maziere, B. *J. Labelled Cmpd. Radiopharm.* **1995**, *37*, 144. (b) Hunter, D. H.; Zhu, X. Z. *J. Labelled Cmpd. Radiopharm* **1999**, *42*, 653.

10.1021/om990630d CCC: $18.00

Scheme 1

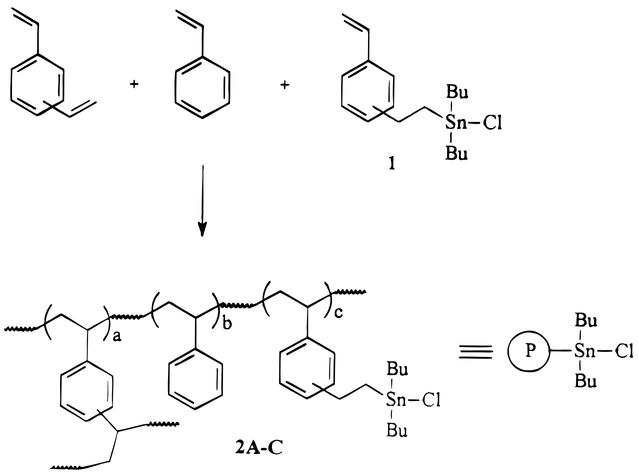


Table 1. Quantities of Monomers Used in the Preparation of Poly-3- and Poly-4-(2-(dibutylchlorostannyl)-ethylstyrene-*co*-divinylbenzene-*co*-styrene Copolymers

copolymer	**1**, mmol	styrene, mmol	divinyl-benzene, mmol	yield, wt %	loading capacity, mmol/g
2A	225	0	40	50	1.6
2B	112	112	40	73	1.1
2C	22.5	202	40	55	0.24

as tributylchlorostannane at 141 ppm[1a] or **1** at 143 ppm. The absence of additional peaks indicated that there was no hydrolysis of the chlorostannane copolymers during polymerization despite the refluxing biphasic aqueous conditions employed. The MAS ^{13}C NMR spectrum of copolymer **2A** showed signals consistent with the anticipated structure. No signals typical of vinyl carbons were observed, indicating complete reaction of each double bond of the divinylbenzene. Energy-dispersive X-ray (EDX) analyses were consistent with approximately equal amounts of tin and chlorine atoms within each copolymer.

Overnight treatment of each copolymer in ethanolic sodium hydroxide solution led to complete hydrolysis, as evidenced by solid-state MAS ^{119}Sn NMR spectroscopy. The signal at 148−150 ppm, attributed to a trialkylchlorostannane, completely disappeared and was replaced by overlapping signals at 91 and 101 ppm. These signals are attributed to trialkyltin oxides and will be discussed later.

The effective proportion of **1** present in each copolymer was evaluated by argentometric titration[10] of the chloride released upon basic hydrolysis. These values, in mmol Cl/g polymer, represent the loading capacity for all three copolymers and are included in Table 1. These loading capacities translate to 68, 46, and 10 wt % of monomer **1** in copolymers **2A**, **2B**, and **2C**, respectively. In comparison, the proportions of monomer **1** used in the polymer preparations correspond to 94, 73, and 25 wt %, respectively. Thus it seems monomer **1** is being incorporated into these copolymers in decidedly lower proportions than is present in the polymerization reaction mixture.

Solution phase organotin reagents including hexa-*n*-butyldistannoxane, tri-*n*-butylchlorostannane, and di-*n*-butyltin oxide are known to catalyze esterfication reactions.[2] Tri-*n*-butylchlorostannane and hexa-*n*-butyldistannoxane have also found use in protecting group chemistry.[11] The polymer-supported tin oxides (**4A−C**), obtained by hydrolysis, provide a potential solid phase substitute for these solution phase reagents. As well as overcoming solution phase problems of purification and toxicity, the solid phase may impart special reactivity due to the spatially discrete catalytic centers and the possible effects of anchoring.

Conversion to Tin Carboxylates. Trialkylsilyl groups are commonly used as protecting groups, and trialkylstannyl groups have also been investigated.[12] With trialkystannyl groups, carboxylic acids can be both protected and deprotected under mild conditions, although tri-*n*-butylstannyl carboxylates prove sensitive to moisture. Attachment of the trialkylstannyl protecting group to an insoluble solid support could provide the advantage of simplifying isolation and purification procedures during multistep syntheses, as well as reducing the rate of tin carboxylate hydrolysis.

As a model for solid-phase carboxylic acid protecting groups, the copolymer-supported stannyl toluate **3** was prepared using the highest loading capacity trialkylchlorostannane **2A**. As illustrated in Scheme 2, reaction of copolymer **2A** with sodium toluate led to a new polymeric material, **3**. The solid-state MAS ^{119}Sn NMR spectrum showed a disappearance of the signal at 148 ppm and the appearance of a new tin signal at 104 ppm consistent with a tin carboxylate.[13] In addition, IR spectroscopy further confirmed the structure with a characteristic tin carboxylate C=O stretch at 1645 cm^{-1}.[14] The loading capacity of copolymer **3** was determined from the amount of toluic acid released upon treatment with trifluoroacetic acid and was found to be 1.57 mmol/g.

The stability of this tethered tin carboxylate was determined under conditions of aqueous acetic acid, anhydrous trifluoroacetic acid, and methanol. The amount of toluic acid cleavage was quantified by HPLC, and a time course for each reaction was obtained. The polymer-supported stannyl toluate **3** displayed poor stability under these conditions, ranging from 50% to 100% cleavage within 15 min of exposure. Under protic conditions. transesterification was observed. For example, trifluoroacetic acid in methylene chloride resulted in quantitative release of toluic acid. An IR spectrum of the recovered copolymer indicated a tin carboxylate with an IR stretch at 1645 cm^{-1} and solid-state MAS ^{119}Sn NMR signal at 151 ppm, attributed to stannyl trifluoroacetate.

From these limited cleavage studies, it can be anticipated that most carboxylates will react readily and quantitatively with the copolymeric chlorostannanes to produce tin carboxylates. The cleavage studies indicate that tethering the protecting group to a solid support

---

[10] Day, R. A., Jr.; Underwood, A. L. *Quantitative Analysis,* 2nd ed.; Prentice Hall: Englewood Cliffs, NJ, 1967.

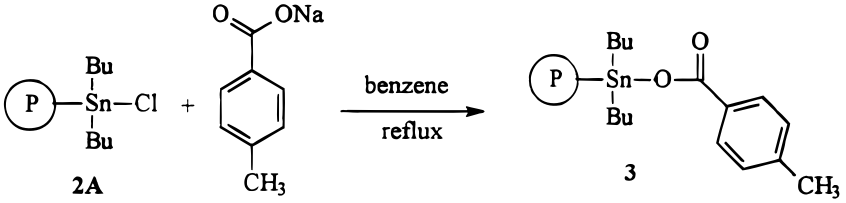
[11] Frankel, M.; Gertner, D.; Wagner, D.; Zilka, A. *J. Org. Chem.* **1965**, *30*, 1596.

[12] Greene, T. *Protective Groups in Organic Synthesis*; John Wiley and Sons: New York, 1981.

[13] Klein, J.; Borsdorf, R. *J. Prakt. Chem.* **1993**, *335*, 465.

[14] Sandhu, G. K.; Kaur, G.; Holecek, J.; Lycka, A. *J. Organomet. Chem.* **1988**, *345*, 51.

Scheme 2



Scheme 3

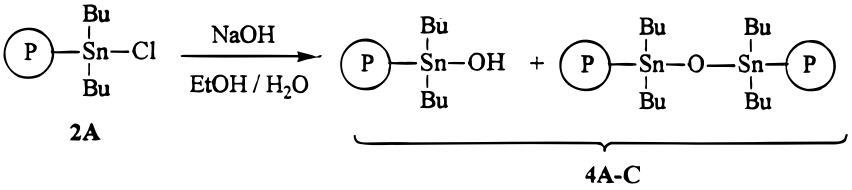


Table 2. Distannoxane/Stannol Ratios of Copolymers 4A−C and Their Loading Capacities

copolymer	loading capacity,[a] mmol/g	ratio[b] of distannoxane to stannol	distannoxane, mmol/g	stannol, mmol/g
4A	1.6	1.5	0.6	0.4
4B	1.1	1.0	0.37	0.37
4C	0.24	0.25	0.04	0.16

[a] Calculated from the loading capacity of the appropriate chlorostannane polymer, **2A**−**C**, prior to hydrolysis. [b] Calculated from the ratio of the peaks at 92 and 101 ppm in the MAS ^{119}Sn NMR spectra.

does not improve chemical stability of the tin carboxylate bond under acidic conditions. As a result of this chemical instability, no tin carboxylates were prepared at reduced loading capacities from copolymers **2B** and **2C**. While this chlorostannane copolymer system is not a practical protecting group for carboxylic acids, perhaps it has applicability to amino acids, as has been reported[11] for the tri-*n*-butylstannyl group.

Conversion to Tin Oxides. As previously mentioned, stannols, distannoxanes, and stannoxides have found application as catalysts for esterification, deesterification, and lactonization reactions.[2] Since hydrolysis of the chlorostannane copolymers led to mixtures of polymer-bound stannols and distannoxanes **4**, as indicated in Scheme 3, the three copolymers were prepared and characterized for their potential as catalysts. Thus each of the copolymers, **2A**−**C**, was treated with alcoholic sodium hydroxide and characterized spectroscopically. The solid-state MAS ^{119}Sn NMR spectra of each of these organotin oxides, **4A**−**C**, showed two overlapping signals, one at 91 and a second at 101 ppm. The ratio of these peaks differed according to the loading capacity of the original chlorostannane copolymers, Table 2. On the basis of solution and solid phase precedent, the peak at 91 ppm was assigned to distannoxane and the peak at 101 ppm to stannol. Our own solution phase ^{119}Sn NMR spectra ($CDCl_3$) for hexa-*n*-butyldistannnoxane gave a peak at 93.7 ppm and for tri-*n*-butylstannol at 105.8 ppm. Hexa-*n*-butyldistannnoxane is reported to give a peak at 92.0 ppm in $CDCl_3$ and at 84.8−84.3 ppm in benzene-d_6.[15] Previously prepared and structurally analogous polymer-supported trialkyldistannoxanes were reported[16] to give a signal at 83 ppm.

In addition to presenting the observed ratio of the peaks at 91 and 101 ppm, Table 2 also includes the observed loading capacity of the chlorostannane copolymers **2A**−**C**, used to prepare the tin oxide derivatives, **4A**−**C**. On the basis of these loading capacities and the ratio of NMR signal intensities, loadings of the distannoxanes and stannols were calculated and are listed. The copolymer with the highest loading capacity, **4A**, also gave the highest ratio of distannoxane relative to stannol, 1.5, and also the largest amount of distannoxane, 0.6 mmol/g. As the total loading capacity decreased, so did the distannoxane/stannol ratio.

In solution, an equilibrium between hexa-*n*-butyldistannoxane and tri-*n*-butylstannol occurs, and the observed distannoxane/stannol ratios may reflect a similar equilibrium within the copolymer backbone. The trend of decreasing distannoxane/stannol ratio with decreasing loading capacity is in accordance with a lower "effective concentration" of monomer **1** in the copolymer as a result of dilution with styrene. Attempts to drive additional water from **4A** at reflux in benzene and convert the remaining stannol to distannoxane were unsuccessful. The ratio of the overlapping peaks at 91 and 101 remained unchanged. This indicates more than a simple equilibrium is involved in determining the distannoxane/stannol ratio. Also, proximity of tin sites may play a critical role. Two tin sites in close proximity are needed to allow for distannoxane formation, while tin sites in isolation result in stannols.

Application of Tin Oxide Copolymers to ω-Hydroxycarboxylic Acid Lactonizations. Although there are many existing methods for lactonization[17] of ω-hydroxycarboxylic acids, there are limitations to their general usefulness. Formation of medium and large ring-size lactones from the corresponding ω-hydroxycarboxylic acids are often plagued by a competition between intramolecular and intermolecular reaction. Intermolecular reaction leads to oligomeric products, resulting in lower lactonization yields. In addition, these existing methods utilize either acidic or basic conditions,

---

(15) Lockhart, T. P., Manders, W. F., Brinckman, F. E. *J. Organomet. Chem.* **1985**, *286*, 153.

(16) Dumartin, G.; Kharboutli, J.; Delmond, B.; Pereyre, M. *Organometallics* **1996**, *15*, 19.

(17) Ishihara, K.; Kubota, M.; Kurihara, H.; Yamamoto, H. *J. Org. Chem.* **1996**, *61*, 4560, and references therein.

Table 3. Effect of 3A Stoichiometry on Hexadeconolide and Oligomer Yields

molar ratio[a] of **4A**/**5**	lactone yield,[b] mol %	oligomer yield,[c] wt %
no catalyst	0	0
0.05	0	6
0.10	55	27
0.50	29	27
1.0	18	25
2.0	7	1

[a] Calculated assuming 1.6 mmol/g of tin sites on copolymer **4A**. [b] Determined by HPLC. [c] Determined by gravimetry.

limiting the compatibility with other functional groups present. Tin mediation has been used under nearly neutral reaction conditions in an attempt to solve this latter problem. Hexa-*n*-butyldistannoxane, dibutyltinoxide,[18] tri-*n*-butylchlorostannane, and tri-*n*-butylmethoxystannane[19] have been shown to catalyze ω-hydroxycarboxylic acid lactonizations, although mixtures of lactones and oligomers resulted. Longer chain ω-hydroxycarboxylic acids resulted in moderate yields of lactone accompanied by substantial amounts of oligomeric byproducts. Attempts to prepare medium ring-size lactones (8−12) resulted in oligomeric byproducts almost exclusively.

Copolymers **4A**−**C** were applied to lactonization reactions of ω-hydroxycarboxylic acids to determine the effect of loading capacity on their reactivity as lactonization catalysts. Also, there is a possibility that lower loading capacities or altered distannoxane/stannol ratios might optimize lactonization over oligomerization yields. Since organotin oxides activate ω-hydroxycarboxylic acids toward esterification, spatially discrete tin oxide sites could improve the competition between lactonization and oligomerization without resorting to the inconvenience of infinite dilution techniques. In addition, the tin-containing solid phase catalyst could be easily removed following lactonization.

The four ω-hydroxycarboxylic acids chosen for this study were 16-hydroxyhexadecanoic acid **5**, 12-hydroxydodecanoic acid, 10-hydroxydecanoic acid, and 7-hydroxyheptanoic acid. These starting materials represent two large and two medium-sized lactones.

Optimized reaction conditions were determined for **5** using the highest loading capacity tin oxide copolymer, **4A**, as catalyst. As summarized in Table 3, the molar ratio of **4A**/**5** was systematically changed from 0 to 2.0 in significant intervals. As detailed in the Experimental Section, lactonization reactions were run at reflux in mesitylene for 19 h with 0.03 M concentration of **5**. Lower boiling solvents resulted in reduced yields. A concentration of 0.03 M, near the anticipated effective molarity[20] for this lactonization, was chosen. At this concentration, rates of lactonization and oligomerization should be equal. Thus a minor effect of catalyst on product ratios should be fairly apparent.

The residue obtained after solvent removal was separated into two components by trituration with methanol. The lactones were soluble in the methanol fraction. The methanol-insoluble material was comprised of oligomeric lactones, the nature of which will be described below. The yield of lactone was determined by HPLC analysis against known standards, and the yield of oligomeric lactones was determined by gravimetry.

Table 4. Lactonization of 16-Hydroxyhexadecanoic Acid, 5, Using 4A−C as 10% Catalysts

copolymer	polymer loading,[a] mmol/g	**5** remaining,[b] mol %	lactone yield,[b] mol %	oligomer yield,[c] wt %
4A	1.6	≤1	55	27
4B	1.1	≤1	35	41
4C	0.24	≤1	21	20

[a] Calculated from the loading capacity of the appropriate chlorostannane polymer, **2A**−**C**, prior to hydrolysis. [b] Determined by HPLC. [c] Determined by gravimetry.

As the data in Table 3 indicate, copolymer **4A** acts as a catalyst for lactonization. There is an optimum ratio for both lactone and oligomer yields, which parallel each other. A maximum lactone yield, as well as maximum conversion, was observed with a **4A**/**5** ratio of 0.1. The lactone yield drops sharply at smaller ratios of catalytic sites/**5** and more slowly for higher ratios. The observed optimum lactone yield of 55% is comparable to other reported methods using tin catalysis.[18,19]

Copolymers **4B** and **4C** were employed under the same conditions described above for **4A**. In Table 4 are the observed yields of lactone and oligomers. Since copolymers **4B** and **4C** had reduced loading capacities, the amount of polymer was increased to keep the ratio of catalytic sites/**5** constant at 0.1. Although this ratio was kept constant, the yield of lactone decreased with decreasing loading capacity. The oligomer yield increased and declined again with decreasing loading capacity. For synthetic purposes, the maximum yield of the 17-membered lactone product and the highest overall conversion was observed with the highest loading capacity polymer, **4A**. Presumably, the lactone/oligomer ratio could be improved by lowering the concentration of **5** below 0.03 M, but this was not pursued.

The reaction conditions optimized for **5** were applied to 12-hydroxydodecanoic acid, 10-hydroxydecanoic acid, and 7-hydroxyheptanoic acid for the preparation of 13-, 11-, and eight-membered lactones. The 10-hydroxydecanoic acid and 7-hydroxyheptanoic acid produced no lactone products, but modest yields of oligomers did result, 49 and 17 wt %, respectively. With 12-hydroxydodecanoic acid, a lactone yield of 10 mol % was observed with a 78 wt % yield of oligomers being produced. For each of these hydroxycarboxylic acids, the concentation of 0.03 M is above the anticipated effective molarity for these ring sizes, particularly for eight- and 11-membered lactones. Unless the copolymers exerted a special effect on the lactone/oligomer ratio, little lactone product was anticipated and little was observed.

Competition Studies. In an attempt to determine the preferred mode of reaction of ω-hydroxycarboxylic acids with the copolymer **4A**, three experiments were performed. In one instance, equimolar amounts of phenylacetic acid, benzyl alcohol, and hexa-*n*-butyldi-

---

[18] (a) Steliou, K.; Poupart, M. A. *J. Am. Chem. Soc.* **1983**, *105*, 7130. (b) Steliou, K.; Szczygielska-Nowosielska, A.; Favre, A.; Poupart, M. A.; Hanessian, S. *J. Am. Chem. Soc.* **1980**, *102*, 7578. (c) Otera, J.; Yano, T.; Himeno, Y.; Nozaki, H. *Tetrahedron Lett.* **1986**, *27*, 4501.

[19] White, J. D.; Green, N. J.; Fleming, F. F. *Tetrahedron Lett.* **1993**, *34*, 3515.

[20] Illuminati, G.; Mandolini, L. *Acc. Chem. Res.* **1981**, *14*, 95.

stannoxane were refluxed in benzene. A ^{119}Sn NMR spectrum in benzene-d_6 showed peaks for unreacted hexa-*n*-butyldistannoxane (89.2 ppm) and for tri-*n*-butylstannol (102 ppm) and a peak at 104.5 ppm attributed to tri-*n*-butylstannyl phenylacetate. A stannyl alkoxide would be anticipated near 80 ppm[21] and was not observed. Since tin alkoxides are hydrolytically unstable, care was taken to limit moisture and air exposure of the reaction products. This solution phase result suggests that tin carboxylates form in preference to tin alkoxides under these conditions.

This competition study was extended to the solid phase using copolymer **4A**, phenylacetic acid, and benzyl alcohol. The IR spectrum of the recovered polymer showed a carbonyl stretch at 1649 cm^{-1}, consistent with a tin carboxylate. Finally, equimolar amounts of **5** and copolymer **4A** were refluxed for 1 h in benzene. The IR spectrum of the recovered solid showed a carbonyl stretch at 1637 cm^{-1}, consistent with a tin carboxylate, and a broad peak centered at 3320 cm^{-1} attributed to an alcohol OH. These findings suggest that a ω-hydroxycarboxylic acid reacts selectively through the carboxyl group rather than the hydroxyl group and that reaction is fairly complete. How this bound ω-hydroxycarboxylate proceeds to lactone and oligomeric lactones is a matter of conjecture.

Role of the Catalyst. The results in Tables 3 and 4 suggest a complicated catalytic role for the polymer-supported tin oxides. The data in Table 3 show that at high ratios of **4A**/**5** esterification, be it lactonization or oligomerization, slows or stops. At this high ratio all of the hydroxyacid is presumably bound to the polymer. On the other hand since these polymers do act as catalysts, some amount of bound hydroxyacid must be involved. These competing effects of polymer-supported tin oxides first increasing and then decreasing the extent of esterification lead to an optimum catalytic ratio. It is not yet clear why high ratios of **4A**/**5** lead to decreased esterification yields.

A mechanism in which lactonization occurs through an anchored 16-hydroxyhexadecanoate which bites back on itself is not supported by the results of either Table 3 or 4. Either high ratios of **4A**/**5** or lower loading capacities should lead to more spatially discrete sites. Spatially discrete sites within the polymer matrix would presumably favor lactone formation over oligomerization. The results of Table 4 show the opposite trend and are suggestive of a scheme in which both ends of **5** are activated by binding to tin sites. Thus, higher loading capacity improves the opportunity for both activated ends to meet and result in lactone formation. Such a double activation scenario has been previously proposed for solution reactions involving di-*n*-butyltin oxide catalysis.[18a,b]

Oligomeric Byproducts. The methanol-insoluble oligomeric byproducts isolated by trituration were characterized by mass spectrometry and ^{13}C, ^{1}H NMR and FTIR spectroscopy. All of these anaylyses pointed to polylactones rather than polyesters. Both EI- and CI-MS showed peaks for monomeric through pentameric lactones. The relative proportions of these peaks changed with the lactone ring size targeted. IR spectra gave carbonyl absorptions at 1730 cm^{-1} for a lactone or ester but no peak at 1684 cm^{-1} for a carboxylic acid carbonyl, as seen in the starting hydroxycarboxylic acids. The typical OH absorptions were also absent. Both the ^{13}C and ^{1}H NMR spectra had shifts and splitting patterns for the $-CH_2-$O$-$ more consistent with lactones than with hydroxycarboxylic acids.

In the mass spectra, ions resulting from polylactone fragmentation could not be distinguished with certainty from secondary ions generated in the spectrophotometer. Consequently, the approximate polylactone molecular weights were obtained using camphor freezing point depression.[22] In this way, a M_n of 586 ± 16 g/mol, or an average of 2.3 lactone units per ring, was obtained for the oligomeric mixture from **5** and of 911 ± 2 g/mol, or 4.6 lactone units per ring, for 12-hydroxydodecanoic acid.

Conclusions

Three novel copolymers, **2A**−**C**, of monomer **1**, styrene, and divinylbenzene, differing in their loading capacity, have been prepared and characterized. Hydrolytic conversion to tin oxides lead to polymers as mixtures of stannols and distannoxanes, **4A**−**C**. The ratio of stannol/distannoxane was dependent on loading capacity of the copolymers and thus, presumably, on the "effective" concentration of tin sites. These tin oxides proved to be viable as lactonization catalysts. While no beneficial effect on lactone/oligomer ratios was observed, the solid phase has simplified purification procedures.

Copolymers **2A** and **4A** were converted to tin carboxylates. The stannyl toluate, **3**, proved to be acid sensitive. Competition studies between carboxylic acids and alcohols gave preferential formation of tin carboxylates over tin alkoxides.

Experimental Section

Tri-*n*-butylchlorostannane and hexa-*n*-butyldistannoxane were purchased from Gelest. Styrene (Aldrich, tech.) and divinylbenzene (Aldrich, tech., 80%) were chromatographed through a silica gel column to remove stabilizers prior to use. Solution phase NMR spectra were recorded on a Varian Gemini XL-300 spectrometer and MAS solid-state NMR spectra on a Bruker 200 spectrophotometer after swelling samples in chloroform prior to analysis. All spectra were referenced against tetramethylsilane (^{1}H, ^{13}C) or tetramethylstannane (^{119}Sn). IR spectra were obtained from neat powders on a Bruker ISS55 FT-IR using a diffuse reflectance infrared FT spectroscopy (DRIFTS) accessory manufactured by Spectratech. EDX analyses were performed on an EDAX-CDU leap detector instrument.

HPLC analyses to quantify lactonization yields employed a Hewlett-Packard 1047A refractive index detector, SSI 300 LC pump, Varian 905320 pulse damper, Waters 746 data module, and Rheodyne injector. Eluent composition, prepared with spectrophotometric grade solvents, varied depending on the analysis. All HPLC samples were injected manually onto a Waters Bondapak C18 10 μm reverse phase column. Oligomeric product yields (wt %) were quantified by gravimetry. Lactone yields (mol %) were determined by comparison to calibration curves for each of the authentic lactones prepared[23]

---

[21] Smith, P. J.; White, R. F. M.; Smith, L. *J. Organomet. Chem.* **1972**, *40*, 341.

[22] Atkins, P. W. *Physical Chemistry*, 4th ed.; Freeman and Company: New York, 1990.

[23] Meyer, W. L.; Patterson, W. T.; Reed, S. A.; Leister, M. C.; Schneider, H. J.; Schmidt, G.; Evans, F. E.; Levine, R. A. *J. Org. Chem.* **1992**, *57*, 291.

from commercially available cycloketone precursors. Synthesis of the authentic lactones was confirmed by high-resolution mass spectrometry and comparison to NMR spectral data available from the literature.

Preparation of 3- and 4-(2-Di-*n*-butylchlorostannyl)-ethyl)styrene (Monomer 1). This polymer was prepared following a method similar to Neumann.[5] Di-*n*-butylstannane was prepared by lithium aluminum hydride reduction of dibutyldichorostannane. Equimolar di-*n*-butylstannane and di-*n*-butyldichlorostannane were combined to produce di-*n*-butylchlorostannane in situ, and this was reacted with equimolar divinylbenzene and AIBN, yielding monomer **1**. At reaction completion, an aliquot of the crude reaction mixture was removed for spectroscopic analysis. No attempt was made to purify this monomer, which was used immediately in subsequent polymerizations. ^{1}H NMR spectrum (benzene-d_6): 7.5−7.1 (m, 4H, CH$_{ar}$), 6.75 (m, 1H, CH$_{vinyl}$), 5.8 (m, 1H, CH$_{vinyl}$), 5.25 (m, 1H, CH$_{vinyl}$), 3.0 (m, 2H, CH$_2$), 1.9−0.9 (m, 20H, Sn−CH$_2$ and *n*-Bu). Ethylvinylbenzene was also visible as approximately a 22% impurity. ^{13}C NMR spectrum (benzene-d_6): 136.7, 136.5 (CH, C$_{vinyl}$ $m+p$), 128.9, 128.1, 128.0, 127.3, 126.5, 125.6, 124.3 (CH and C, C$_{AR}$ $m+p+$ethylvinylbenzene), 114.1, 113.9 (CH, CH$_{vinyl}$), 113.1 (CH, CH$_{vinyl,}$), 31.5 (CH, CH$_2$−Ph), 27.7 (CH, *n*Bu), 26.8 (CH, *n*Bu), 19.8, 19.6 (CH, CH$_2$−Sn), 17.7 (CH, *n*Bu), 13.6 (CH, *n*Bu). ^{119}Sn NMR spectrum (benzene-d_6): +143 (Sn−Cl).

Preparation of Poly-3- and Poly-4-(2-(di-*n*-butylchlorostannyl)ethyl)styrene-*co*-divinylbenzene Copolymers (2A, 2B, and 2C). The copolymers were prepared in a resin kettle from the amounts of monomer **1**, styrene, and divinylbenzene shown in Table 1. Each polymerization was carried out at reflux with stirring (~1000 rpm) in the presence of octanol (70 mL), aqueous methylcellulose solution (0.25%, 250 mL), and azobisisobutyronitrile (1.25 g). After 7.5 h, the reaction mixture was cooled and the resultant solid was isolated by decantation. The solid was washed with water until the supernatant ran clear, and similarly with methanol and acetone. Drying at 70 °C at about 1 Torr yielded white granular solids with yields in the range 50−73%. The spectroscopic characterization of each copolymer follows.

2A: MAS solid-state ^{13}C NMR spectrum (swollen in CHCl$_3$): 144, 128 (C+CH, C$_{AR}$), 42 (very broad, CH−Ph, CH$_2$−Ph, CH$_2$ backbone), 28.6 (CH, *n*Bu), 27.7 (CH, *n*Bu), 18.6 (CH, *n*Bu), 14.6 (CH, *n*Bu). MAS solid-state ^{119}Sn NMR spectrum (swollen in CHCl$_3$): +148 (Sn−Cl). IR (cm^{-1}): 3060, 3022 (CH$_{ar}$), 2960, 2925, 2856 (CH$_{aliph}$), 1602, 1500 (C$_{vinyl}$), 1451, 707. EDX atom %: Sn 2.32, Cl 2.10.

2B: MAS solid-state ^{119}Sn NMR spectrum (swollen in CDCl$_3$): +149.8 ppm. IR (cm^{-1}): 3060, 3026 (CH$_{ar}$), 2927, 2857 (CH$_{aliph}$), 1940−1800 (aromatic overtones), 1601, 1495 (C$_{vinyl}$), 796, 705, 535. EDX atom %: Sn 0.94, Cl 0.84.

2C: MAS solid-state ^{119}Sn NMR spectrum (swollen in CDCl$_3$): +149.3 ppm. IR (cm^{-1}): 3060, 3026 (CH$_{ar}$), 2927, 2857 (CH$_{aliph}$), 1940−1800 (aromatic overtones), 1601, 1495 (C$_{vinyl}$), 796, 705, 535. EDX atom %: Sn 0.37, Cl 0.32.

Preparation of Poly-3- and Poly-4-(2-(di-*n*-butylstannol/tetra-*n*-butyldistannoxane)ethyl)styrene-*co*-divinylbenzene-*co*-styrene Copolymers (4A, 4B, and 4C). Each of copolymers **2A−C** (1.0 g) and sodium hydroxide solution (50% in ethanol) was shaken for 16 h and then filtered through a coarse sintered glass filter. The filter cake was washed liberally with additional water and ethanol. The solid was dried at about 1 Torr overnight at 70 °C. All hydrolysis filtrates were collected and set aside for Mohr[10] analysis, and the results are included in Table 2. The characterization of each copolymer follows.

3A: MAS solid-state ^{119}Sn NMR spectrum: 103 (Sn−OH), 91 (Sn−O−Sn), 2:3 relative peak intensity. IR (cm^{-1}): 3026, 3010 (CH$_{ar}$), 2927, 2850 (CH$_{aliph}$), 1601, 1492 (C$_{vinyl}$), 1440, 1360, 755, 703.

4B: MAS solid-state ^{119}Sn NMR spectrum: 100.8 (Sn−OH), 92.2 (Sn−O−Sn), 1:1 relative peak intensity. IR (cm^{-1}): 3026, 3110 (CH$_{ar}$), 2927, 2850 (CH$_{aliph}$), 1594, 1490 (C$_{vinyl}$), 789, 754, 705.

4C: MAS solid-state ^{119}Sn NMR spectrum: 100.6 (Sn−OH), 92.0 (Sn−O−Sn), 4:1 relative peak intensity. IR (cm^{-1}): 3060, 3026 (CH$_{ar}$), 2927, 2850 (CH$_{aliph}$), 1594, 1488 (C$_{vinyl}$), 1453, 754, 705.

Preparation of Poly-3- and Poly-4-(2-(di-*n*-butyl(stannyl-4-toluate)ethyl)styrene-*co*-divinylbenzene (3). Polymer **2A** (760 mg, 1.29 mmol) and sodium toluate (203 mg, 1.28 mmol) were refluxed in benzene (15 mL) for 16 h. The polymer was then isolated by filtration with a sintered glass filter, rinsed with fresh benzene, and vacuum-dried. Solid-state MAS ^{119}Sn NMR spectrum: 104.0 (Sn−O−C═O). IR (cm^{-1}): 3019 (CH$_{ar}$), 2963, 2927, 2857 (CH$_{aliph}$), 1639 (C═O), 1601, 1540 (C$_{vinyl}$), 1350, 750, 700.

Typical Lactonization of *ω*-Hydroxycarboxylic Acids Using Catalytic Organotin Oxide Copolymers 4A−C. To a flask fitted with a Barrett water trap and a condenser was added 16-hydroxyhexadecanoic acid (345 mg, 1.27 mmol), organostannol/distannoxane copolymer **4A** (1.7 mmol/g, 87.7 mg, 0.13 mmol), and mesitylene (45 mL). After 19 h reflux with stirring under an argon atmosphere, the reaction solution was filtered. The solid was washed with fresh mesitylene and chloroform, and the filtrates were concentrated in a vacuum to produce a solid residue.

The resultant residue was triturated with methanol, followed by centrifugation to give solids, which were characterized as detailed below. The solution, containing primarily hexadecanolide, was diluted to a known volume for HPLC analysis. HPLC conditions: 85% methanol, 15% H$_2$O (1 mL H$_3$PO$_4$/1 L), pH 3.0, flow rate 1 mL/min, 32×10^{-5} RIU/FS, 40 °C. Calibration curves were constructed for both hexadecanolide (retention time = 16.5 min) and 16-hydroxyhexadecanoic acid (retention time = 7.6 min). The hexadecanolide identity was confirmed by co-injection with authentic hexadecanolide.

Characterization of Solid Byproducts from Lactonization. The solid remaining after trituration of the 16-hydroxyhexadecanoic acid lactonization was dried at about 1 Torr at room temperature and analyzed by ^{1}H NMR spectroscopy (CDCl$_3$): 4.1 (m, 2H, CH$_2$), 2.3 (m, 2H, CH$_2$), 1.6 (m, 4H, CH$_2$), 1.4−1.2 (m, 22H, CH$_2$). IR (cm^{-1}): 2942, 2857 (aliphatic CH), 1728 (ester C═O). LR-MS gave peaks at 255, 490, 744, and 998, which coincide with monomer through tetrameric polylactones. Camphor freezing point depression was used to determine a number average molecular weight for the mixture of polylactones. Hexadecanolide was used to prepare a standard calibration curve. The solid isolated after trituration gave a number average molecular weight of the polylactone products at 586 ± 16 g/mol.

In a similar manner the solid byproducts from the lactonization of 12-hydroxydodecanoic acid were dried in vacuo and analyzed by ^{1}H NMR spectroscopy (CDCl$_3$): 4.15 (m, 2H, CH$_2$), 2.35 (m, 2H, CH$_2$), 1.65 (m, 4H, CH$_2$), 1.5−1.25 (m, 14H, CH$_2$). LR-MS indicated peaks at 199, 397, 595, 793, and 989, consistent with monomeric through pentameric lactones. Camphor freezing point depression using cyclododecanone as a standard gave an average molecular weight of 911 ± 2 g/mol.

Reaction of Benzyl Alcohol and Phenylacetic Acid with Hexa-*n*-butyldistannoxane. To a flask fitted with a Barrett water trap and a condenser was added benzyl alcohol (80.4 mg, 0.74 mmol), phenylacetic acid (103.1 mg, 0.76 mmol), benzene (25 mL), and hexa-*n*-butyldistannoxane (451.0 mg, 0.76 mmol). After 16 h reflux with stirring under an argon atmosphere, a reaction aliquot was removed and a ^{119}Sn NMR spectrum (benzene-d_6) was obtained: 89.2 (Sn−O−Sn), 102 (Sn−OH), 104.5 (Sn−O−C(O)R)).

Reaction of Benzyl Alcohol and Phenylacetic Acid with Copolymer 4A. To a flask fitted with a Barrett water trap and a condenser was added benzyl alcohol (23 μL, 0.22 mmol), phenylacetic acid (30.4 mg, 0.22 mmol), benzene (15 mL), and copolymer **4A** (1.67 mmol/g, 298 mg, 0.50 mmol). After 2 h reflux with stirring under an argon atmosphere, the polymer was removed by filtration under argon and rinsed with fresh benzene. DRIFTS analysis was performed attempting to keep air exposure at a minimum. IR (cm^{-1}): 3088, 3020 (CH$_{ar}$), 2958, 2917, 2862 (CH$_{aliph}$), 1649 (Sn−O−C(O)R), 1620, 1580 (C$_{vinyl}$), 1066, 792, 703.

Reaction of Copolymer 4A with 5. To a flask fitted with a Barrett water trap and a condenser was added **5** (59 mg, 0.22 mmol), polymer **4A** (1.8 mmol/g, 123 mg, 0.22 mmol), and benzene (15 mL). After 1 h at reflux, an aliquot was removed and filtered under an argon atmosphere, rinsing with fresh benzene. An additional aliquot was removed at 4 h. DRIFTS analysis was performed attempting to keep air exposure at a minimum for both samples. IR (cm^{-1}) 1 h aliquot: 3320 (alcohol), 3020 (CH$_{ar}$), 2929, 2856 (CH$_{aliph}$), 1637 (Sn−O−C(O)-R), 1604, 1557 (C$_{vinyl}$), 1062, 794, 707. The 4 h aliquot gave essentially the same IR spectrum.

Acknowledgment. The authors wish to give particular thanks to Dr. Gian Gobbi, Dow Chemical Inc., Sarnia, Canada, for his generous and unfailing assistance in running the MAS solid-state NMR spectra. Mary Jane Walzak and Ross Davidson of Surface Science Western are to be thanked for their help with DRIFTS and EDX spectroscopies. Also we wish to thank NSERC, Canada, and Merck-Frosst, Canada, for their support of our research through an IOR grant.

OM990630D