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Organotin catalysts grafted onto cross-linked polystyrene supports through polar spacers

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The present study investigates the suitability of a HypoGel support bearing oligomeric poly(ethylene glycol) (PEG) chains to act as an insoluble carrier for grafted organotin catalysts. Through the introduction of polar spacers, an improved swelling and site accessibility in the polar media typically involved in transesterification reactions are targeted. Advanced structural investigation shows that quantitative conversion into the targeted HypoGel-supported organotin trichloride is hampered by the existence of intra- and/or intermolecular donor-acceptor O→Sn interactions caused by the presence of donor moieties in the PEG-linker. Support is provided to the proposal that the latter interactions are at the origin of the moderate catalytic performance displayed by these HypoGel-supported catalysts, achieving only 41% conversion after 2 hours in the transesterification of ethyl acetate and *n*-octanol. In contrast with similar organotin catalysts supported by an alkyl spacer, the HypoGel-supported materials appear to be poorly recyclable and display poor leaching resistance. Copyright © 2009 John Wiley & Sons, Ltd.

Keywords: tin; HypoGel resin; supported catalyst; transesterification; HRMAS NMR spectroscopy

Introduction

It is well established that organotin compounds are efficient catalysts in a large variety of organic reactions, providing them tremendous potential for widespread industrial application. In particular, tin-based Lewis acids such as mono- or dialkyltin compounds[1–6] and tetraalkyldistannoxane derivatives[7–10] display high catalytic efficiency in transesterification reactions under mild and neutral conditions. Nevertheless, their routine use in an industrial context is hampered by their intrinsic toxicity and by the generally tedious quantitative removal of tin-containing remnants or by-products from the final reaction product. A scientifically rewarding strategy to overcome the latter concerns – and nowadays a general trend in catalysis – involves grafting of the organotin reagent onto an insoluble support.

In previous work,[11–17] our research group has contributed to the development and optimization of efficient cross-linked polystyrene-supported organotin catalysts, and has explored their application potential as sustainable, recyclable and environmentally benign transesterification catalysts. Among these investigations, the polystyrene-grafted undecyltin trichloride (**P-C11-SnCl$_3$**) displayed short half-life times of hardly half an hour to reach transesterification equilibrium, good recyclability up to at least 10 runs, and high leaching resistance with tin leaching degrees averaging around 5 ppm in the end product.[15] Taking these promising results as a benchmark, the present paper aims at expanding the potential of polystyrene-grafted organotin derivatives as catalysts in transesterification reactions by investigating the impact of local polarity changes around the tin atom on the catalytic activity through the introduction of polar spacers of the polyethylene glycol type. In this way, it is targeted to improve the swellability of the support in polar solvents, aiming at an increased molecular mobility of the anchored functional groups at the solid-liquid interface. In this respect, previous HRMAS (high-resolution magic angle spinning) NMR studies have shown that the adequacy of the solvent used for this technique is highly dependent on its polarity and on the nature of the grafted organotin functionality.[12,18] Non-polar solvents were shown to be more appropriate media for a supported dialkyldiphenyltin functionality but less efficient for a dialkyltin dichloride, whereas the opposite is true for polar solvents. These observations have demonstrated that the swellability of the material is very sensitive to local polarity effects in the vicinity of the grafted organotin functionalities. Consequently, their reactivity and catalytic activity is *a priori* anticipated to improve with increasing local polarity as a result of the introduction of polar spacers, an assumption strengthened by the fact that organotin-catalyzed reactions often take place in polar solvents and that donor–acceptor interactions, responsible for the catalytic effect at the level of the tin sites, imply polar coordinative bonds.

Experimental Section

General Aspects

All reactions and manipulations were conducted under a strictly dry N_2 atmosphere using standard Schlenk-tube techniques. The HypoGel resins were purchased from Rapp Polymere. Thionyl chloride (99 + %), mercury(II) chloride (anhydrous), butyllithium (2.5 M in hexane) and triphenyltin hydride were purchased from Aldrich. Triphenyltin hydride was purified prior to use by column chromatography using petroleumether–benzene (4 : 1) as an eluent. Tetrahydrofurane (Aldrich, 99 + %) and tetrahydropyrane (Fluka, 98%) were dried over sodium and distilled prior to use. Diisopropylamine (Aldrich, 99%) was dried over calcium hydride and distilled prior to reaction. Ethyl acetate (Aldrich,

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99.5 + %) and *n*-octanol (Aldrich, 99 + %) were distilled prior to all transesterification experiments.

Synthesis Procedures

Synthesis of $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5Cl]_t$ (**HG-Cl**)

Under dry N_2 atmosphere, 2 g (5.43 mmol) of $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5OH]_t$, **HG-OH** (elemental analysis: H 8.37, C 80.82, O 10.63, resulting in $t = 0.173$), was immersed in freshly distilled tetrahydropyrane (THP) and 0.6 ml of thionyl chloride ($SOCl_2$) was added. The mixture was stirred under reflux for 24 h. After reaction, the target compound $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5Cl]_t$, **HG-Cl**, was successively washed with tetrahydrofurane (THF, 8 × 30 ml) and ethanol (2 × 30 ml). The beads were dried under vacuum at 35 °C.

Experimental mass fractions (wt%): H 7.89, C 77.41, O 8.91, Cl 5.04, resulting in $t = 0.204$; calculated mass fractions for $t = 0.173$ as obtained for **HG-OH**: H 7.89, C 79.06, O 9.04, Cl 4.01. HRMAS NMR ($CDCl_3$, chemical shifts in ppm): ^{1}H: 3.65 (α-CH_2), 3.77 (β-CH_2); ^{13}C: 42.9 (α-CH_2), 71.4 (β-CH_2).

HG-Bz-Cl [**P**-$(CH_2)_2(OCH_2CH_2)_5$O-Bz-Cl] was synthesized from **HG-Bz-OH** (elemental analysis: H 8.18, C 79.61, O 10.83, resulting in $t = 0.189$), using exactly the same procedure as applied for the synthesis of **HG-Cl**.

Experimental mass fractions (wt%): H 7.58, C 76.31, O 9.73, Cl 5.03, resulting in $t = 0.235$; calculated mass fractions for $t = 0.189$ as obtained for **HG-Bz-OH**: H 7.65, C 78.35, O 10.22, Cl 3.78. HRMAS NMR ($CDCl_3$, chemical shifts in ppm): ^{1}H: 4.56 (Bz-CH_2), 6.92 (Bz-CH_o), 7.31 (Bz-CH_m), 4.15 (1-CH_2), 3.88 (2-CH_2); ^{13}C: 46.4 (Bz-CH_2), 114.8 (Bz-C_o), 130.0 (Bz-C_m), 130.0 (Bz-C_p), 158.9 (Bz-C_i), 67.6 (1-CH_2), 69.8 (2-CH_2).

Synthesis of $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5SnPh_3]_t$ (**HG-SnPh$_3$**)

HG-SnPh$_3$ was synthesized from **HG-Cl** using the same procedure as described previously for the cross-linked polystyrene-supported **P-C11-SnPh$_3$**.[15] Diisopropylamine (DIA, 0.11 g, 1.13 mmol) and butyllithium (*n*-BuLi, 2.5 M in hexane, 1.13 mmol) were added to dry THF (2 ml) at 0 °C under a dry nitrogen atmosphere. After 10 min, Ph_3SnH (0.41 g, 1.18 mmol) was added and the mixture was stirred for 20 min. Using a capillary tube and under N_2 atmosphere, the obtained solution of Ph_3SnLi was transferred into another Schlenk tube containing 0.5 g of **HG-Cl** in dry THF at room temperature. The mixture was stirred for 4 h at room temperature. Subsequently, the beads were washed twice with 30 ml of dry THF and the lithiostannylation reaction was repeated with the same amounts of reagents overnight. The obtained target organotin graft $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5SnPh_3]_t$, **HG-SnPh$_3$**, was washed with THF–$H_2O$ (2 : 1; 30 ml), THF (6 × 30 ml) and CH_2Cl_2 (2 × 30 ml). The beads were dried under vacuum at 35 °C.

Experimental mass fractions (wt%): H 7.23, C 76.15, Sn 7.34, O 7.69, resulting in $t = 0.171$; calculated mass fractions for $t = 0.204$ as obtained for **HG-Cl**: H 7.03, C 75.06, Sn 10.70. HRMAS NMR ($CDCl_3$, chemical shifts in ppm, coupling constants in Hz): ^{1}H: 1.90 [$^2J(^{119/117}Sn,^1H)$ 58] (α-CH_2), 3.85 (β-CH_2), 7.62 (Ph-CH_o), 7.38 (Ph-CH_m), 7.38 (Ph-CH_p); ^{13}C: 13.6 [$^1J(^{119/117}Sn,^{13}C)$ 380] (α-CH_2), 69.0 (β-CH_2), 137.2 (Ph-C_o), 128.5 (Ph-C_m), 128.9 (Ph-C_p), 139.1 (Ph-C_i); ^{119}Sn: −103.

HG-Bz-SnPh$_3$ [**P**-$(CH_2)_2(OCH_2CH_2)_5$O-Bz-$SnPh_3$] was synthesized from **HG-Bz-Cl** using exactly the same procedure as applied for the synthesis of **HG-SnPh$_3$**. Experimental mass fractions (wt%): H 7.02, C 75.99, Sn 6.87, O 7.89, resulting in $t = 0.180$; calculated mass fractions for $t = 0.235$ as obtained for **HG-Bz-Cl**: H 6.86, C 74.43, Sn 10.34, O 8.37. HRMAS NMR ($CDCl_3$, chemical shifts in ppm, coupling constants in Hz): ^{1}H: 2.95 [$^2J(^{119/117}Sn,^1H)$ 62] (Bz-CH_2), 6.73 (Bz-CH_o), 6.98 (Bz-CH_m), 4.08 (1-CH_2), 3.85 (2-CH_2), 7.45 (Ph-CH_o), 7.36 (Ph-CH_m), 7.36 (Ph-CH_p); ^{13}C: 18.8 [$^1J(^{119/117}Sn,^{13}C)$ 325] (Bz-CH_2), 114.8 (Bz-C_o), 128.7 (Bz-C_m), 132.6 (Bz-C_p), 155.8 (Bz-C_i), 137.0 (Ph-C_o), 128.4 (Ph-C_m), 128.9 (Ph-C_p), 138.4 (Ph-C_i), 67.6 (1-CH_2), 69.8 (2-CH_2); ^{119}Sn: −118.

Synthesis of $[P\text{-}H]_{(1-t)}[P\text{-}(CH_2)_2(OCH_2CH_2)_5SnPh_nCl_{3-n}]_t$ ($n = 1$, *2*) (**HG-SnPh$_n$Cl$_{3-n}$**)

At room temperature and under an inert N_2 atmosphere, $HgCl_2$ (0.66 g, 2.43 mmol) was dissolved in dry THF and transferred via a capillary tube into a Schlenk flask containing 0.4 g of **HG-SnPh$_3$** immersed in dry THF. The reaction was monitored for reaction times of 1 h, 2.5 h, 4 h and 7 h. After reaction, the beads were thoroughly washed with THF (8 × 15 ml) and CH_2Cl_2 (2 × 15 ml), and dried under reduced pressure at 35 °C.

Experimental mass fractions (wt%): (1 h) H 6.99, C 68.09, Sn 7.91, O 10.35, Cl 4.88; (2.5 h) H 7.01, C 67.61, Sn 8.03, O 10.37, Cl 4.65; (4 h) H 7.04, C 67.67, Sn 7.91, O 10.06, Cl 4.44; (7 h) H 7.14, C 67.75, Sn 7.03, O 10.44, Cl 5.10.

Catalysis Experiments

Ethyl acetate and *n*-octanol were used in a 4 : 1 molar ratio. A mixture of ethyl acetate (3.9 g, 44 mmol), *n*-octanol (1.4 g, 11 mmol) and supported catalyst (0.11 mmol Sn; 1 mol% Sn) was gently stirred at reflux temperature while the generated ethanol was distilled off to drive the reaction to completion. For monitoring the time evolution of the conversion in the course of the transesterification, negligibly small aliquots of 50 µl of reaction mixture were regularly tapped and analyzed by ^{1}H NMR spectroscopy after evaporation of ethyl acetate and ethanol. The ratio of initial octanol to obtained octyl acetate was determined by integration (±1%) of the respective CH_2O ^{1}H NMR resonances. After each transesterification run, the catalyst was filtered off and gently washed with ethyl acetate.

Results and Discussion

Synthesis

In the present work, it is aimed to develop novel supported organotin catalysts starting from readily available materials. The followed strategy consists of anchoring organotin functionalities onto commercially available solid supports called HypoGel resins.[19] In these systems, linear poly(ethylene glycol) (PEG) chains are grafted onto a weakly cross-linked (1% divinyl benzene comonomer – DVB) polystyrene matrix, carriers of which have already been successfully used in solid-phase peptide synthesis.[20–24] In the present study, two types of HypoGels are used as suitable precursors for the desired organotin grafts, differing only by the nature of the terminal functional group X of the PEG spacer (Fig 1).

Organotin moieties are incorporated stepwise at the free chain end of the supported PEG, initially following the standard synthetic methodology used for the polystyrene-grafted **P-C11-SnCl$_3$**,[15] and aiming likewise at synthesizing a functionally pure grafted organotin trichloride. The general reaction scheme toward the HypoGel-grafted organotin derivatives is presented in Scheme 1.

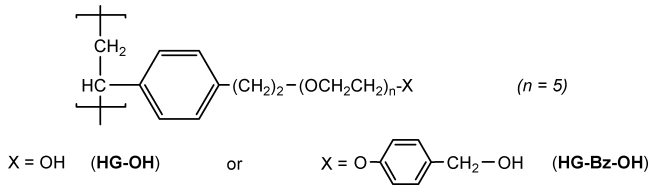


Figure 1. HypoGel (HG) resins used as precursors in the synthesis toward grafted organotins.

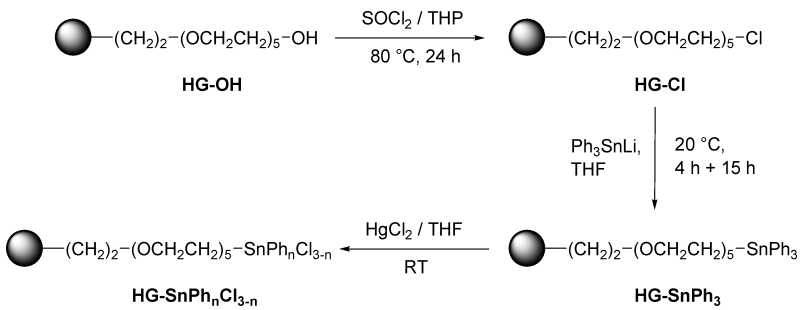
In the first step, the hydroxyl group at the spacer end is substituted for a chlorine atom. In this way, the polystyrene–PEG grafts become susceptible to subsequent lithiostannylation, allowing for the end-functionalization with the organotin moiety. The chlorination reaction of both types of hydroxy-terminated HypoGels is carried out with thionyl chloride ($SOCl_2$) at reflux temperature, using tetrahydropyrane (THP) as the solvent (Scheme 1). After 24 h, the reaction mixture is cooled to room temperature and the target graft undergoes a thorough washing procedure, after which the resin beads are dried under reduced pressure. Subsequently, the stannylated HypoGel grafts are synthesized following the same procedure as previously used for the polystyrene-supported undecyltriphenyltin, **P-C11-SnPh$_3$**.[15] Triphenyltin lithium is prepared by lithiation of purified, commercially available triphenyltin hydride and is subsequently allowed to react with the supported chlorine-terminated spacer, yielding the desired grafted triphenyltin moiety.

The last synthesis step in the reaction pathway toward HypoGel-grafted organotin catalysts consists of substituting the three tin-bound phenyl groups for chlorine atoms. Since a first attempt based on a previously established procedure involving the use of a HCl–MeOH solution[15] failed to yield the desired organotin graft, other strategies were explored in order to chlorinate the tin atom under phenyl group splitting in **HG-SnPh$_3$** and **HG-Bz-SnPh$_3$**. Kemmer *et al*. reported the synthesis of (4,7-dioxaoctyl)phenyldichlorostannane by treatment of the corresponding triphenyltin compound with anhydrous HCl at −78 °C in methylene chloride.[25] Extending this procedure to the HypoGel-supported triphenyltin derivatives did however not result in the targeted organotin trichloride. For **HG-SnPh$_3$**, the reaction provided no observable ^{119}Sn HRMAS resonance at all, while for **HG-Bz-SnPh$_3$**, a single sharp resonance at −28 ppm indicated the generation of non-grafted Ph_2SnCl_2 (see below). Therefore, as an alternative to the above mentioned synthesis routes, a procedure in which the phenyl groups on tin are chlorinated using mercury(II) chloride ($HgCl_2$), has been explored. After successfully performing model reactions with $HgCl_2$ both on molecular $BuSnPh_3$ and on polystyrene-grafted **P-C11-SnPh$_3$**, yielding quantitative conversion into the targeted alkyltin trichloride functionality after respectively 4 and 14 h at reflux, the same reaction procedure is investigated on the HypoGel-supported organotin graft **HG-SnPh$_3$**. A series of experiments were performed both at reflux and room temperature, monitoring the obtained organotin graft after various reaction times. In all cases, its ^{119}Sn HRMAS spectrum pointed toward a mixture of two supported organotin species, which were identified to be the respective PEG-grafted organotin mono- and dichloride, i.e. **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**. In contrast with the C11-grafted organotins, further substitution of the tin-bound phenyl groups toward the targeted organotin trichloride does not occur with these PEG-grafted derivatives. In order to elucidate why the incorporation of a more polar spacer impedes the successful substitution of all three phenyl groups, these particular PEG-grafts have been the object of a detailed and advanced structural investigation presented hereunder.

Structural Investigation

Reaction monitoring and structural elucidation of the HypoGel resin and its supported (organotin) functionalities is achieved using a combination of 1D and 2D ^{1}H, ^{13}C and ^{119}Sn HRMAS NMR. After substitution of the hydroxyl group at the spacer end in **HG-OH** and **HG-Bz-OH** for a chlorine atom, both ^{1}H and ^{13}C spectra of **HG-Cl** and **HG-Bz-Cl** display a new characteristic resonance for a terminal chloromethyl moiety, while the one from the terminal hydroxymethyl group of the precursor is no longer present. This presence or absence of characteristic fingerprint resonances from one synthesis step to the next enabled us to ascertain the degree of completion of the reaction. The assignments of most important ^{1}H and ^{13}C chemical shifts are summarized in the Experimental section.

After lithiostannylation, the functional identity of both organotin grafts **HG-SnPh$_3$** and **HG-Bz-SnPh$_3$** was confirmed in their ^{119}Sn HRMAS spectra (Fig 2, left contour plot), displaying a resonance at −103 and −118 ppm, respectively, characteristic for alkyl-[26,27] and benzyltriphenyltins.[26a] However, the ^{119}Sn spectra of the stannylated target grafts **HG-SnPh$_3$** and **HG-Bz-SnPh$_3$** indicated the additional, undesired presence of a minor side-functionality at −100 ppm (accounting for *ca* 6%) for the former and −103 ppm (accounting for *ca* 7%) for the latter. Since these triphenylstannylated grafts serve as precursors for subsequent grafted target catalysts, it is important to identify the nature of these undesired side-functionalities, an issue which is addressed using information from 2D ^{1}H–^{119}Sn HSQC HRMAS NMR spectra (Fig 2).



Scheme 1. General synthesis procedure toward the HypoGel-grafted organotins (n = 1, 2). The second class of HypoGels with benzyl anchoring group (denoted as **HG-Bz-X**; X = OH, Cl, $SnPh_3$) are synthesized according to the same procedure.

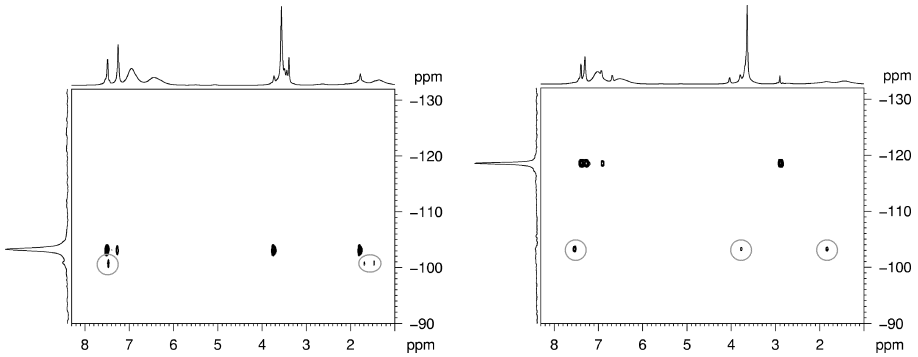


Figure 2. ^{1}H-^{119}Sn HSQC HRMAS spectra of the target **HG-SnPh$_3$** (*left*) and **HG-Bz-SnPh$_3$** (*right*) grafts, with indication of the side-functionalities (*encircled*).

In the ^{119}Sn spectrum of **HG-SnPh$_3$**, only a slight difference in chemical shift between the side-functionality and the target resonance is observed, indicative of very similar chemical environments around the tin atom. On the other hand, the non-existence of a ^{1}H–^{119}Sn correlation between the ^{119}Sn nucleus of the side-functionality and ethylene oxide protons (Fig 2, left), along with the observation of two cross-peaks at ^{1}H chemical shifts of 1.75 and 1.54 ppm, suggests the absence of a PEG spacer in the grafted side-functionality. Combining the latter data with the existence of a ^{1}H–^{119}Sn correlation peak with an aromatic ^{1}H resonance, the grafted side-product has to involve a functionality of the type **P**-$(CH_2)_2SnPh_3$. In the case of **HG-Bz-SnPh$_3$**, the side-functionality found at $\delta(^{119}Sn)$ −103 ppm (Fig 2, right encircled) displays the same 2D cross-peak pattern as the identified target graft **HG-SnPh$_3$** (Fig 2, left), only the cross-peak of the meta phenyl protons collapsing into the noise in the case of the side-functionality of the **HG-Bz-SnPh$_3$** target graft.

In addition, characteristic 2D cross-peak satellites from the unresolved $^{1}J(^{119/117}Sn,^{13}C) = 380$ and 325 Hz and $^{2}J(^{119/117}Sn,^{1}H) = 58$ and 62 Hz couplings in the 2D ^{1}H–^{13}C HSQC HRMAS spectrum unambiguously identify the organotin grafts **HG-SnPh$_3$** and **HG-Bz-SnPh$_3$**, respectively. These coupling constants, together with the respective ^{119}Sn chemical shift values (see Experimental section), unambiguously provide evidence for four-coordination at the tin center, as expected from the properties of the grafts and the non-coordinating nature of the solvent, $CDCl_3$, used for the measurement.[26]

The final synthesis step in the reaction pathway toward HypoGel-grafted organotin catalysts originally aimed at substituting all three tin-bound phenyl groups for chlorine atoms. ^{119}Sn HRMAS monitoring of the functionalized resin after various reaction times however indicates that the targeted organotin trichloride could not be obtained. After treatment of **HG-SnPh$_3$** with $HgCl_2$ during one hour at reflux temperature, the ^{119}Sn spectrum displays two broad resonances at −16 and −40 ppm. This observation points toward a mixture of two supported organotin species, which are identified as the PEG-grafted organotin mono- and dichlorides, **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, as shown by 2D ^{1}H–^{13}C and ^{1}H–^{119}Sn HSQC HRMAS NMR experiments (Fig 3). Next to an additional minor resonance at −101 ppm, attributed to residual unconverted precursor **HG-SnPh$_3$**, a sharp resonance at −27 ppm can be assigned to the presence of a non-grafted organotin compound that could not be completely removed from the resin beads in spite of thorough washing after reaction. On the basis of its ^{1}H and ^{119}Sn chemical shifts, this undesired side-product turns out to be diphenyltin dichloride, Ph_2SnCl_2, as shown by ^{1}H and ^{119}Sn NMR measurements performed on the obtained graft to which aliquots of Ph_2SnCl_2 have been added.[26]

Unfortunately, next to the formation of organotin grafts **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, characteristic cross-peaks in the ^{1}H–^{13}C HSQC HRMAS spectrum indicate the additional generation of an undesired alcoholic side-functionality **HG-OH**. This observation clearly indicates that only partial phenyl group cleavage from the grafted organotin functionalities can occur and that even part of the organotin itself is cleaved from its polar spacer, consequently leading both to functionally non-pure grafts and undesired recovery of starting **HG-OH** functionality. Treating **HG-SnPh$_3$** with $HgCl_2$ for longer reaction times, up to 2.5 and 4 h, results in an additional loss in ^{119}Sn signal, while the corresponding ^{13}C spectra reveal the increasing generation of the alcoholic functionality **HG-OH**. At this point, the exact origin of this split-off of grafted organotins is not yet fully understood since all reactions are conducted under strictly inert N_2 atmosphere using dried and freshly distilled solvents for the reaction and washing procedures, in the same way as for the successfully obtained grafted undecyl-$SnCl_3$ catalyst.[15]

Fig 3 (top right) illustrates the power of the 2D ^{1}H–^{13}C HSQC HRMAS technique, as both carbon atoms adjacent to the tin atom in the two organotin grafts can be differentiated, and their $^{1}J(^{119/117}Sn, ^{13}C)$ coupling constants can be extracted separately.

The $^{1}J(^{13}C, ^{119}Sn)$ coupling constants of **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, respectively 555 and 643 Hz, are fairly higher than those of the similar molecular compounds (*n*Bu)$SnPh_2Cl$ [$^{1}J(^{13}C, ^{119}Sn) = 429$] and (*n*Bu)$SnPh_2Cl$ [$^{1}J(^{13}C, ^{119}Sn) = 503$ Hz], taken as references. These moderately high $^{1}J(^{13}C, ^{119}Sn)$ coupling constant values point toward the existence of an intra- or intermolecular coordination expansion at tin in **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, most probably due to the presence of oxygen atoms in the PEG spacer. Obviously, such a nucleophilic interaction toward tin is not possible in the reference compounds (*n*Bu)$SnPh_2Cl$ and (*n*Bu)$SnPhCl_2$. Expansion of the coordination state of tin by additional intramolecular interactions with electronegative substituents containing an O or N atom has indeed been reported before.[25,28] More specifically, similar coordination expansions were observed for the compound (4,7-dioxaoctyl)phenyldichlorostannane[25] (Fig 4).

As compared with the investigated graft **HG-SnPhCl$_2$**, the latter compound, having a tin chemical shift of −74 ppm in solution,[25] displays only a slight low-frequency shift of about 30 ppm. Also, its $^{1}J(^{119/117}Sn,^{13}C)$ coupling constant of 629 Hz is not very different from the value of 643 Hz measured for **HG-SnPhCl$_2$**. These additional observations are further evidence for

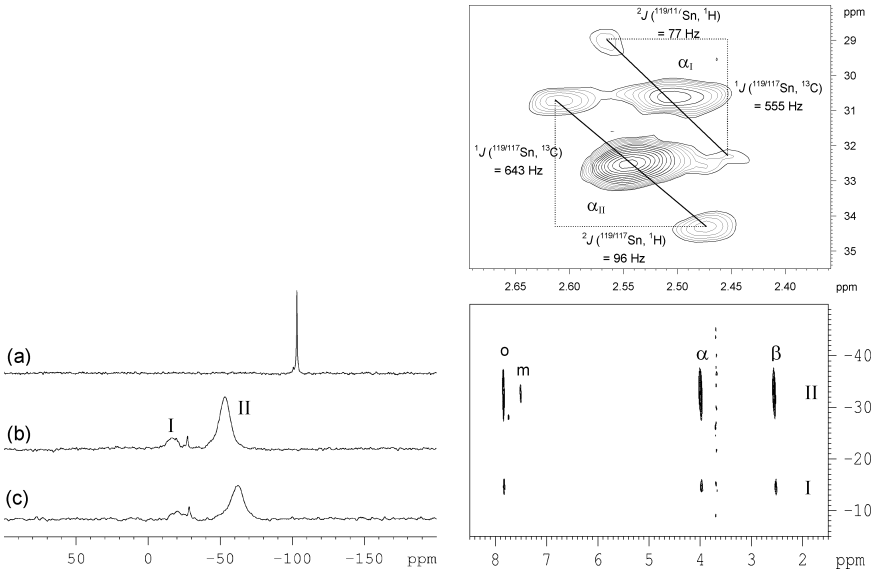


Figure 3. (*left*) ^{119}Sn HRMAS NMR spectra of **HG-SnPh$_3$** (a), and after reaction with $HgCl_2$ at room temperature during (b) 1 h; (c) 7 h. (*top right*) Detail of the α-(CH_2) cross-peaks of **HG-SnPh$_2$Cl** (I) and **HG-SnPhCl$_2$** (II) in the 2D ^{1}H-^{13}C HSQC spectrum, displaying the fine structure as a result of scalar coupling interactions involving the $^{119/117}$Sn nuclei. (*bottom right*) 2D ^{1}H-^{119}Sn HSQC HRMAS NMR spectrum displaying, next to the α- and β-(CH_2) cross-peaks, correlations with the aromatic ortho and meta protons of the tin-bound phenyl groups.

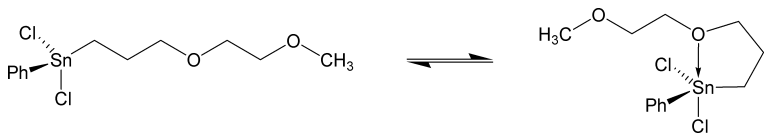


Figure 4. Dynamic equilibrium for (4,7-dioxaoctyl)phenyldichlorostannane as proposed by Kemmer *et al.*[25].

the existence of such O → Sn interactions in the latter organotin graft. It is reasonable to assume that they are also responsible for the partial cleavage of the organotin functionality observed in the course of the final reaction step. It has indeed been reported that fairly remarkable changes in reactivity can occur due to intramolecular nucleophilic assistance at tin,[29] with examples in which the cleavage of alkyltin bonds is preferred over aryltin bond cleavage.

A second set of experiments in which the reaction temperature is reduced to room temperature seems to avoid the dramatic loss in ^{119}Sn resonance with increasing reaction times (Fig 3, left), even though the formation of some undesired **HG-OH** is still observed in the ^{13}C spectra of all reaction products. Furthermore, independently of the reaction duration, the ^{119}Sn spectra continuously display a mixture of two different organotin grafts, most likely involving **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$** as suggested above. The further substitution of the tin-bound phenyl groups appears to be hampered by the intra- and/or interspacer donor–acceptor O → Sn interactions due to the presence of oxygen atoms in the linker. This assumption is strengthened by a 2D ^{1}H–^{119}Sn HSQC correlation experiment (Fig 3, right) in which both ^{119}Sn resonances are found to be correlated to aromatic ^{1}H resonances, confirming the incomplete splitting off of all three phenyl groups on tin. Additionally, for both grafts **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, the spectrum exhibits clear ^{1}H–^{119}Sn correlations between the tin resonance and the protons of methylene groups α- and β-(CH_2).

Finally, the same reaction procedure using $HgCl_2$ in THF at room temperature is also investigated on the second type of HypoGel-supported organotin grafts **HG-Bz-SnPh$_3$**. Overall, this approach does not lead to successful results. After a reaction duration of 2.5 h, the ^{119}Sn HRMAS spectrum displays a sharp resonance at −28 ppm (similar to the one previously observed for the other HypoGels) on top of a weakly intense and broad signal, rising from an organotin graft we failed to identify. The low signal-to-noise ratio of this broad ^{119}Sn resonance presumably indicates loss of grafted tin with respect to the original input quantity of grafted organotin. ^{119}Sn HRMAS monitoring of the reaction product at a shorter reaction time of half an hour again demonstrates the generation of Ph_2SnCl_2 resonating at −28 ppm next to residual unconverted **HG-Bz-SnPh$_3$**. In view of the latter data and considering the moderate results previously obtained for the first type of HypoGels, along with the hypothesized intra- and/or interspacer O → Sn associations, it was decided not to proceed with further refinement of the synthesis pathway for the benzyl-containing HypoGels.

Catalysis

In order to investigate the effect of increased spacer polarity on the catalytic activity, the performance of the HypoGel-supported organotin catalyst, *i.e.* a mixture of grafted **HG-SnPh$_2$Cl** and **HG-SnPhCl$_2$**, is explored in the same model transesterification of ethyl acetate and *n*-octanol (4 : 1) used earlier for the cross-linked polystyrene-supported catalysts.[15] As such, unambiguous comparison can be made between catalytic activities obtained by both type of grafted organotin catalysts.

Fig 5 shows that in a first transesterification run with the HypoGel-supported catalyst (▲), only 41% conversion is achieved

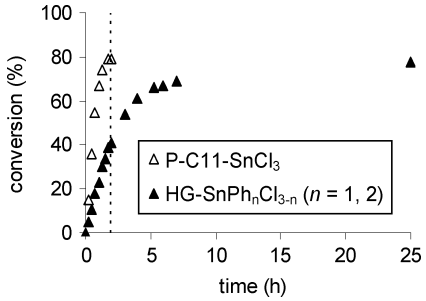


Figure 5. Time evolution towards equilibrium in a first transesterification run of ethyl acetate and *n*-octanol, using the polystyrene-supported **P-C11-$SnCl_3$** (△) and the HypoGel-supported **HG-S_nPhnCl_{3-n}** (▲) as a catalyst. The dashed vertical line corresponds to a reaction time of 2 hours.

after two hours. Consequently, the latter proves to be much less efficient than the polystyrene-supported alkyltin trichloride **P-C11-$SnCl_3$**, (Fig 5, △) leading to chemical equilibrium at 80% conversion in a reaction time of *ca* 2 h.

In view of the possible presence of inter- and/or intraspacer O → Sn interactions in the HypoGel-supported catalyst, it is legitimate to assume that the reaction rate – even if dealing with a hypothetic functionally pure HypoGel-supported organotin trichloride – is considerably influenced by these interactions, hampering the accessibility of the reactants to the catalytic sites, and therefore negatively affecting the overall conversion rate. Intramolecular interactions are believed to lower the Lewis acidity of the tin atom as well, and accordingly, its catalytic activity. Moreover, monitoring of the catalyst with ^{119}Sn HRMAS NMR after the first catalytic run (Fig 6, bottom left) revealed the complete collapse of the two ^{119}Sn resonances characteristic for **HG-$SnPh_2Cl$** and **HG-$SnPhCl_2$**, which were present in the non-used catalyst (Fig 6, top left). No ^{119}Sn HRMAS resonance was observed either at lower frequencies, whereas the solid-state ^{117}Sn MAS NMR spectrum of the used catalyst displayed an anisotropy pattern around −600 ppm. In line with previous results obtained for the polystyrene-supported catalyst **P-C11-$SnCl_3$**, these parallel observations can be ascribed to organotin cross-linking at the interface.[15]

Furthermore, the HypoGel-supported catalyst shows to be poorly recyclable. Reusing the catalyst in a second transesterification run, results in a severe decrease in catalytic activity, reaching a conversion degree of only 9% after 2 h. An explanation for this observation can be found in the high leaching degree displayed by the HypoGel catalyst. After a single run with fresh catalyst, a tin content as high as 5860 ppm was measured in the final reaction product. The latter corresponds to a dramatic loss of 70% with respect to the initial amount of grafted tin present in non-used catalyst. After the second run, another 420 ppm of leached Sn was detected in the reaction mixture. Again, it is reasonable to assume that the O → Sn interactions are at the origin of the moderate catalytic efficiency observed for these HypoGel-supported organotins. In addition, as nucleophilic assistance at tin has been reported to aid the cleavage of the aliphatic carbon–tin bond,[29] the poor leaching resistance of the catalyst is readily explained.

Conclusion

The object of the present study was to increase the local polarity around the tin atom in polystyrene-supported organotin derivatives. In this context, an increased Lewis acidity of the tin site was aimed for through the introduction of polar spacers; the suitability of a HypoGel support bearing oligomeric poly(ethylene glycol) chains to act as an insoluble carrier for organotin catalysts was therefore investigated. Yet the targeted HypoGel-supported organotin trichloride could not be obtained; the rather simple and straightforward synthesis procedure set up for the C11-grafted polystyrenes proved to be inappropriate when applied to this type of support. Only by reaction of a grafted triphenyltin moiety with the highly toxic mercury derivative $HgCl_2$ did we succeed in obtaining a mixture of a PEG-grafted diphenyltin chloride and phenyltin dichloride. The further substitution of the tin-bound phenyl groups appeared to be hampered by intra- and/or interspacer donor-acceptor O → Sn interactions due to the presence of oxygen atoms in the polar linker. It is also assumed that these O → Sn interactions are at the origin of the moderate catalytic efficiency observed for these HypoGel-supported organotins. For this reason, and in view of their low leaching resistance and their inability to be recycled, the HypoGel-supported catalysts show to be less suitable for transesterification than the C11-grafted polystyrenes. As a conclusion, it can be stated that tuning the spacer toward higher polarities by the incorporation of electronegative atoms such as oxygen does not offer a new track toward improved catalytic performances of grafted organotins. Rather is it even recommended from the present study to avoid any additional source of coordination expansion of the tin atom, except for the one caused by the transesterification reaction components themselves.

In terms of characterization of any grafted species, 1D and 2D ^{1}H, ^{13}C and ^{119}Sn HRMAS NMR spectroscopy confirmed its high potential for monitoring solid-phase synthetic procedures, conveniently allowing the assessment of the functional purity of the synthesized grafts. Clearly identifiable tin coupling patterns in the 2D ^{1}H–^{13}C HSQC spectra provided crucial information with regard to the tin coordination state and the identification of the target organotin graft.

Acknowledgments

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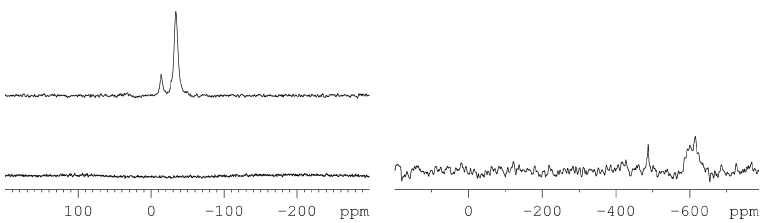

Figure 6. (*left*) ^{119}Sn HRMAS NMR spectrum of non-used HypoGel-supported catalyst (*top*) and after the first transesterification run (*bottom*). (*right*) ^{117}Sn CP-MAS spectrum after the first run.

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References

[1] A. G. Davies, *Organotin Chemistry*, Wiley: Weinheim, **2004**.
[2] P. J. Smith, *Chemistry of Tin*, Blackie Academic & Professional: London, **1998**.
[3] I. Omae, *Applications of Organometallic Compounds*, Wiley: Chichester, **1998**.
[4] C. J. Evans, S. Karpel, *Organotin Compounds in Modern Technology*, Elsevier: Amsterdam, **1985**.
[5] O. A. Mascaretti, R. L. E. Furlán, *Aldrichim. Acta* **1997**, *30*, 55.
[6] G. Deshayes, F. A. G. Mercier, P. Degée, I. Verbruggen, M. Biesemans, R. Willem, P. Dubois, *Chem. Eur. J.* **2003**, *9*, 4346.
[7] J. Otera, *Chem. Rev.* **1993**, *93*, 1449.
[8] S. Shyamroy, B. Garnaik, S. Sivaram, *J. Polym. Sci.* **2005**, *43*, 2164.
[9] A. Orita, A. Mitsutome, J. Otera, *J. Org. Chem.* **1998**, *63*, 2420.
[10] J. Xiang, A. Orita, J. Otera, *Adv. Synth. Catal.* **2002**, *344*, 84.
[11] F. A. G. Mercier, M. Biesemans, R. Altmann, R. Willem, R. Pintelon, J. Schoukens, B. Delmond, G. Dumartin, *Organometallics* **2001**, *20*, 958.
[12] 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.
[13] G. Deshayes, K. Poelmans, I. Verbruggen, C. Camacho-Camacho, P. Degée, V. Pinoie, J. C. Martins, M. Piotto, M. Biesemans, R. Willem, P. Dubois, *Chem. Eur. J.* **2005**, *11*, 4552.
[14] 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.
[15] V. Pinoie, K. Poelmans, H. E. Miltner, I. Verbruggen, M. Biesemans, G. Van Assche, B. Van Mele, J. C. Martins, R. Willem, *Organometallics* **2007**, *26*, 6718.
[16] K. Poelmans, V. Pinoie, I. Verbruggen, M. Biesemans, G. Van Assche, G. Deshayes, P. Degée, P. Dubois, R. Willem *Appl. Organomet. Chem.* **2007**, *21*, 504.
[17] K. Poelmans, V. Pinoie, I. Verbruggen, M. Biesemans, G. Deshayes, E. Duquesne, C. Delcourt, P. Degée, H. E. Miltner, P. Dubois, R. Willem, *Organometallics* **2008**, *27*, 1841.
[18] F. A. G. Mercier, Synthesis, characterization and catalytic activity of dialkyltin compounds grafted onto insoluble cross-linked polystyrene, Ph.D. Thesis, VUB, **2002**.
[19] Rapp Polymere GmbH, http://www.rapp-polymere.com.
[20] H. S. Hiemstra, W. E. Benckhuijsen, R. Amons, W. Rapp, J. W. Drijfhout, *J. Pept. Sci.* **1998**, *4*, 282.
[21] W. Rapp, in *Combinatorial Peptide and Nonpeptide Libraries* (Ed.: G. Jung), VCH: Weinheim, **1996**, p. 425.
[22] W. Rapp, in *Combinatorial Chemistry, Synthesis and Application* (Eds.: S. R. Wilson, A. W. Czarnik, Wiley: Chichester, **1997**, p. 65.
[23] P. Wright, D. Lloyd, W. Rapp, A. Andrus, *Tetrahedron Lett.* **1993**, *34*, 3373.
[24] M. Zeppezauer, R. Hoffmann, A. Schönberger, S. Rawer, W. Rapp, E. Bayer, *Z. Naturforsch.* **1993**, *48b*, 1801.
[25] M. Kemmer, M. Biesemans, M. Gielen, E. R. T. Tiekink, R. Willem, *J. Organomet. Chem.* **2001**, *634*, 55.
[26] a) B. Wrackmeyer, *Annu. Rep. NMR Spectrosc.* **1985**, *16*, 73; b) B. Wrackmeyer, *Annu. Rep. NMR Spectrosc.* **1999**, *38*, 203.
[27] M. Gielen, *Bull. Soc. Chim. Belges* **1983**, *92*, 409.
[28] a) H. C. Clark, V. K. Jain, R. C. Mehrotra, B. P. Singh, G. Srivastava, T. Birchall *J. Organomet. Chem.* **1985**, *279*, 385; b) M. A. Buntine, V. J. Hall, E. R. T. Tiekink, *Z. Kristallogr.* **1998**, *213*, 669; c) J. S. Casas, A. Castiñeiras, E. Garcia Martinez, P. Rodriguez, U. Russo, A. Sanchez, A. Sanchez-Gonzalez, J. J. Sordo, *Appl. Organomet. Chem.* **1999**, *13*, 69; d) J. Susperregui, M. Bayle, J. M. Léger, G. Déléris, M. Biesemans, R. Willem, M. Kemmer, M. Gielen, *J. Organomet. Chem.* **1997**, *545–546*, 559; e) P. Novák, Z. Padělková, L. Kolářová, I. Císařová, A. Růžička, J. Holeček, *Appl. Organomet. Chem.* **2005**, *19*, 1101; f) P. Novák, A. Lyčka, I. Císařová, V. Buchta, L. Silva, L. Kolářová, A. Růžička, J. Holeček, *Appl. Organomet. Chem.* **2005**, *19*, 500; g) P. Novák, J. Brus, I. Císařová, A. Růžička, J. Holeček, *J. Fluorine Chem.* **2005**, *126*, 1531; h) M. Biesemans, R. Willem, S. Damoun, P. Geerlings, M. Lahcini, P. Jaumier, B. Jousseaume, *Organometallics* **1996**, *15*, 2237; i) P. Jaumier, B. Jousseaume, E. R. T. Tiekink, M. Biesemans, R. Willem, *Organometallics* **1997**, *16*, 5124; j) M. Biesemans, R. Willem, S. Damoun, P. Geerlings, E. R. T. Tiekink, P. Jaumier, M. Lahcini, B. Jousseaume, *Organometallics* **1998**, *17*, 90.
[29] J. L. Wardell, in *Chemistry of Tin* (Ed.: P. J. Smith), Blackie Academic & Professional: London, **1998**, p. 95.

