Immobilization of Oligostyrene-Prolinol Conjugates into Polystyrene via Electrospinning and Applications of these Fibers in Catalysis

Caren Röben,[a] Michael Stasiak,[b] Birgit Janza,[a] Andreas Greiner,[b] Joachim H. Wendorff,*[b] Armido Studer*[a]

[a] Institute of Organic Chemistry, Westfälische Wilhelms-Universität Münster, Corrensstrasse 40, 48149 Münster, Germany
Fax +49(251)8336523; E-mail: studer@uni-muenster.de

[b] Department of Chemistry, Philipps-Universität Marburg, Hans-Meerwein-Strasse, 35032 Marburg, Germany
E-mail: wendorff@staff.uni-marburg.de

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Dedicated to Prof. Reinhard W. Hoffmann on the occasion of his 75th birthday

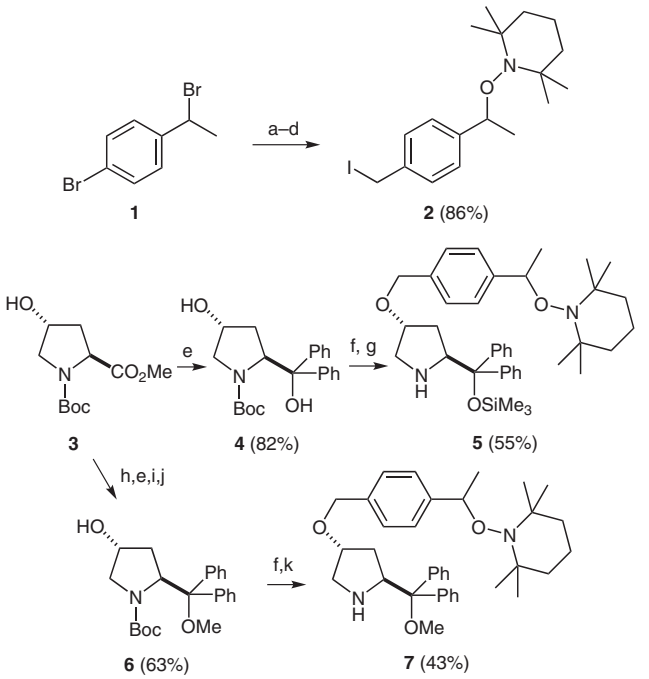
Abstract: This paper reports the synthesis of prolinol-oligostytrene conjugates and their immobilization into a polystyrene matrix by using the electrospinning process. Via this approach fibers with a large surface area (fiber diameter of 1.2 μm) containing the prolinol conjugate are readily obtained. The fibers are shown to be catalytically active in a test Michael reaction. The fibrous catalyst system can readily be removed from the reaction mixture and be reused. However, a decrease of the catalyst activity was noticed upon recycling the fibrous catalyst systems.

Key words: organocatalysis, polymer, stereoselective synthesis, synthetic methods

Organocatalysis has received great attention during the last seven years.[1] Different approaches for the immobilization of organocatalysts have been reported.[2] The separation of the catalyst from the product is often a serious problem. For economic reasons its recovery is highly desirable, in particular, if expensive catalysts are used. In pharmaceutical industry product contamination might be a problem. Furthermore, on going from batch to continuous reactions one faces the problem of keeping the catalyst in the reaction vessel while the reaction components are pumped through.

We recently reported that the electrospinning process[3] can be used for the immobilization of homogeneous catalysts into polymer nanofibers.[4] Scandium triflate was readily immobilized in polystyrene fibers during electrospinning and the fibrous catalytic system obtained was shown to be active in imino aldol and aza-Diels–Alder model reactions. Moreover, we showed that catalysts covalently bound to low-molecular weight polystyrene (M_n >4000 g/mol) can be immobilized into high molecular weight polystyrene nanofibers by using the electrospinning process.[5] The oligostyrene catalyst conjugates were well dispersed in the polystyrene matrix. Leaching of the oligostyrene-tagged catalysts out of the polystyrene matrix was suppressed in DMSO. Herein we present the synthesis of oligostyrene-prolinol conjugates, their immobilization into high-molecular weight polystyrene by using the electrospinning process, and finally first applications of these fibrous systems in organocatalysis. The advantage of this immobilization technique over other immobilization methods (copolymerization) lies in the high surface area of the polymer fibers obtained during electrospinning. The high surface area may lead to a highly active catalyst system.

The nitroxide-mediated controlled radical polymerization[6] was chosen as polymerization technique for the preparation of well-defined oligostyrene-prolinol conjugates. The synthesis of the polymerization initiators is depicted in Scheme 1. Benzylic iodide **2** was readily prepared in four steps starting from the dibromide **1** in 86% overall yield.[5,7] Grignard addition of phenylmagnesium chloride to ester **3** (→ **4**), etherification of the secondary alcohol with iodide **2**, and silylation provided initiator **5** in 45% overall yield. The methyl derivative **7** was prepared from ester **3** in 6 steps via ether **6** in acceptable overall yield (27%).



Scheme 1 *Reagents and conditions*: a) TEMPO, Cu, $Cu(OTf)_2$, 4,4′-di(*tert*-butyl)bipyridine, benzene; b) *n*-BuLi, DMF, THF; c) $LiAlH_4$, THF; d) NaI, TMSCl, MeCN; e) PhMgCl, THF; f) NaH, **2**, THF; g) TMS-imidazole, CH_2Cl_2; h) TBDMSCl, imidazole, DMF; i) MeI, NaH; j) HF·pyridine, THF; k) aq 4 N HCl, dioxane.

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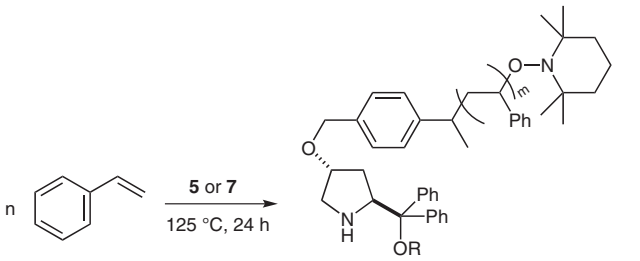
All polymerizations were performed in neat styrene (Scheme 2). To this end, the alkoxyamine **6** (or **7**) was dissolved in styrene (100 equiv), the solution was degassed in three freeze-thaw cycles, and the reaction mixture was sealed under argon and heated to 125 °C for 24 hours. The polymerization was stopped upon cooling to room temperature and the polymer was dissolved in dichloromethane. The solution was poured into a Petri dish and the residual styrene monomer was removed in a vacuum drying cabinet at elevated temperature (60 °C for 12 h). The conversion was determined gravimetrically (**8**: 67%; **9a**: 64% and **9b**: 58%); molecular weight and polydispersity index (PDI) were determined by size exclusion chromatography (SEC).



8 (R = $SiMe_3$, Mn = 7500 g/mol, PDI = 1.30)
9a (R = Me, Mn = 6700 g/mol, PDI = 1.16)
9b (R = Me, Mn = 5600 g/mol, PDI = 1.11)

Scheme 2 Preparation of oligostyrene-prolinol conjugates **8**, **9a**, and **9b**

For the electrospinning[3] of the polystyrene fibers we applied a strong electric field in the order of 10^3 V/cm to the droplet of the polymer solution emerging from a cylindrical die. The electric charges accumulate on the surface of the droplet and cause it to become deformed along the field direction, even though the surface tension counteracts droplet evolution. In supercritical electric fields, the field strength overcomes the surface tension and a fluid jet emanates from the droplet tip. The jet is accelerated towards the counter electrode. During this transport phase, the jet is subjected to strong electrically-driven circular bending motion, which causes a strong elongation and thinning of the jet into a solvent evaporation until the solid fiber is finally deposited on the counter electrode.

To obtain the PS-fibers containing the oligostyrene-prolinol conjugates we performed electrospinning using *N*,*N*-dimethylacetamide solutions containing high molecular weight polystyrene (M_n = 150 000 to 300 000 g/mol; 18 weight%) and the oligostyrene **8**, **9a**, or **9b** (9 weight%) to give fibrous catalyst systems **A** (from **8**) and **B** (from **9a**, see Experimental Section). We obtained fibers free of beads with diameters around 1.2 μm (from **8** = 1.15 μm; from **9a** = 1.16 μm). SEM images of the fibrous catalyst system **A** are presented as examples in Figure 1. To further stabilize the fibers we decided to coat the fibers carrying the organocatalyst with a thin polymer film to obtain core shell fibers via chemical vapor deposition (CVD) starting from [2.2]paracyclophane as a precursor.[8,9] To this end, poly-*p*-xylylene (PPX) was deposited at 30 °C to the electrospun fiber. Importantly, PPX is known to be resistant to most common solvents. The fibrous catalyst system containing **9b** with a PPX shell prepared via this route (diameter of core fiber: 1.16 μm, PPX shell thickness: 0.19 μm) is designated herein as system **C**. As a test reaction we investigated the 1,4-addition of dimethyl malonate to cinnamaldehyde to give aldehyde **10** (Scheme 3).[10]

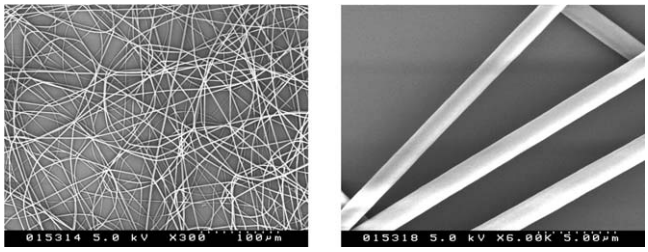
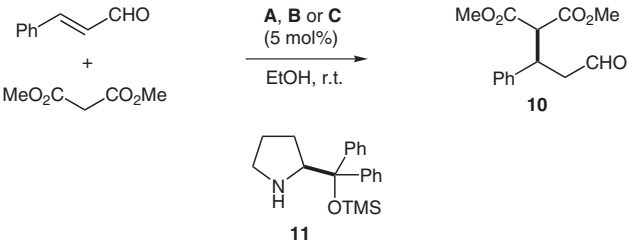


Figure 1 SEM images of catalyst system **A** (average diameter of the fibers: 1.16 μm)



Scheme 3 Test reaction

The Michael additions were conducted in EtOH (48 mM) at room temperature for three days. The aldehyde was added in a 2-fold excess. About 5 mol% of catalyst was used in each run as calculated, based on the SEC data of the polymer conjugates immobilized. The fibrous catalyst system was fixed in a home made clamp and was readily removed from the reaction mixture by simply removing the clamp. After separation from the reaction mixture, the fibrous catalyst system was thoroughly washed with EtOH. In Figure 2, a picture of the reaction vessel is depicted. For some reactions the enantioselectivity was determined by chiral HPLC after derivatization of **10** according to a literature procedure.[10] Reactions were repeated 9 times (for **A** and **C**) and 6 times (for **B**), respectively. Yields were determined based on isolated product **10**. The results are presented in Figure 3.

Pleasingly, the immobilized catalyst **A** turned out to be active in the test reaction and **10** was isolated in 42% yield with an enantiomer ratio of 96:4. It has often been observed that catalyst immobilization leads to reduced activity. Therefore, we repeated the experiment under identical conditions (48 mM) with the homogeneous catalyst **11**. As expected, a higher yield was achieved in this experiment under similar conditions (84%, er = 97:3). Hence, immobilization of the catalyst using our new approach does slightly reduce its activity if compared with the result obtained with the nonimmobilized homogenous catalyst.

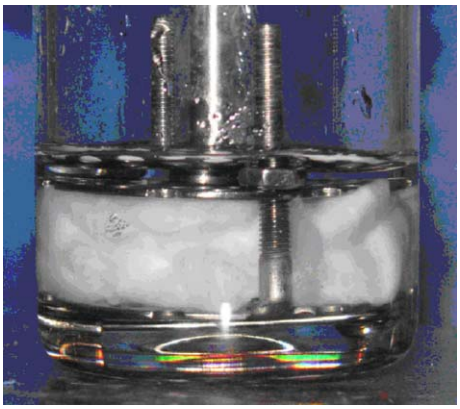


Figure 2 Reaction vessel containing the fibrous catalyst system **A**

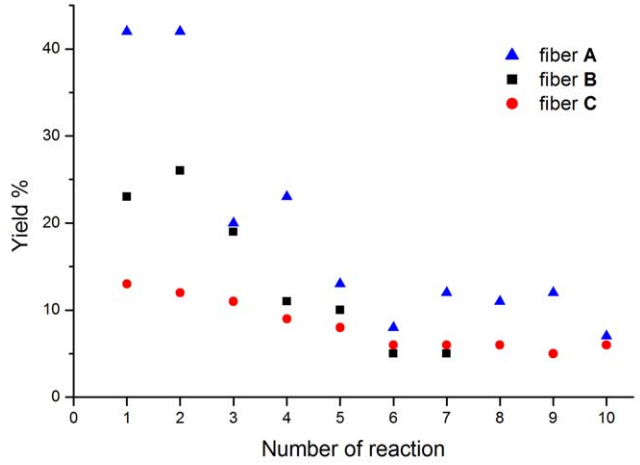


Figure 3 Results of the Michael additions using catalysts **A**, **B**, and **C**

Importantly, a similar selectivity was obtained in these two experiments. Based on our previous results[5] we ruled out that catalyst leaching for conjugates bearing polystyrene tails larger than 4000 g/mol occurred during the prewashing process. Moreover, we did not identify any catalyst conjugate **8** in the reaction mixture after removal of the fibrous system **A**. However, we cannot rule out that some of the catalytically active prolinol moieties of the fibers were decomposed during electrospinning via electron-transfer processes. Catalyst system **A** was recycled 9 times. We found that the initial activity remained for the second run (42%, er = 96:4). However, the activity decreased in the third run and leveled at about 25% of the initial activity in the following runs (see runs 5–10). We assumed that desilylation might occur under the reaction conditions since the fiber system stayed more than 30 days in EtOH at room temperature. The desilylation might be the reason for the decrease of activity. Therefore, catalyst system **B**, bearing a methyl ether instead of the rather labile silyl ether was tested under the same conditions. Compared to system **A**, a lower yield and a slightly lower selectivity (er = 91:9) were obtained for the first two runs (1st run: 23%, 2nd run: 26%). As with fibrous catalyst **A**, a decrease of activity was noticed in runs 3–7. Hence, desilylation in **A** is probably not the reason for catalyst deactivation. We thought that physically stabilizing the fibers by coating PPX might lead to systems where catalytic activity will not be reduced after recycling of the catalyst. To this end, we tested fiber system **C** in the Michael addition. Due to the PPX layer, diffusion of substrates into the fiber mat and products out of the fiber mat might be slower and hence activity was expected to be reduced as compared to system **B**. In fact, a lower yield was obtained for runs 1 and 2 under similar conditions (13% and 12%, respectively). Unfortunately, the PPX-coat could not suppress catalyst deactivation. Yields leveled at around 6% for runs 6 to 10 (about 50% of initial activity).

The reason for the catalyst deactivation is not clearly understood. We assumed that the morphology of the fibers might be changed during catalysis. The solvent might lead to a change of the fiber structure as already noticed for other solvents.[5] Therefore, we reanalyzed catalyst system **B** after run 7 by SEM. In Figure 4 the SEM images are presented. It is obvious that small changes on the fiber mat occurred during the reaction (compare the left panel of Figure 1 with the left panel of Figure 4); fibers seem to be cut (lower aspect ratios). However, the fibers themselves (right hand side) seem not to be damaged. Therefore, we believe that the small changes in the macrostructure of the fibrous systems lead to a decrease of the catalyst activity probably due to a change of the diffusion rates.

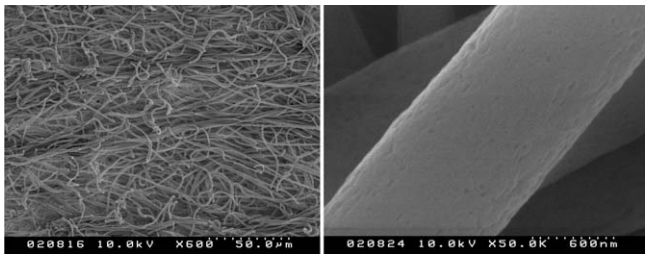


Figure 4 SEM images of catalyst system **B** after 7 runs

In conclusion, we have shown that prolinol derivatives could be conjugated with low molecular weight oligostyrene. By using the nitroxide-mediated radical polymerization method the length of the oligostyrene tail could be adjusted. The oligostyrene-prolinol conjugates were readily immobilized into a high molecular weight polystyrene matrix by co-electrospinning of the conjugate with polystyrene. The fibers obtained were free of beads. All fiber systems tested were catalytically active in the test Michael addition. However, catalyst deactivation was observed and activity decreased to 25–50% of the initial activity after 10 runs. We believe that the approach presented herein is promising and future experiments will be devoted to further stabilize the macrostructure of the catalytically active fibers.

^{1}H NMR (600 MHz, 300 MHz) and ^{13}C NMR (150 MHz, 75 MHz) spectra were recorded on a Bruker ARX 300 spectrometer or Varian Associated Unity Plus 600 spectrometer. Chemical shifts (δ) in ppm

are referenced to the solvent residue peak as an internal standard and are reported relative to TMS. To allocate the NMR signals H,H-COSY and C,H-correlations (GHSQC, GHMBC) were recorded for (2*S*,4*R*)-2-(methoxydiphenylmethyl)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidine-1-carboxylic acid *tert*-butyl ester. These were also used to allocate the signals for all analogue compounds diphenyl-((2*S*,4*R*)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidin-2-yl)methanol, **5** and **7**. TLC was carried out on Merck silica gel 60 F_{254} plates; detection by UV or dipping into a solution of $KMnO_4$ (1.5 g), $NaHCO_3$ (5.0 g) and H_2O (400 mL), or a solution of $Ce(SO_4)_2 \cdot H_2O$ (10 g), phosphomolybdic acid hydrate (25 g), concd H_2SO_4 (60 mL), followed by heating. Flash chromatography (FC) was carried out on Merck silica gel 60 (40–63 μm) at about 0.4 bar additional pressure. Solvents were purified and dried by standard methods. Compounds sensitive to air and moisture were handled under argon by means of modified Schlenk techniques.

IR spectra were recorded on a Digilab FTS 4000 equipped with a Specac MKII Golden Gate Single Reflection ATR System, or a Bruker IFS-28. ESI-MS and HRMS were performed using a Bruker MicroTof. Size exclusion chromatography (SEC) was carried out with THF as eluent at a flow rate of 1.0 mL/min at r.t. on a system consisting of a Merck Hitachi L-6200A Intelligent Pump, a set of two Polymer Laboratories PLgel 5 μm MIXED-C columns (300 × 7.5 mm, linear range of molecular weight: 200–2 000 000 g/mol), and a Knauer Differential refractometer (λ = 950 ± 30 nm) detector. Data were analyzed with PSS WinGPC compact V 7.20 software based upon calibration curves built upon polystyrene standards (Polymer Laboratories polystyrene medium MW calibration kit S-M-10) with peak molecular weights ranging from 500–3000000 g/mol. HPLC was performed using a system consisting of a Hewlett Packard Binary Pump and a Diacel Chiracel AD-H column. Data were analyzed with Hewlett Packard Series 1100 Chem Station for LC.

Scanning Electron Microscopy (SEM) was performed with a Hitachi S-4100 microscope using acceleration voltages between 5 and 10 kV.

Diphenyl-((2*S*,4*R*)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidin-2-yl)methanol

NaH (60% in mineral oil, 109 mg, 2.72 mmol, 4.0 equiv) was added slowly to a solution of **4** (250 mg, 0.677 mmol, 1.0 equiv) in THF (10 mL) at r.t. and the mixture was then heated at reflux for 3 h. The mixture was allowed to cool to r.t. and nitroxide **2** (273 mg, 0.681 mmol, 1.0 equiv) was added. The mixture was heated at reflux for 5 h, stirred overnight at r.t. and the reaction was quenched by the addition of H_2O (10 mL). The aqueous layer was extracted with Et_2O (3 × 10 mL) and the combined organic layers were dried ($MgSO_4$) After concentration in vacuo, purification of the residue by flash chromatography (acetone–CH_2Cl_2, 1:4) yielded the title compound (1.07 g, 79%).

IR (neat): 3362, 3058, 2972, 2931, 1764, 1598, 1491, 1449, 1375, 1360, 1259, 1210, 1182, 1064, 1020, 821, 748, 701 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$, 300 K): δ = 7.52 (d, *J* = 7.3 Hz, 2 H_{arom}), 7.39 (d, *J* = 7.3 Hz, 2 H_{arom}), 7.26–7.06 (m, 10 H, C_6H_5), 4.71 (q, *J* = 6.6 Hz, 1 H, C*H*CH_3), 4.54 (dd, *J* = 9.6, 6.8 Hz, 1 H, C*H*OR), 4.35 (s, 2 H, CH_2O), 4.01–3.92 (m, 1 H, C*H*NH), 3.07–3.01 (m, 2 H, CH_2NH), 1.80–1.70 (m, 1 H, CH_aH$_b$CHOR), 1.64–1.58 (m, 1 H, CH$_a$$H_b$CHOR), 1.39 (d, *J* = 6.6 Hz, 3 H, CHCH_3), 1.36–0.95 (m, 15 H, 3 × CH_2, TEMPO, 3 × CH_3, TEMPO), 0.61 (br s, 3 H, CH_3, TEMPO).

^{13}C NMR (75 MHz, $CDCl_3$, 300 K): δ = 145.6 (C), 145.1 (C), 136.8 (C), 128.6 (CH), 128.2 (CH), 127.6 (CH), 127.0 (CH), 126.9 (CH), 126.7 (CH), 126.3 (CH), 125.3 (CH), 83.0 (CH), 79.3 (CH), 77.1 (C), 70.9 (CH_2), 63.8 (CH), 59.9 (C), 52.6 (CH_2), 40.6 (CH_2), 33.2 (CH_2), 23.8 (CH_3), 20.6 (CH_3), 17.4 (CH_2).

MS (ESI): *m*/*z* = 1085.7 $[2 M + H]^+$, 543.3 $[M + H]^+$.

HRMS (ESI): *m*/*z* calcd for $C_{35}H_{46}N_2O_3$ $[M + H]^+$: 543.3581; found: 543.3585.

1-(1-{4-[(3*R*,5*S*)-5-(Diphenyltrimethylsilyloxymethyl)pyrrolidin-3-yloxymethyl]phenyl}ethoxy)-2,2,6,6-tetramethylpiperidine (5)

N-(Trimethylsilyl)imidazole (0.66 M in CH_2Cl_2, 4.5 mL, 3.0 mmol, 3.3 equiv) was added slowly to a solution of diphenyl-((2*S*,4*R*)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidin-2-yl)methanol (500 mg, 0.921 mmol, 1.0 equiv) in CH_2Cl_2 (3 mL). The mixture was stirred overnight at r.t. The conversion was monitored via TLC and *N*-(trimethylsilyl)imidazole (0.66 M in CH_2Cl_2, 4.5 mL, 3.0 mmol, 3.3 equiv) was added for a second time. The mixture was stirred at r.t. for 2 h and the reaction was quenched by the addition of sat. aq NH_4Cl (10 mL). The aqueous layer was extracted with CH_2Cl_2 (2 × 10 mL) and the combined organic layers were dried ($MgSO_4$). After concentration in vacuo, purification of the residue by flash chromatography (acetone–CH_2Cl_2, 1:4) yielded the desired silyl ether **5** (389 mg, 69%).

IR (neat): 3058, 2932, 1663, 1599, 1492, 1447, 1375, 1361, 1250, 1210, 1133, 1070, 1022, 936, 880, 839, 734, 701 cm^{-1}.

^1H NMR (300 MHz, $CDCl_3$, 300 K): δ = 7.52–7.48 (m, 2 H_{arom}), 7.40–7.35 (m, 2 H_{arom}), 7.31–7.21 (m, 10 H, C_6H_5), 4.80 (q, *J* = 6.6 Hz, 1 H, C*H*CH_3), 4.45–4.37 (m, 3 H, C*H*OR, CH_2O), 3.85–3.80 (m, 1 H, C*H*NH), 3.01 (dd, *J* = 2.7, 11.6 Hz, 1 H, CH_aH$_b$NH), 2.85 (dd, *J* = 5.0, 11.6 Hz, 1 H, CH$_a$$H_b$NH), 1.77–1.70 (m, 2 H, CH_2CHOR), 1.48 (d, *J* = 6.6 Hz, 3 H, CHCH_3), 1.47–0.62 (m, 15 H, 3 × CH_2, TEMPO, 3 × CH_3, TEMPO), 0.71 (br s, 3 H, CH_3, TEMPO), –0.07 (s, 9 H, $SiCH_3$).

^{13}C NMR (75 MHz, $CDCl_3$, 300 K): δ = 147.1 (C), 145.3 (C), 145.1 (C), 137.3 (C), 128.6 (CH), 127.9 (CH), 127.8 (CH), 127.7 (CH), 127.6 (CH), 127.1 (CH), 127.0 (CH), 126.7 (CH), 83.1 (C), 83.0 (CH), 79.4 (CH), 70.9 (CH_2), 63.9 (CH), 59.9 (C), 53.1 (CH_2), 40.6 (CH_2), 34.5 (CH_2), 23.8 (CH_3), 20.5 (CH_3), 17.4 (CH_2), 2.41 (CH_3).

MS (ESI): *m*/*z* = 615 $[M + H]^+$.

HRMS (ESI): *m*/*z* calcd for $C_{38}H_{54}N_2O_3Si$ $[M + H]^+$: 615.3976; found: 615.3984.

(2*S*,4*R*)-2-(Methoxydiphenylmethyl)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidine-1-carboxylic Acid *tert*-Butyl Ester

NaH (60% in mineral oil, 192 mg, 4.80 mmol, 4.0 equiv) was added slowly to a solution of **6** (458 mg, 1.20 mmol, 1.0 equiv) in THF (18 mL) at r.t. and the mixture was then heated at reflux for 2.5 h. The mixture was allowed to cool to r.t. and then **2** (530 mg, 1.32 mmol, 1.1 equiv) was added. The mixture was heated at reflux for 6 h, stirred overnight at r.t. and the reaction was quenched by the addition of H_2O (15 mL). The aqueous layer was extracted with Et_2O (3 × 15 mL) and the combined organic layers were dried ($MgSO_4$). After concentration in vacuo, purification of the residue by flash chromatography [pentane–*tert*-butyl methyl ether (TBME), 20:1 → 10:1] yielded the title compound (447 mg, 57%).

IR (neat): 2973, 2931, 1698, 1599, 1448, 1390, 1363, 1257, 1160, 1076, 1074, 936, 880, 822, 760, 704 cm^{-1}.

^1H NMR (600 MHz, CD_2Cl_2, 253 K): δ = 7.43–7.30 (m, 10 H, C_6H_5), 7.25–7.20 (m, 2 H_{arom}), 7.19–7.13 (m, 2 H_{arom}), 5.17–5.13 (m, 1 H, C*H*OR), 4.69 (q, *J* = 6.6 Hz, 1 H, C*H*CH_3), 4.31 (d, *J* = 11.0 Hz, 1 H, CH_aH$_b$O), 4.25–4.19 (m, 1 H, CH$_a$$H_b$O), 3.77–3.73 (m, 1 H, C$H_aH_b$NBoc), 3.51–3.47 (m, 1 H, CH$_a$$H_b$NBoc), 3.46–3.40 (m, 1 H, C*H*NBoc), 2.89 (s, 3 H, OCH_3), 2.19–1.83 (m, 2 H, CH_2CHOR), 1.50–1.42 (m, 4 H, 2 × CH_2, TEMPO), 1.39 (d,

J = 6.6 Hz, 3 H, CHCH_3), 1.37 (s, 9 H, t-C_4H_9), 1.23 (br s, 2 H, CH_2, TEMPO), 1.19 (br s, 3 H, CH_3, TEMPO), 1.10 (br s, 3 H, CH_3, TEMPO), 0.94 (br s, 3 H, CH_3, TEMPO), 0.57–0.53 (m, 3 H, CH_3, TEMPO).

^{13}C NMR (150 MHz, CD_2Cl_2, 253 K): δ = 156.0 (C), 145.4 (C), 140.2 (C), 140.0 (C), 136.5 (C)*, 128.0 (CH), 129.7 (CH), 127.8 (CH), 127.7 (CH), 127.4 (CH), 127.3 (CH), 126.7 (CH), 126.6 (CH), 87.2 (C), 83.0 (CH), 79.3 (C), 77.9 (CH), 71.0 (CH_2), 59.5 (CH), 53.0 (CH_3), 52.3 (CH_2), 40.3 (CH_2), 40.2 (CH_2), 34.3 (CH_2), 28.3 (CH_3), 23.7 (CH_3), 20.6 (CH_3), 20.1 (CH_3), 17.4 (CH_2). * Found in GHMBC-spectrum.

MS (ESI): m/z = 657 $[M + H]^+$.

HRMS (ESI): m/z calcd for $C_{41}H_{56}N_2O_5$ $[M + H]^+$: 657.4262; found: 657.4270.

1-(1-{4-[(3*R*,5*S*)-5-(Methoxydiphenylmethyl)pyrrolidin-3-yl-oxymethyl]phenyl}ethoxy)-2,2,6,6-tetramethylpiperidine (7)

(2*S*,4*R*)-2-(Methoxydiphenylmethyl)-4-{4-[1-(2,2,6,6-tetramethylpiperidin-1-yloxy)ethyl]benzyloxy}pyrrolidine-1-carboxylic acid *tert*-butyl ester (340 mg, 0.518 mmol) was dissolved in a solution of HCl in dioxane (4 M, 6 mL) at 0 °C. The mixture was stirred for 4 h and was allowed to warm to r.t. Sat. aq $NaHCO_3$ (10 mL) was then added to adjust the pH to 7. The aqueous layer was extracted with CH_2Cl_2 (3 × 10 mL) and dried ($MgSO_4$). After concentration in vacuo, purification of the residue by flash chromatography (acetone–CH_2Cl_2, 1:4) yielded the desired amine **7** (215 mg, 75%).

IR (neat): 3056, 2973, 2932, 1492, 1447, 1375, 1360, 1258, 1210, 1183, 1132, 1075, 936, 882, 822, 757, 702 cm^{-1}.

^{1}H NMR (300 MHz, $CDCl_3$, 300 K): δ = 7.39–7.33 (m, 4 H_{arom}), 7.26–7.14 (m, 10 H, C_6H_5), 4.70 (q, J = 6.6 Hz, 1 H, C*H*CH_3), 3.49 (dd, J = 7.6, 7.6 Hz 1 H, C*H*OR), 4.32 (s, 2 H, CH_2O), 3.58 (m, 1 H, C*H*NH), 3.01 (s, 3 H, OCH_3), 2.81 (dd, J = 1.2, 11.9 Hz, 1 H, C$H_a$$H_b$NH), 2.39 (dd, J = 4.6, 11.9 Hz, 1 H, C$H_a$$H_b$NH), 2.24 (s, 1 H, NH), 1.95 (dd, J = 7.6, 13.8 Hz 1 H, C$H_a$$H_b$CHOR), 1.67 (m, 1 H, C$H_a$$H_b$CHOR), 1.38 (d, J = 6.6 Hz, 3 H, CHCH_3), 1.37–0.94 (m, 15 H, 3 × CH_2, TEMPO, 3 × CH_3, TEMPO), 0.60 (br s, 3 H, CH_3, TEMPO).

^{13}C NMR (75 MHz, $CDCl_3$, 300 K): δ = 145.4 (C), 143.0 (C), 141.7 (C), 137.0 (C), 129.4 (CH), 129.2 (CH), 127.9 (CH), 127.6 (CH), 127.6 (CH), 127.5 (CH), 127.3 (CH), 126.8 (CH), 85.1 (C), 83.0 (CH), 79.6 (CH), 71.0 (CH_2), 61.2 (C), 59.9 (CH), 52.6 (CH_2), 51.7 (CH_3), 40.6 (CH_2), 34.5 (CH_2), 23.8 (CH_3), 20.5 (CH_3), 17.4 (CH_2).

MS (ESI): m/z = 1114 $[2 M + H]^+$, 557 $[M + H]^+$.

HRMS (ESI): m/z calcd for $C_{41}H_{56}N_2O_5$ $[M + H]^+$: 557.3738; found: 557.3738.

Nitroxide-Mediated Polymerization (NMP) with 5 or 7; General Procedure (GP 1)

The alkoxyamine (1.0 equiv) was dissolved in styrene (100–102 equiv) and the solution was degassed in three freeze-thaw cycles. The mixture was sealed under argon and heated to 125 °C for 24 h. The polymerization was stopped by cooling to r.t. and the polymer was dissolved in CH_2Cl_2 (2 mL). The solution was poured into a Petri dish and the residual styrene monomer was removed in a vacuum drying cabinet at 60 °C for 12 h. The conversion was determined gravimetrically, molecular weight and polydispersity index (PDI) were determined by size exclusion chromatography (SEC).

Oligostyrene-Prolinol Conjugate 8

According to GP 1, NMP was conducted by using alkoxyamine **5** (41.0 mg, 66.8 μmol, 1.0 equiv) in styrene (0.780 mL, 6.80 mmol, 102 equiv) leading to oligostyrene-prolinol conjugate **8** (543 mg, 67%, M_n = 7500 g/mol, PDI = 1.30).

Oligostyrene-Prolinol Conjugate 9a

According to GP 1, NMP was conducted by using alkoxyamine **7** (71.0 mg, 0.128 mmol, 1.0 equiv) in styrene (1.50 mL, 13.1 mmol, 102 equiv) leading to oligostyrene-prolinol conjugate **9a** (936 mg, 64%, M_n = 6700 g/mol, PDI = 1.16).

Oligostyrene-Prolinol Conjugate 9b

According to GP 1, NMP was conducted by using alkoxyamine **7** (51.0 mg, 91.7 μmol, 1.0 equiv) in styrene (1.05 mL, 9.14 mmol, 100 equiv) leading to oligostyrene-prolinol conjugate **9b** (603 mg, 58%, M_n = 5600 g/mol, PDI = 1.11).

Fibrous Catalyst Systems A, B, and C

Polystyrene (PS, 1.000 g, M_n = 150 000 to 300 000 g/mol) and the oligostyrene conjugate (OS) **8**, **9a** or **9b** (0.500 g) were dissolved in dimethylacetamide (DMAc) (4.31 mL). The solution, stored within a reservoir, was pumped through a metal capillary connected with a voltage supply using a peristaltic pump. The circular orifice of the capillary had a diameter of 0.45 mm. A circular shaped counter electrode with a diameter of 18 cm was located below the reservoir, so that a vertical arrangement of the electrodes resulted. Fibers were collected on an aluminum foil. The distance between the tip of the capillary and the counter electrode was typically of the order of 15 cm, the applied voltage was 20 kV. PPX deposition from the gas phase was accomplished by evaporization of the starting material [2.2]paracyclophane at 175 °C and 55 mbar and subsequent pyrolysis at 650 °C. The polymerization of the pyrolysis product 1,4-quinodimethane on the fiber surface (r.t.) yielded homogeneously coated fibers.

Application of the Fibrous Catalyst Systems A, B, and C; General Procedure (GP 2)

The fibrous catalyst system (5 mol%) was dipped into a solution of dimethyl malonate (1.0 equiv) and cinnamaldehyde (2.0 equiv) in EtOH (see Figure 2). The mixture was stirred at r.t. for 3 d. The reaction was stopped by simply removing the fiber mat, which was immersed in EtOH (3 × 7–12 mL) for 30 min to completely extract the product. After concentration in vacuo, purification of the residue by flash chromatography (pentane–TBME, 4:1 → 1:1) yielded the desired aldehyde. The recycled catalyst system was reused under identical reaction conditions.

Application of the Fibrous Catalyst System A

According to GP 2, the activity of catalyst system **A** [385 mg (125 mg OS **8**, 260 mg PS), 16.7 μmol of the catalytic active species, 5 mol%] was tested in a Michael reaction of dimethyl malonate (38.4 mL, 334 mmol, 1.0 equiv) with cinnamaldehyde (84.1 mL, 668 mmol, 2.0 equiv) in EtOH (7.0 mL). The reaction was repeated 9 times (Figure 3). Enantiomeric ratio (er) was determined by chiral HPLC after derivatization according to reference 10 (*i*-PrOH–cyclohexane, 1.5:98.5, flow rate 0.8 mL/min, major enantiomer t_R = 23.5 min, minor enantiomer t_R = 23.5 min).

Application of the Fibrous Catalyst System B

According to GP 2, the activity of catalyst system **A** [1.06 g (354 mg OS **8**, 707 mg PS), 52.8 mmol of the catalytic active species, 5 mol%] was tested in a Michael reaction of dimethyl malonate (122 mL, 1.06 mmol, 1.0 equiv) with cinnamaldehyde (267 mL, 2.12 mmol, 2.0 equiv) in EtOH (22 mL). The reaction was repeated 6 times.

Application of the Fibrous Catalyst System C

According to GP 2, the activity of catalyst system **C** [928 mg (308 mg OS **8**, 620 mg PS), 1.16 mm PPX, 55.0 mmol of the catalytic active species, 5 mol%] was tested in a Michael reaction of dimethyl malonate (127 mL, 1.10 mmol, 1.0 equiv) with cinnamal-

dehyde (277 mL, 2.20 mmol, 2.0 equiv) in EtOH (11 mL). The reaction was repeated 9 times.

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