Chiroptical study and conformation analysis of helical polymers surrounded by helical hydrogen-bonding strands

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Abstract

The chiroptical properties of poly((S)-N-(3-butynyl)-3-methylpentanamide) (poly(1)) were studied, and the conformation was analyzed. Poly(1) exhibited a large specific rotation and Cotton effect in CHCl₃, indicating that it took a helical structure with predominantly one-handed screw sense. From liquid state IR spectroscopic analysis along with molecular mechanics and semiempirical molecular orbital calculations, it was concluded that the helix was stabilized by intramolecular hydrogen-bonding strands between the amide groups of nth and (n+3)th units.

Keywords: Helix; Polyacetylene; Hydrogen bonding; Conformation analysis

1. Introduction

Synthesis of helical polymers has attracted much attention. It possibly leads to understanding the elaborated structures and functions of naturally occurring well-ordered helical biopolymers such as peptide and DNA. Several helical polymers have been successfully synthesized, which include poly(alkyl methacrylates) [1], polychloral [2], polyisocyanates [3], polyisocyanides [4], polysilanes [5], and polyacetylenes [6]. These synthetic helical polymers show unique properties like chiral recognition and separation of asymmetric molecules, based on the chiral higher order structures. Steric repulsion between the side chains is the essential factor for these polymers to take helical structures. Poly(N-propargylamides) with suitable chiral substituents form helix [7]. They effectively utilize hydrogen bonding as well as steric repulsion to stabilize the helix similarly to peptide. It is considered that poly(N-propargylamides) form hydrogen-bonding strands between the amide groups of the nth and (n+2)th units, and the dihedral angle at the single bond in the main chain is 130–140° [8]. This biomimetic way of helix formation may develop a new methodology of designing synthetic helical polymers. We have incorporated a wide variety of pendant groups into poly(N-propargylamides) including linear and branched alkyl groups [9], aryl groups [10], hydroxyl groups [11], carboxyl groups [12], cyclics [13], esters [14], photo-responsive [15] and photoluminescent groups [16] to find that the stability and sense of the helical structure are tunable with external stimuli such as polar solvents, pH, heat and light. In the course of our study on a series of poly(N-propargylamides), we have examined the chiroptical properties of poly(N-(3-butylnyl)amide), an analog of poly(N-propargylamide), to find it exhibits a completely different CD spectroscopic pattern from that of poly(N-propargylamide) [17]. This article deals with chiroptical properties of poly(N-(3-butylnyl)amide), and examination of the conformation by molecular mechanics and semiempirical molecular orbital calculations.

2. Experimental procedure

2.1. Materials

The acetylene monomer, (S)-N-(3-butylnyl)-3-methylpentanamide (1) was synthesized by the condensation of
3-butynylamine with (S)-3-methylpentanoic acid, and polymerized according to the literature [17]. The polymerization of 1 with (nbd)Rh\[^{+}\][C\(_6\)H\(_5\)B(C\(_6\)H\(_5\))\(_3\)] (1 mol\%) in CHCl\(_3\) (initial concentration of 1: 1 M) at 30 °C for 24 h gave a polymer in 85% yield, whose \(M_n\) and \(M_w/M_n\) were 14,000 and 1.53, respectively. The polymer structure was identified to be poly(1) in Scheme 1 by \(^1\)H NMR spectroscopy. The cis content of the main chain was quantitative. Specific rotation of poly(1): +268° (CHCl\(_3\), \(c = 0.0425\) g/dL, room temperature); specific rotation of 1: +4.75° (CHCl\(_3\), \(c = 0.198\) g/dL, room temperature).

2.2. Measurements

\(^1\)H NMR spectra were recorded on a JEOL EX-400 spectrometer. IR spectra were measured using a Shimadzu FTIR-8100 spectrophotometer. Specific rotations ([\(\alpha\])\()_D\) were measured on a JASCO DIP-100 digital polarimeter with a sodium lamp as a light source. The number- and weight-average molecular weights (\(M_n\) and \(M_w\)) of polymers were determined by gel permeation chromatography (GPC) on a JASCO Gulliver system (PU-980, CO-965, RI-930, and UV-1570) equipped with polystyrene gel columns (Shodex columns K804, K805, and J806), using CHCl\(_3\) as an eluent at a flow rate of 1.0 mL/min, calibrated by polystyrene standards at 40 °C. CD and UV-vis spectra were measured in a quartz cell (thickness: 1 cm) at room temperature using a JASCO J-820 spectropolarimeter.

2.3. Molecular mechanics and semiempirical molecular orbital calculations

Molecular mechanics calculation was carried out by MMFF94, using Wavefunction Inc., Spartan ‘04 Windows version 1.0.3. Semiempirical molecular orbital calculation

![Scheme 1. Polymerization of (S)-\(N\)-(3-butynyl)-3-methylpentanamide (1).](image)
was carried out by INDO/S, using Fujitsu Ltd., MOS-F version 4.2.

3. Results and discussion

Fig. 1(A) depicts the CD and UV-vis spectra of poly(1) along with those of poly((S)-N-propargyl-2-methylbutanamide) measured in CHCl₃. Poly(1) exhibited an intense CD signal ([θ] = 50,000 deg cm² dmol⁻¹) based on the conjugated main chain at 310 nm. The Cotton effect of poly(1) disappeared by the addition of methanol as shown in Fig. 1(B). From these chiroptical properties, it is considered that poly(1) takes a helical structure in CHCl₃, and it is sensitive to methanol.

The IR spectra of I and poly(1) were measured in CHCl₃ under diluted conditions (c = 50 mmol/L). As shown in Fig. 2, the IR absorption peaks of νC=O and δN–H of poly(1) were observed at 37 and 25 cm⁻¹ lower and higher wavenumber regions than those of I, respectively. On the basis of this as well as the finding that the νC=O and δN–H of poly(1) were constant irrespective of the concentration, it is concluded that the amide groups form hydrogen bonding intramolecularly. Thus, we can say that poly(1) forms a helix stabilized by intramolecular hydrogen bonding between the amide groups in the side chain. This is also supported by the effect of methanol addition on the Cotton effect as depicted in Fig. 1(B).

It is noteworthy that poly(1) exhibits the Cotton effect at 310 nm, which is as much as 80 nm shorter than the wavelength poly(N-propargylamides) do. Poly(1) should take a quite different helical conformation from that of poly(N-propargylamides). Prior to the conformation analysis of poly(1), we constructed molecular models of a 20-mer of achiral N-(3-butynyl)acetamide (Fig. 3, R = CH₃) as the model system. The dihedral angle at the double bond in the main chain of the 20-mer of N-(3-butynyl)acetamide (R = CH₃) and the energy calculated by MMFF94.

![Fig. 3. Hydrogen bonding between the amide groups in side chains of poly(N-(3-butynyl)acetamide), and the relationships between the dihedral angle \(\phi\) at the single bond in the main chain of the 20-mer of N-(3-butynyl)acetamide (R = CH₃) and the energy calculated by MMFF94.](image)

The initial geometries

Fig. 2. IR spectra of I and poly(1) measured in CHCl₃ (c = 50 mmol/L).
were constructed to form intramolecular hydrogen bonding between the amide groups in the side chains [19]. Hydrogen bonding was possibly formed between \( n \)th and \( (n+2) \)th units, and also \( n \)th and \( (n+3) \)th as illustrated in Fig. 3. The conformer with \( \phi = 130^\circ \) was the most stable when hydrogen bonding was formed between \( n \)th and \( (n+2) \)th units. On the other hand, the conformer with \( \phi = 70^\circ \) was the most stable when hydrogen bonding was formed between \( n \)th and \( (n+3) \)th units. The latter one was 64 kcal/mol more stable than the former. This can be explained by the balance between the strength of hydrogen bonding and steric factor. As shown in Fig. 4, the average interatomic distance \( d_{\text{H-O}} \) between the amide hydrogen atom in \( n \)th unit and the amide carbonyl oxygen atom in \( (n+2) \)th unit becomes longer with decreasing \( \phi \), while \( d_{\text{H-O}} \) between \( n \)th and \( (n+3) \)th units becomes longer with increasing \( \phi \). The shorter \( d_{\text{H-O}} \) is, the stronger and energetically more favorable the hydrogen bonding becomes. However, the distance between the alkyl groups also becomes smaller, resulting in the increase of steric repulsion. Due to these conflicting factors, the 20-mer exhibits energy minima at 130° \( (d_{\text{H-O}} = 1.86 \text{ Å}) \) and 70° \( (d_{\text{H-O}} = 1.72 \text{ Å}) \) when hydrogen bonding is formed between \( n \)th and \( (n+2) \)th units, and \( n \)th and \( (n+3) \)th units, respectively. It is considered that the energy difference between the two conformers is mainly caused by the difference in \( d_{\text{H-O}} \).

From the results described above, we can conclude that the most stable helical conformer of the 20-mer of \( N-(3\text{-butynyl})\text{-acetamide} \) is the one with \( \phi = 70^\circ \) forming...
hydrogen bonding between the amide groups in \( n \)th and \((n + 3)\)th units. We next substituted the methyl group of the most stable conformer into optically active 2-methylbutyl group to elucidate the conformation of poly(1). In this case, the conformers with right- and left-handed helical main chains are diastereomers because the side chains have chiral centers. The energies of the conformers with \( \phi = +70^\circ \) (right-handed helix) and \( \phi = -70^\circ \) (left-handed helix) were \(-247\) and \(-250\) kcal/mol, and the average lengths of hydrogen bonding of these two conformers were 1.733 and 1.711 A, respectively. The left-handed helical conformer can form hydrogen bonding more favorably than the right-handed counterpart, presumably due to the balance between the steric restriction around the chiral centers and the helical sense. Fig. 5 illustrates the conformer of the 20-mer of 1, which is considered to be the most stable. Three helical hydrogen-bonding strands and alkyl chain strands surround the helical polyacetylene main chain.

We further performed the INDO/S calculation of the conformer depicted in Fig. 5 to estimate the molecular orbital levels at ground and excited states. The \( \lambda_{\text{max}} \) of UV-vis absorption of the 20-mer of 1 was assumed to be 240 nm. On the other hand, the \( \lambda_{\text{max}} \) of a 20-mer of \( N \)-propargylacetamide with \( \phi = 130^\circ \) accompanying hydrogen-bonding strands between the amide units in \( n \)th and \((n + 2)\)th units was estimated to be 319 nm. The difference of predicted \( \lambda_{\text{max}} \) between poly(1) and poly(\( N \)-propargylamide) was 79 nm, which well agreed with the observed value (80 nm). It has been reported that the \( \lambda_{\text{max}} \) of conjugated compounds predicted by the INDO/S calculation tends to be shorter than the experimental value as shown in Fig. 6(A) [20]. The difference between the predicted and observed \( \lambda_{\text{max}} \) of polyacetylenes reaches 30–40 nm at the degree of polymerization is 20. The predicted \( \lambda_{\text{max}} \) of \( cis \) polyacetylenes with \( \phi = 70^\circ \) and 130° becomes saturated around the polymerization degree is 20 (Fig. 6(B)). Judging from the degree of polymerization of poly(1) (87, estimated from the \( M_n \)), the calculation seems to predict the \( \lambda_{\text{max}} \) of poly(1) reasonably.

4. Conclusion

We have analyzed the conformation of an optically active poly(\( N \)-(3-butynyl)amide), poly(1) based on the chiroptical properties, molecular mechanics, and semiempirical molecular orbital calculations. Poly(1) exhibited a large specific rotation and an apparent Cotton effect at 310 nm. It was considered that poly(1) took a left-handed helix stabilized with triple helical hydrogen-bonding strands formed at the amide groups in the side chain between \( n \)th and \((n + 3)\)th units. The dihedral angle \( \phi \) at the single bond in the main chain was estimated to be \(+70^\circ\). The way of formation of helical structure is very unique, and it is expected to become one basis for designing synthetic helical polymers.

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