Enolesters as Chain End-Functionalizing Agents for the Living Ring Opening Metathesis Polymerization

This manuscript is dedicated to the 75th birthday of Professor Bob Grubbs for his life-long extraordinary achievement in research and education.

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ABSTRACT: Functional enolethers have previously been used to introduce functional end groups at the chain end of ruthenium carbene complex initiated living ring opening metathesis polymers. Here, we investigated whether the weaker π-donating enolesters could equally be used in regio selective reactions with ruthenium carbene complexes and thus as polymer end-functionalization reagents. Enolesters such as vinyl acetate, butenyl acetate, 3-(4-(*tert*-butoxy)phenyl)propenyl acetate and 6-(((benzyloxy)carbonyl)amino)hex-1-en-1-yl acetate were used as living ROMP terminating agents. All gave the expected end groups proving that enolesters are synthetically easily accessible targets for living ROMP end-functionalization. © 2017 Wiley Periodicals, Inc. J. Polym. Sci., Part A: Polym. Chem. **2017**, *55*, 2983–2990

KEYWORDS: enolesters; functionalization of polymers; Grubbs catalyst; metathesis; ROMP

INTRODUCTION The living ring opening metathesis polymerization (ROMP) using ruthenium based carbene complexes developed by Grubbs et al. is one of the most functional group tolerant polymerization methods known today.[1] Despite the principal problem of functionalizing a functional group tolerant propagating species, many selective methods for introducing a number of functional groups have been reported over the last ten years.[2–4] Alcohols,[5–7] thiols,[8,9] and amine[10] end groups have been introduced via the sacrificial block copolymer synthesis. Aldehydes[11,12] and carboxylic acids[11] could be prepared via the reaction of the propagating ruthenium carbene complex with unsaturated lactones, cyclic vinyl acetals, and unsaturated cyclic carbonates. Terminal cross-metathesis with symmetrical acyclic olefins is another method that allows the introduction of functional groups at the polymer chain end.[13,14] Substituted vinyl ethers have been used to attach a variety of functional groups or molecules to the end of polymer chains.[15–17] The group of Slugovc successfully used acrylates for the functional termination of ROMP polymers.[18] Combinations of termination techniques allowed the preparation of hetero-telechelic ROMP polymers.[19] Furthermore, functional end-groups on ROMP polymers were recently used to control molecular weight and polydispersity in a living catalytic ROMP.[20] Ethyl vinyl ether (**EVE**) has long been known to selectively terminate living ROMP polymers by transferring a methylene group onto the polymer chain end forming a so-called Fischer-carbene.[21] Substituted vinyl ethers have therefore been employed to attach larger molecular fragments to the ends of polymer chains.[22,23] A high *cis*-content in these vinyl ethers is, however, crucial to achieve rapid termination as the *cis*-vinyl ethers react significantly faster with the ruthenium alkylidene than the *trans*-vinyl ethers. A cis-selective synthesis of a functionalizable chain terminating agent based on vinyl ethers was recently reported.[24]

Considering our previous findings that vinyl lactones reacted rapidly and regioselectively with ruthenium carbene complexes[11] we hypothesized that acyclic enolesters and in particular functional enolesters could be suitable and readily accessible terminating agents for living ROMP. Here, we report the synthesis of enolester derivatives and their use as functional chain termination agents in living ROMP.

EXPERIMENTAL

Materials

Benzene, ε-caprolactone, caesium iodide, Celite, Dess-Martin periodinane, DIBAL-H, diethyl ether, dimethylsulfide, ethyl vinyl acetate, Grubbs first generation catalyst, Grubbs third generation catalyst, magnesium perchlorate, methyl 3-(4-hydroxyphenyl)-propanoate, pyridinium chlorochromate, sodium carbonate,

triethyl amine, and Benzyl (6-hydroxyhexyl)carbamate were purchased from Sigma-Aldrich and used without further purification. Butyraldehyde was purchased from Sigma-Aldrich, distilled, and stored under an argon atmosphere before use. Potassium carbonate was purchased from Sigma-Aldrich and was dried under vacuum before use. Acetic anhydride, carbic anhydride, methylamine in cyclohexane, and methyl 3-(4-hydroxyphenyl)propanoate were purchased from Acros Organics and used without further purification. *N*-Chlorosuccinimide was purchased from Acros and recrystallized from benzene. Magnesium sulfate, sodium chloride, and sodium thiosulfate were purchased from rectolab and used without further purification. Acetic acid, sodium acetate and sodium hydroxide are purchased from Merck and used without further purification. Solvents of analytical grade were purchased from Honeywell, Acros Organics, Sigma Aldrich, Fischer Scientific, and were used without further purification. Solvents of technical grade were purified by distillation. Deuterated solvents ($CDCl_3$, C_6D_6 and CD_2Cl_2) were purchased from Cambridge Isotope Laboratories. *Exo-N*-methyl-5-norbornene-2,3-dicarboximide (**MNI**),[25] *exo-N*-hexyl-5-norbornene-2,3-dicarboximide (**HNI**)[25] and *exo-N*-methyl-7-oxanorbornene-2,3-dicarboximide were synthesized according to the described procedure.[26]

Instrumentation

ESI-MS analysis for synthesized compounds was carried out on a Bruker 4.7T BioAPEX II. MALDI-ToF MS analysis of the polymers was carried out on a Bruker ultrafleXtreme™ using 2-[(2E)-3-(4-tertbutylphenyl)-2-methylprop-2-enylidene]malononitrile (DCTB) as the matrix and silver trifluoroacetate or sodium trifluoroacetate as the added salt. Relative molecular weights and molecular weight distributions were measured by gel permeation chromatography (GPC) with a Viscotek GPCmax VE2001 GPC Solvent/Sample Module, a Viscotek UV detector 2600, a Viscotek VE3580 RI detector, and two Viscotek T6000 M columns (7.8 Å, 300 mm, 103–107 Da) at a flow rate of 1 mL/min for samples measured in THF and with a system consisting of a Duratec vacuum degasser, a JASCO PU-2087 plus pump, an Applied Biosystems UV absorbance detector 759A (set to 254 nm wavelength). Calibrations were carried out using Malvern Polycal™ UCS-PS polystyrene (PS) standards. NMR spectra were recorded on a Bruker Avance III 300 MHz NMR spectrometer (^{1}H NMR 300 MHz, ^{13}C-NMR 75 MHz) and Bruker Avance III 400 MHz NMR spectrometer (^{1}H NMR 400 MHz, ^{13}C-NMR 101 MHz).

Syntheses of Terminating Agents

Butenyl Acetate (1)

Butyraldehyde (1 eq, 12.2 mL, 139 mmol), acetic anhydride (2.3 eq, 30 mL, 314 mmol), potassium carbonate (0.12 eq, 2.3 g, 16.7 mmol), and sodium acetate (0.26 eq, 3.0 g, 36.6 mmol) were heated under reflux for 3 h. The reaction was quenched with water and the organic layer was extracted with DCM. The organic phase was washed with aqueous solution of sodium bicarbonate until the pH of the aqueous phase was higher than 8. The organic layer was dried over magnesium sulfate and the product was distilled under vacuum (48 °C at 40 mbar) to obtain butenyl acetate (***Bac*****;** 4.1 g, 26%, cis:trans = 60:40) as a colorless liquid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.05 (dt, J = 12.4, 1.6 Hz, 0.6H, trans), 6.96 (dt, J = 6.4, 1.6 Hz, 0.4H, cis), 5.44 (dt, J = 12.4, 7.1 Hz, 0.6H, trans), 4.86 (dd, J = 13.8, 7.4 Hz, 0.4H, cis), 1.97-2.17 (m, 5H), 0.96-1.03 (m, 3H). ^{13}C NMR (75 MHz, $CDCl_3$) δ 168.32, 168.16, 134.99, 133.46, 116.66, 115.88, 20.71, 20.67, 17.88, 13.97, 13.85.

Methyl 3-(4-(Tert-butoxy)phenyl)propanoate (2)

Methyl 3-(4-hydroxyphenyl)propanoate (1 eq, 3.0 g, 16.6 mmol) and $Mg(ClO_4)_2$ (0.2 eq, 0.75 g, 3.3 mmol) were dissolved in dry DCM (15 mL) in a the purged flask with Argon. Boc_2O (2.3 eq, 8.35 g, 38.2 mmol) in dry DCM (8 mL) was added by syringe pump at a rate of 8 mL/h and the reaction mixture was stirred for 2 h at room temperature. Water (15 mL) was added to quench the reaction and the reaction mixture was stirred for 1 h. DCM was added and the reaction mixture was extracted with DCM (30 mL¤2). The organic phases were collected, dried over Na_2SO_4, filtered and concentrated. The crude product was purified by chromatography (Hexane: EtOAc = 10:1) to afford methyl 3-(4-(*tert*-butoxy)phenyl)propanoate **2** (3.2 g, 81%) as colouless liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.07 (d, J = 8.5 Hz, 2H), 6.90 (d, J = 8.5 Hz, 2H), 3.66 (s, 3H), 2.88–2.93 (m, 2H), 2.40–2.71 (m, 2H), 1.32 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 173.44, 153.69, 135.34, 128.60, 124.22, 51.58, 35.85, 30.31, 28.84. HR-MS (ESI) calcd. For $C_{14}H_{20}O_3Na^+$ [M + Na^+]: 259.1305; Found: 259.1304.

3-(4-(Tert-butoxy)phenyl)propanal (3)

Methyl 3-(4-(tert-butoxy)phenyl)proponate 2 (1 eq, 3.1 g, 13.1 mmol) was dissolved in dry THF (25 mL) and cooled in a Dewar flask by acetone to −78 °C with a cryostat. Then DIBAL-H 1M in cyclohexane (1 eq, 13.1 mL, 13.1 mmol) was added dropwise by syringe pump at a rate of 13 mL/h. The stiring was continued for 90 min. Water (15 mL) was slowly added to quench the reaction. The stiring was continued for 15 min then the reaction was allowed to warm up to 0 °C. $MgSO_4$ and NaCl were added and the reaction mixture was decanted. The decanted solution was washed with brine. The aqueous layer was then extracted with THF. The organic layer was collected and concentrated under reduced pressure. The crude reaction mixure was purified by chromatography (Hexane:EtOAc = 10:1) to afford 3-(4-(tert-butoxy) phenyl)propanal **3** (1.8 g, 70%) as colorless liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 9.82 (t, J = 1.5 Hz, 1H), 7.07 (d, J = 8.6 Hz, 2H), 6.91 (d, J = 8.5 Hz, 2H), 2.92 (t, J = 7.5 Hz, 2H), 2.76 (t, J = 7.4 Hz, 2H), 1.32 (s, 9H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 201.75, 153.73, 135.10, 128.62, 124.31, 78.29, 45.37, 28.83, 27.46. HR-MS (ESI) calcd. For $C_{13}H_{18}O_2Na^+$ [M + Na^+]: 229.1200; Found: 229.1199.

3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

3-(4-(Tert-butoxy)phenyl)propanal **3** (1 eq, 1.4 g, 6.78 mmol), acetic anhydride (2 eq, 1.3 mL, 13.6 mmol), potassium carbonate (0.12 eq, 113.3 mg, 0.82 mmol) and sodium acerate (0.3 eq, 167.3 mg, 2.04 mmol) were heated under

reflux for 4 h. The reaction was quenched with water and the organic layer was extracted with DCM. The organic phase was washed with aqueous solution of sodium bicarbonate until the pH of the aqueous phase was higher than 8. The organic layer was dried over magnesium sulfate and the product was concentrated under reduced pressure. The crude product was purified by chromatography (Hexane:EtOAc = 10:1) to afford 3-(4-(tert-butoxy)phenyl)propenyl acetate **4** (893 mg, 53%, cis:trans = 57:43) as a light yellow liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13–7.19 (m, 1H, cis and trans), 7.06–7.09 (m, 2H, cis and trans), 6.89–6.93(m, 2H, cis and trans), 5.54–5.61 (m, 0.5H, cis), 5.06–5.11 (m, 0.38H, trans), 3.46 (d, J = 7.6 Hz, 0.78H, cis), 3.29 (d, J = 7.6 Hz, 1.04H, cis), 2.17 (s, 1.12H, trans), 2.12 (s, 1.50H, cis), 1.33 (d, 9H, cis and trans). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.20, 168.06, 153.75, 153.60, 136.22, 134.83, 134.57, 134.50, 128.68, 128.58, 124.26, 113.98, 112.77, 78.26, 78.23, 32.92, 29.98, 28.84, 20.76, 20.71. HR-MS (ESI) calcd. For $C_{15}H_{20}O_3Na^+$ [M + Na^+]: 271.1305; Found: 271.1304.

Benzyl-(6-oxohexyl)carbamate (5)

PCC (1.5 eq, 1.3 g, 6 mmol) was suspended in dry THF (32 mL) in a 100 mL round bottom flask and cooled to 0 °C with an ice bath. Benzyl (6-hydroxyhexyl)carbamate (1 eq, 1 g, 40 mmol) in dry THF (8 mL) was added dropwise to the PCC suspension by syringe pump at a rate of 8 mL/h. After adding, the reaction was followed by TLC until the reaction was finished. Silica was added and THF was evaporated. The deposit on silica was washed with diethyl ether to afford the crude product. The crude product was purified by chromatography (Hexane:EtOAc = 2:1) to afford pure benzyl (6-oxohexyl)carbamate **5** (512.8 mg, 52%) as colorless liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 9.66 (s, 1H), 7.11–7.34 (m, 5H), 5.00 (s, 2H), 3.11 (dd, J = 13.2, 6.6 Hz, 2H), 2.34 (t, J = 7.0 Hz, 2H), 1.13–1.61 (m, 6H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 202.38, 156.41, 136.61, 128.53, 128.12, 66.65, 43.72, 40.79, 29.80, 26.21, 21.63. HR-MS (ESI) calcd. For $C_{14}H_{19}NO_3Na^+$ [M + Na^+]: 272.1257; Found: 272.1257.

6-(((Benzyloxy)carbonyl)amino)hex-1-en-1-yl Acetate (6)

Benzyl-(6-oxohexyl)carbamate **5** (1 eq, 510 mg, 2 mmol), acetic anhydride (2 eq, 0.38 mL, 4 mmol), potassium carbonate (0.12 eq, 33.2 mg, 0.24 mmol) and sodium acerate (0.3 eq, 49.2 mg, 0.6 mmol) were heated under reflux for 4 h. The reaction was quenched with water and the organic layer was extracted with DCM. The organic phase was washed with aqueous solution of sodium bicarbonate until the pH of the aqueous phase was higher than 8. The organic layer was dried over magnesium sulfate and the product was concentrated under reduced pressure. The crude product was purified by chromatography (Hexane:EtOAc = 10:1) to afford 6-(((benzyloxy)carbonyl)amino)hex-1-en-1-yl acetate **6** (135.5 mg, 23%, cis:trans = 50:50) as a colorless liquid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13-7.33 (m, 5H), 6.96 (d, J = 12.4 Hz, 0.5H), 6.92 (d, J = 6.4 Hz, 0.5H), 5.25–5.32 (m, 1H), 5.00 (s, 2H), 4.72–4.77 (m, 0.5H), 3.08–3.14 (m, 2H), 1.90–2.10 (m, 5H), 1.28–1.47 (m, 4H). ^{13}C NMR (101 MHz, $CDCl_3$) δ 168.25, 168.11, 156.40, 136.63, 135.75, 134.42, 128.53, 128.12, 114.39, 113.44, 66.64, 40.86, 29.40, 26.90, 26.61, 26.22, 23.95, 20.74, 20.70. HR-MS (ESI) calcd. For $C_{16}H_{21}NO_4Na^+$ [M + Na^+]: 314.1363; Found: 314.1362.

Polymer 1 Terminated with Vinyl Acetate (VA)

Exo-N-methyl-5-norbornene-2,3-dicarboximide (16.89 eq, 450 mg, 2.54 mmol) was dissolved in degassed DCM (2 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1** (1 eq, 105 mg, 0.13 mmol) in degassed DCM (2.5 mL). After 1 h, 1.5 mL of the polymer solution was added to VA (50 eq, 186 mg, 2.17 mmol) and stirred for 12 h. A second portion (1.5 mL) of the polymer solution was added to **EVE** (see **polymer 2**, below) and a third portion to ***BAc*** (see **polymer 3**, below). The solution was concentrated by a slight flow of nitrogen and the polymer recovered by precipitation into a vigorously stirred ten-fold volume of methanol. The mixture was filtered to afford the respective polymer [143 mg, 95% yield, $Mn_{(GPC, THF)}$ = 5400 g/mol, PDI: 1.23] as a colorless solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.16-7.33 (m), 5.42–5.71 (m), 3.41 (s), 2.64–3.23 (m), 1.19–2.13(m), 0.76–0.83 (m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.36, 133.41, 132.07, 131.88, 131.84, 131.70, 128.55, 128.32, 126.31, 52.67, 51.12, 51.02, 45.82, 45.62, 42.14, 41.97, 40.87, 29.70, 24.76. MALDI-ToF MS calcd. For $C_{148}H_{162}N_{14}O_{28}Na^+$ [M + Na^+]: 2606.16; Found: 2606.18.

Polymer 2 Terminated with EVE

EVE (50 eq, 157 mg, 2.17 mmol) was added to a propagating solution of **polymer 1** (1.5 mL, see above) and the reaction stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer [146 mg, 97% yield, $Mn_{(GPC, THF)}$ = 5300 g/mol, PDI: 1.26] as a gray solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.16–7.33 (m), 5.40–5.71 (m), 2.64–3.21 (m), 1.99–2.11 (m), 1.47–1.75 (m), 1.17–1.23 (m), 0.76–0.81 (m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.37, 133.52, 132.07, 131.86, 131.84, 128.56, 126.31, 52.67, 51.11, 51.02, 45.82, 45.63, 42.14, 41.98, 40.87, 31.77, 29.88, 29.70, 27.98, 26.66, 24.83, 24.77. MALDI-ToF MS calcd. For $C_{158}H_{173}N_{15}O_{30}Na^+$ [M + Na^+]: 2783.24; Found: 2783.24.

Polymer 3 Terminated with But-1-en-1-yl Acetate (BAc)

But-1-en-1-yl acetate (50 eq, 247 mg, 2.17 mmol) was added to a propagating solution of **polymer 1** (1.5 mL, see above) and the reaction stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer [142 mg, 94% yield, $Mn_{(GPC, THF)}$ = 5800 g/mol, PDI: 1.21].

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.16–7.33 (m), 5.36–5.71 (m), 2.64–3.23(m), 1.47–2.07 (m), 1.19 (s), 0.90–0.97 (m). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.37, 133.46, 132.06, 131.88,

131.84, 131.71, 128.56, 126.31, 52.67, 51.11, 51.02, 45.82, 45.63, 42.15, 41.98, 40.87, 29.88, 27.98, 26.66, 24.83, 24.77. MALDI-ToF MS calcd. For $C_{150}H_{166}N_{14}O_{28}Na^+$ [M + Na^+]: 2634.19; Found: 2634.19.

Polymer 4 Terminated with 3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

Exo-N-methyl-5-norbornene-2,3-dicarboximide (10 eq, 88.6 mg, 0.5 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1**(1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 3-(4-(tert-butoxy)phenyl)propenyl acetate (5 eq, 62.1 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a ten-fold excess of methanol. The mixture was filtered to afford the respective polymer [111 mg, 81% yield, $M_{n(GPC,\ THF)}$ = 3900 g/mol, PDI: 1.12] as a light yellow solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.21–7.37 (m), 6.97 (dd, J = 65.6, 8.3 Hz), 5.52–5.75 (m), 2.57–3.32 (m), 1.53–2.16 (m), 1.22–1.31 (m). ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.36, 153.51, 136.85, 136.20, 135.07, 133.49, 132.06, 131.87, 131.84, 131.71, 130.88, 130.58, 130.36, 128.79, 128.67, 128.64, 128.55, 128.32, 127.50, 126.30, 124.25, 124.18, 52.66, 51.11, 51.01, 45.81, 45.62, 42.13, 41.96, 40.86, 31.77 (t, J = 9.9 Hz), 29.87, 28.85, 27.97 (t, J = 5.3 Hz), 26.66, 24.82, 24.76. MALDI-ToF MS calcd. For $C_{189}H_{209}N_{17}O_{35}Na^+$ [M + Na^+]: 3299.5; Found: 3299.6

Polymer 5 Terminated with 3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

Exo-N-methyl-5-norbornene-2,3-dicarboximide (20 eq, 177.2 mg, 1.0 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1** (1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 3-(4-(tert-butoxy)phenyl)propenyl acetate (5 eq, 62.1 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer [201 mg, 89% yield, $M_{n(GPC,\ THF)}$ = 5400 g/mol, PDI: 1.18] as a light yellow solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.13–7.37 (m), 6.97 (dd, J = 65.7, 8.3 Hz), 5.51–5.75 (m), 2.56–3.34 (m), 1.53–2.15 (m), 1.16-1.31 (m). ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.36, 136.20, 133.49, 132.06, 131.88, 131.84, 128.79, 128.67, 128.55, 126.30, 124.25, 124.18, 113.97, 52.66, 51.11, 51.01, 45.81, 45.62, 42.14, 41.97, 40.86, 31.77 (t, J = 10.0 Hz), 29.87, 28.85, 28.82, 27.97 (t, J = 5.4 Hz), 26.66, 24.83, 24.76. MALDI-ToF MS calcd. For $C_{259}H_{286}N_{24}O_{49}Na^+$ [M + Na^+]: 4539.1; Found: 4539.1.

Polymer 6 Terminated with 3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

Exo-N-methyl-5-norbornene-2,3-dicarboximide (30 eq, 265.8 mg, 1.5 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1**(1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 3-(4-(*tert*-butoxy)phenyl)propenyl acetate (5 eq, 62.1 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a ten-fold excess of methanol. The mixture was filtered to afford the respective polymer [305.7 mg, 97% yield, $M_{n(GPC,\ THF)}$ = 6800 g/mol, PDI: 1.18] as a light yellow solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.10–7.36 (m), 6.97 (dd, J = 66.0, 8.3 Hz), 5.50–5.74 (m), 2.69–3.33 (m), 1.53–2.15 (m), 1.19–1.32 (m). ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.37, 136.19, 133.48, 132.05, 131.87, 131.84, 128.78, 128.67, 128.56, 128.55, 126.30, 124.25, 124.18, 113.97, 112.76, 52.65, 51.10, 51.01, 45.80, 45.62, 42.14, 41.98, 40.86, 31.76 (t, J = 10.1 Hz), 29.96, 29.87, 28.84, 28.82, 27.97 (t, J = 5.4 Hz), 24.82, 24.76. MALDI-ToF MS calcd. For $C_{249}H_{278}N_{23}O_{47}Na^+$ [M + Na^+]: 4362.0; Found: 4362.1.

Polymer 7 Terminated with 6-(((Benzyloxy)carbonyl)amino)hex-1-en-1-yl Acetate (6)

MNI (20 eq, 177.2 mg, 1.0 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1**(1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 6-(((benzyloxy)carbonyl)amino)hex-1-en-1-yl acetate (5 eq, 73 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer [190.7 mg, 82% yield, $M_{n(GPC,\ THF)}$ = 5800 g/mol, PDI: 1.18] as a brown solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.12–7.30 (m), 5.43–5.68 (m), 2.84–3.18 (m), 2.63 (s), 1.16–2.09 (m). ^{13}C NMR (101 MHz, $CDCl_3$) δ 178.36, 133.48, 132.06, 131.88, 131.83, 128.55, 128.52, 128.11, 126.31, 52.67, 51.11, 51.02, 45.81, 45.62, 42.14, 41.97, 40.87, 24.83, 24.76. MALDI-ToF MS calcd. For $C_{120}H_{133}N_{11}O_{22}Na^+$ [M + Na^+]: 2103.0; Found: 2103.0.

Polymer 8 Terminated with 3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

Exo-N-hexyl-5-norbornene-2,3-dicarboximide (20 eq, 247.3 mg, 1.0 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1** (1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 3-(4-(tert-butoxy)phenyl)propenyl acetate (5 eq, 62.1 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12 h. After addition of **EVE** (50 eq) the solution was stirred for 15 min and then concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer

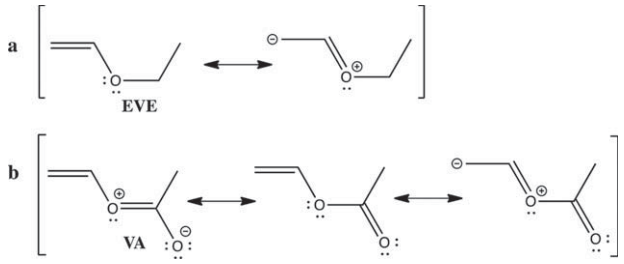


FIGURE 1 Resonance structures of **EVE** (a) and **VA** (b).

[280 mg, 95% yield, $Mn_{(GPC,\ THF)} = 5200$ g/mol, PDI: 1.16] as a brown solid.

^{1}H NMR (300 MHz, $CDCl_3$) δ 7.07–7.35 (m), 7.00 (d, $J = 8.4$ Hz), 6.84 (d, $J = 8.4$ H), 5.69 (d, $J = 6.2$ Hz), 5.38–5.50 (m), 3.27–3.44 (m), 2.92 (s), 2.61 (s), 2.00–2.16 (m), 1.59 (s), 1.41–1.52 (m), 1.26 (s), 1.21 (s), 0.81 (t, $J = 6.5$ Hz). ^{13}C NMR (75 MHz, $CDCl_3$) δ 178.32, 136.90, 132.05, 131.86, 131.81, 128.55, 124.20, 52.63, 50.99, 50.89, 45.85, 42.21, 42.04, 40.90, 38.57, 31.38, 31.30, 28.85, 27.64, 26.55, 26.45, 22.48, 14.00. MALDI-ToF MS calcd. For $C_{274}H_{379}N_{17}O_{35}Na^+$ [M + Na^+]: 4490.83; Found: 4490.98.

Polymer 9 Terminated with 3-(4-(Tert-butoxy)phenyl)propenyl Acetate (4)

Exo-N-methyl-7-oxanorbornene-2,3-dicarboximide (20 eq, 179.2 mg, 1.0 mmol) was dissolved in degassed DCM (1 mL) in a Schlenk flask, which was evacuated and charged with argon three times. The polymerization was initiated by quick addition of **G1**(1 eq, 41.1 mg, 0.05 mmol) in degassed DCM (1 mL). After 1 h, 3-(4-(tert-butoxy)phenyl)propenyl acetate (5 eq, 62.1 mg, 0.25 mmol) was added to the polymer solution and the mixture stirred for 12 h. The solution was concentrated by a slight flow of nitrogen. The polymer was precipitated by slow addition into a 10-fold excess of methanol. The mixture was filtered to afford the respective polymer [198.5 mg, 88% yield, $Mn_{(GPC,\ THF)} = 3200$ g/mol, PDI: 1.11] as a brown solid.

^{1}H NMR (400 MHz, $CDCl_3$) δ 7.30–7.41 (m), 6.98 (dd, $J = 66.0$, 8.2 Hz), 5.91 (d, $J = 106.9$ Hz), 4.99 (s), 4.49 (s), 3.34 (s), 2.96 (s), 2.14 (d, $J = 21.8$ Hz), 1.74 (s), 1.28 (d, $J = 27.7$ Hz). ^{13}C NMR (101 MHz, $CDCl_3$) δ 175.82, 130.98, 128.68, 126.81, 124.25, 80.83, 53.46, 52.36, 28.82, 25.11. MALDI-ToF MS calcd. For $C_{100}H_{103}N_9O_{28}Na^+$ [M + Na^+]: 1900.7; Found: 1900.7.

RESULTS AND DISCUSSION

The reaction of Grubbs-type ruthenium carbene complexes with **EVE** always occurs in a regioselective manner resulting in the formation of a Fischer-carbene. An explanation for this regioselectivity can be found in one of the resonance structures of **EVE** in which the β-carbon of the vinyl group carries a negative charge [Fig. 1(a)]. This very simple resonance theory model illustrates the polarization of the HOMO of **EVE,** which undergoes the reaction with the LUMO of the ruthenium carbene. As the ruthenium carbene π-bond is polarized towards the ruthenium center[27] [see Fig. 2(a)] this simplified model can be used to understand the regioselectivity of the reaction with electron rich olefins such as **EVE**.

The lone pair of the oxygen in **VA**, however, is less π-donating than that of **EVE** [Figs. 1(b) and ^{2}(b)] and we were interested in investigating whether this would result in a reduced regioselectivity in the reaction with Grubbs-type ruthenium carbene complexes.

In an NMR experiment Grubbs first generation complex (benzylidene-bis(tricyclohexylphosphine)-dichlororuthenium, **G1**) was exposed to **VA** in benzene-d_6 (Fig. 3). An immediate shift of the carbene proton signal from 20.7 to 15.8 ppm was observed. Furthermore, this acyl-Fischer-carbene[28–30] reacted with **EVE** to form the vinyl ether Fischer carbene with a carbene signal at 14.7 ppm in a Fischer-carbene to Fischer-carbene transformation. While the observed upfield shift of the carbene signal was in agreement with the respective π-donation strength of oxygen lone pairs on **EVE** and **VA**, the NMR experiment gave no indication about a loss of regioselectivity.

A model polymer (poly(**MNI**)) was therefore prepared using **G1** and *exo-N*-methyl-5-norbornene-2,3-dicarboximide (**MNI**). The solution of the propagating ruthenium carbene complex was divided into three reaction vessels and the first was reacted with excess **VA** (polymer 1) and the second with excess **EVE** (polymer 2). MALDI-ToF mass spectrometric analysis of the isotopically resolved signals revealed that in both cases all polymer chains were terminated with methylene groups therefore indicating that the reaction with **VA** and **EVE** occurred regioselectively.

We next prepared a cis/trans mixture of but-1-en-1-yl acetate **BAc** and used it to terminate the propagating ruthenium carbene complex of poly(MNI) (third reaction vessel, polymer 3). An NMR-scale reaction of **G1** benzylidene and **BAc** carried out in parallel showed that the *cis*-**BAc** was consumed much faster than the *trans*-**BAc**. Reaction of the cis/trans mixture of **BAc**

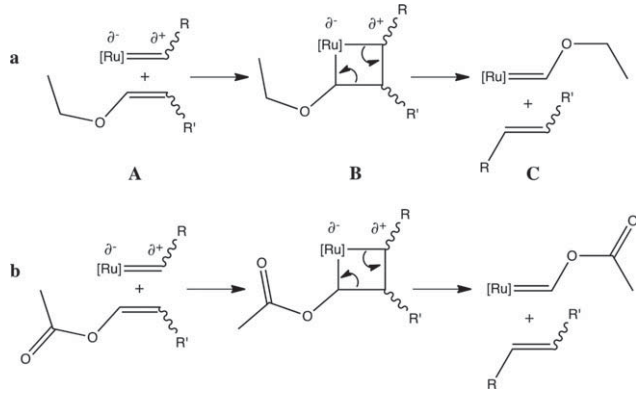


FIGURE 2 Reaction of substituted vinyl ethers (a) and substituted enolesters (b) with ruthenium carbene complexes (A) forming a metallacyclobutane (B) and the corresponding Fischer carbene complexes (C).

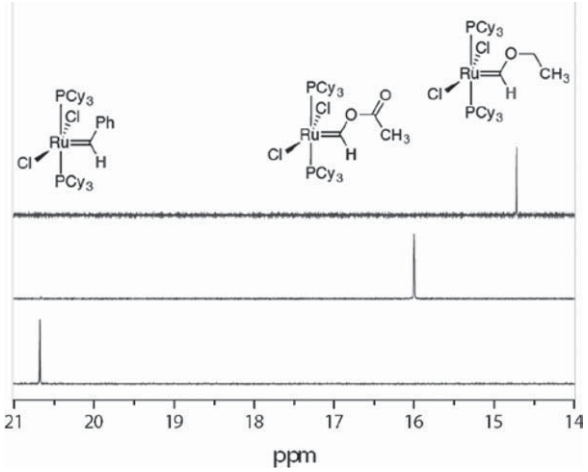
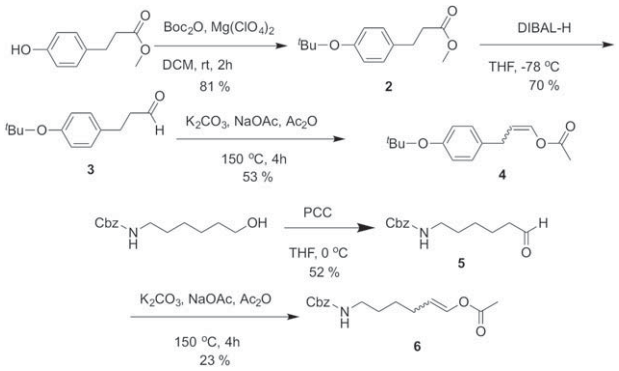


FIGURE 3 ^{1}H NMR spectra (400 MHz, benzene-d_6). Bottom: Carbene proton signal of Grubbs first generation (**G1**) initiator (20.7 ppm) Middle: Acylcarbene of the **G1** initiator (15.8 ppm) Top: Fischer carbene from **EVE** and **G1** (14.7 ppm). The signal for the Fischer-carbene shifts from $\delta = 15.8$ ppm to $\delta = 14.7$ ppm indicating metathesis activity of the acyl carbene.

with the propagating chain end of poly(**MNI**) and subsequent MALDI-ToF mass spectrometric analysis (polymer 3) showed that all polymer chains carried the corresponding propenyl (CH_3CH_2CH═) end group as expected from a regioselective reaction between the propagating **G1** alkylidene and **BAc**.

Enolacetates can be prepared readily from the corresponding aldehydes. Although both, enol ethers and enol acetates are readily synthetically accessible in few reaction steps the cis:trans ratio for enolacetates was slightly more favorable than those reported for enol ethers.[23,31] We therefore investigated the synthesis of functional enolacetates carrying either a protected phenolic alcohol or an amine group. As shown in Scheme 1, methyl 3-(4-hydroxyphenyl)propanoate was first protected as the *tert*-butyl ether **2** (81% yield) followed by DIBAL reduction to give aldehyde **3** (70% yield). Enolisation and acetylation under basic conditions gave the target enolacetate **4** (53% yield). The protected amine carrying enolacetate **6** (23% yield) could be prepared readily via oxidation of benzyl (6-hydroxyhexyl)carbamate using PCC to give the corresponding aldehyde **5** (52% yield), followed by reaction with acetic anhydride under basic condition.

An excess of **4** was subsequently employed in a functional termination experiment using poly(**MNI**) prepared from **G1** and **MNI** (Scheme 2, polymer 4). As can be seen from the MALDI-ToF (matrix: DCTB, sodium trifluoroacetate = NaTFA) mass spectrometric analysis of the obtained polymer (Fig. 4), every polymer chain carries the *tert*-butyl protected phenol end group. ^{1}H-NMR spectroscopy of the polymer showed both required end groups, one resulting from the reaction with **4** and the other resulting from initiation with **G1** benzylidene (Supporting Information). GPC analysis in tetrahydrofuran (THF) showed a monomodal distribution (Mn = 3900, PDI = 1.12, vs. PS standards, see Supporting Information). Similarly, if an excess of **6** was added to terminate the reaction with poly(MNI), the vast majority of polymer



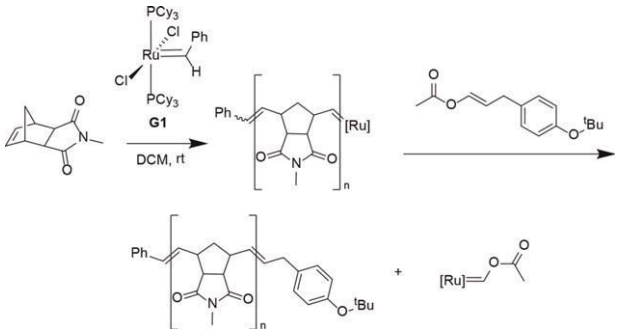
SCHEME 1 Synthesis of the functional enol esters **4** and **6**.

chains carried the protected amine end group at one chain end [Mn$_{(GPC,\ THF)}$ = 5900, PDI = 1.18, vs. PS standards, polymer 7, see Supporting Information]. A second mass distribution was attributed to the aldehyde terminated polymer chains, a known side reaction between the propagating ruthenium carbene complex and oxygen (Supporting Information).[32]

The observed difference between the molecular weight measured by GPC (THF) vs. PS standards and the observed mass distribution in the MALDI-ToF mass spectrum is due to the difference in hydrodynamic radius of polynorbornenes versus PS and has been described before in a similar context.[3]

Poly(MNI)s of different molecular weight (Mn = 3900, 5400, 6800, see Supporting Information, polymers 4–6) were prepared by varying the ratio of **G1** to **MNI** and all were functionally terminated with **4** to give *tert*-butyl protected phenol end groups (Supporting Information). Low PDI values and a linear relationship between the ratio of monomer to initiator and the molecular weight was found. This strongly indicates that the polymerization reactions were living (Supporting Information).

Exo-*N*-methyl-7-oxanorbornene-2,3-dicarboximide and exo-*N*-hexyl-5-norbornene-2,3-dicarboximide were synthesized and polymerizations initiated with **G1**. Both, poly(exo-*N*-hexyl-5-norbornene-2,3-dicarboximide) [Mn$_{(GPC,\ THF)}$ = 5200 g/mol, PDI: 1.16, polymer 8, Supporting Information] and poly(exo-*N*-methyl-7-oxanorbornene-2,3-dicarboximide) [Mn$_{(GPC,\ THF)}$ = 3200 g/mol, PDI: 1.11, polymer 9, Supporting Information] were



SCHEME 2 Functional end-capping of a propagating poly(**MNI**) ruthenium carbene complex with enol acetate end-capping reagent **4**.

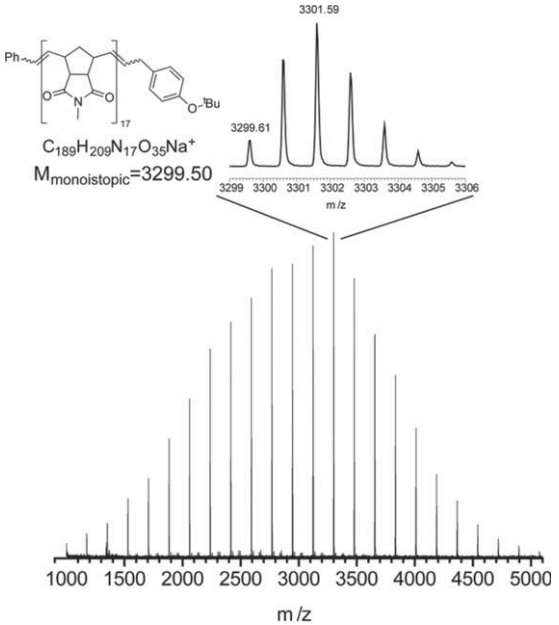


FIGURE 4 MALDI-ToF MS of poly(**MNI**) quenched with **4** (DCTB matrix and NaTFA). Top: isotopically resolved signals for a *tert*-butoxyphenyl propylidene end-capped poly(**MNI**) (*m*/*z*) $[M + Na^+]$ calculated for $[C_{189}H_{209}N_{17}O_{35}Na^+]$, 3301.59 (100%), 3300.58 (90.9%), 3302.59 (75.1%), 3303.6 (43.3%), 3299.61 (42.4%), 3304.6 (20.4%), and 3305.6 (8.1%). Bottom: overview of the entire mass distribution.

functionally terminated with **4** to show the protected phenolic end groups in the ^{1}H-NMR spectra and the MALDI-ToF mass spectrometric data as expected (see Supporting Information).

The rate of termination was investigated by following the decrease of the propagating ruthenium carbene signal via ^{1}H-NMR spectroscopy. All propagating ruthenium carbene signals vanish within 90 min using 1 equivalent of terminating agent (**4**) indicating a completion of the reaction. If more than 5 equivalents of terminating agent (**4**) were added, the reaction was completed within 5 min (see Supporting Information).

MNI (10, 20, and 30 eq) were initiated with Grubbs' third generation initiator (**G3**, 1 eq), functionally terminated with **4** (5 eq) and then **EVE**. MALDI ToF mass spectrometry revealed three polymeric mass distributions, the major one corresponding to the desired product carrying the *tert*-butyl protected phenol end group, the smallest one corresponding to a methylene end group (from reaction with EVE) and the third distribution corresponding to a terminal enol acetate (see Supporting Information). This result clearly indicates that the reaction of **G3** with **4** is less regioselective than the corresponding reaction carried out with **G1**. No further functional termination reactions were therefore carried out with **G3**.

CONCLUSIONS

In summary, we have shown that functional enolesters react regioselectively with Grubbs' first generation ruthenium carbene complex yielding acyl Fischer-carbenes. Grubbs' third generation complex, however, does not react regioselectively with enolester substrates. Reactions with the first generation complex were employed to end-functionalize several poly(norbornene) derivatives of different molecular weights with protected phenols and protected amines. This new method describes a synthetically straight-forward route to functional terminating reagents for ROMP which can be prepared readily from functional enolisable aldehydes.

ACKNOWLEDGMENTS

A.F.M. Kilbinger, P. Liu, M. Yasir, N. Hanik, and M. Schäfer thank the Swiss National Science Foundation (SNF) for funding of this research.

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