CHEMISTRY
A EUROPEAN JOURNAL

Polystyrene-Supported Organotin Dichloride as a Recyclable Catalyst in Lactone Ring-Opening Polymerization: Assessment and Catalysis Monitoring by High-Resolution Magic-Angle-Spinning NMR Spectroscopy

Gaëlle Deshayes,[b] Kevin Poelmans,[a] Ingrid Verbruggen,[a] Carlos Camacho-Camacho,[a, c] Philippe Degée,[b] Vanja Pinoie,[a] José C. Martins,[d] Martial Piotto,[e] Monique Biesemans,*[a] Rudolph Willem,[a] and Philippe Dubois[b]

Abstract: Dialkyltin dichloride grafted to a cross-linked polystyrene, with the formula $[P{-}H]_{(1-t)}[P{-}(CH_2)_nSnBuCl_2]_t$ ($P=[CH_2CH(pC_6H_4)]$, $t=$ the degree of functionalization, and $n=6$ or 11), is investigated as a recyclable catalyst in the ring-opening polymerization (ROP) of ε-caprolactone (CL). It is demonstrated that high-resolution magic-angle-spinning (HR-MAS) NMR spectroscopy is an invaluable tool to characterize completely the supported catalyst. The 2D ^1H–^{13}C HSQC HR-MAS spectrum, in particular, allowed extensive assignment of the ^1H and ^{13}C resonances, as well as accurate measurement of the $^nJ(^1H{-}^{117/119}Sn)$ and $^nJ(^{13}C{-}^{117/119}Sn)$ coupling constants. ^1H and ^{119}Sn HR-MAS NMR spectroscopy is presented as a monitoring tool for catalytic processes based on organotin compounds, particularly for the investigation of the extent to which polymerization residues are observable in situ in the material pores and for the assessment of the chemical integrity and recycling conditions of the grafted catalyst. From polymerization experiments with CL, initiated by *n*-propanol and with $[P{-}H]_{(1-t)}[P{-}(CH_2)_nSnBuCl_2]_t$ of various compositions as the supported catalyst, it appears that a partial 'burst' of the polystyrene support occurs when the length of the alkyl spacer is limited to $n=6$, as a result of polymer chains growing within the pores of the support. However, extension of the length of the aliphatic polymethylene spacer from 6 to 11 carbon atoms preserves the support integrity and allows the production of catalyst-deprived poly(ε-caprolactone) (PCL) oligomers. A preliminary attempt to recycle the heterogeneous catalyst has shown that very good reproducibility can be obtained, in terms of both catalyst activity and molecular-weight parameters of the as-recovered PCL polyester chains.

Keywords: catalysis · lactones · NMR spectroscopy · polymerization · supported catalysts

[a] K. Poelmans, I. Verbruggen, Prof. Dr. C. Camacho-Camacho, V. Pinoie, Prof. Dr. M. Biesemans, Prof. Dr. R. Willem
High Resolution NMR Centre (HNMR)
Department of Polymer Science and Structural Chemistry (POSC)
Vrije Universiteit Brussel, Pleinlaan 2, 1050 Brussels (Belgium)
Fax: (+32) 2-629-3291
E-mail: mbiesema@vub.ac.be

[b] G. Deshayes, Dr. P. Degée, Prof. Dr. P. Dubois
Laboratory of Polymeric and Composite Materials (LPCM)
University of Mons-Hainaut, Place du Parc 20, 7000 Mons (Belgium)

[c] Prof. Dr. C. Camacho-Camacho
Universidad Autónoma Metropolitana
Unidad Xochimilco, Departamento de Sistemas Biológicas
Calzada del Hueso 1100, Col. Villa Quietud
México DF, 04960 (Mexico)

[d] Prof. Dr. J. C. Martins
Eenheid NMR en Structuuranalyse, Vakgroep Organische Chemie
Universiteit Gent, Krijgslaan 281 S4, 9000 Ghent (Belgium)

[e] Dr. M. Piotto
Bruker Biospin S.A.
34 rue de l'Industrie, 67166 Wissembourg Cedex (France)

Introduction

Aliphatic (co)polyesters, prepared by ring-opening polymerization (ROP) of (di)lactones, are versatile polymers with attractive and valuable properties as polymeric and composite materials. In addition, they are biocompatible and degradable by enzymatic and/or hydrolytic chain cleavage of ester bonds, properties that have contributed to their success in biomedical and pharmaceutical applications, such as their use as temporary implant materials and resorbable carriers for controlled drug delivery.[1] Extensive research efforts have focused on the development of effective initiator/catalyst systems for the controlled ROP of (di)lactones. These systems include many organometallic compounds that activate the synthesis of aliphatic polyesters according to anionic or coordination–insertion mechanisms.[2] The main drawback of these organometallic initiators or catalysts results

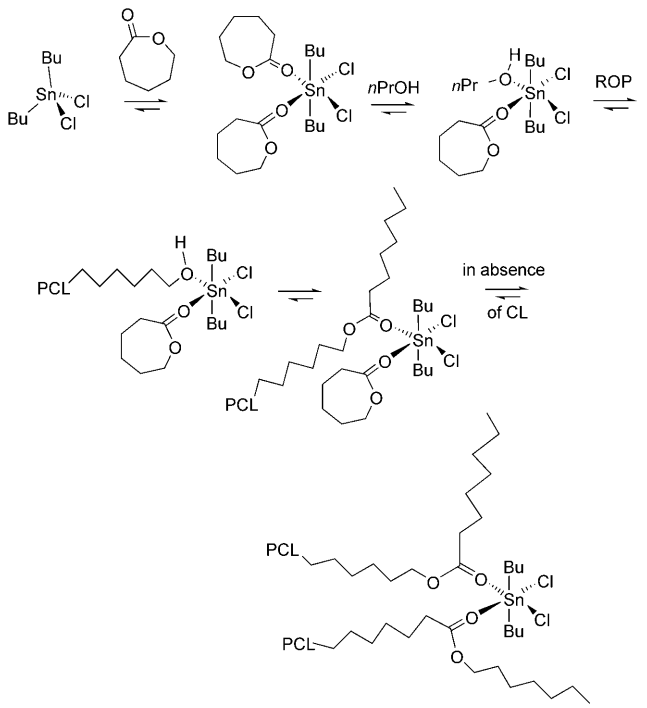
DOI: 10.1002/chem.200500065

from their typical heavy-metal toxicity. Consequently, the remnants have to be removed before use, particularly for biomedical and pharmaceutical applications. In order to alleviate this serious shortcoming, some lower toxicity metals[3] and also enzymes have been used as initiators or catalysts for ROP of (di)lactones, with variable success in terms of control of molecular parameters and the range of number-average molar masses available.[4] An alternative strategy involves grafting the initiator/catalyst systems onto an insoluble support, which is easy to separate from the liquid polymerization medium by filtration and to recycle without systematic mineralization of the organometallic active species. As early as 1994, Spitz and co-workers worked on this concept by developing a system based on aluminum alkoxides grafted onto porous silica that were used as immobilized initiators for the ROP of ethylene oxide, in a case in which homogeneous aluminum triisopropoxide was quite inefficient.[5] After thermal treatment of the silica in order to control the nature and amount of silanol groups, the active aluminum alkoxide centers were grafted according to a two-step procedure involving the reaction of triethylaluminum on the silanol groups followed by the subsequent alcoholysis of the remaining alkylaluminum groups into aluminum alkoxides. When used for the ROP of ε-caprolactone (CL) in the presence of a large excess of alcohol molecules relative to aluminum atoms, a rapid exchange reaction occurred between the grafted active centers and the free alcohol molecules in such a way that poly(ε-caprolactone) (PCL) oligomers were formed and functionalized by end groups originating from the alcohol.[6] Higher metal activities were observed with rare earth alkoxides, with functionalized PCL oligomers being obtained within 5 minutes at 50 °C in toluene by using a silica support preliminarily treated at 450 °C and treated with yttrium trialkoxides.[7] More recently, a further step towards the controlled ROP of CL initiated by yttrium isopropoxide grafted onto silica was achieved by treating preformed diisopropoxide yttrium (hexamethyldisilyl)amide, $(i\mathrm{PrO})_2\mathrm{Y}[\mathrm{N}(\mathrm{SiMe}_3)_2]$, with previously thermally treated silica.[8] In the presence of 2-propanol, the degree of polymerization could be predicted from the initial monomer-to-(alcohol+alkoxide) molar ratio, while the molar-mass distribution of the PCL oligomers recovered by washing the support with 2-propanol was remarkably narrow ($M_w/M_n = 1.1$).[9] Sudo and Endo also reported on the immobilization of 2-(*N*-methylamino)ethanol on acryloyl-functionalized cross-linked polystyrene, followed by acid-catalyzed ROP of CL in the presence of molecular sieves. After polymerization of CL, which was actually initiated by the grafted hydroxy functions, α-allyl, ω-hydroxy PCL oligomers were isolated from the support by selective cleavage of the β-amino ester linker by using various halogenated alkyl and allyl derivatives.[10]

The similarity between these strategies is the preliminary grafting of the true initiating species onto an insoluble support, which required both the PCL oligomers to be selectively untied from the support in order to isolate them, and the active centers to be regenerated prior to recycling the support.

The present paper aims at testing a recently proposed dialkyltin dichloride grafted to a cross-linked polystyrene support,[11] with the formula $[\mathrm{P{-}H}]_{(1-t)}[\mathrm{P{-}(CH_2)}_n\mathrm{SnBuCl_2}]_t$ ($\mathrm{P} = [\mathrm{CH_2CH}(p\mathrm{C_6H_4})]$, $n = 6$ or 11, $t =$ degree of functionalization), as a catalyst in a ROP of CL that is actually being initiated by *n*-propanol molecules. Analogous heterogeneous polystyrene-supported organotin dichloride catalysts (1 or 0.1 mol %) have already been shown to be efficient in model transesterification reactions between ethyl acetate and 1-octanol under refluxing conditions; the catalyst can be easily recycled without any decrease in catalytic activity.[12,13] Moreover, some of us have reported a mechanistic study of the dibutyltin dichloride ($\mathrm{Bu_2SnCl_2}$)-mediated ROP of CL in the presence of 1-propanol (*n*PrOH) by using multinuclear spectroscopy, mainly based on the ^{119}Sn nucleus.[14] At 100 °C in toluene, CL coordinates the tin atom and brings, at least partially, the four-coordinate $\mathrm{Bu_2SnCl_2}$ into five- and/or six-coordinate configurations that are more favorable for initiation of the coordination–insertion polymerization. Although *n*PrOH is the actual initiator, it is prone neither to coordinating irreversibly nor to reacting substantially with $\mathrm{Bu_2SnCl_2}$ to form tin alkoxide species such as $\mathrm{Bu_2Sn(Cl)}_{(2-n)}\mathrm{-(OC_3H_7)}_n$. Indeed, no additional single resonance accounting for tin(IV) alkoxide and no significant ^{119}Sn chemical-shift modification indicating possible fast exchange can be detected by ^{119}Sn NMR spectroscopy. At high monomer conversion, the polyester remains partially coordinated to the tin atom, at the expense of hydroxy groups end-capping the PCL chains, and this will decrease the occurrence of noxious transesterification reactions (Scheme 1). As a result, the molar mass of PCL can be predicted from the initial $[\mathrm{CL}]_0/[n\mathrm{PrOH}]_0$ molar ratio corrected for monomer conversion ($M_{\mathrm{ntheor}} = ([\mathrm{CL}]_0/[n\mathrm{PrOH}]_0 \times \mathrm{conv} \times \mathrm{MW_{CL}}) + \mathrm{MW}_{n\mathrm{PrOH}}$, in which M_{ntheor} is the theoretical number-average molar mass of PCL, conv is the monomer conversion, and $\mathrm{MW_{CL}}$ and $\mathrm{MW}_{n\mathrm{PrOH}}$ are the molecular weights of CL and *n*PrOH, respectively) and a remarkably narrow polydispersity index can be reached (weight-average/number average molar mass $M_w/M_n < 1.1$).

In parallel to these goals, the present paper also demonstrates how ^{1}H and ^{119}Sn HR-MAS NMR spectroscopy, a method recently applied to the characterization of synthesized target organotins grafted to insoluble supports,[11,13,15] can be used as a tool to monitor catalytic processes. More particularly, it is demonstrated how HR-MAS NMR spectroscopy enables one to evaluate the status of the catalyst after its use, to investigate to what extent reaction residues, whether desired or not, are observable in situ in the material pores after a catalytic run, and to assess the chemical integrity and recycling conditions of the grafted catalyst.



Scheme 1. Mechanism of ring-opening polymerization (ROP) of ε-caprolactone (CL), catalyzed by Bu_2SnCl_2 in solution. PCL = poly(ε-caprolactone).

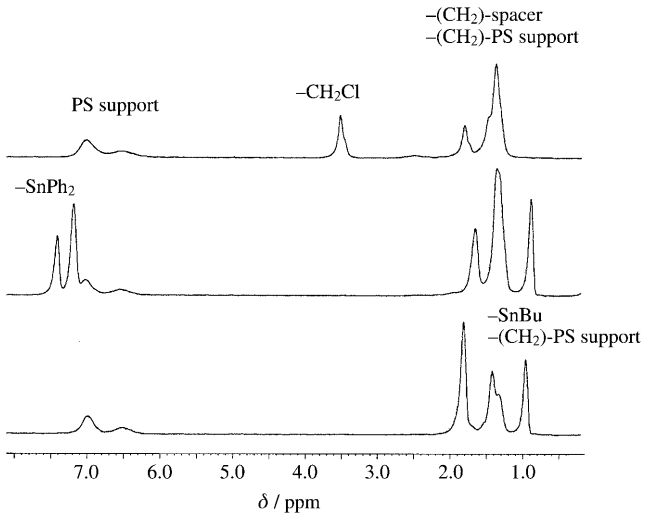
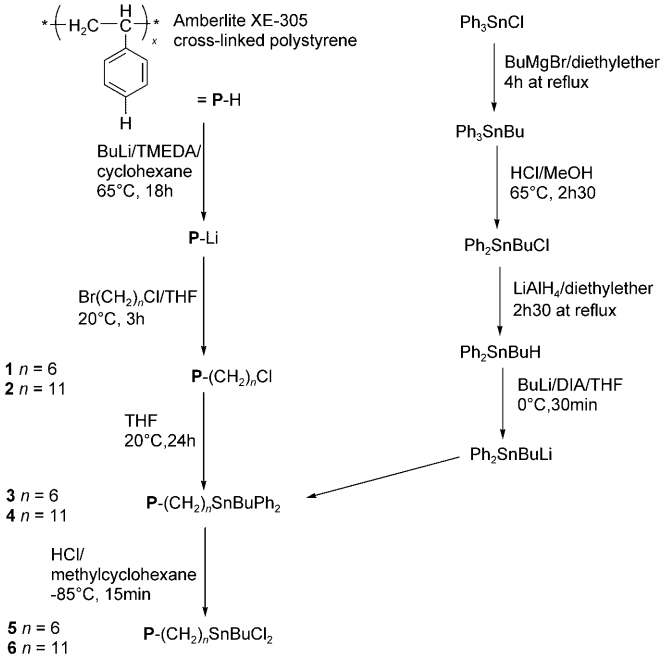


Figure 1. Diffusion-filtered HR-MAS ^{1}H NMR spectrum of compound **2**, P–$(CH_2)_{11}$Cl (top), compound **4**, P–$(CH_2)_{11}SnBuPh_2$ (middle), and compound **6**, P–$(CH_2)_{11}SnBuCl_2$ (bottom). PS = polystyrene.



Scheme 2. Synthesis of organotins grafted to cross-linked polystyrenes. TMEDA = tetramethylethylenediamine, THF = tetrahydrofuran, DIA = diisopropylamine.

Results and Discussion

Synthesis and characterization: Polystyrene-supported diorganotin dichloride catalysts of general formula $[P–H]_{(1-t)}$-$[P–(CH_2)_nSnBuCl_2]_t$ ($n = 6$ or 11) have been synthesized from Amberlite XE-305, that is, cross-linked polystyrene beads (P–H) with a diameter in the range of 500–850 μm, according to procedures previously described.[11–13] The importance of the spacer choice was likewise discussed previously.[11,13] We present here (Figure 1) a nice example of the suitable use of so-called diffusion-filtered[11,15] ^{1}H HR-MAS NMR spectroscopy, which enables one to monitor the succession of reaction conversions (Scheme 2), as well as to assess the completeness of the reactions.

Actually, HR-MAS NMR spectroscopy is a powerful tool that allows the application of most high-resolution techniques, well known from solution-phase NMR spectroscopy, to the direct characterization of molecules grafted onto solid-phase supports in situ, at the heterogeneous solid–liquid interface.[15–18] This is achieved by removing the contribution of magnetic-susceptibility-induced line broadenings, which are present in such heterogeneous systems, through spinning at the magic angle.[15–18] The use of longitudinal eddy current delay (LED) diffusion-filtered 1D HR-MAS NMR spectroscopy[19] enables one to distinguish resonances arising from grafted species that are translationally immobile from those of translationally mobile species, that is, all free reagents, free products, and unbound solvent molecules, with the signals from all the latter species being completely suppressed.

The chlorinated alkyl chains of the organotin precursor compounds **1** and **2** provide well-separated resonances at characteristic ^{1}H chemical shifts of around 3.5 ppm for the methylene moieties at the CH_2Cl end of the spacer. The introduction of the organotin moiety in **3–6** complicates the spectrum of the grafted moiety, as the ^{1}H resonances of the methylene spacer are now obscured by those from the tin

butyl fragment. However, the presence or absence of the characteristic fingerprint resonances from one synthesis step to the next enables one to ascertain the degree of completion of the reaction, as well as the purity of the compounds, in a very short time. The complete disappearance of the CH_2Cl signal of **1** (or **2**) in step 2 and of the signals from the tin phenyl groups of **3** (or **4**) in step 3 of the synthesis route indicates that a high level of conversion has indeed been achieved (Figure 1). The power of 1D ^{119}Sn HR-MAS NMR spectroscopy as a means of detecting and identifying possible grafted impurities or incomplete conversions at the level of the tin functionality is illustrated in Figure 2, which displays the ^{119}Sn HR-MAS spectra of compounds **3** and **5**. Small amounts of tin-containing impurities, if present, can be identified and quantified from these spectra.

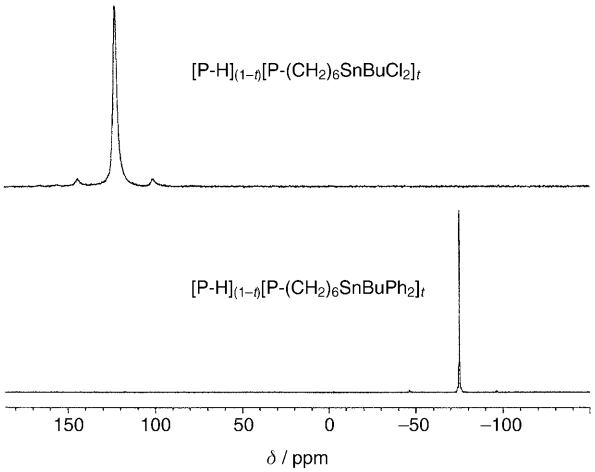


Figure 2. ^{119}Sn HR-MAS spectra of [P−H]$_{(1-t)}$[P−(CH$_2$)$_6$SnBuPh$_2$]$_t$ (**3**) and [P−H]$_{(1-t)}$[P−(CH$_2$)$_6$SnBuCl$_2$]$_t$ (**5**). The two small signals flanking the major resonance in the spectrum of the $SnCl_2$ compound **5** are spinning side bands.

Although the ^{1}H HR-MAS spectra for these compounds are complex due to overlapping resonances of the methylene groups, from which extraction of $^nJ(^1H–^{119}Sn)$ coupling constants is not possible, a 2D ^{1}H-^{13}C HSQC[15,20] HR-MAS spectrum recorded on a 700 MHz instrument allowed us to assign extensively the ^{1}H and ^{13}C resonances, as well as to measure accurately the $^nJ(^1H–^{117/119}Sn)$ and $^nJ(^{13}C–^{117/119}Sn)$ coupling constants from the E.COSY pattern of the coupling satellites.[21] These constants are, together with the ^{119}Sn chemical shifts, extremely valuable parameters for a positive identification of the exact chemical nature of the grafted organotin functionality, as well as of the coordination state of the tin atom. Figure 3 (top) shows a detail of the 2D ^{1}H-^{13}C HSQC HR-MAS spectrum of **6**, which reveals the fine structure arising from scalar couplings involving the $^{117/119}$Sn nucleus. The chemical shifts and coupling constants obtained in this way for **4** and **6** are summarized in Table 1. These data illustrate the power of the 2D ^{1}H-^{13}C HSQC HR-MAS technique, as even the α-carbon atoms of the spacer and the butyl groups, with very similar chemical environments and, accordingly, very similar chemical shifts, can be differentiated and their $^1J(^{13}C–^{117/119}Sn)$ coupling constants determined separately (Figure 3, bottom). The numerical values are all unambiguous indicators of four coordination at the tin center, as is expected both from the properties of the grafts and from the measurement conditions used.

Table 1. Chemical shifts (δ) in ppm and $^{117/119}$Sn unresolved $^nJ(^1H-^{117/119}Sn)$ and $^nJ(^{13}C-^{117/119}Sn)$ coupling constants in Hz (given in square brackets) of the polymer-supported organotin compounds **4** and **6**.

	4		**6**	
	^{1}H	^{13}C	^{1}H	^{13}C
butyl α(CH$_2$)	1.29	10.8 [361]	1.97 [48]	27.6 [416]
butyl β(CH$_2$)	1.61	29.6	1.98 [103]	25.5 [22]
butyl γ(CH$_2$)	1.34	27.9 [56]	1.57	26.9 [84]
butyl δ(CH$_3$)	0.84	14.1	1.10	14.1
CH(*o*)	7.48	137.2	–	–
CH(*m*)	7.23	128.7	–	–
C(*ipso*)	–	141.0	–	–
spacer α(CH$_2$)	1.30	11.1 [357]	1.98 [50]	27.9 [412]
spacer β(CH$_2$)	1.63	29.4	1.96 [104]	27.6 [25]
spacer γ(CH$_2$)	1.34	34.8 [57]	1.55	33.8 [81]

Catalysis in ring-opening polymerization of ε-caprolactone: Table 2 shows monomer conversion and molecular-weight parameters of PCL samples obtained by initiating the ROP of CL with *n*PrOH in the presence of the polystyrene-supported diorganotin dichloride catalyst with a hexamethylene spacer, [P−H]$_{(1-t)}$[P−(CH$_2$)$_6$SnBuCl$_2$]$_t$, for two different functionalization degrees and polymerization temperatures. In the absence of *n*-propanol, no substantial polymerization occurs at 100 °C within 72 h, and the support, when allowed to settle and separated from the supernatant, is recovered intact. In practical terms, monomer conversion has been determined gravimetrically by weighing the PCL after selective precipitation of the polyester chains from heptane and drying. The M_{ntheor} value has been calculated from the initial

Table 2. Monomer conversion and molecular-weight parameters of PCL as obtained by ROP of CL initiated by *n*PrOH and catalyzed by [P−H]$_{(1-t)}$[P−(CH$_2$)$_6$SnBuCl$_2$]$_t$ in toluene for 72 h ([CL]$_0$ = 4.51 mol L^{-1}, [CL]$_0$/[*n*-PrOH]$_0$ = 100, [PrOH]$_0$/[Sn]$_0$ = 20).

Entry	t	T	Conv[a]	M_{ntheor}[a]	M_{nexp}[a]		M_w/M_n[a]
		[°C]	[%]		NMR	SEC	
1	0.32	100	58	6700	8300	8200	4.40
2	0.32	70	10	1200	1800	1150	4.80
3	0.11	100	> 99	11500	17100	17000	2.42

[a] Conv = monomer conversion, M_{ntheor} = theoretical number-average molar mass, M_{nexp} = experimental number-average molar mass, M_w = weight-average molar mass, M_n = number-average molar mass.

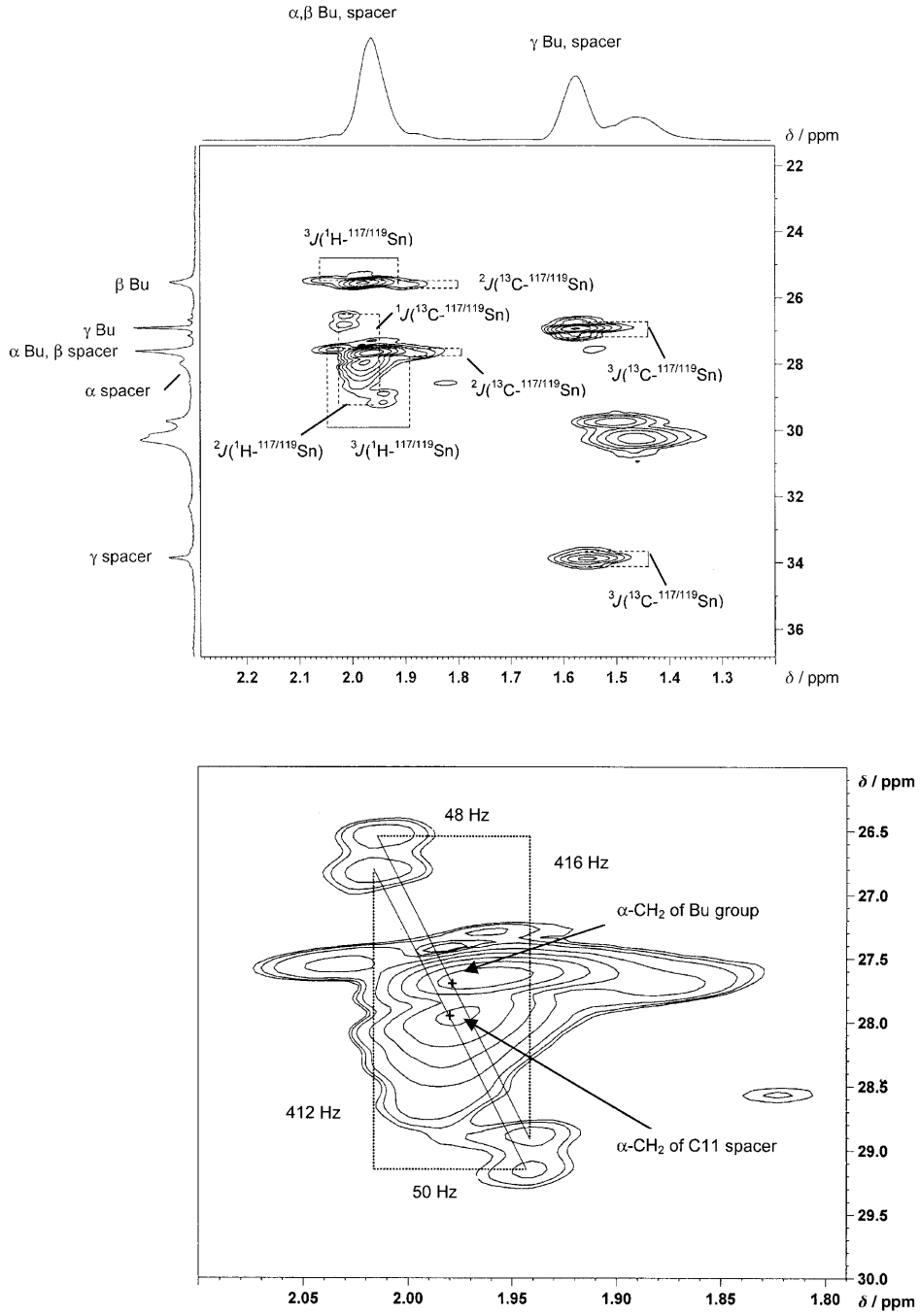


Figure 3. Top: Detail of various ^1H–^{13}C cross-peaks in the 700 MHz HSQC spectrum of **6**. The resonances of interest are labeled over the separately recorded ^1H and ^{13}C spectra, shown on top and to the left of the 2D spectrum. Horizontal dashed lines connect the E.COSY[21] peaks to their associated $^{117/119}Sn$ unresolved $^nJ(^1H$–$^{117/119}Sn)$ couplings, while vertical dashed lines indicate the unresolved $^nJ(^{13}C$–$^{117/119}Sn)$ couplings. Bottom: Expansion of the α-CH_2 cross-peaks with their E.COSY satellites.

monomer-to-alcohol molar ratio with the assumption of a living coordination–insertion mechanism initiated by *n*-propanol molecules ($M_{ntheor} = ([CL]_0/[n\text{PrOH}]_0 \times \text{conv} \times MW_{CL}) + MW_{n\text{PrOH}}$). Experimental number-average PCL molar masses (M_{nexp}) have been determined either by size-exclusion chromatography (SEC) with reference to polystyrene standards and with the Mark–Houwink–Sakaruda relationship, or by ^1H NMR spectroscopy in $CDCl_3$ from the relative intensity of the signals of methylene protons of the CL repetitive units (CH_2-O-CO) at $\delta = 4.1$ ppm and α-hydroxy methylene protons (CH_2-OH) at $\delta = 3.6$ ppm (Figure 4). When the results are compared to previously reported data on the homogeneous polymerization of CL carried out in similar experimental conditions by substituting Bu_2SnCl_2 for $(P{-}H)_{(1-t)}$-$[P{-}(CH_2)_6SnBuCl_2]_t$,[12] the most striking features are that the molar mass distribution (M_w/M_n) is broader and bimodal (Figure 5) and the M_{nexp} value is systematically higher than the theoretical value. As an example, the $M_{nexp(SEC)}$ value reached 6100 for a monomer conversion of 47% ($M_{ntheor} = 5900$) and the M_w/M_n value was 1.05 under homogeneous catalysis conditions at 100 °C. A decrease in the polymerization temperature from 100 to 70 °C does not afford a better control over the molecular parameters, but does contribute to decreasing the polymerization rate (entry 2, Table 2). In contrast, a reduction in the molar fraction of styrene repetitive units grafted by organotin dichloride species (*t*) accelerates the ROP, a result that is probably due to an enhancement of the accessibility of the diorganotin dichloride functions, but the molar mass distribution remains broad and bimodal (Figure 6). It is worth pointing out that partial 'burst' of the polystyrene-supported catalyst has been indicated by optical microscopy whatever the temperature and *t* value (Figure 7). This phenomenon is well known in heterogeneous Phillips and Ziegler–Natta catalyses, and results from polymer chains growing within the pores of the support.[22] Growth of polyester chains within the meshes of the functionalized polystyrene network is probably responsible for such similar behavior, and this prompts us to limit the molar

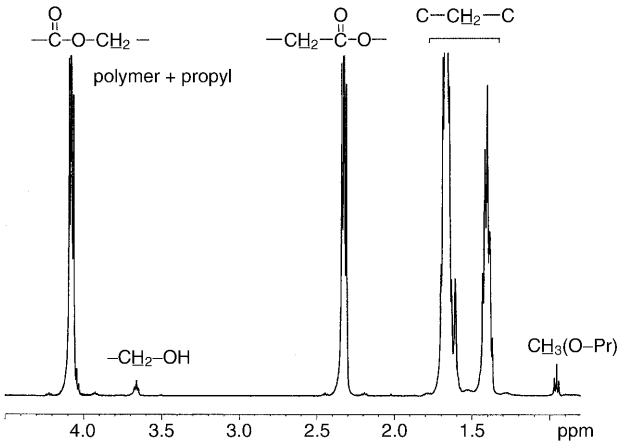


Figure 4. ^{1}H NMR spectrum of PCL as obtained by polymerization of CL initiated by *n*-propanol in the presence of $[P{-}H]_{0.68}[P{-}(CH_2)_6SnBuCl_2]_{0.32}$ (**5**) in toluene at 100 °C for 72 h (entry 1, Table 2).

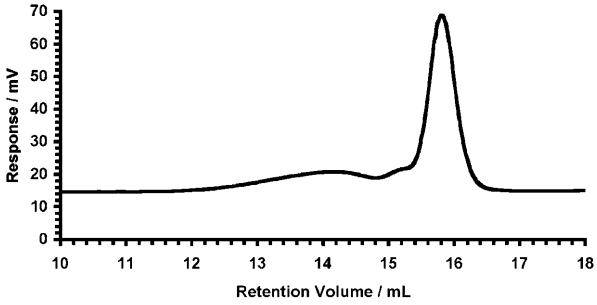


Figure 5. SEC of PCL as obtained by ROP of CL initiated by *n*-propanol in the presence of $[P{-}H]_{0.68}[P{-}(CH_2)_6SnBuCl_2]_{0.32}$ in toluene at 100 °C for 72 h (entry 1 in Table 2).

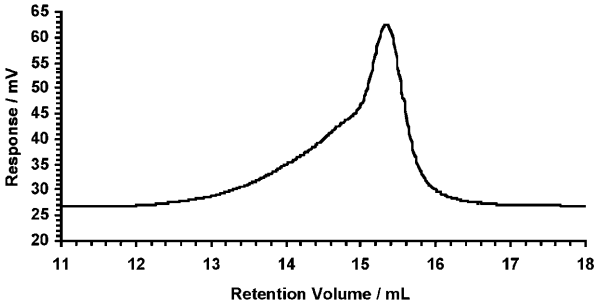


Figure 6. SEC of PCL as obtained by ROP of CL initiated by *n*-propanol in the presence of $[P{-}H]_{0.89}[P{-}(CH_2)_6SnBuCl_2]_{0.11}$ in toluene at 100 °C for 72 h (entry 3 in Table 2).

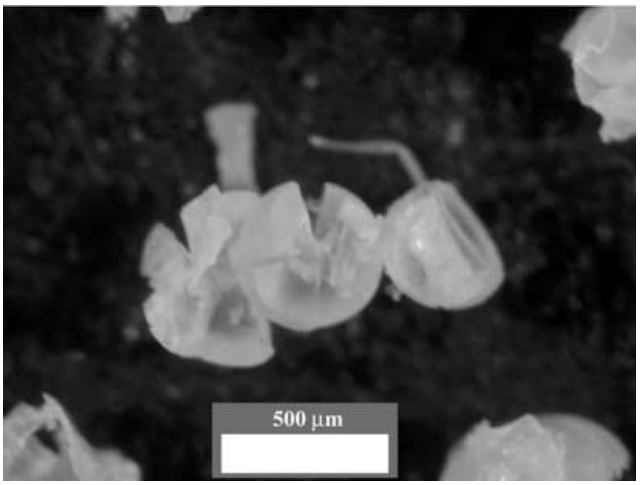


Figure 7. Optical microscopy of $[P{-}H]_{0.89}[P{-}(CH_2)_6SnBuCl_2]_{0.11}$ after ROP of CL initiated by *n*-propanol in toluene at 100 °C for 72 h (entry 3 in Table 2).

mass of the PCL chains by reducing the initial monomer-to-alcohol molar ratio from 100 to 10 (entry 1, Table 3).

Surprisingly, a reduction in the number-average molar mass of PCL chains to approximately 1000, through reduction of the CL/initiator ratio, does not avoid the burst of the polystyrene-supported catalyst when using the hexamethylene spacer; however, by contrast, the integrity of the catalyst beads is preserved when the undecamethylene spacer is used (entries 2–4 in Table 3 and Figure 8). Also, the polydispersity index is highly reduced with values close to 1.8–1.9, although two populations can still be distinguished by SEC (Figure 9). An attempt to recycle the heterogeneous catalyst has shown that very good reproducibility can be obtained in terms of both the catalyst activity and the molecular-weight parameters (entries 2 and 3 in Table 3). Extension of the reaction time above 5 h allows higher monomer conversion to be reached, and also tends to reduce the discrepancy between the theoretical and experimental molar masses, a result that might be consistent with a quite slow initiation rate compared to that of the propagation (entry 4 in Table 3).

The following data illustrate the power of ^{1}H and ^{119}Sn HR-MAS NMR spectroscopy for the purpose of monitoring possible consequences of the catalytic processes on the tin coordination pattern of the grafted organotin catalysts. When compared to the spectra of unused, fresh catalyst, some additional signals show up in the ^{1}H HR-MAS NMR

Table 3. Monomer conversion and molecular-weight parameters of PCL as obtained by ROP of CL initiated by *n*PrOH and catalyzed by $[P{-}H]_{(1-t)}[P{-}(CH_2)_nSnBuCl_2]_t$ in toluene at 100 °C ($[CL]_0 = 4.51$ mol L^{-1}, $[CL]_0/[n\text{PrOH}]_0 = 10$, $[n\text{PrOH}]_0/[Sn]_0 = 20$).

Entry	*t*	*n*	time [h]	Conv [%]	M_{ntheor}	M_{nexp} NMR	M_{nexp} SEC	M_w/M_n
1	0.32	6	5	75	900	2000	1400	5.18
2	0.26	11	5	59	700	1700	1200	1.93
3[a]	0.26	11	5	59	700	1800	1300	1.77
4	0.26	11	7	72	900	1500	1100	1.89

[a] After recycling of the supported catalyst used in entry 2.

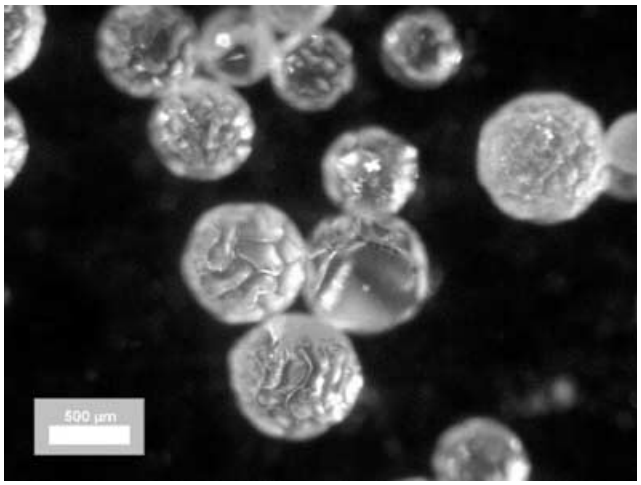


Figure 8. Optical microscopy of $[P{-}H]_{0.74}[P{-}(CH_2)_{11}SnBuCl_2]_{0.26}$ after ROP of CL initiated by *n*-propanol in toluene at 100 °C for 5 h (entry 3 in Table 3). The white bar represents 500 µm.

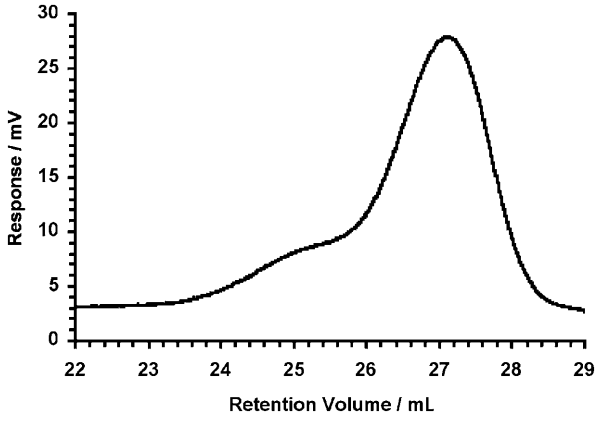


Figure 9. SEC of PCL as obtained by ROP of CL initiated by *n*-propanol in the presence of $[P{-}H]_{0.74}[P{-}(CH_2)_6SnBuCl_2]_{0.26}$ in toluene at 100 °C for 5 h (entry 2 in Table 3).

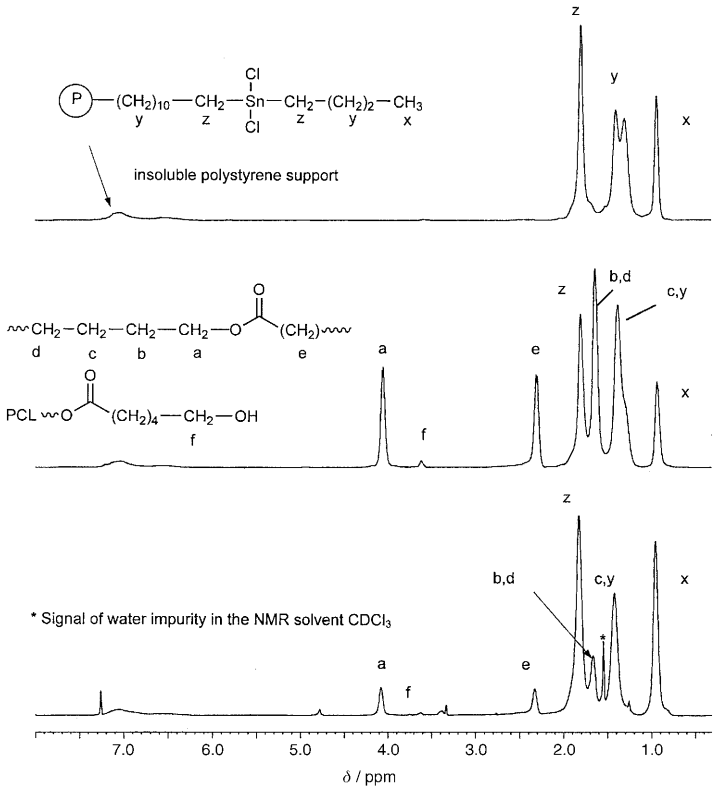


Figure 10. 1D ^{1}H HR-MAS NMR spectra of fresh, unused organotin catalyst **6** (top), used catalyst **6** after one run of polymerization of CL (middle), and catalyst **6** after Soxhlet extraction for 72 h at 110 °C in toluene (bottom), with the assignment of the ^{1}H resonances from both residual PCL (a–e) and grafted catalyst (x, y, and z).

spectra for the catalyst sample after one catalytic run of ring-opening polymerization (Figure 10, middle). Broad and interfering ^{1}H resonances in both the aliphatic and aromatic spectral ranges, arising from the cross-linked polymer matrix, were suppressed by applying a T_2 filter, consisting of a Carr–Purcell–Meiboom–Gill echo sequence. The additional resonances could be assigned to residual poly(ε-caprolactone) that was not completely removed from the beads after the reaction and the succinct washing of the support with a small volume of toluene (see the Experimental Section).

A careful estimation of the NMR spectrum integration data reveals that only 1 % of the product of the total mass of isolated PCL had remained in the pores of the beads.

In order to assess the extent to which this residual PCL can be extracted further from the beads, the organotin catalyst **6** was submitted to a Soxhlet extraction for 72 h at 110 °C in toluene. Under such conditions, more than 85 % of the remaining PCL was removed. Also, the characteristic fingerprint of the grafted organotin catalyst was almost completely regained (Figure 10, bottom) in the proton spectra, with only small proton resonances from the PCL remaining visible; this residual PCL was therefore not amenable to extraction after 72 h. Some minor additional species resulting from the rather drastic Soxhlet extraction conditions were also visible, in addition to residual $CHCl_3$ from the $CDCl_3$ NMR solvent and also a small amount of water ($\delta =$ 1.5 ppm) from the latter. The LED diffusion filter identifies them all to be nongrafted.

^{119}Sn HR-MAS spectra were likewise recorded for all the catalysts. In the unused organotin derivatives (**5**, **6**), the tin atom does not, of course, undergo coordination from the $CDCl_3$ NMR solvent molecules; in both cases, a rather broad ^{119}Sn resonance results at the well-known chemical shift of about 124 ppm, which is characteristic for nonpolar media (Figure 11, top). In a former study by our group with the homogenous organotin Bu_2SnCl_2 catalyst, it was demonstrated[14] that in the presence of CL or PCL, a significant low-frequency shift is observed for the ^{119}Sn chemical shift of Bu_2SnCl_2, which is larger with CL than with PCL. This was explained by the fact that the monomer coordinates the tin atom more strongly than the polymer.[14] Furthermore, the single ^{119}Sn resonance observed in both cases indicates fast exchange between noncomplexed Bu_2SnCl_2 and tin di-

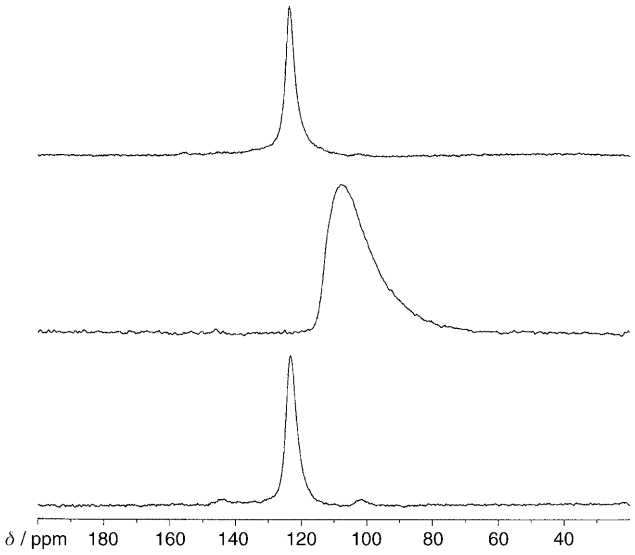


Figure 11. 1D ^{119}Sn HR-MAS NMR spectra of unused, freshly prepared catalyst **6** (top), catalyst **6** after one run of polymerization, with PCL remaining in the pores (middle), and catalyst **6** after Soxhlet extraction (bottom). In the bottom spectrum, the broad satellites are spinning side bands.

chloride complexed by monomer, polymer, or both, depending on the composition of the solution from which the ^{119}Sn NMR spectrum was recorded. By using these findings, the 1D ^{119}Sn HR-MAS NMR spectrum found in the present work for catalyst **6** after one poly(ε-caprolactone) synthesis run (Figure 11, middle) can be readily explained. Thus, in the presence of PCL in the pores, the interaction between the polymer and the tin atom of the grafted P–$(CH_2)_{11}$–$BuSnCl_2$ catalyst causes a slight low-frequency shift. With the latter polymer being present in the pores only residually and hence, in rather low molar amounts with respect to the catalyst, when compared to the reaction conditions in the homogeneous phase, the low-frequency shift remains limited to approximately 16 ppm; this is in contrast to the shift of 40–50 ppm observed for the higher ratios of polymer-to-Bu_2SnCl_2 in the homogeneous-solution catalysis. The same low relative amount of residual PCL in the pores is responsible for the kinetics of the exchange between the uncomplexed grafted P–$(CH_2)_{11}$–$BuSnCl_2$ catalyst and its analogue complexed by the polymer, an exchange that is significantly slower than in the case of the homogeneous poly(ε-caprolactone)/Bu_2SnCl_2 mixture. This explains the observed broadened asymmetric ^{119}Sn resonance, characteristic for a not-yet-complete coalescence regime that approaches exchange-averaging for the residual PCL/grafted P–$(CH_2)_{11}$–$BuSnCl_2$ system, rather than the narrow resonance that is characteristic for a fast-exchange regime in the case of the homogeneous PCL/Bu_2SnCl_2 reaction mixture. When Soxhlet extraction is complete, however, and sufficient polymer has been extracted away from the bead pores, it appears that the ^{119}Sn resonance (Figure 11, bottom) virtually completely recovers the characteristic features for unused, freshly synthesized catalyst, thereby demonstrating its robustness.

These data indicate that the catalyst can be recycled, although this is not absolutely necessary because only a minute amount of PCL appears to be present in the bead pores after isolation from the catalyst and this does not hamper reuse of the catalyst, a fact that was also indicated by our previous study with the homogeneous model Bu_2SnCl_2 catalyst.[14]

In conclusion, HR-MAS NMR spectroscopy appears to be an extremely powerful tool for monitoring catalytic processes of organometallic compounds grafted to cross-linked insoluble polymeric supports, amenable to swelling by an appropriate solvent. The monitoring HR-MAS NMR tool presented here is not restricted to organotins, and is indeed applicable to any grafted organometallic catalyst amenable to NMR spectroscopy, provided the material to which it is anchored is amenable to swelling in the appropriate solvent, so as to induce sufficient molecular mobility at the interface, in order to generate the line narrowing needed for high-resolution NMR spectroscopy.

Experimental Section

Materials: ε-Caprolactone (CL, Acros, 99%), tetramethylethylenediamine (TMEDA, Aldrich, 99.5+%), diisopropylamine (DIA, Aldrich, 99%), and 1-propanol (*n*PrOH, Aldrich, 99.5%) were dried over calcium hydride at room temperature for 48 h and then distilled under reduced pressure. Toluene (Labscan, 99%) was dried by refluxing over calcium hydride and distilled just before use under an inert atmosphere. Prior to polymerization experiments, the polystyrene-supported organotin dichloride catalysts were dried by two successive azeotropic distillations of toluene. For the sake of accuracy, the *n*PrOH solution in dry toluene was prepared just before use ($[n\text{PrOH}] = 0.45\ \text{mol L}^{-1}$ and $2.70\ \text{mol L}^{-1}$). Amberlite XE305 was purchased from PolySciences Inc. and was washed thoroughly before use.[23] Cyclohexane (Aldrich, 99%) was dried over sodium at room temperature and distilled just before the reaction under an inert atmosphere. 2.5 M Butyl lithium in a hexane solution, triphenyltin chloride (95%), 1,6-bromochlorohexane, and 11-bromo-1-undecanol (98%) were purchased from Aldrich. Tetrahydrofuran (THF, Aldrich, 99+%) was dried over lithium aluminum hydride ($LiAlH_4$) under reflux conditions and distilled just before use.

Catalyst preparation: The catalysts were prepared according to a procedure described previously, as summarized in Scheme 2.[11–13] In all cases, divinylbenzene cross-linked polystyrene (Amberlite XE305) was used as the insoluble support (P–H). In short, a hexa- or undecamethylene spacer with a terminal chloride functionality was grafted onto the insoluble P–H (compounds **1** and **2**), which had been preliminarily lithiated in the *para* position. Next, a stannylation reaction with $Ph_2SnBuLi$ in dry THF substituted the chlorine atom for the $BuPh_2Sn$ group (compounds **3** and **4**). The $BuCl_2Sn$ functionalities in compounds **5** and **6** were obtained by conversion of compounds **3** and **4**, as previously described.[13]

Characterization of $[P–H]_{(1-t)}[P–(CH_2)_nCl]_t$ (1, 2): IR: $\tilde{\nu} = 651\ \text{cm}^{-1}$ (CCl; w); ^{1}H HR-MAS NMR: $\delta = 3.48$ ppm ((CH_2)Cl); elemental analysis: $[P–H]_{(1-t)}[P–(CH_2)_6Cl]_t$ (**1a**): calcd: H 8.23, C 82.74, Cl 9.03; found: H 8.58, C 82.82, Cl 8.88; $t = 0.38$; $[P–H]_{(1-t)}[P–(CH_2)_6Cl]_t$ (**1b**): calcd: H 8.03, C 86.66, Cl 5.32; found: H 7.82, C 86.74, Cl 4.97; $t = 0.19$; $[P–H]_{(1-t)}$-$[P–(CH_2)_{11}Cl]_t$ (**2**): calcd: H 8.94, C 84.59, Cl 6.47; found: H 8.93, C 84.34, Cl 5.97; $t = 0.29$.

Characterization of $[P–H]_{(1-t)}[P–(CH_2)_nSnBuPh_2]_t$ (3, 4): IR: $\tilde{\nu} = 1074$ (Sn–Ph, m), 507 ($(Sn–Bu)_{sym}$, w), 595 ($(Sn–Bu)_{asym}$, w), 656 cm^{-1} ($(Sn–C)_{rock}$, w), $\delta_{oop} = 727\ \text{cm}^{-1}$ ($(C–C)_{mono}$, w); ^{119}Sn HR-MAS NMR: $\delta =$

−71 ppm; elemental analysis: $[P-H]_{(1-t)}[P-(CH_2)_6SnBuPh_2]_t$ (**3a**): calcd: H 7.50, C 76.01, Sn 16.50, Cl 0; found: H 7.96, C 75.79, Sn 16.09, Cl 0.37; $t=0.34$; $[P-H]_{(1-t)}[P-(CH_2)_6SnBuPh_2]_t$ (**3b**): calcd: H 7.61, C 83.66, Sn 8.73, Cl 0; found: H 7.72, C 83.19, Sn 7.56, Cl 0.72; $t=0.11$; $[P-H]_{(1-t)}[P-(CH_2)_{11}SnBuPh_2]_t$ (**4**): calcd: H 8.07, C 78.50, Sn 13.43, Cl 0; found: H 7.87, C 78.27, Sn 12.61, Cl <0.2; $t=0.26$.

Characterization of $[P-H]_{(1-t)}[P-(CH_2)_nSnBuCl_2]_t$ (5, 6): IR: $\tilde{\nu}=340$ (Sn−Cl, m), 515 ($(Sn-Bu)_{sym}$, w), 595 cm^{-1} ($(Sn-Bu)_{asym}$, w); ^{119}Sn HR-MAS NMR: $\delta=124$ ppm; elemental analysis: $[P-H]_{(1-t)}[P-(CH_2)_6SnBuCl_2]_t$ (**5a**): calcd: H 6.92, C 64.15, Sn 18.11, Cl 10.82; found: H 6.92, C 63.97, Sn 18.22, Cl 10.89; $t=0.32$; $[P-H]_{(1-t)}[P-(CH_2)_6SnBuCl_2]_t$ (**5b**): calcd: H 7.32, C 77.83, Sn 9.30, Cl 5.55; found: H 7.34, C 77.47, Sn 9.53, Cl 6.32; $t=0.11$; $[P-H]_{(1-t)}[P-(CH_2)_{11}SnBuCl_2]_t$ (**6**): calcd: H 7.65, C 68.67, Sn 14.83, Cl 8.86; found: H 7.71, C 68.49, Sn 13.77, Cl 8.72; $t=0.26$.

Table 4 shows the functionalization degree (t) and the molar tin content (x) of the $[P-H]_{(1-t)}[P-(CH_2)_nSnBuCl_2]_t$ compounds (**5**, **6**) synthesized and used in catalytic experiments, expressed in mmol g^{-1}. The variation

Table 4. Molecular characteristics of $[P-H]_{(1-t)}[P-(CH_2)_nSnBuCl_2]_t$ supports.

Entry	n	t	x [mmol g^{-1}]
1	6	0.32	1.53
2	6	0.11	0.80
3	11	0.26	1.16

in functionalization degree (t, molar fraction of styrene repetitive units functionalized with the grafted dialkyltin dichloride species) of the tin catalyst was actually embodied in the first lithiation step.

Synthesis of molecular tin precursors: The molecular tin precursor $Ph_2BuSnLi$ was prepared as described previously from Ph_3SnCl (Aldrich).[24]

Synthesis of $Cl(CH_2)_{11}Br$: This compound was prepared from $Br(CH_2)_{11}OH$ by a reaction with $SOCl_2$, by an established literature procedure:[25] MW = 269.65 g mol^{-1}; b.p. 126 °C at 0.4 mmHg; ^{1}H NMR: $\delta=$ 3.52 (t, CH_2Cl), 3.40 ppm (t, CH_2Br); IR: $\tilde{\nu}=651$ cm^{-1} (CCl, w).

Polymerization procedure: Typically, polystyrene-supported catalyst (90.2 mg; 0.138 mmol of tin, entry 1 in Table 2) was introduced into a preliminarily flame-dried and nitrogen-purged round-bottomed flask equipped with a three-way stopcock and a rubber septum. After three cycles of vacuum/nitrogen purging and an azeotropic distillation of toluene, toluene (2 mL) and CL (3 mL, 27.07 mmol) were injected into the flask. The reaction medium was heated up to 100 °C before adding *n*PrOH (1 mL) in toluene solution (2.71 mmol). After 5 h of polymerization time with slow-speed shaking, the reaction medium was rapidly cooled down with tap water and dry toluene (50 mL) was added. The polystyrene-supported catalyst was allowed to settle, and the supernatant was poured through a preliminarily flamed capillary into an excess of heptane in order to precipitate the PCL. An additional toluene volume was used to wash the polystyrene particles. The precipitate was recovered by filtration and dried under reduced pressure at 30 °C until constant weight. The polystyrene-supported catalyst was dried under reduced pressure for 18 h at room temperature and maintained under an inert atmosphere to be either observed by optical microscopy or reused in a further polymerization experiment.

Characterization: Size-exclusion chromatography (SEC) was performed in THF at 35 °C by using a Polymer Laboratories liquid chromatograph equipped with a PL-DG802 degasser, an isocratic LC1120 HPLC pump (flow rate = 1 mL min^{-1}), a Marathon autosampler (loop volume = 200 μL, solution concentration = 1 mg mL^{-1}), a PL-DRI refractive-index detector, and three columns: a PL gel 10-μm guard column and two PL gel Mixed-B 10-μm columns (linear columns for the separation of polystyrene with molecular weights of 500–10^6 Da). Molar masses were calculated by reference to a polystyrene standard calibration curve, by using the Mark–Houwink–Sakaruda relationship: [η] = intrinsic viscosity in THF at 35 °C, M = number-average molar mass, K and a = Mark–Houwink–Sakaruda constants for PS (polystyrene) ($K_{PS}=1.25\times10^{-4}$ dL g^{-1}, $a_{PS}=0.707$) and PCL (poly(ε-caprolactone)) ($K_{PCL}=1.09\times10^{-3}$ dL g^{-1}, $a_{PCL}=0.600$). The polystyrene particles were observed by optical microscopy with a Leica MZ8 stereoscopic microscope equipped with an optical fiber Euromex EK-1. A specific adapter allows the use of a photographic-extension Nikon Coolpix 990 MDC lens.

IR and Raman spectroscopy: IR spectra were recorded on a Bruker Equinox 55 FT-IR spectrometer, equipped with an MIR source, a KBr beam splitter, and a DGTS detector, from dry KBr (200 mg) pellets with approximately 5 mg of substance. The RAMAN spectra were recorded on a Perkin–Elmer 2000 NIR FT-RAMAN spectrometer by using a Raman dpy2 beam with 310 mW power.

NMR spectroscopy: The ^{1}H and ^{119}Sn HR-MAS NMR spectra were recorded on a Bruker AMX500 instrument operating at 500.13 and 186.50 MHz, respectively, with a specially dedicated Bruker ^{1}H/^{13}C/^{119}Sn HR-MAS probe equipped with gradient coils, by using full rotors containing approximately 20 mg of resin beads, swollen in approximately 100 μL of $CDCl_3$ and with magic angle spinning at 4000 Hz. $(CH_3)_4Sn$ was used as an internal reference.

The ^{13}C HR-MAS NMR spectra and the 2D ^{1}H–^{13}C HSQC[15,20] spectra of compound **6** were recorded on a 700 MHz Bruker Avance spectrometer equipped with a gradient ^{1}H/^{13}C/^{2}H HR-MAS probe at 298 K, while spinning with a rotation frequency of 4 kHz. 2048 and 256 complex points were acquired in the acquisition dimension and the indirect dimension, respectively. 32 scans were used for each $t1$ increment, thereby resulting in a total acquisition time of 10 h. Sine-shaped gradient pulses of 1.3 ms length and with 40 G cm^{-1} and 10.05 G cm^{-1} of strength were used to select the correct coherence order pathway. The sample was prepared by adding compound **6** (6 mg) to a HR-MAS rotor (50 μL). Swelling of the resin was achieved by adding CD_2Cl_2 directly into the rotor.

Acknowledgements

The financial support for a sabbatical leave (Scholarship) from the Consejo Nacional de Ciencia y Tecnologia (CONACYT-Mexico) and Universidad Autonoma Metropolitana-X is gratefully acknowledged (C.C.-C.). M.B. and R.W. are indebted to the Fund for Scientic Research—Flanders (FWO), Belgium (grant no.: G.0016.02), and to the Research Council of the VUB (grant nos.: GOA31, OZR362, OZR875) for financial support. The LPCM is very grateful to the "Région Wallonne" and European Community (FEDER, FSE) for general support within the frame of "Objectif 1-Hainaut: Materia Nova", as well as to the Belgian Federal Government Office of Science Policy (SSTC-PAI 5/3).

[1] a) S. Li, M. Vert, *Biodegradation of aliphatic polyesters* (Ed.: G. Scott), Kluwer, Dordrecht, **2002**, pp. 71 and 132; b) A.-C. Albertsson, I. K. Varma, *Biomacromolecules* **2003**, *4*, 1466–1486; c) A. Sodergard, M. Solt, *Prog. Polym. Sci.* **2002**, *27*, 1123–1163.

[2] D. Mecerreyes, R. Jérôme, P. Dubois, *Adv. Polym. Sci.* **1999**, *147*, 1–59.

[3] a) H. R. Kricheldorf, I. Kreiser-Saunders, D.-O. Damrau, *Macromol. Symp.* **1999**, *144*, 269–276; b) W. Xie, D. Chen, X. Fan, J. Li, *J. Polym. Sci. Part A* **1999**, *37*, 3486–3491; c) A. F. Reema, A. C. Albertsson, *J. Polym. Sci. Part A* **2003**, *41*, 3074–3082.

[4] a) S. Kobayashi, H. Uyama, S. Kimura, *Chem. Rev.* **2001**, *101*, 3793–3818; b) A. Gross, A. Kumar, B. Kalra, *Chem. Rev.* **2001**, *101*, 2097–2124.

[5] T. Hamaide, R. Spitz, J. P. Letourneux, J. Claverie, A. Guyot, *Macromol. Symp.* **1994**, *88*, 191–200.

[6] C. Miola, T. Hamaide, R. Spitz, *Polymer* **1997**, *38*, 5667–5676.

[7] C. Miola-Delaite, E. Colomb, E. Pollet, T. Hamaide, *Macromol. Symp.* **2000**, *153*, 275–286.

[8] E. Martin, P. Dubois, R. Jérôme, *J. Polym. Sci. Part A* **2003**, *41*, 569–578.

[9] E. Martin, P. Dubois, R. Jérôme, *Macromolecules* **2003**, *36*, 7094–7099.
[10] A. Sudo, T. Endo, *J. Polym. Sci. Part A* **2003**, *41*, 116–118.
[11] C. Camacho-Camacho, M. Biesemans, M. Van Poeck, F. A. G. Mercier, R. Willem, K. Darriet-Jambert, B. Jousseaume, T. Toupance, U. Schneider, U. Gerigk, *Chem. Eur. J.* **2005**, *11*, 2455–2461.
[12] F. A. G. Mercier, M. Biesemans, R. Altmann, R. Willem, R. Pintelon, J. Schoukens, B. Delmond, G. Dumartin, *Organometallics* **2001**, *20*, 958–962.
[13] M. Biesemans, F. A. G. Mercier, M. Van Poeck, J. C. Martins, G. Dumartin, R. Willem, *Eur. J. Inorg. Chem.* **2004**, 2908–2913.
[14] G. Deshayes, F. A. G. Mercier, P. Degée, I. Verbruggen, M. Biesemans, R. Willem, P. Dubois, *Chem. Eur. J.* **2003**, *9*, 4346–4352.
[15] J. C. Martins, F. A. G. Mercier, A. Vandervelden, M. Biesemans, J.-M. Wieruszeski, E. Humpfer, R. Willem, G. Lippens, *Chem. Eur. J.* **2002**, *8*, 3431–3441.
[16] G. Lippens, M. Bourdonneau, C. Dhalluin, R. Warass, T. Richert, C. Seetharaman, C. Boutillon, M. Piotto, *Curr. Org. Chem.* **1999**, *3*, 147–169.
[17] G. Lippens, R. Warass, J.-M. Wieruszeski, P. Rousselot-Pailley, G. Chessari, *Comb. Chem. High Throughput Screening* **2001**, *4*, 333–351.
[18] P. A. Keifer, *Progress Drug Res.* **2001**, *3*, 137–211.
[19] R. Warrass, J.-M. Wieruszeski, G. Lippens, *J. Am. Chem. Soc.* **1999**, *121*, 3787–3788.
[20] C. Griesinger, H. Schwalbe, J. Sleucher, M. Sattler in *Two-dimensional NMR Spectroscopy—Applications for Chemists and Biochemists* (Eds.: W. R. Croasmun, R. M. K. Carlson), VCH, New York, **1994**, pp. 458–572.
[21] M. Eberstadt, G. Gemmecker, D. F. Mierke, H. Kessler, *Angew. Chem.* **1995**, *107*, 1813–1838; *Angew. Chem. Int. Ed. Engl.* **1995**, *34*, 1671–1695.
[22] M. P. McDaniel, *J. Polym. Sci. Polym. Chem. Ed.* **1981**, *19*, 1967–1976.
[23] M. J. Farrall, J. M. J. Frechet, *J. Org. Chem.* **1976**, *41*, 3877–3882.
[24] G. Ruel, N. K. The, G. Dumartin, B. Delmond, M. Pereyre, *J. Organomet. Chem.* **1993**, *444*, C18–C20.
[25] *Vogel's Textbook of Practical Organic Chemistry*, 5th ed., Longman Scientific & Technical, Chelmsford, **1989**, p. 558.

Received: January 18, 2005
Published online: May 18, 2005

