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Analysis of a Technical Poly(ethylene oxide) by On-Line HPLC/^{1}H-NMR

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ABSTRACT: The analysis of a technical poly(ethylene oxide) with respect to chemical structure and degree of polymerization has been performed by on-line HPLC/^{1}H-NMR analysis. Liquid chromatography separates the poly(ethylene oxide) according to the functional end groups. The functionality fractions are directly introduced into a 500 MHz ^{1}H-NMR spectrometer and analyzed with respect to the configuration of the end groups and the molar mass of the polymer chain. The experiments have been conducted under conditions which are common for HPLC separations, i.e. a sufficiently high flow rate, moderate sample concentration, and on-flow detection.

Introduction

Poly(ethylene oxide)s (PEO) are important intermediates in organic and polymer chemistry. In particular, alkyloxy- and aryloxy-terminated PEO's are in widespread use as surfactants. Depending on the length of the polymer chain and the chemical structure of the terminal groups, the amphiphilic properties change, thus influencing the surface activity.

The chemical structure of alkyl/aryloxy PEO oligomers is characterized by distributions in molar mass and functionality. As a result of different initiation, chain propagation, and termination mechanisms, species of different terminal groups bound to the poly(ethylene oxide) chain are formed. To elucidate the structure−property relationships of these products, it is important to know the molar mass distribution (MMD) as well as the chemical structure and number of the terminal groups.

It has been shown in a number of studies that the functionality type distribution (FTD) of PEO may be determined by liquid chromatography at the critical point of adsorption.[1,2] The determination of FTD and MMD of functional polyethers is possible by using two-dimensional chromatography.[3,4] The oligomer distribution and the mass of the end groups can be investigated by mass spectrometry. In particular, matrix-assisted laser desorption/ionization mass spectrometry (MALDI-MS) is capable of producing intact macromolecular ions up to high molar masses.[5,6]

However, even the most sophisticated liquid chromatographic and spectroscopic techniques alone cannot completely determine all structural features. In particular, the determination of the isomeric structure and the number of end groups is complicated, if not impossible, for a number of alkyl/aryloxy PEO's. The combination of HPLC with the most powerful spectroscopic technique—nuclear magnetic resonance (NMR)—has been attempted numerous times. Early experiments of coupled HPLC/^{1}H-NMR were conducted in a stop-flow mode or with very low flow rates.[7−9] This was necessary to accumulate a sufficient number of spectra per sample volume in order to improve the signal-to-noise ratio. For example, Hatada et al. described the analysis of isotactic poly(methyl methacrylate) by on-line LC/NMR using a flow rate of 0.2 mL/min.[10] Problems associated with the implementation of on-line HPLC/NMR have included the need for deuterated solvents, inadequate solvent suppression techniques, and low sensitivity. However, recent rapid advances in HPLC/NMR provide evidence that many of the major technical obstacles have been overcome.[11,12]

With the development of more powerful NMR spectrometers combined with new NMR techniques for solvent suppression, it has become much easier to obtain well-resolved spectra in the on-flow mode. In particular, the solvent suppression technique recently developed by Smallcombe et al.[13] significantly improves the spectra during the HPLC/NMR run. This experiment, which is based on the WET solvent suppression technique of Ogg et al.,[14] combines shaped rf pulses, pulsed-field gradients (PFG), and selective ^{13}C decoupling and allows acquisition of high-quality spectra at on-flow conditions even with high HPLC gradients. Based on this new technique, the present study describes the analysis of a technical PEO by HPLC/NMR with respect to chemical structure and molar mass. Emphasis has been paid to the use of experimental conditions which are common in HPLC regarding flow rate and sample concentration.

Experimental Section

Sample. The poly(ethylene oxide) under investigation is a technical product of BASF AG, Ludwigshafen, Germany.

HPLC. The chromatographic separations were carried out on a Varian modular HPLC system, comprising a Varian 9012 pump, a Valco injection valve, and a Varian 9050 UV detector. The UV detector was operating at a wavelength of 260 nm. The column was a Varian Res Elut C18 90A, 150 × 4.6 mm i.d. The mobile phase was acetonitrile−deuterium oxide 50:50% by volume. Sample concentration was 15 mg/mL in acetonitrile, and 100 μL of the sample solution was injected. The flow rate was 1 mL/min.

NMR. The NMR measurements were conducted on a Varian 500 MHz NMR spectrometer UNITY*plus*. The HPLC/NMR probe containing a 60 μL flow cell was an indirect detection probe with PFG. All measurements were carried out at room temperature. The signal-to-noise ratio of the LC/NMR probe is given by the following specifications: 22:1 for the anomeric proton of sucrose (41 μg/60 μL) at 500 MHz. In the case of on-line measurements, this corresponds to a detection limit of 10 μg per compound in the flow cell or 300 ng in the

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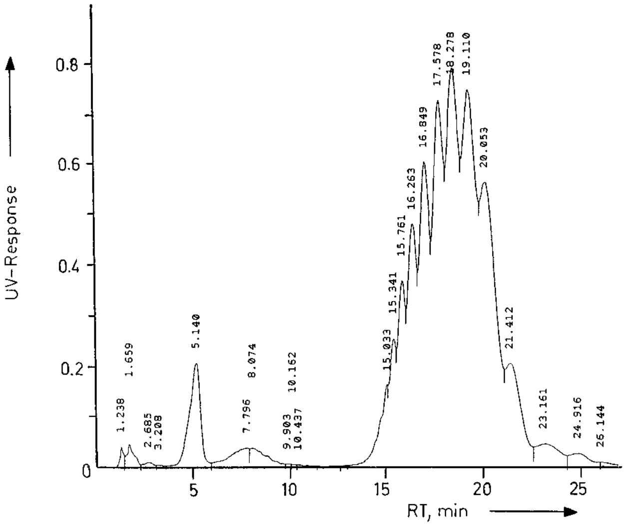


Figure 1. HPLC chromatogram of a technical poly(ethylene oxide) (stationary phase, RP-18; mobile phase, acetonitrile–deuterium oxide 50:50% by volume).

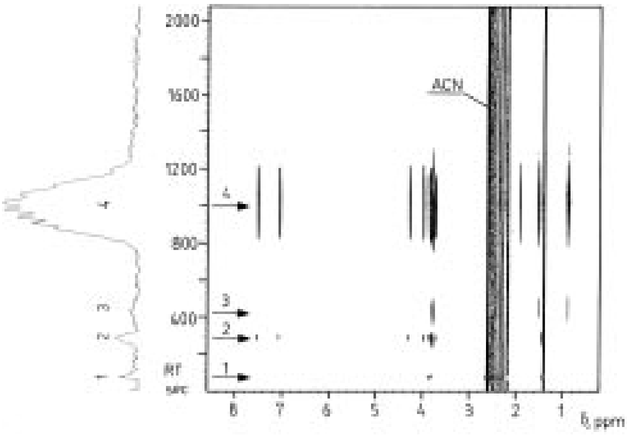


Figure 2. Contour plot of chemical shift vs retention time and chemigram of the on-line HPLC/NMR analysis of a technical poly(ethylene oxide).

case of stop-flow measurements (M_w = 300–400). The line width is measured using a solution of 1% of chloroform in acetone-d_6 and specified as follows: 10 and 20 Hz at 0.55 and 0.11%, respectively, of the total peak height.

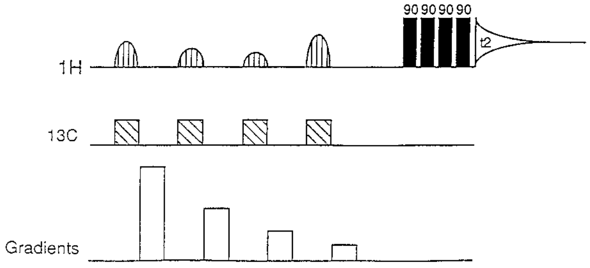
Results and Discussion

Liquid chromatography is a versatile tool for analyzing technical poly(ethylene oxide)s. The molar mass distribution is preferably determined by size exclusion chromatography (SEC), whereas a separation with respect to the end groups can be obtained by adsorption chromatography or liquid chromatography at the critical point of adsorption. The functionality type separation of the present sample is shown in Figure 1. Using an octadecyl-modified silica gel as the stationary phase, the sample is separated into functionality fractions when the eluent composition is acetonitrile–deuterium oxide 50:50% by volume. The first elution peaks appear between 1.2 and 1.7 min in the region of the injection peak. Further elution peaks are obtained at retention times of 5.14 and 7.80 min. The major fraction of the sample elutes between 14 and 25 min, and for this fraction additionally a partial oligomer separation is obtained.

The identification of the fractions by UV detection is not possible; it can be stated, however, that the fractions at 5.14 and 7.80 min and the major fraction exhibit a significant UV response at 280 nm. This is a first indication for the presence of aromatic moieties. Since the PEO polymer chain is aliphatic, the end groups are assumed to be aromatic.

For structural identification of the fractions, HPLC is coupled on-line to the NMR spectrometer. The injection of the sample into the HPLC system is automatically initiated by the NMR console via a trigger pulse when starting acquiring NMR data. The following pulse sequence was used (see Scheme 1):[13] the WET sequence applied to HPLC/NMR consisting of four 20 ms selective SEDUCE pulses (98.2, 80.0, 75.0, and 152.2° for the B_1-insensitive WET), four gradient pulses (duration 1 ms) with amplitudes of 24, 12, 6, and 3 G/cm, respectively, followed by an additional 3 ms delay and a composite 90° read pulse. Carbon decoupling was applied during the selective proton pulses using Waltz-16 decoupling. Using this sequence and applying shifted laminar pulses,[15] both solvent resonances (acetonitrile at 2.4 ppm and water at 4.4 ppm) could be suppressed simultaneously using only one rf channel and keeping phase coherence with the transmitter.

Scheme 1. Pulse Sequence Used for the HPLC/NMR Experiment



After leaving the UV detector, the eluate is directly introduced into the NMR cell via capillary tubing. Since a series of free induction decays (FID) was collected, a Fourier transformation via the acquisition times and a combination of the spectra could be carried out with the two-dimensional NMR software. As a result of the on-line HPLC/NMR experiment, a contour plot of ^{1}H chemical shift vs retention time can be generated (see Figure 2). Different from previous investigations, where the solvent suppression techniques are not as efficient as in the present case, the obtainable structural information relates to the entire chemical shift region. Residual signals of the eluent are obtained at 2.1–2.6 and 1.4 ppm due to acetonitrile and its impurities. From the contour plot, four different elution peaks can clearly be identified. The peaks exhibit NMR signals at about 3.8 ppm, which can be attributed to the protons of $-CH_2O-$groups. Accordingly, it can be assumed that all four elution peaks are due to ethylene oxide oligomers (repeat unit $-CH_2CH_2O-$).

The remarkable feature of the present investigation is that even the low-concentration components in peaks 1–3 can clearly be identified in the contour plot. Different from HPLC of organic compounds where usually very sharp elution peaks are obtained, in polymer chemistry broad elution peaks appear due to the effect of the molar mass distribution. As a result, peak intensity at each point of the chromatogram is rather low, making it difficult to detect these peaks. However, as can be seen from Figure 2, the present NMR detection method is sufficiently sensitive to detect even very small peaks.

Much more detailed structural information can be obtained from the individual NMR spectra of the frac-

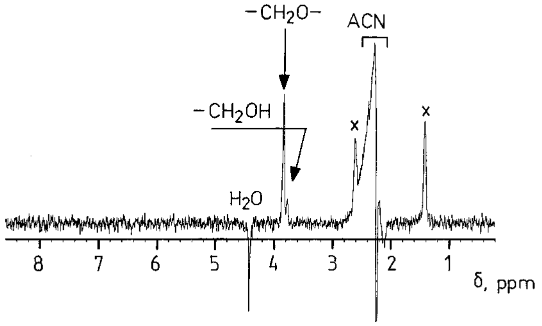


Figure 3. ^{1}H-NMR spectrum of fraction 1, taken at peak maximum. ACN indicates signal of acetonitrile; *x* indicates impurities.

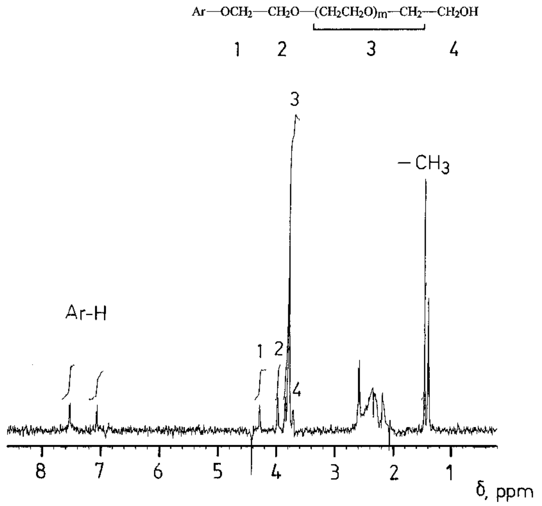


Figure 4. ^{1}H-NMR spectrum of fraction 2, taken at peak maximum.

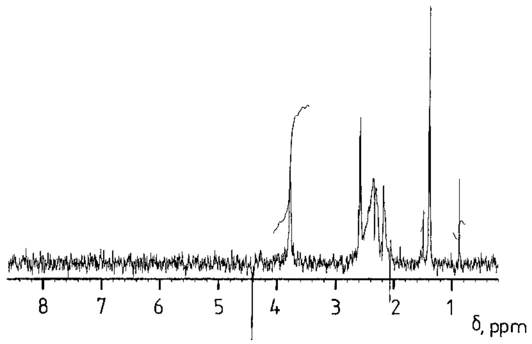


Figure 5. ^{1}H-NMR spectrum of fraction 3, taken at peak maximum.

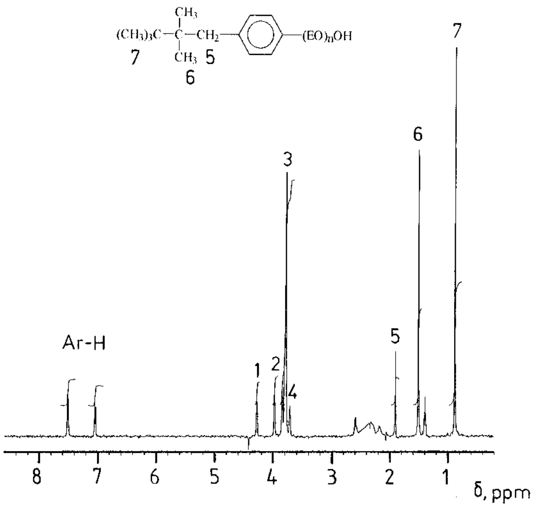
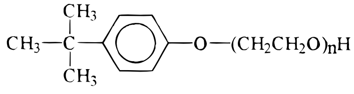


Figure 6. ^{1}H-NMR spectrum of fraction 4, taken at peak maximum. Numbers indicate chemical structures given in the formulas of Figures 4 and 6.

tions at the peak maximum. Figure 3 shows the spectrum of the first fraction, eluting at a retention time of 1.33 min. Since this fraction is present in the sample only in minor amounts, the spectrum is noisy and the most intense peaks are due to the mobile phase. Nevertheless, signals for the sample fraction are obtained at 3.80 and 3.73 ppm. These signals are characteristic for ethylene oxide units in the middle and at the end of the polymer chain. Since further signals are not obtained in the spectrum, it can be assumed that the first fraction is poly(ethylene glycol) (PEG). PEG is well known to be present in technical poly(ethylene oxide)s as an unwanted byproduct. The fact that the first fraction elutes in the vicinity of the injection peak further supports this assumption.

The NMR spectrum of the second fraction eluting at about 5.1 min shows much more intense sample signals (see Figure 4). These signals are much stronger than the solvent signals and can be readily identified and quantified. In addition to the signals of the PEO chain and chain end at 3.80 and 3.73 ppm, signals are obtained in the region of the aromatic protons (7–8 ppm) and methyl protons (~1.5 ppm). The aromatic protons appear as two doublets at 7.05 and 7.53 ppm and indicate a symmetric disubstituted aromatic end group. The methyl group signal surprisingly is a singlet. This means that the methyl groups must be bound to a quaternary carbon. The presence of an aromatic end group gives rise to signals at 4.00 and 4.28 ppm, which obviously relate to the ethylene oxide unit bound to the aromatic system.

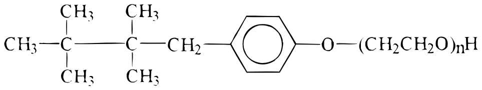
The integration of the different signals yields a quantitative picture of the chemical structure of fraction 2. The relative abundancies of the aromatic protons and the protons of signals 1, 2, and 4 are equal. Each of these signals is equivalent to two protons. The signal of the methyl group is equivalent to nine protons, and signal 3 of the PEO chain is equivalent to 18 protons. The relative proton abundancies suggest the following structure of fraction 2:



The degree of polymerization *n* can be calculated from the intensities of signals 3 and 4. For fraction 2, $n = 6$ is obtained.

The NMR spectrum of fraction 3, eluting at about 7.8 min, is given in Figure 5. Due to low concentration, a noisy spectrum is obtained, where the solvent peaks appear very strongly. This fraction also relates to PEO and shows the characteristic signals at 3.80 and 3.73 ppm. Further signals appear at about 0.9 and 1.45 ppm, indicating methyl groups; in the region of the aromatic protons signals could not be detected. The signals in the spectrum would correspond to an alkyloxy-terminated PEO; however, due to the poor quality of the spectrum, an interpretation is questionable.

For fraction 4, the major fraction of the sample, an excellent spectrum is obtained, which compares to conventional off-line measurements (see Figure 6). The structural features can be easily identified and suggest the chemical structure of an isooctylphenoxy-PEO. The degree of polymerization is calculated to be $n = 5.5$.



Based on the total intensity distribution, a calculated chromatogram (or chemigram) can be generated from the NMR contour plot. Comparing the real chromatogram (Figure 1) with the chemigram (Figure 2), an excellent agreement is obtained.

Conclusion

On-line HPLC/NMR offers unique opportunities for analyzing complex polymer systems. Using a selective chromatographic technique, the sample can be separated according to chemical structure. The structural analysis with respect to the polymer chain and the end groups can then be conducted by on-line ^{1}H-NMR. Using a high-resolution spectrometer, it is possible to work under experimental conditions which are common in liquid chromatography of polymers.

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