MALDI−TOF Mass Spectrometry for Detecting Impurities in Ester-End-Functionalized Poly(tetrahydrofuran), Poly(propylene glycol), and Poly(caprolactone) Telechelics

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ABSTRACT: MALDI−TOF mass spectrometry has been used to characterize several hydroxy- and ester-end-functionalized polyether-diols and polyester-diols. Mass spectra have provided information on the number-average molecular weights for low-monol poly(propylene glycol)s that are available through polymerization of propylene oxide in the presence of nonbasic double-metal cyanide complexes. Independent of polydispersity, MALDI−TOF MS proved a powerful method for detecting monofunctional impurities in end-modified telechelics. Although the expected diesters were clearly the main products after the telechelic's OH termini had been reacted with *p*-nitrobenzoyl chloride, monoester byproducts could be identified when the reaction time for the esterification was too short. Both GPC and NMR analysis were of limited value for detecting monofunctional impurities in ester-modified polyether-diols and polyester-diols. In contrast, MALDI−TOF and electrospray MS could more easily distinguish between diesters and monoesters, and both mass spectrometric techniques gave rise to independent peak series in the mass spectrum provided that the masses of the ions differed by at least 5 Da.

Introduction

Matrix-assisted laser desorption ionization time-of-flight mass spectrometry (MALDI−TOF MS) is a soft-ionization technique that has made it possible to ionize and analyze macromolecules with little to no fragmentation in a mass spectrometer.[1,2] Polymer molecules can be charged by proton transfer from an acidic matrix or by formation of an ion complex between the polymer and a suitable electrolyte that has been added to the matrix. The method is capable of giving valuable information about the molecular weight distribution of a polymer. Its usefulness for determining absolute molecular weights is, however, limited to polymers of low molecular weight and with a narrow polydispersity.[3] In such a case, MALDI−TOF MS can indeed provide molecular weight averages as well as the molecular weight distribution in a single experiment. Polymers with broad distributions can still be investigated, but then it is advantageous to fractionate the polymer and narrow its molecular weight distribution, for example by gel permeation chromatography (GPC), prior to MALDI analysis.[4]

The number-average molecular weight M_n (eq 1) and the weight-average molecular weight M_w (eq 2) are readily calculated from the masses of the observed ion peaks and their intensities, using the usual definitions[5]

$$M_n = \frac{\sum_i N_i M_i}{\sum_i N_i} \qquad (1)$$

$$M_w = \frac{\sum_i N_i M_i^2}{\sum_i N_i M_i} \qquad (2)$$

where M_i is the mass of a molecular ion with a degree of polymerization i and N_i is the number of molecules of mass M_i. For simplicity, N_i is assumed to be proportional to the signal intensity in the MALDI mass spectrum. The ratio of the two averages denotes the polydispersity index PDI (eq 3).

$$\mathrm{PDI} = \frac{M_w}{M_n} \qquad (3)$$

Polydispersity provides a good indication of the breadth of the molecular weight distribution. Whereas a step-growth polymerization has typically a PDI of around 2, a living polymerization technique produces polymers with an M_w/M_n as low as 1.02 − 1.10.[5] Polydispersities are most frequently determined by GPC. They can also be deduced from MALDI mass spectra, but in practice, the MALDI technique gives the best results if M_w (<10 000 Da in linear mode) and PDI are low. MALDI−TOF MS cannot be used routinely for PDI measurements of polymers with high PDI or polymers with high molecular weight due to problems at the source and detector and sometimes the analyzer. The result is that M_w and PDI values derived by MALDI are frequently too small. However, this will be of little concern if the analysis remains limited to polymers with polydispersities < 1.2.[6]

Despite problems with regard to the determination of M_n and M_w, MALDI−TOF MS has become an invaluable tool for end-group analysis in polymer character-

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ization.[7] When two polymers vary only in the type (and mass) of their end groups (whether introduced by design or accident), they will show more than one series of ion peaks in the MALDI mass spectrum, each separated by the mass of the repeat unit. MALDI−TOF MS can thus assist in the identification of end groups and in the estimation of their relative amounts and ultimately serve as a purity check. This will be especially important if the polymer is supposed to have only a single type of end group.

Thermoplastic polyurethanes (TPUs) are segmented copolymers with a rubbery polyether or polyester (soft) segment that alternates with a crystalline oligourethane (hard) segment. Good elastic properties are obtained when the TPU is made from a telechelic diol (of an M_n around 2000 g mol^{-1}), an aromatic diisocyanate, and a low-molar-mass diol (a chain extender that joins two nearby hard segments together) in a roughly 1:2:1 molar ratio. We and others have recently become interested in segmented polyamide elastomers in which the replacement of urethane groups by amides improves both fracture strain and toughness.[8,9] Our own synthetic approach required that the OH end groups of a polyether-diol or of a polyester-diol were transformed first into α,ω-bis(4-aminobenzoate)s. Quantitative functionalization of the telechelic was imperative to guarantee that high-molar-mass materials were obtained in a subsequent condensation polymerization. A good estimate of the number-average molar mass M_n of the modified telechelic was another prerequisite for minimizing errors in stoichiometry, since deviations from an equimolar ratio between two monomers in a step-growth polymerization brings about a significant drop in molar mass of the polymer. This has been long known, and it is immediately apparent from the modified Carother's equation (eq 4)

$$\bar{x}_n = \frac{1 + r}{1 + r - 2rp} \tag{4}$$

where both the ratio r of the number of molecules of the reactants and the extent of the reaction p determine the number-average chain length x_n.[5] At high conversion (p approaching 1), the degree of polymerization is highest for an equimolar ratio ($r = 1$) of the two monomers, whereas x_n decreases drastically if the polymerization mixture is even slightly deficient in one of the monomers (i.e., $r < 1$).

As we shall outline in this paper, GPC and NMR analysis turned out to have limitations when it came to the analysis of modified polyether-diols and polyester-diols. We have tested the suitability of MALDI−TOF MS (i) for detecting impurities in end-functionalized telechelics, (ii) for identifying the amount and type of these impurities, and (iii) for determining the M_n of the polymer. Three different types of telechelics were investigated on the basis of a poly(tetrahydrofuran), a poly(propylene glycol), and a poly(caprolactone) backbone, all esterified at the OH terminus.

Experimental Section

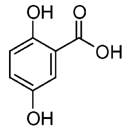
Materials. Poly(tetrahydrofuran) Terathane 2000 was purchased from Aldrich. Ultralow-monol-content (≤0.005 mequiv/g) poly(propylene glycol)s with M_n of 2000 and 4200 g mol^{-1} were obtained from Bayer AG. Poly(caprolactone) Premium Grade CAPA 2200P (with an M_n of 2000 g mol^{-1}) was supplied by Solvay Polycaprolactones.

Synthetic Procedures. The synthesis was adapted from a literature procedure for the esterification of a poly(tetrahydrofuran)-diol.[10] Triethylamine (16 mL, 115 mmol) was added to a solution of PPG 2000 (100 g, 50.1 mmol) in toluene (200 mL). After stirring for 10 min, the solution was heated to 50 °C. A solution of 4-nitrobenzoyl chloride (20.5 g, 110 mmol) in toluene (300 mL) was then added dropwise over 30 min, and the mixture was refluxed for 4 days. The reaction mixture was allowed to cool to room temperature and filtered to remove precipitated triethylammonium chloride. The filtrate was washed with a 5% aqueous solution of $NaHCO_3$ (ca. 500 mL), and the organic phase was separated and concentrated on a rotary evaporator (40 °C/40 mbar). The dark red, oily residue was finally dried in a vacuum (120 °C/0.2 mbar). Yield: 69%. Esterification was repeated on a smaller scale with a nitrobenzoate end-functionalized PPG containing diester and monoester in a ratio of about 8:1 (3.84 g, 1.7 mmol), 4-nitrobenzoyl chloride (0.36 g, 1.9 mmol), triethylamine (0.3 mL, 2.2 mmol), and toluene (40 mL) for 5 days. PPG 4200 was modified analogously.

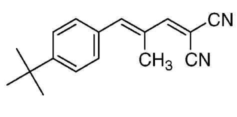
A 2 L three-necked round-bottomed flask (fitted with a dropping funnel, a condenser, and a mechanical stirrer) was charged with iron powder (56 g, 0.60 mol), toluene (400 mL), water (160 mL), and acetic acid (4 mL). The resulting slurry was refluxed until an emulsion had formed. A solution of the nitrobenzoate end-capped PPG 4200 (213 g, ca. 50 mmol) in toluene (200 mL) was then added dropwise over 30 min, and refluxing was continued for 18 h. The mixture was filtered while hot, and the filtrate was washed with water (2 × 500 mL). The toluene phase was separated and concentrated on a rotary evaporator (40 °C/40 mbar). The waxy, dark residue was finally dried in a vacuum (120 °C/0.2 mbar) until toluene could no longer be detected by ^{1}H NMR. Yield: 148 g (70%).

Esterification of poly(tetrahydrofuran) and poly(caprolactone) with 4-nitrobenzoyl chloride was conducted as described above, but the reaction time was shortened to 1−2 days. The subsequent reduction with iron was carried out according to literature procedures.[10,11]

Mass Spectrometry. MALDI−TOF mass spectra were obtained in reflectron mode on a Bruker Daltonics (Bremen) Reflex IV instrument equipped with a 337 nm nitrogen laser (Anorganisch-Chemisches Institut, University of Münster). Several poly(caprolactone)s were measured using a home-built MALDI−TOF mass spectrometer: Lazarus III DE home-built (H.L.), linear TOF with N_2 laser (337 nm, 3 ns), delayed extraction, 19 kV acceleration voltage, 2 m path length. The resolution, fwhm, was ca. 20 000 for the Reflex IV (under optimal conditions) and 4000 for the Lazarus III mass spectrometer. 2,5-Dihydroxybenzoic acid (DHB) or 2-[(2*E*)-3-(4-*tert*-butylphenyl)-2-methylprop-2-enylidene]malononitrile (DCTB) served as the matrix. Samples were prepared by combining chloroform solutions of the polymer (50 μL) and matrix (50 μL, at a concentration of ca. 50 mg/mL) with saturated methanolic $NaBF_4$ (10 μL). While both solvents are good solvents for the telechelics, a chloroform−methanol mixture was chosen to dissolve the matrix and electrolyte together. A typical ratio of matrix/polymer/$NaBF_4$ was 50:1:2 (w/w/w), and 1 μL of this mixture was dropped onto the target, at which point the solvent was allowed to evaporate. Spectra were averaged over 50−200 laser shots (pulse length 3 ns) distributed over different parts of the target. The spectrometer was calibrated with poly(ethylene glycol) (Na^+) in the mass range 600−4000 Da, which gave a mass accuracy of ±0.02% (Bruker Reflex IV) and ±0.05% (Lazarus III DE) for all polymer samples throughout the whole *m*/*z* range. Theoretical isotope distributions were calculated with Bruker's Xmass program.

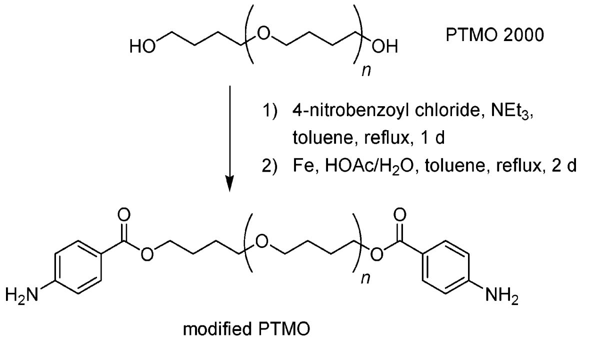


DHB



DCTB

Scheme 1



GPC Analysis. All analyses were carried out on a Polymer Laboratories GPC system equipped with a refractive index detector and two PLgel 5 μm mixed bed D columns (30 cm), calibrated with polystyrene standards (eluent: THF or chloroform; flow rate: 1.0 mL min^{-1}; temperature: 30 °C). Viscotek's Trisec 3.0 software was used for data capture and subsequent data handling.

NMR. ^{1}H NMR spectra were recorded on a Bruker AC 200 and DPX 400 (at Heriot-Watt University).

Results and Discussion

Poly(tetrahydrofuran)s. Poly(tetrahydrofuran) or poly(tetramethylene oxide) (PTMO) is produced by cationic ring-opening polymerization of tetrahydrofuran at low temperature. Poly(tetrahydrofuran)s are the preferred soft segments in TPUs where tensile strength, low-temperature performance, and dynamic properties are concerned. Furthermore, PTMO soft segments are equally suitable for polyamide elastomers,[8] which we prepared in one step from aminobenzoate end-functionalized poly(tetrahydrofuran)s.[9]

Both PTMO 2000 and its end-functionalized derivative (synthesized as shown in Scheme 1) gave rise to a mass spectrum with a comparatively broad, nonsymmetric distribution and a long tail toward higher masses (Figure 1). The product was pure by ^{1}H NMR (Figure 2). GPC analysis indicated a polydispersity index for the polyether around 2.0, which is typical for a Schulz−Flory distribution.[5]

MALDI−TOF mass spectra were obtained with DHB as matrix to which $NaBF_4$ was added to promote ion formation. Most ions belonged to the $[M + Na]^+$ series, and only the largest ion peaks were accompanied by weak $[M + K]^+$ satellites. At *m*/*z* values below 600 Da the MALDI−TOF mass spectrum of PTMO 2000 showed traces of cyclic THF (with an 18 Da lower mass than the main series), which are the only noteworthy impurities, apart from stabilizers, in commercial poly(tetrahydrofuran)-diols.[12] No other impurities, such as monoester or reduction byproducts, were evident from the mass spectrum or the ^{1}H NMR spectrum. MALDI−TOF MS, in particular, substantiated that the modified polyether consisted exclusively of a difunctional telechelic (with aminobenzoate end groups) and that the prepared batch was pure enough for a condensation polymerization. This was subsequently confirmed by the formation of high-molar-mass thermoplastic elastomers with good mechanical and dynamic properties, when the telechelic was polymerized with terephthaloyl dichloride or naphthalene-2,6-dicarbonyl dichloride.

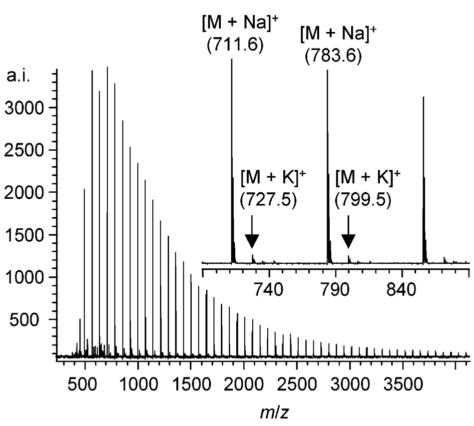


Figure 1. MALDI−TOF mass spectrum (DHB matrix) of an aminobenzoate ester-modified PTMO 2000 (a.i. = arbitrary intensity). Inset: a minor peak series stems from $[M + K]^+$ species.

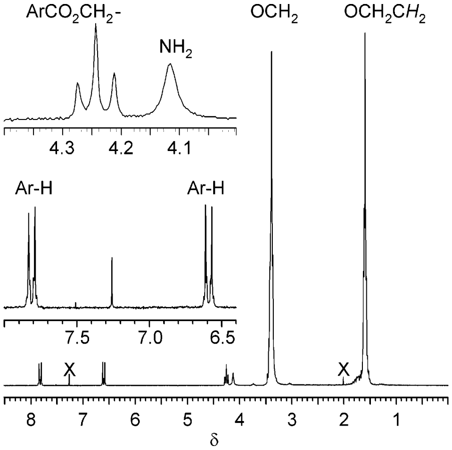


Figure 2. ^{1}H NMR spectrum (200 MHz, $CDCl_3$) of the modified PTMO 2000. Inset: expansion of the aminobenzoate end group signals. Solvent and acetone signals are marked by an "X".

Poly(propylene glycol)s. Poly(propylene glycol)s or PPGs are employed in the commercial synthesis of polyurethane and poly(urethane−urea) elastomers. While PPGs are considerably cheaper than poly(tetrahydrofuran)s, the manufacture of PPGs by base-catalyzed polymerizations of propylene oxide is susceptible to side reactions that produce a certain amount of monohydroxy-terminated ("monol") PPGs with allyl or propenyl ether groups at one end of the polymer chain. The presence of monol sustains an imbalance in stoichiometry, with the effect that any attempt to make thermoplastic elastomers by a subsequent polymerization with a diisocyanate (and a chain extender) tends to furnish materials of inferior quality. PPGs have therefore been restricted to the manufacture of polyurethane foams in which problems with the difunctionality of the telechelic are offset by cross-linking. Substantial improvements in lowering the monol content have been achieved recently by the introduction of nonbasic double-metal cyanide catalysts for the polymerization of propylene oxide.[13,14] In combination with a low-molar-mass diol (e.g., tripropylene glycol) as part of the initiating system, these catalysts are able to produce atactic PPG-diols with a very low monol content. The PPGs 2000 and 4200 used in this work were manufactured by polymerization of propylene oxide in the presence of a zinc hexacyanocobaltate catalyst and tripropylene glycol as initiator. Low levels of unsaturation (≤2 mol % monol for PPG 4200) and narrow molar mass distributions (with polydispersities of 1.02−1.15) have even made such PPGs promising soft segments for the preparation of TPUs.[15] The difference in polydispersity between poly(tetrahy-

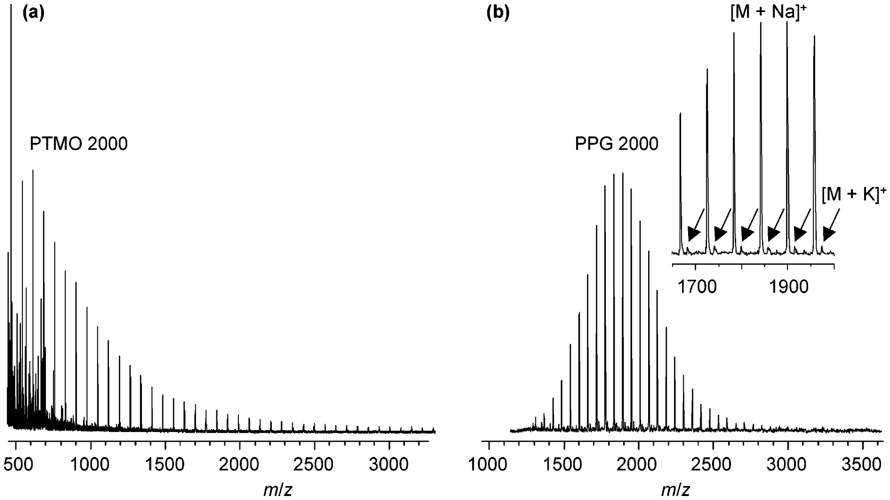
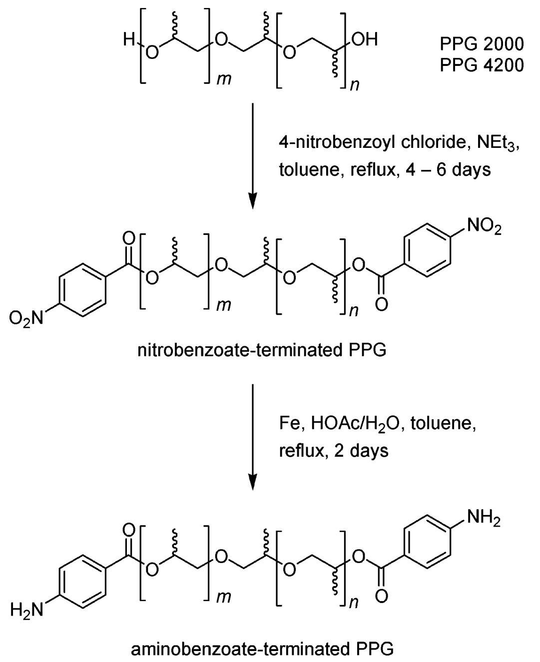


Figure 3. MALDI−TOF mass spectra (DHB matrix) of (a) poly(tetrahydrofuran) and (b) a low-monol PPG, both with an M_n of 2000 g mol^{-1}. Inset: a minor peak series originates from $[M + K]^+$ adducts.

Scheme 2



drofuran) and PPG, both of M_n 2000 g/mol, is immediately apparent from a comparison of their MALDI−TOF mass spectra (Figure 3). PTMO 2000 gives rise to a broad distribution of ion peaks that tails off toward higher *m*/*z* values. In contrast, the MALDI mass spectrum of PPG 2000 is much sharper. The distribution centers around *m*/*z* 1870 and is, apart from a slight tail toward higher masses, almost symmetrical, resembling a Poisson distribution that is anticipated for a polymer prepared by a living polymerization.[5] The observed mass values agree within ±0.02% with the sodium adduct ions $[M + Na]^+$ for a poly(propylene glycol). Only singly charged ions are found. The mass spectrum of PPG 2000 shows no ion peaks at 18 Da below the principal series (apart from a few very weak peaks between 1300 and 1600 Da), consistent with a low monol content for the commercial sample.

Unlike poly(tetrahydrofuran)-diols and polyester-diols, which are commonly used for making thermoplastic polyurethanes, low-monol PPGs have predominantly secondary OH end groups that are, of course, much less reactive than primary alcohols. Consequently, functionalization at the terminus is an important way to increase the reactivity of PPG-diols. Reaction times tend to be long, and even the end-capping with a diisocyanate requires 7−9 h at 80 °C.[15b,c] It was therefore not surprising that esterification of PPG 2000 or 4200 with *p*-nitrobenzoyl chloride proceeded sluggishly as well (Scheme 2). The ^1H NMR spectrum of the product isolated after several days appeared to be consistent with an end-functionalized PPG. Esterification gave rise

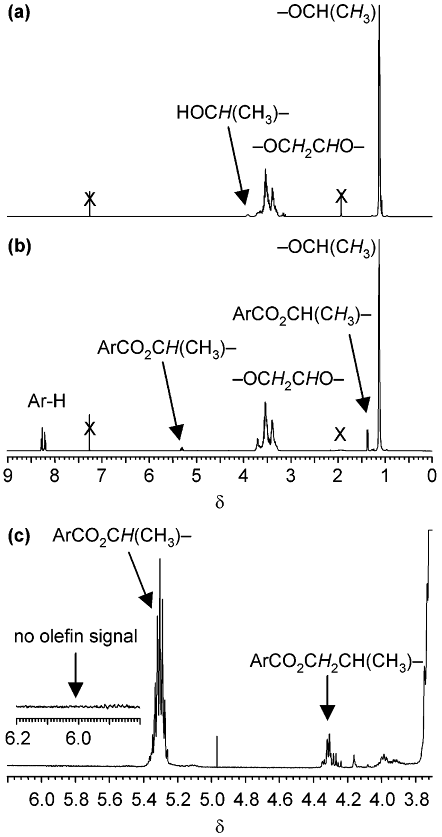


Figure 4. ^1H NMR spectrum (400 MHz, $CDCl_3$) of (a) PPG 2000 and (b) the modified PPG 2000 obtained after esterification with *p*-nitrobenzoyl chloride. (c) Expansion of (b) reveals the absence of olefinic impurities. The multiplet at $\delta_H = 4.3$ (with an integral of about 15% of the signal at $\delta_H = 5.3$) is attributed to the end group of an isomeric ester. Solvent and water signals are marked by an “X”.

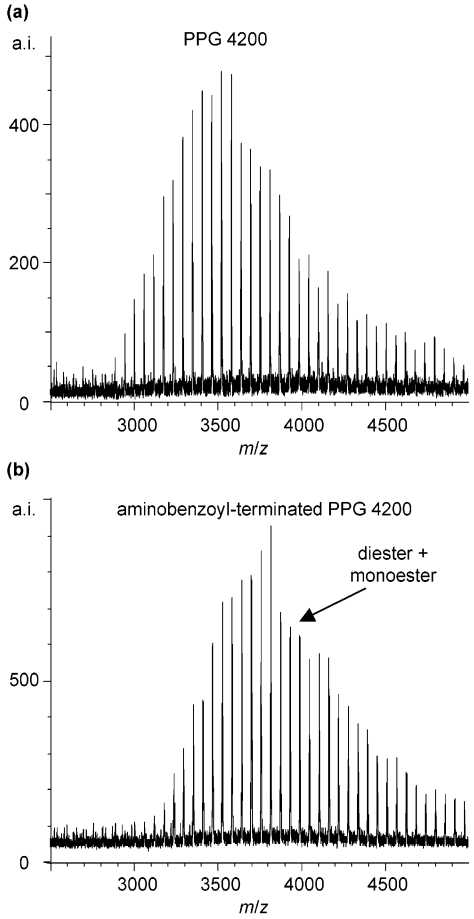


Figure 5. MALDI−TOF mass spectrum of (a) a low-monol PPG with an M_n of 4200 g mol^{-1} and (b) a 4-aminobenzoate-terminated PPG 4200 (a.i. = arbitrary intensity). The matrix was DHB in both cases.

to a characteristic downfield shift for both the methine multiplet and the CH_3 signal of the terminal propylene glycol unit (Figures 4a,b and S2). Similar downfield shifts have also been observed in prepolymers derived from PPG and toluene diisocyanate.[16] The ^1H NMR spectrum (Figure 4c) showed no evidence of allyl (δ_H 5.1, 5.25, 5.9) or propenyl ether end groups (δ_H 4.45, 6.05)[17] that might have originated from monol impurities in the commercial PPG or from side reactions (elimination) during esterification. The multiplet at $\delta_H = 4.3$ could be assigned to a PPG with an isomeric end group; like the modified polytetrahydrofuran, it possessed a typical chemical shift for an ester of a primary alcohol. A ^{13}C/^1H correlation in combination with a ^{13}C DEPT spectrum confirmed unambiguously that this signal belonged to a CH_2 group (Figures S3−S5).

The MALDI−TOF mass spectrum of the aminobenzoate-substituted PPG consists, as might be expected, of a single ion series at a higher mass than the PPG-diol (Figure 5). However, it should be pointed out that the mass of a $H_2N{-}C_6H_4{-}CO$ end group (120 Da) is almost twice the mass of the C_3H_6O repeat unit (58 Da), and as a consequence, the masses of mono- and diester series differ by just 3 Da. Although the product looks pure at a first glance, overlap between the isotope clusters of diester and monoester series (especially in the higher m/z range) makes it difficult to differentiate the two components. The isotope pattern of the doubly charged species of diester and monoester, the latter originating from incomplete functionalization of PPG 4200, could just about be resolved in an electrospray mass spectrum (Figures S6 and S7).[18]

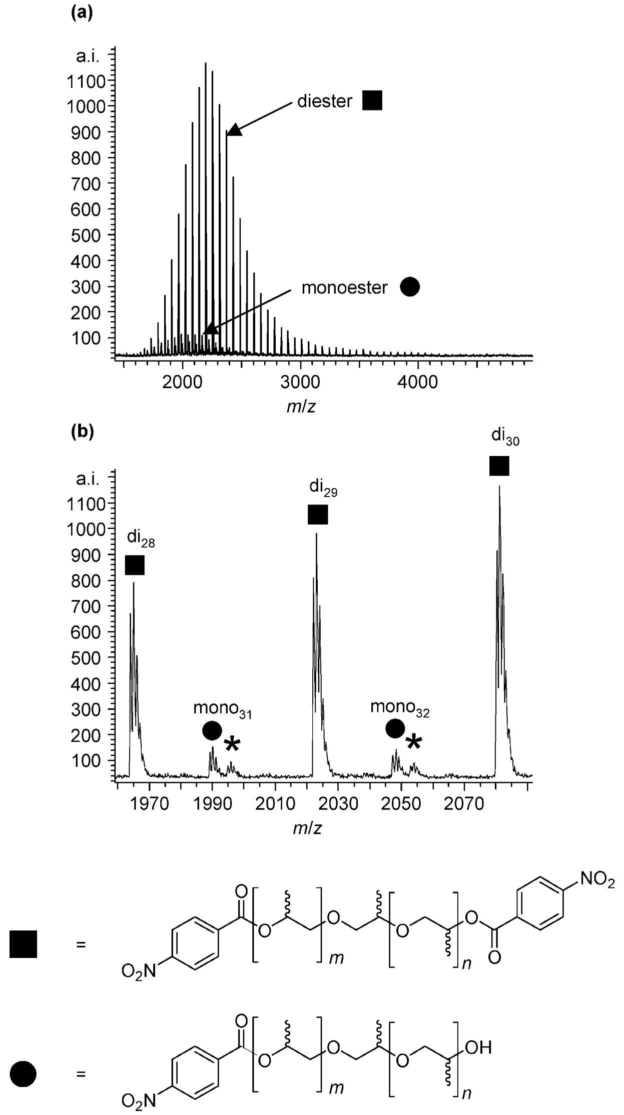


Figure 6. (a) MALDI−TOF mass spectrum (DCTB matrix) of PPG 2000 after esterification with 4-nitrobenzoyl chloride (a.i. = arbitrary intensity); (b) enlarged detail of the distribution near the maximum intensity. Ions are marked to facilitate the assignment: diester (filled squares), monoester (filled circles), photodegradation product (asterisks).

The nitrobenzoate end-modified PPG was therefore investigated instead, since in this case the ion peaks of the diester and monoester series are 25 Da apart. However, whereas DHB worked well as a matrix for PPG itself, MALDI−TOF MS analysis of a nitrobenzoate-functionalized PPG embedded in this acidic matrix gave rise to a rather complex peak pattern owing to photochemical decomposition of the polymer. We note that peptides containing 3-nitrotyrosine are reported to show the loss of one or two oxygen atoms under standard MALDI conditions, and this reduction process is facilitated by the use of an acid matrix.[19] Similarly, some nitro-aromatic compounds are prone to rearrange and eliminate NO under irradiation; the photo-rearrangement of an aromatic nitro compound $Ar{-}NO_2$ to a nitrite ester $Ar{-}ONO$ was recently shown to be followed by homolytical cleavage of the $O{-}NO$ bond.[20] DCTB has been known to produce good-quality mass spectra at a much lower threshold laser power.[21] By

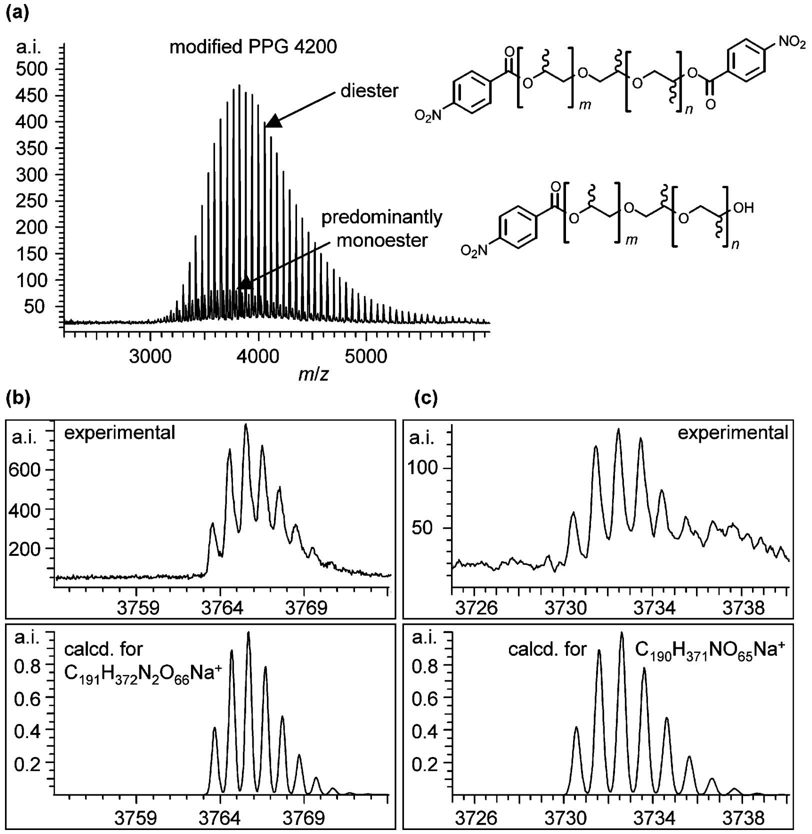


Figure 7. (a) MALDI−TOF mass spectrum (DCTB matrix) of a modified PPG 4200 (a.i. = arbitrary intensity). (b) Observed and calculated isotope pattern for a diester (59-mer) and (c) for a monoester (61-mer).

selecting DCTB instead of DHB as matrix, we were able to halve the laser power and thus reduce the likelihood of laser-induced degradation almost completely (Figures 6a, S8, and S9). The distribution appears to be only slightly broadened, with the maximum shifted by 298 Da, as expected. While PPG 2000 is pure according to MS, the modified PPG derived from it gives rise to more than one series of peaks. Small amounts of monoester $[HO(C_3H_6O)_nCOC_6H_4NO_2 + Na]^+$ are present in the product and lead to a series with a 25 Da difference in mass. Prior calibration of the mass spectrometer with poly(ethylene glycol) in the mass range 600−4000 Da made it possible to achieve an accuracy of ±0.02% within this *m*/*z* range (Table S1). The mass of the peak at, for example, *m*/*z* 1989.2 is within 0.1 Da of the expected value (1989.3) for the monoester of a 31-mer and supports our assignment. The ratio of di- to monosubstituted species was estimated from the corresponding peak heights to be approximately 8:1. Such an amount of monoester easily escaped detection by NMR (Figure 4b,c) because (i) its signals overlap with those of the diester and (ii) integration tends to have an error margin of ±10%.

Figure 7a displays the MALDI−TOF mass spectrum of the product isolated after esterification of PPG 4200 with *p*-nitrobenzoyl chloride. Unlike in the case of the aminobenzoate-terminated PPG (Figure 5b), the series belonging to diester and monoester can now be clearly distinguished. The resolution of the mass spectra is sufficient to resolve the naturally occurring isotopes (predominantly $^{12}C/^{13}C$) of the major components, and the agreement between theoretical and observed isotope distribution in Figure 7b,c is excellent. Again, the masses of the ion series of modified telechelic and any impurities are well-separated for MALDI−TOF MS analysis to prevent overlap between isotope clusters.

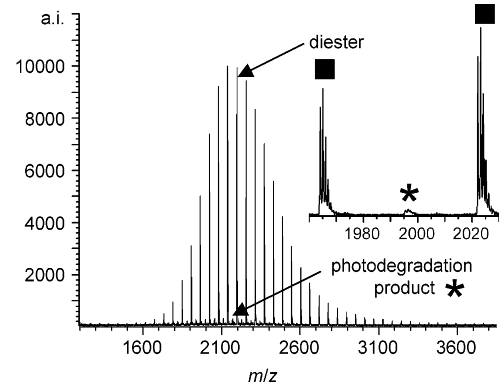


Figure 8. MALDI−TOF mass spectrum (DCTB matrix) of a nitrobenzoate end-functionalized PPG after PPG 2000 had been treated twice with 4-nitrobenzoyl chloride and triethylamine (a.i. = arbitrary intensity).

With monofunctional products present, the usefulness of ester-modified PPGs for the synthesis of thermoplastic elastomers is likely to be limited unless the preparation method can be optimized. The reaction was finally driven to completion after treating the diester/monoester mixture once more with fresh *p*-nitrobenzoyl chloride and triethylamine in toluene for 5 days. The monoester could no longer be detected after the second esterification. However, a series with a 31 Da higher mass than the diester remained (marked with an asterisk in Figures 6b and 8). From its mass this species must contain an odd number of nitrogen atoms, and we presume it to be a photodegradation product of the diester which, after loss of a nitro group, has added to

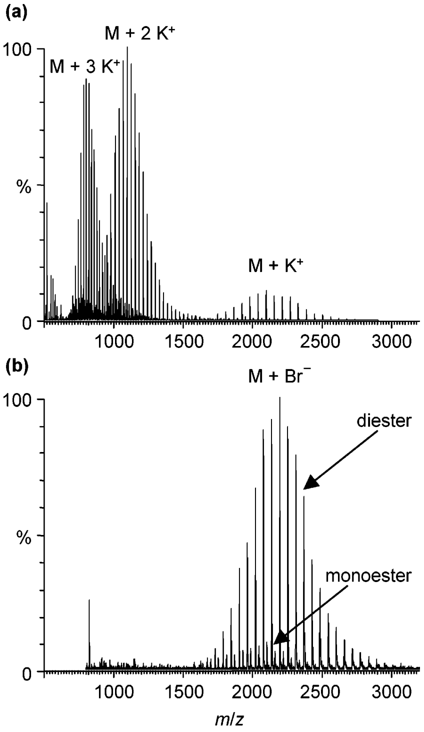


Figure 9. (a) Positive and (b) negative ion mass spectrum (electrospray, KBr) of a modified PPG 2000 that has been reacted just once with 4-nitrobenzoyl chloride.

the matrix DCTB. The calculated masses for [diester $-$ NO_2 + DCTB + H + Na]$^+$ agree with the experimental *m/z* values. Proof that it was indeed an artifact of the MALDI method came from electrospray mass spectra in which the extra series was absent (Figure 9). With KBr as electrolyte, the positive ion mass spectrum of the nitrobenzoate-functionalized PPG 2000 exhibited several series, owing to singly, doubly, and triply charged ions. The negative ion mass spectrum, albeit about 10 times less sensitive, consisted of only singly charged ions. In both cases, ion peaks originated from diester and monoester, but no third series could be detected. We note that the ratio of di- to monosubstituted species was more or less the same (about 8:1) as in the MALDI experiment. It also emphasized that the ratio between diester and monoester is not distorted by changes in ionization efficiencies of the end groups in the MALDI−TOF MS as has been observed in other cases, such as blends of nylons and poly(butylene terephthalate).[7c] Electrospray MS showed furthermore that the diester remained the sole component after the second esterification treatment (Figure 10).

Poly(caprolactone)s. TPUs made with a poly(caprolactone) (PCL) soft segment are potentially biodegradable, particularly if nonaromatic diisocyanates are used for polyurethane formation.[22] For this reason, poly(caprolactone)s currently receive much attention in the design of thermoplastics and elastomers for biomedical applications.

The commercial polyester-diol selected for our investigation had an M_n of 2000 g mol^{-1}. Its MALDI−TOF mass spectrum possesses a relatively broad and nonsymmetric distribution (Figure 11a), and the peaks of the main series agree with the calculated mass for the Na$^+$ adduct of a neopentyl glycol-initiated poly(caprolactone).

The poly(caprolactone)-diol was esterified with 4-nitrobenzoyl chloride, followed by reduction of the nitro groups with iron (Scheme 3). The main series of the MALDI mass spectrum can be assigned to the α,*ω*-bis-(4-aminobenzoate) derivative. Additional peaks with masses 5 Da below those of the main series originate from a monoester byproduct (Figure 11b,c). The monoester impurity could not be detected by routine ^{1}H NMR spectroscopy, since its signals were effectively hidden by the NMR signals of the diester.

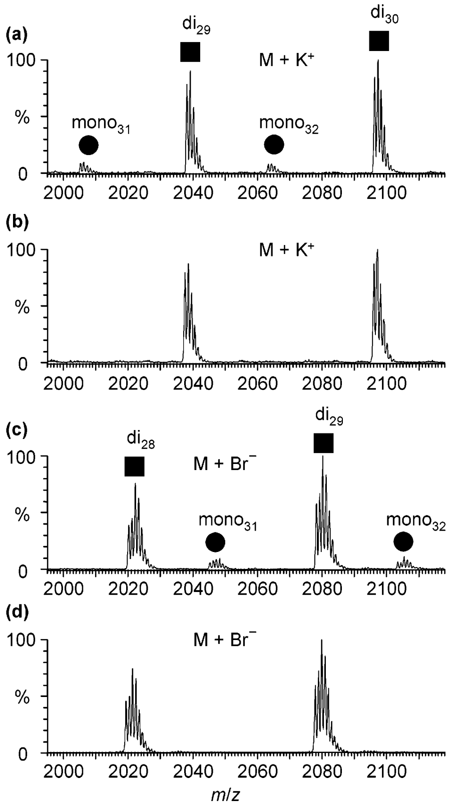


Figure 10. Positive ion mass spectra (electrospray, KBr) of a modified PPG 2000 (a) before and (b) after the second treatment with 4-nitrobenzoyl chloride. Negative ion mass spectra (electrospray, KBr) of the same modified PPG (c) before and (d) after the second treatment with 4-nitrobenzoyl chloride.

Determination of Molar Mass Averages. While end-group titration and NMR are popular techniques for determining the molecular weight average of telechelics, they are only applicable if the number and structure of end groups per oligomer are known with certainty.[5] In contrast, the results obtained by GPC depend very much on the choice of calibration. It was therefore our intention to assess MALDI−TOF MS as an alternative for ascertaining accurate M_n values. For this, the resolution of the mass spectra was reduced to incorporate all isotopes into a single peak. A peak list was generated, and using the main series of ion peaks for each polymer, average molecular weights were calculated according to eq 1 and 2 and corrected for the contribution of the Na$^+$ cation. The results are compiled in Table 1. The PPGs gave reasonably good correlations between the M_n values derived from the MALDI mass spectra and those specified by the manufacturer. The PPGs were, however, the only polymers investigated with a polydispersity low enough ($\leq$1.03 according to MALDI) that the M_n was hardly affected by a truncation of the ion peak distribution.

The polydispersity index of the poly(tetrahydrofuran) was significantly larger (2.0 by GPC) than for the PPGs

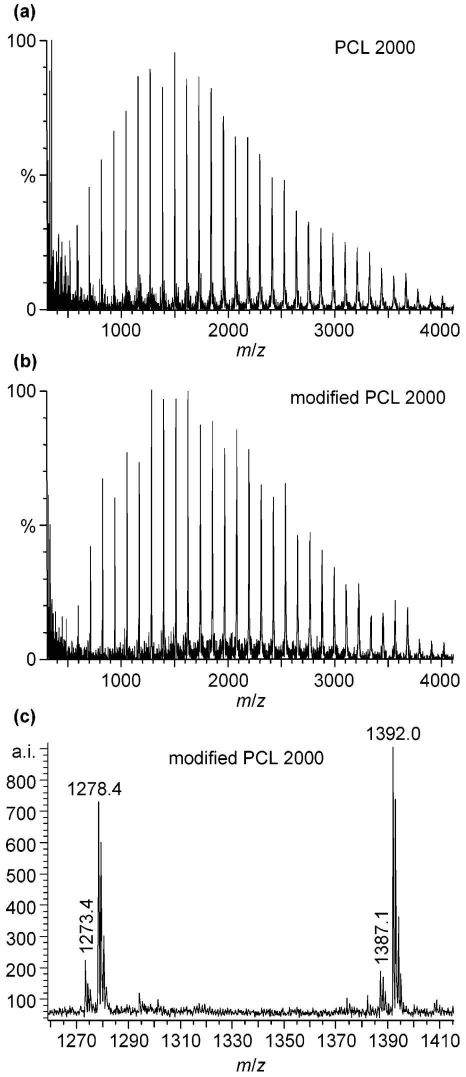


Figure 11. (a) MALDI−TOF mass spectrum of a poly(caprolactone) with an M_n of 2000 g mol^{-1} and (b) after esterification according to Scheme 3. (c) The expansion (reflectron mode) shows ion peaks of the poly(caprolactone) with two aminobenzoate end groups and a minor series, with masses 5 Da below those of the main peaks, due to a monoester impurity. The matrix was DHB in all cases.

Scheme 3

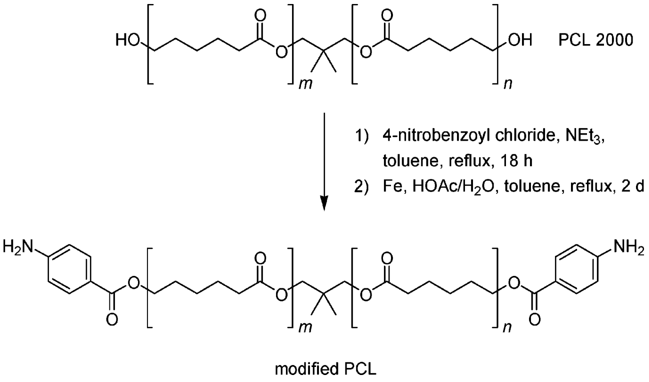


Table 1. Molar Mass Averages and Polydispersities Obtained for the Telechelics by MALDI

polymer	nominal M_n [g mol^{-1}]	M_n by MALDI [Da]	M_w by MALDI [Da]	M_w/M_n by MALDI
PPG 2000	2000	1910	1950	1.02
mod PPG 2000	2300	2330	2400	1.03
PPG 4200	4200	3800	3920	1.03
mod PPG 4200	4500	4060	4110	1.01
PCL 2000	n.d.[a]	n.d.	n.d.	n.d.
mod PCL 2000	n.d.	n.d.	n.d.	n.d.
mod PTMO 2000	2240	1190	1630	1.37

[a] Not determined.

and comparable to the PDI of the poly(caprolactone)s. Intense oligomer ion peaks were observed in the mass spectrum of the poly(tetrahydrofuran), even more so than for the poly(caprolactone)s. In fact, there seemed to be little difference between the mass spectra of a modified PTMO with an M_n of 2200 g mol^{-1} and a batch with an M_n of 1600 g mol^{-1}. With a maximum of the distribution at 711 Da (Figure 1), the calculated M_n and M_w obtained from the experimental peak heights were much too small for a telechelic with a molar mass of 2200 g mol^{-1} and in sharp contrast to the number-average molar mass M_n determined by NMR. Integration of the ^{1}H NMR signals of the aromatic end groups and the aliphatic polyether of the modified PTMO gave an average degree of polymerization P_n of 29.5 ± 1.5, which corresponded to an M_n of 2380 ± 360 g mol^{-1}. This is yet another example for the limits of MALDI−TOF MS for analyzing molar mass averages of polymers with relatively broad distributions.

Conclusions

We have analyzed the MALDI−TOF mass spectra of poly(tetrahydrofuran)-diols, poly(propylene glycol)-diols, and poly(caprolactone)-diols before and after functionalization with ester end groups. MALDI−TOF MS turned out to be well-suited for detecting and characterizing impurities provided that the masses of individual components differed by at least 5 Da. MALDI was, however, of limited value for the determination of M_n and seemed to be applicable only for polymers with narrow molecular weight distributions (viz. PPGs). Molecular weight averages could be calculated from the masses and peak intensities of the ion peaks observed in the MALDI mass spectrum, using the usual definitions. Whereas low-monol PPGs gave reasonable results with regard to M_n, this was no longer the case for both poly(tetrahydrofuran)s and poly(caprolactone)s owing to limited sensitivity and the MALDI experiment's bias toward lower masses. For polymers with a polydispersity >1.2, neither MALDI nor GPC seems to recommend itself for determining molar mass averages with the accuracy required for telechelics destined to be used in step-growth polymerizations.

While GPC and NMR analysis have limitations when it comes to purity control, MALDI−TOF MS is a powerful method for establishing the presence or absence of small amounts of monoester or diol impurities. In our examples, conditions were chosen so that the principal series consisted of $[M + Na]^+$ ions and could be easily assigned to the telechelic with OH, 4-nitrobenzoate, or 4-aminobenzoate end groups. Prior calibration with poly(ethylene glycol) made it possible to achieve a good mass accuracy throughout an m/z range of 600−4000 Da. With mass spectra obtained this way, identification of end groups was further supported by comparison of the experimental and simulated isotope clusters, particularly at higher m/z values. Additional satellite peaks around the principal distribution tended to have several origins. First, a weak $[M + K]^+$ series was observed in some cases and caused by the presence of K^+ ions in the matrix. Second, the major impurity after esterification consisted of the monoester as a result of incomplete end-functionalization of the polyether- or polyester-diol. In particular, the secondary OH end groups of the PPGs reacted rather sluggishly and required long reaction times. In one case, significant amounts of monoester was also detected by MALDI−TOF MS in a batch of modified poly(caprolactone) 2000. Third, laser-induced photodegradation byproducts were observed in MALDI mass spectra of nitrobenzoate ester-functionalized telechelics. Although they could be largely suppressed by the choice of DCTB as matrix, their complete avoidance was only possible by using the electrospray method for analysis instead.

We conclude that MALDI−TOF MS is well-suited for detecting and identifying impurities in end-functionalized telechelics even if byproducts (for example, small amounts of monoester in a sample consisting mainly of a diester-end-modified polymer) may elude detection by ^{1}H NMR spectroscopy.

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Supporting Information Available: A table comparing the MALDI data with the theoretical masses for the PPG diester; figures of ^{13}C NMR, DEPT, and ^{1}H, ^{13}C correlation spectra of modified PPG 2000; electrospray mass spectrum (NaBF$_4$) of 4-aminobenzoyl-terminated PPG 4200; and comparison of the MALDI mass spectra of 4-nitrobenzoate-functionalized PPG 2000 measured with DHB or DCTB as matrix. This material is available free of charge via the Internet at http://pubs.acs.org.

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