NMR Studies of Poly(2-Hydroxy Ethyl Methacrylate-*co*-2-Vinyl Pyridine)

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ABSTRACT: Copolymers of 2-hydroxy ethyl methacrylate-2-vinyl pyridine (H/V) of different composition were synthesized by free radical bulk polymerization using azobisisobutyronitrile (AIBN) as an initiator under nitrogen atmosphere. The copolymer compositions were calculated from ^{1}H NMR spectra. The reactivity ratios for H/V copolymers obtained from a linear Kelen-Tudos method (KT) and nonlinear error-in-variables method (EVM) are r_H = 0.50 ± 0.10, r_V = 1.04 ± 0.08 and r_H = 0.55, r_V = 1.06 respectively. The complete spectral assignment of methine, methylene, methyl, carbonyl, and aromatic carbon regions in term of compositional and configurational sequences of H/V copolymers were done with the help of ^{13}C{^{1}H} NMR, distortionless enhancement by polarization transfer (DEPT), two-dimensional heteronuclear single quantum coherence (HSQC) along with total correlated spectroscopy (TOCSY). © 2008 Wiley Periodicals, Inc. J Appl Polym Sci 109: 1114–1121, 2008

Key words: 2-hydroxy ethyl methacrylate; 2-vinyl pyridine; copolymerization; microstructure; NMR; configuration

INTRODUCTION

The high resolution NMR spectroscopy[1–4] is the most versatile, reliable, and generally acceptable technique for the determination of microstructure of polymers. Copolymers based on 2-hydroxy ethyl methacrylate have found wide application in contact lenses, surgery, and clinical medicine because of their ability to form biocompatible hydrogels with excellent tolerance and good stability.[5–10] Copolymerization of 2-hydroxy ethyl methacrylate with vinyl pyridine may be of practical interest as these copolymers are widely utilized in ophthalmic industry, as a controlled drug release matrix, as nonthrombogenic materials and surgical prostheses etc.[11–14] Various coworkers have reported the controlled polymerization of poly (2-hydroxy ethyl methacrylate) (PHEMA) by atom transfer radical polymerization.[15–17] The sequence distribution in 4-vinyl pyridine copolymers with methyl acrylate and acrylonitrile have been well reported earlier.[18–20] To the best of our knowledge, the microstructure of 2-hydroxy ethyl methacrylate and 2-vinyl pyridine (H/V) copolymers has not been reported so far. In this manuscript, we report the microstructure of 2-hydroxy ethyl methacrylate-2-vinyl pyridine (H/V) copolymers. The reactivity ratio of comonomers were calculated using a linear Kelen-Tudos method,[21] and nonlinear least square error-in-variables method.[22] The complete assignment of ^{1}H and ^{13}C{^{1}H} NMR spectra of 2-hydroxy ethyl methacrylate and 2-vinyl pyridine (H/V) copolymers were done with the help of DEPT and 2D (HSQC and TOCSY) NMR experiments.

EXPERIMENTAL

2-hydroxy ethyl methacrylate and 2-vinyl pyridine (H/V) monomers were distilled under reduced pressure and stored below 5°C. A series of H/V copolymers of different composition were synthesized by bulk polymerization using AIBN as an initiator at 80°C under nitrogen atmosphere. The percent conversion was kept below 10% by precipitating the copolymers in hexane. The copolymers were further purified using methanol/hexane for higher composition of H-unit and chloroform/hexane for lower composition of H-unit in copolymer. All NMR spectra were recorded on Bruker DPX-300 spectrometer in DMSO-d_6 at 80°C. The details of recording NMR spectra have been explained elsewhere.[23]

RESULTS AND DISCUSSION

Reactivity ratios determination

The composition of H/V copolymers was determined from completely assigned one-dimensional

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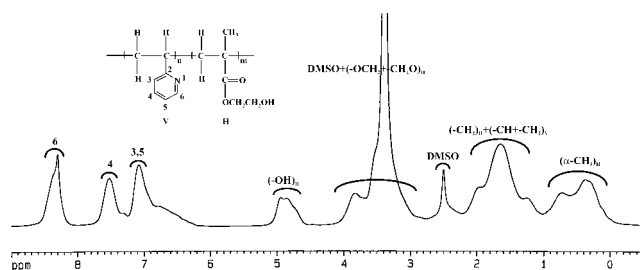
Figure 1 The ^{1}H-NMR spectrum of H/V copolymer (F_H = 0.44) in DMSO-d_6 at 80°C.

^{1}H-NMR spectrum (Fig. 1). The intensity of —OH proton of H-unit and aromatic H^6 proton of V-unit were used for determination of copolymers composition as given in following equation:

$$F_H = \frac{I(OH)_H}{I(OH)_H + I(H^6)_v}$$

where, F_H represents the composition of H-unit in the copolymer while $I(OH)_H$ represents the intensity of —OH proton of H-unit and $I(H^6)_V$ represents the intensity of aromatic hydrogen (H^6) of V-unit. Table I shows the copolymer composition data of H/V copolymer. According to Kelen-Tudos (KT) method, the terminal model reactivity ratios were calculated using the copolymer composition data. The reactivity ratios from error in variable method (EVM) were calculated using the reactivity ratio values obtained from KT method along with copolymer composition data. The values of reactivity ratios obtained from Kelen-Tudos (KT)[21] and nonlinear error in variable methods (EVM)[22] are r_H = 0.50 ± 0.10, r_V = 1.04 ± 0.08 and r_H = 0.55, r_V = 1.06 respectively. The reported values[24] of reactivity ratios for H/V copolymers are r_H = 0.53, r_V = 1.14, the difference in two values is due to different experimental conditions.

^{13}C{^{1}H} NMR studies

The ^{13}C{^{1}H} NMR spectrum of 2-hydroxy ethyl methacrylate-*co*-2-vinyl pyridine (H/V) (F_H = 0.44) copolymer in DMSO-d_6 at 80°C is shown in Figure 2(a). The signal around δ 16.50–21.50 ppm is due to α-CH$_3$ carbon resonances of H-unit in the copolymer. The resonance signal around δ 36.5–52.5 ppm is assigned to the overlap of methylene carbon of both H- and V-unit, methine carbon of V-unit and quaternary carbon of H-unit in H/V copolymer. The overlap of β methylene and methine carbon resonance signals was resolved completely by DEPT-135 NMR spectrum [Fig. 2(b)]. The carbonyl carbon signal of H-unit of H/V copolymer is assigned around δ 175.0–178.0 ppm, whereas the signals around δ 58.60 and δ 65.50 ppm are assigned to (—CH$_2$O)$_H$ and (—OCH$_2$)$_H$ carbons of

H-unit respectively. The resonance signals around δ164.0, δ 148.76, δ 136.0, δ 123.60, and δ 121.30 ppm are assigned to C-2, C-6, C-4, C-3, and C-5 aromatic carbons of V-unit respectively. The stereochemical configurational assignment of various carbon resonance signals was done completely on the basis of shielding and deshielding of various carbon resonances because of dipole–dipole interaction between carbonyl and hydroxyl groups.

The expanded α-methyl carbon region of H-unit of H/V copolymers along with poly(2-hydroxy ethyl methacrylate) are shown in Figure 3(a–d). Although the splitting pattern of α-CH$_3$ carbon resonances seem to be well separated but spread over a wide range of chemical shifts due to tacticity effects in the spectrum of poly(2-hydroxy ethyl methacrylate).[25] The rr fraction in PHEMA is less than that in PMMA due to dipole–dipole interaction in PHEMA. The multiplet in methyl carbon region of H-unit of the copolymer is assigned to both the compositional and configurational sequences. The assignment to various signals has been carried out with the help of spectrum of poly(2-hydroxy ethyl methacrylate) and by observing change in intensity of signals with change in composition of copolymers. The resonance signal at δ 16.20 ppm is assigned to HrHrH triad on comparison with spectrum of poly(2-hydroxy ethyl methacrylate). The intensity of signal at δ 18.10 ppm increases with increase in composition of 2-vinyl pyridine in comparison to PHEMA, so this resonance signal is assigned to the overlap of HrHrV and HrHmH triads. The signals around δ 19.50–21.70 ppm appeared on further increasing the concentration of V-unit in the copolymer and its intensity increases with increase in concentration of V-unit. So this signal was assigned to the overlap of HrHmV/HmHrV, HmHmH, VHV, and HmHmV triads respectively.

The carbonyl carbon resonance signals of H-unit in copolymer of different composition along with poly(2-hydroxy ethyl methacrylate) are shown in Figure 4. The various resonance signals in carbonyl carbon region have been assigned on the basis of variation in intensity of signals with copolymer composition and on comparison with spectrum of poly(2-hydroxy ethyl

TABLE I
Copolymer Composition Data of H/V Copolymers

S.No.	Sample no.	f_H	F_H
1	HV$_1$	0.10	0.09
2	HV$_2$	0.20	0.18
3	HV$_3$	0.30	0.26
4	HV$_4$	0.40	0.35
5	HV$_5$	0.50	0.44
6	HV$_6$	0.80	0.69

f_H is the mole fraction of H co-monomer in feed and F_H is the mole fraction of H co-monomer in copolymer.
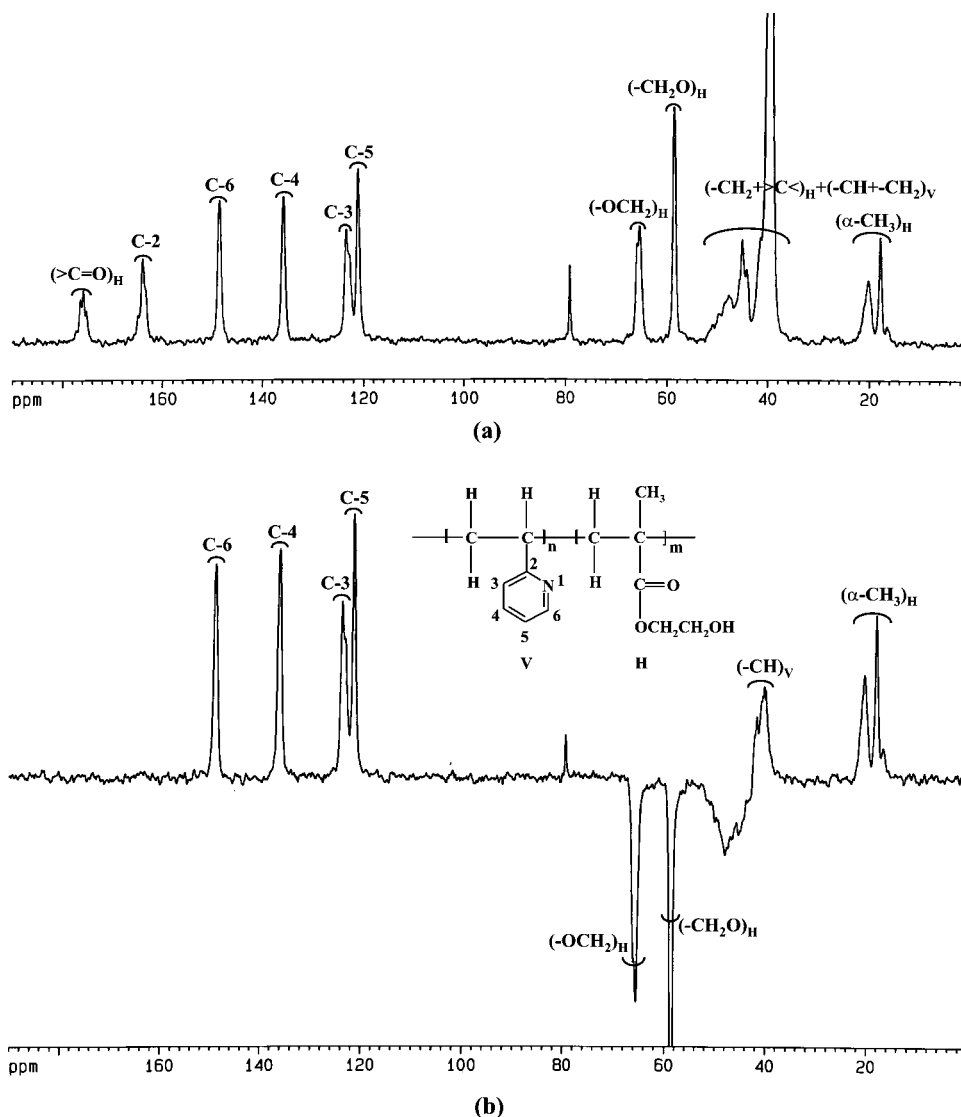
Figure 2 (a) The $^{13}C\{^1H\}$NMR (b) DEPT-135 NMR spectrum of H/V copolymer (F_H = 0.44) in DMSO-d_6 at 80°C.

methacrylate). The signal at δ 177.40 ppm was assigned to HrHrH triad. On the basis of variation in intensity of signals with copolymer composition, the resonance signal at δ 176.50 and δ 175.85 ppm were assigned to the overlap of HmHrH+ HrHrV and HmHmH+HrHmV/HmHrV+VrHrV triads of H-monomer respectively. As the composition of V-unit in the copolymer increases the intensity of signal at δ 176.50 ppm decreases so it was assigned to HrHrV triads only in Figure 4(d). The signals at δ 175.25 and δ 175.00 ppm were assigned to VrHmV and VmHmV triads respectively.

2D HSQC AND TOCSY NMR STUDIES

Methylene carbon resonances

2D TOCSY spectrum was used to confirm the 1, 2 bond geminal couplings between nonequivalent pro-

tons of the same methylene group. Methylene proton resonance signals which were overlapped and could not be assigned by ^{1}H-NMR spectral analysis only were assigned from one-to-one correlation between carbon and proton signals in 2D HSQC spectra. The protons in the racemic methylene of VrV and HrH centered tetrads are in same environment, resulting in a single cross-peak in 2D HSQC spectra. The two nonequivalent methylene meso protons, Ha and Hb, of HH and VV-centered tetrads result in two cross-peaks in 2D HSQC spectra and a cross-correlation peak in 2D TOCSY spectra (Ha proton was attributed to the proton having lower chemical shift and Hb having higher chemical shift). Thus, 2D TOCSY spectra enabled to differentiate between the meso and racemic protons and confirm the 2D HSQC assignments.

The expanded β Methylene region in 2D HSQC spectra are given in Figure 5(a,b) and the assignments
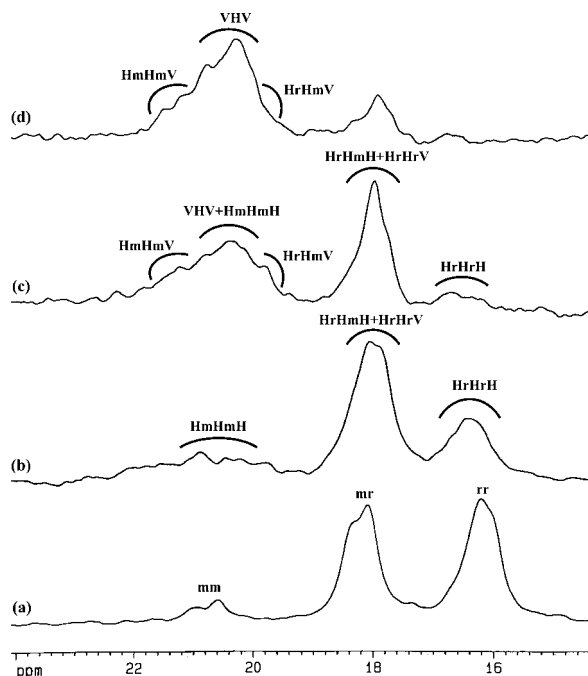
Figure 3 The expanded α-methyl region in $^{13}C\{^1H\}$ NMR spectrum of (a) PHEMA and H/V copolymers with compositions (F_H =), (b) 0.69, (c) 0.44, (d) 0.18 in DMSO-d_6 at 80°C.

are listed in Table II. The cross-peaks 1 and 3 were assigned to VmV(Ha) and VmV(Hb) diads, respectively, while, VrV diad was assigned to the cross-peak 2. Ha and Hb protons of VmV diads, being nonequivalent, resulted in cross-correlation peak 1' in 2D TOCSY spectrum in Figure 6(a). The methylene protons Ha and Hb of both VmH- and VrH-centered tetrads are in different magnetic environment, thus results in two cross-peaks by coupling with the methylene carbon in 2D HSQC spectra. VH diad concentration decreases with increase in composition of H-unit, on this basis VH diad was assigned. VmH(Ha) and VmH(Hb) diads were assigned to the cross-peaks 4 and 7 respectively, as marked in Figure 5. VrH(Ha) and VrH(Hb) diads were assigned to cross-peaks 5 and 6. HH centered diads also showed compositional and configurational sensitivity. HmH(Ha), HrH and HmH (Hb) diads have been assigned to cross-peaks 8, 9, and 10 respectively. In 2D TOCSY spectra the cross-peak 4' was assigned to the coupling of —OCH$_2$ proton of H-unit with —CH$_2$O protons of H-unit while the cross-peaks 5' and 6' were assigned to the coupling of —CH$_2$O and —OCH$_2$ protons with —OH proton of H-unit respectively, [Fig. 6(b)].

Methine carbon resonances

Methine group of 2-vinyl pyridine was assigned up to triad level of compositional sensitivity in the co-

polymer, based on 2D HSQC assignments. 2D TOCSY studies were used to ascertain these assignments by observing 1, 3 bond order couplings between methylene protons and methine proton of V-monomer in VV and VH centered diads. The cross-peak I is assigned to VVV triad while the cross-peaks II and III are assigned to VVH and HVH triads respectively, [Fig. 5(a,b)]. The chemical shifts of methine group on proton axis were in a very narrow range (1.69–2.38 ppm). The cross-correlation peaks 2' and 3' as shown in Figure 6(a), were assigned to the 1, 3 bond order couplings of —CH in VVV with —CH$_2$ of HrH, VrH, VrV, and —CH of V in HVH triad respectively, (Table III).

Methyl carbon resonances

The expanded α-CH$_3$ region of 2D HSQC NMR spectra of H/V copolymers shows the sensitivity toward compositional and configurational sequences (Fig. 7). The cross-peaks 1, 2, and 3 are assigned to HrHrH, HrHmH, and HmHmH triads respectively, while the cross-peaks 4, 5, and 6 are assigned to HrHrV, HrHmV/HmHrV, and HmHmV triads respectively. The cross-peak 7 is assigned to VHV triad. All the assignments are given in Table IV.

Aromatic region resonances

The expanded aromatic carbon region of 2D HSQC NMR spectra of H/V copolymer is shown in
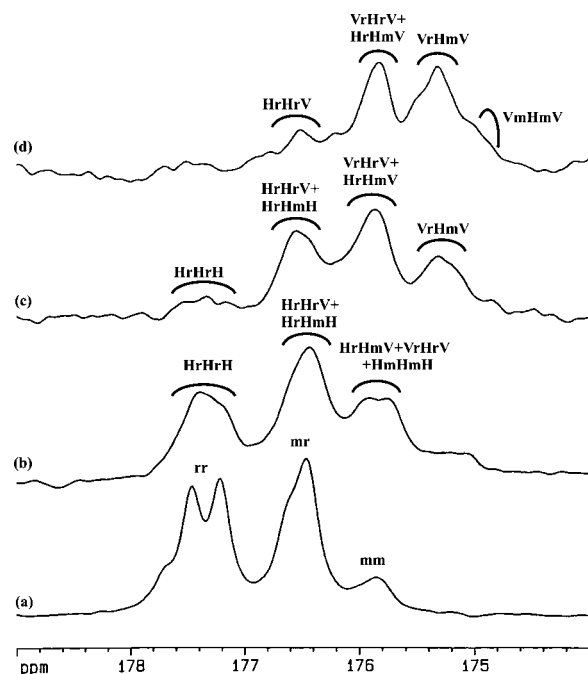
Figure 4 The expanded carbonyl carbon regions of (a) PHEMA and H/V copolymers with compositions (F_H =), (b) 0.69, (c) 0.44, (d) 0.18 in DMSO-d_6 at 80°C.
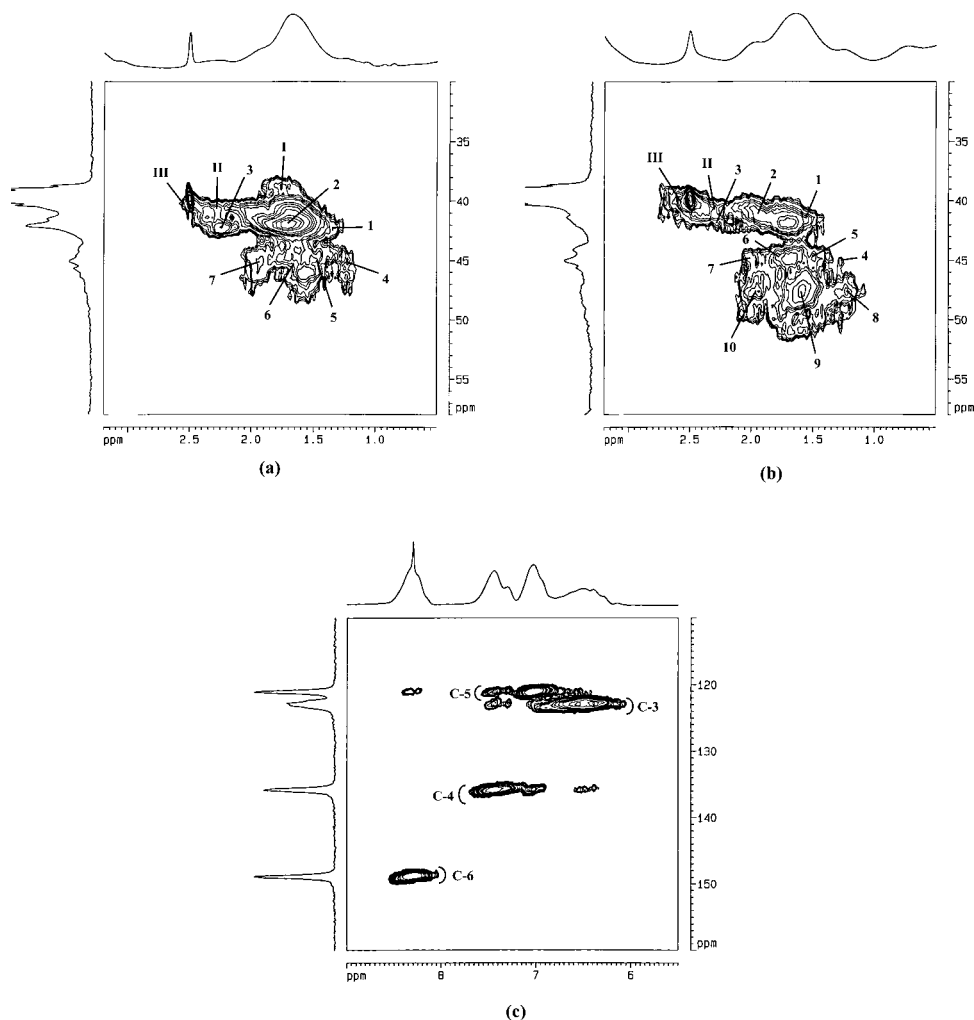
Figure 5 The expanded 2D HSQC spectra of H/V copolymers containing β-methylene, oxy methylene carbons region with composition (F_H =), (a) 0.18, (b) 0.69 and aromatic carbon region with composition (F_H =), (c) 0.18 in DMSO-d_6 at 80°C.

Figure 5(c). The aromatic protons of V-unit are in different environment, hence various types of geminal coupling are also observed in 2D TOCSY spectrum [Fig. 6(c,d)]. The cross-peak 7′ was assigned to 1, 4

coupling of aromatic proton H^5 with proton H^3 while the cross-peaks 8′ and 9′ were assigned to 1, 3 coupling of aromatic proton H^4 with H^3 and H^5 respectively. The cross-peaks 7′ and 8′were found to be sensitive up to triad configurational sequences. The coupling of aromatic proton H^5 with H^6 appeared at cross-peak 10′ while the cross-peak 11′ was assigned to 1, 4 coupling of H^4 with H^6 (Table V). The 1, 5 coupling of aromatic protons H^3 and H^6 appeared as cross-peak 12′, which was found to be sensitive up to triad compositional sequences. ^{1}H-NMR spectrum was analyzed completely with help of 2D HSQC and TOCSY spectra. The completely assigned ^{1}H-NMR spectrum of H/V copolymer is shown in Figure 1.

TABLE II
Assignment of β-Methylene Carbon Resonances of H/V Copolymers From 2D HSQC Spectra

| Cross-peak no	Cross-peak assignment	Peak position (2D HSQC; $^{13}C/^1H$; ppm)
1	VmV(Ha)	41.50/1.40
2	VrV	41.50/1.72
3	VmV(Hb)	41.50/2.20
4	HmV(Ha)	45.0/1.27
5	HrV (Ha)	45.0/1.50
6	HrV(Hb)	45.0/1.72
7	HmV(Hb)	45.0/1.98
8	HmH(Ha)	48.0/1.22
9	HrH	48.0/1.60
10	HmH(Hb)	48.0/1.95

CONCLUSIONS

The reactivity ratio of comonomers in H/V copolymers are $r_H = 0.50 \pm 0.10$, $r_V = 1.04 \pm 0.08$ and $r_H = 0.55$, $r_V = 1.06$ respectively. The complex and
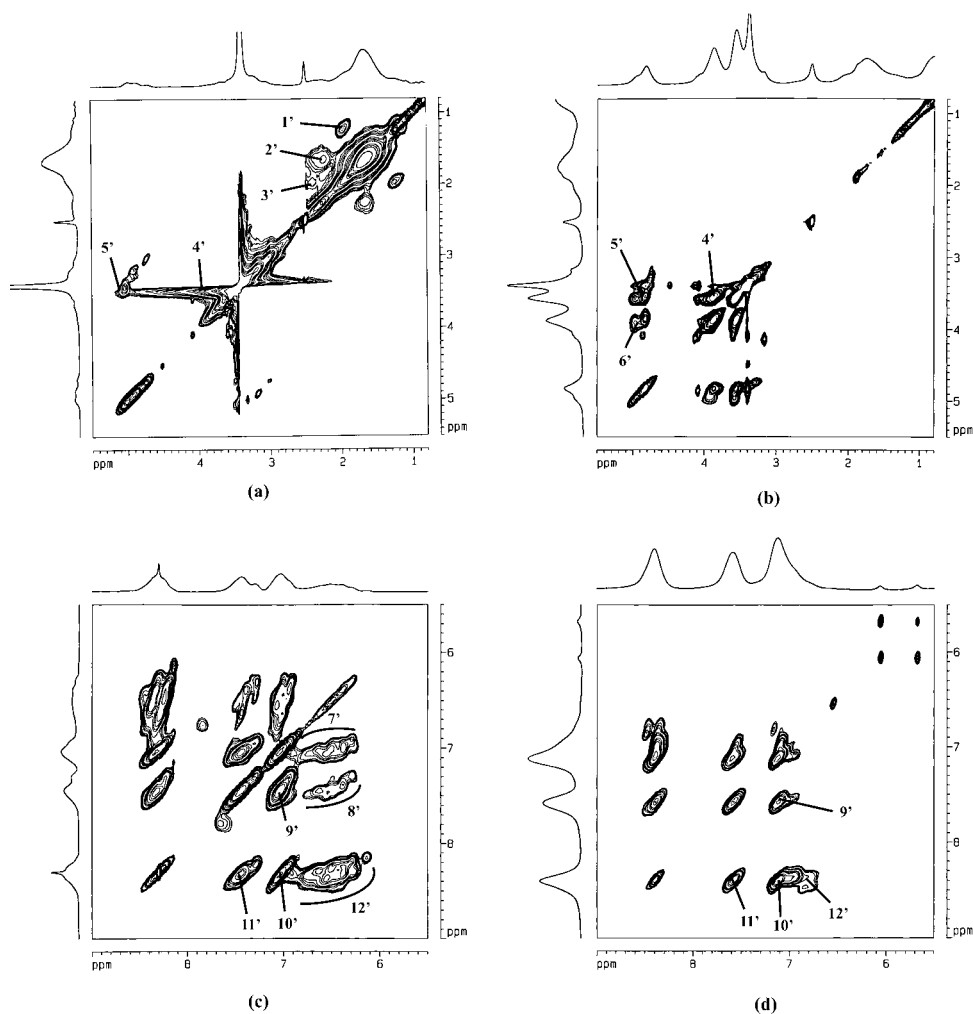
Figure 6 The 2D TOCSY (80 ms) spectra of H/V copolymer containing β-methylene, oxy methylene carbons with compositions (F_H =), (a) 0.18, b) 0.69 and aromatic carbon region with composition (F_H =), (c) 0.18, (d) 0.69 in DMSO-d_6 at 80°C.

TABLE III
^{1}H-^{1}H Cross-Correlation Between Nonequivalent Protons in H/V Copolymers Observed From 2D TOCSY Spectra

Correlation peak no.	Coupled protons		Peak position (2D TOCSY; ^{1}H/^{1}H; ppm)
	Proton I	Proton II	
1′	CH$_2$ of HmH(Ha)	CH$_2$ of HmH(Hb)	1.20/1.85
2′	CH$_2$ of VrV, HrV, HrH	CH of V in VVV	1.67/2.26
3′	CH of V in VVV	CH of V in HVH	1.95/2.35
4′	CH$_2$O of H	OCH$_2$ of H	3.56/3.85
5′	CH$_2$O of H	OH of H	3.56/4.85
6′	OCH$_2$ of H	OH of H	3.85/4.85
7′	Aromatic H^3 of V	Aromatic H^5 of V in VmVmV	6.25/6.92
		VmVrV	6.50/6.98
		VrVrV	6.70/7.02
8′	Aromatic H^3 of V	Aromatic H^4 of V in VmVmV	6.25/7.28
		VmVrV	6.50/7.40
		VrVrV	6.70/7.48
9′	Aromatic H^5 of V	Aromatic H^4 of V	7.05/7.50
10′	Aromatic H^5 of V	Aromatic H^6 of V	7.05/8.30
11′	Aromatic H^4 of V	Aromatic H^6 of V	7.45/8.30
12′	Aromatic H^3 of V	Aromatic H^6 of V in VVV	6.25/8.25
		VVH	6.50/8.30
		HVH	6.75/8.35
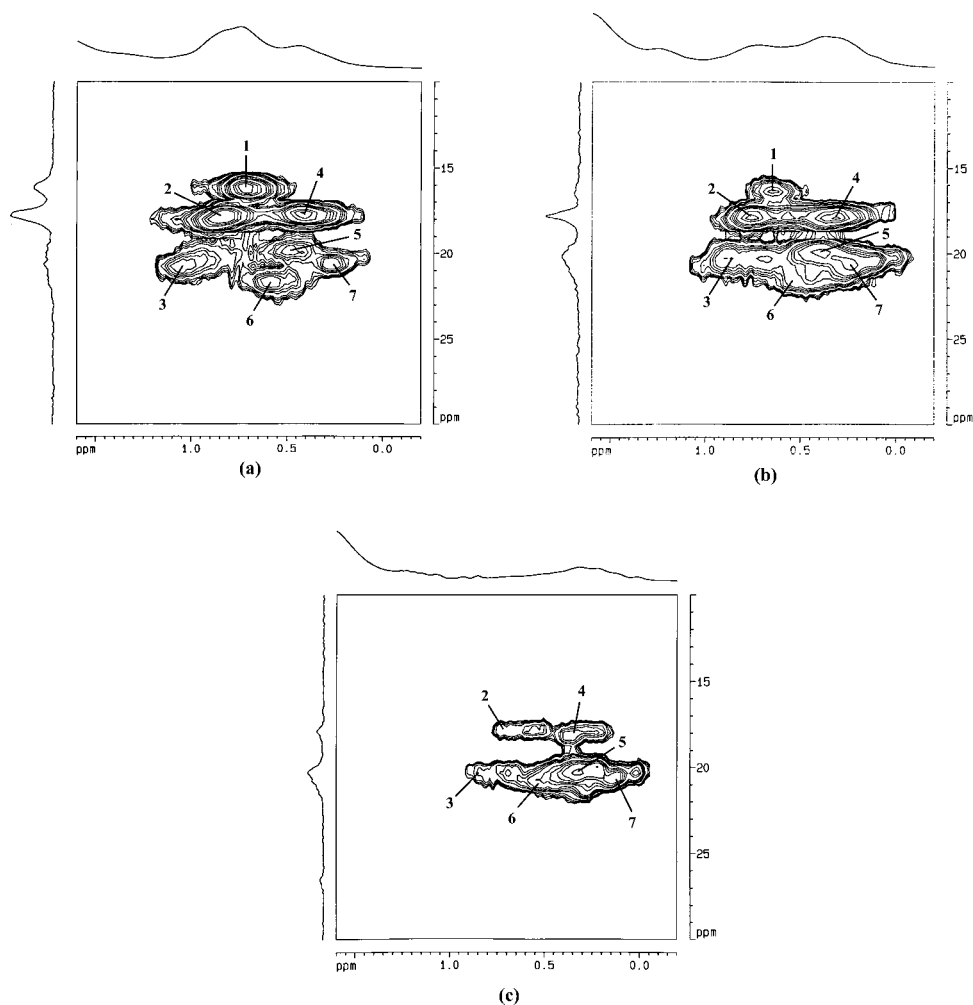
Figure 7 The expanded α-methyl carbon region of 2D HSQC spectra of H/V copolymers with compositions (F_H =), (a) 0.69, (b) 0.44, and (c) 0.18 in DMSO-d_6 at 80°C.

overlapped ^{1}H and ^{13}C$\{^1$H$\}$ NMR spectra of the copolymers were resolved with the help of DEPT and 2D HSQC spectra. The carbonyl and methyl carbons of H-units were assigned up to triad compositional and configurational sequences in ^{13}C$\{^1$H$\}$ NMR spectrum whereas β methylene carbon resonances were assigned up to diad compositional and configurational sequences. The methine carbon of V-unit was assigned up to triad compositional sequences. The geminal coupling within various aromatic protons of V-unit were observed in 2D TOCSY spectrum.

TABLE IV
Assignment of α-CH$_3$ Carbon Resonances of H/V Copolymers From ^{13}C$\{^1$H$\}$ NMR and 2D HSQC Spectra

Peak no.	Peak assignments	Peak position (2D HSQC; ^{13}C/^{1}H; ppm)
1	HrHrH	16.40/0.70
2	HrHmH	18.00/0.80
3	HmHmH	20.90/1.00
4	HrHrV	18.00/0.40
5	HrHmV/HmHrV	20.00/0.50
6	HmHmV	21.70/0.60
7	VHV	20.80/0.25

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