Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Mendeleev Commun., 2013, **23**, 279–281
Mendeleev Communications

Kinetics of radical copolymerization of methyl pheophorbide A with vinyl monomers and the properties of synthesized copolymers

Regina M. Islamova,[*a,b] **Svetlana V. Nazarova,**[a] **Tat'yana A. Ageeva**[c] **and Oscar I. Koifman**[c]

[a] *Institute of Organic Chemistry, Ufa Scientific Centre of the Russian Academy of Sciences, 450054 Ufa, Russian Federation. Fax: +7 347 235 6066; e-mail: rmislamova@mail.ru*
[b] *Department of Chemistry, St. Petersburg State University, 198504 St. Petersburg, Russian Federation*
[c] *Institute of Macroheterocyclic Compounds, Ivanovo State University of Chemistry and Technology, 153000 Ivanovo, Russian Federation*

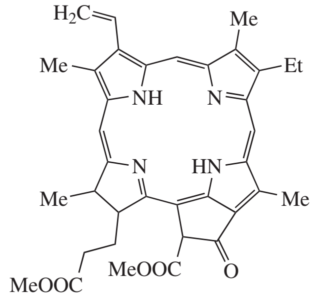
DOI: 10.1016/j.mencom.2013.09.014

The radical copolymerization of methyl pheophorbide A with styrene or methyl methacrylate in bulk or in benzene solution initiated by azobisisobutyronitrile at 60–90 °C was performed and kinetically characterized.

Porphyrins and their derivatives are of interest as new materials for use in microelectronics, biotechnology, *etc.*[1–6] Effective methods for the preparation of polymer macromolecules having macrocycles in the backbone or in side chains have been developed based on the radical homopolymerization of macrocycle-containing monomers or their copolymerization with other monomers.[7–10] However, the bulky porphyrin macrocycle produces steric hindrance for the homopolymerization of vinyl porphyrin derivatives and, in some cases, completely precludes the process.[11]

The aim of this work was to study the radical copolymerization of methyl pheophorbide A (MPP) with styrene or methyl methacrylate (MMA) initiated by azobisisobutyronitrile (AIBN) at 60–90 °C and to characterize the copolymers.[†]

Note that the solubility of MPP in organic media is low; thus, in the case of bulk copolymerization, the highest concentration of MPP in the initial mixture was 0.1 mol%. The copolymerization in benzene solution allowed us to increase the initial concentration of MPP up to 1.0 mol%.



Methyl pheophorbide A

The overall rates of bulk copolymerizations of MPP with styrene or MMA at 60–90 °C are lower than the rate of homopolymerization of styrene or MMA (Figure 1). The copolymerization of MPP–MMA proceeds up to a high conversion with a gel effect, while the copolymerization of MPP–styrene decelerates dramatically.

The overall rates of MPP–styrene and MPP–MMA copolymerization in benzene solutions were found to decrease in comparison with the rate of homopolymerization of styrene or MMA.[‡]

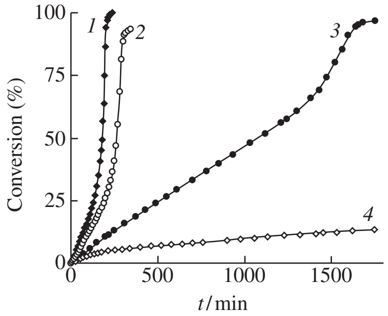


Figure 1 Conversion *vs.* (*1*) MMA homopolymerization time, (*2*) MPP–MMA copolymerization time, (*3*) styrene homopolymerization time and (*4*) MPP–styrene copolymerization time. MPP concentration: (*1*), (*3*) 0 or (*2*), (*4*) 0.1 mol%. [AIBN] = (*1*), (*2*) 5.0 or (*3*), (*4*) 10.0 mmol dm^{-3}. T_{copm} = = 60 °C; copolymerization in bulk.

[†] MMA (Fluka) and styrene (Fluka) were twice distilled before use at a reduced pressure [bp 42 °C (120 Torr) and 66 °C (40 Torr), respectively]. AIBN was recrystallized three times from ethanol and dried at room temperature in a vacuum to constant weight. Purity of substances was controlled by $^{13}C\{^1H\}$ NMR spectroscopy.

MPP was prepared by extraction from spirulina algae in accordance with a published procedure.[12] The product was purified by chromatography on a silica gel column using a CH_2Cl_2–Et_2O mixture as an eluent.

The kinetics of bulk copolymerizations of MPP–styrene and MPP–MMA was studied by dilatometry. The copolymerization of MPP–styrene and MPP–MMA in benzene solutions was performed in glass ampoules after degassing the reaction mixture at a liquid nitrogen temperature by three freeze–thaw cycles to a residual pressure of 1.3 Pa. The reaction was performed at 60–90 °C (±0.1 °C). The resulting copolymer was dissolved in benzene or acetone and precipitated with a 10- to 15-fold excess of methanol. The samples were purified from the remaining initiator and unreacted comonomers by three reprecipitations followed by at least 15–20 cycles of washing in a Soxhlet apparatus. The product was dried to constant weight and analyzed.

The weight average M_w and the number average M_n molecular weights of the copolymers were determined using gel permeation chromatography on a Waters GPC 2000 System liquid chromatograph (eluent, THF; flow rate, 1.0 ml min^{-1}). The system of columns was calibrated against polystyrene standards with $M_w/M_n \leqslant 1.2$.

The luminescence intensity of singlet oxygen $^1O_2$ generated by MPP or synthesized copolymers in chloroform solution under photo irradiation was determined in a lightproof chamber. A photoelectronic multiplier sensitive in a range from 500 to 1300 nm with λ_{max} = 800 nm was used as a detector of $^1O_2$ luminescence. The $^1O_2$ luminescence was induced by irradiation at λ_{max} = 630 nm and detected in a range from 900 nm with λ_{max} = 1274 nm.[13]

The physicochemical characteristics of the purified solvents (methanol, benzene, chloroform, acetone, THF and $CDCl_3$) were consistent with published data.[14]

[‡] See Online Supplementary Materials.

When the MPP concentration is 0.1 mol%, a slight deceleration of the process is observed, whereas an increase in the MPP concentration to 0.5 mol% is accompanied by a decrease in overall rates by a factor of 2–5 depending on the process conditions. The subsequent growth of the MPP content of the initial reaction mixture (to 1.0 mol%) further retards the copolymerization. As noted previously,[11] the inhibiting effect of MPP is due to the monomolecular pseudo-termination of the growing macrochain upon the addition of a methyl pheophorbide unit. As the synthesis temperature is raised from 60 to 90 °C, regular acceleration of the reaction is observed, while a decrease in the initiator concentration from 10.0 to 5.0 mmol dm^{-3} entails a decrease in the overall copolymerization rate at any studied ratios between comonomers.

Considering the impossibility of homopolymerization of vinyl porphyrins containing a vinyl group in the β-position of a macroheterocyclic pyrrole ring,[11] MPP copolymerization constant was assumed to be $r_2 \rightarrow 0$. Styrene copolymerization constant at 90 °C and MMA copolymerization constants at 60 and 80 °C, estimated by the Maio–Lewis equation,[15] were found to be $r_1 = 1.71 \pm 0.06$, 0.36 ± 0.03 and 0.62 ± 0.03, respectively.

The temperature dependence of MMA copolymerization constant, which is not typical of radical-initiated copolymerization, could be due to a large difference between the activation energies of the two elementary propagation reactions ~MMA$^{\bullet}$ + + MMA and ~MMA$^{\bullet}$ + MPP. If the activation energy of the latter is much smaller than that of the former reaction, the rate of the ~MMA$^{\bullet}$ + MPP reaction increases more slowly with temperature than the rate of the ~MMA$^{\bullet}$ + MMA reaction. Hence, the MMA copolymerization constant depends on temperature.[16]

The copolymerization products were identified by UV-VIS, ^{1}H NMR and IR spectroscopy. The ^{1}H NMR spectrum of the MPP–styrene copolymer exhibits a group of signals at 3.5–4.0 ppm corresponding to the protons of ester methoxy groups in the porphyrin macrocycle; this evidently indicates that MPP has entered the polymer backbone.[‡]

The IR spectra of MPP–styrene copolymers (Figure 2) have absorption bands typical of both of the initial comonomers. The bands of skeletal vibrations of MPP pyrrole rings at 1400–1500 cm^{-1} are masked by the C–C stretching bands of the phenyl rings of styrene units. The main information comes from the signals at 1600–1800 cm^{-1}. In the spectrum of MPP, two bands at 1730 and 1741 cm^{-1} correspond to $\nu_{\mathrm{C=O}}$ stretching bands of ester groups, the band at 1701 cm^{-1} corresponds to the $\nu_{\mathrm{C=O}}$ stretching band in the oxo group of the exo ring, and the absorption band at 1622 cm^{-1} corresponds to the $\nu_{\mathrm{C=C}}$ stretching band [Figure 2(*a*)]. In the spectra of MPP–styrene copolymers, bands at 1699 and 1740 cm^{-1} correspond to $\nu_{\mathrm{C=O}}$ stretching bands of matched ester groups of methyl pheophorbide units [Figure 2(*b*),(*c*)], indicating the presence of MPP units in the polymer backbone.

A comparison between band intensities in the IR spectra of copolymers obtained at different initial styrene-to-MPP ratios indicates that the concentration of methyl pheophorbide units in the copolymers increases with the initial MPP concentration.

As compared with the UV-VIS absorption spectrum of the initial MPP, in the spectrum of the MPP–styrene copolymers, the Soret band is broadened; it has a lower intensity and shows a minor (2 nm) hypsochromic shift. The intensity of the Q_x(0–0) and Q_x(0–1) bands also decreases; the positions of the absorption maxima shift to shorter wavelengths by approximately 6 nm; the intensity of the Q_y(0–0) and Q_y(0–1) bands, conversely, slightly increases, and they are also broadened and shifted hypsochromically by about 40 nm.[‡] It is known[17] that the hypsochromic shift in the UV-VIS spectra of porphyrins is caused by a deformation of the planar chromophore structure of the macroheterocycle, which is apparently due to the π–π interaction of the porphyrin macroheterocycles with the phenyl groups of neighboring styrene units.

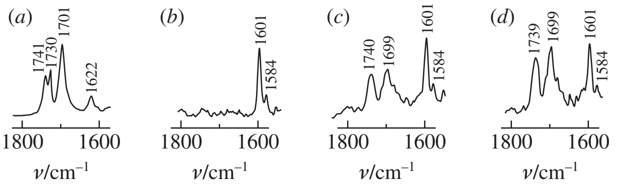


Figure 2 IR spectra of (*a*) MPP, (*b*) polystyrene and (*c*), (*d*) MPP–styrene copolymer. MPP–styrene copolymers were prepared at MPP concentrations of (*c*) 0.5 and (*d*) 1.0 mol%. [AIBN] = 5.0 mmol dm^{-3}. T_{copm} = 90 °C. Conversion, ~20%.

In the UV-VIS absorption spectrum of the MPP–MMA copolymer, every absorption band has a lower intensity and shows a minor (3–6 nm) hypsochromic shift in comparison with the spectrum of the initial MPP, but the spectra are similar.[‡]

By comparing the intensities of the Q_x(0–0) bands in the UV-VIS absorption spectra of the copolymerization products and the initial MPP, the concentration of methyl pheophorbide A incorporated in the copolymer was estimated (considering that the extinction coefficients of methyl pheophorbide units in copolymers are equal to that of the initial MPP).[‡] It can be seen that a decrease of synthesis temperature and concentration of the initiator and an increase in the initial MPP concentration results in higher concentrations of methyl pheophorbide units in copolymer.

The concentration of MPP units in copolymers synthesized in bulk is higher than that in copolymers obtained in benzene solution. This can be due to the specific solvation interaction of a vinyl porphyrin monomer or propagating macro radical capped with a porphyrin unit with benzene molecules resulting in the formation of π–π molecular complexes such as MPP–$n\mathrm{C_6H_6}$ or ~$\mathrm{CH_2}$–$\mathrm{CR^1R^2}$–MPP$^{\bullet}$–$n\mathrm{C_6H_6}$. In these molecular complexes, the coplanar aromatic solvent molecules may cause steric hindrances near the active sites of copolymerization resulting in a decrease in the reactivity of particles participating in copolymerization.[18,19]

To confirm the formation of π–π-type molecular complexes of MPP with benzene, the UV-VIS absorption spectra of MPP in different solvents were recorded.[‡] Methanol was used as a standard due to the low solubility of MPP in this solvent (3.0×10^{-6} mol dm^{-3}), which indicates the absence of strong solvation interaction of MPP with methanol molecules. A change from methanol to benzene through methanol–benzene mixtures results in the bathochromic shifts of the long-wavelength absorption band Q_x(0–0) and the Soret band by 5 and 9 nm, respectively, with a simultaneous considerable decrease of band intensities. The solvatochromic effect evidences the formation of π–π-type molecular complexes MPP–$n\mathrm{C_6H_6}$, where benzene molecules act as π-donors of electron density into the porphyrin macroheterocycle.[18,19]

The molecular weights of MPP–styrene and MPP–MMA copolymers obtained in benzene solution diminish with the initial MPP concentration (Table 1), which confirms the inhibiting effect of vinyl porphyrins during copolymerization. The polydispersity coefficients $M_{\mathrm{w}}/M_{\mathrm{n}}$ of copolymers do not exceed 2.2 and decrease as MPP concentration in the initial polymerization mixture increases; the molecular weight distribution curves of synthesized copolymers are unimodal.

The luminescence spectra of MPP and MPP–MMA copolymer are the mirror images of two long-wave absorption bands of the UV-VIS absorption spectra of these compounds and have maxima at 678 and 726 nm or at 670 and 718 nm, respectively.[‡] The maxima of an MPP–MMA copolymer emission spectrum are shifted hypsochromically by ~8 nm compared to the luminescence spectrum of monomeric MPP. Apparently, as in the case of UV-VIS spectra, the observed shift is a result of polymer chain influence on the electronic structure of the attached porphyrin, *i.e.*, on the ground and excited states of the porphyrin molecule.

Table 1 Dependence of the molecular weights of MPP–styrene and MPP–MMA copolymers obtained in benzene solution on reaction conditions.

Copolymer	T_{copm}/°C	[AIBN]/mmol dm^{-3}	Initial [MPP] (mol%)	$M_w\times10^{-3}$	$M_n\times10^{-3}$	M_w/M_n	Conversion (%)
MPP–styrene	60	10.0	0.0	54.2	36.5	1.5	35
			0.1	23.1	11.7	2.0	17
			1.0	12.9	9.0	1.4	10
	90	5.0	0.0	34.2	21.3	1.6	20
			0.1	27.1	13.2	2.0	23
			0.5	23.2	12.7	1.8	24
			1.0	11.5	6.6	1.7	17
	90	10.0	0.0	22.5	10.4	2.2	38
			0.1	17.8	9.3	1.9	22
			0.5	14.6	8.8	1.7	18
			1.0	12.3	7.8	1.6	29
MPP–MMA	60	5.0	0.0	23.1	13.2	1.8	28
			0.1	24.6	15.6	1.6	26
			1.0	17.5	10.9	1.6	29
	80	5.0	0.0	15.6	10.3	1.5	20
			0.1	13.8	9.8	1.4	19
			1.0	15.7	11.3	1.4	19

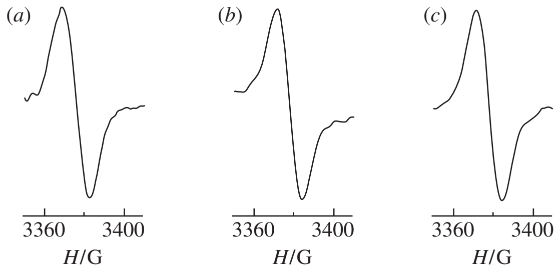


Figure 3 EPR spectra of (*a*) MPP and (*b*), (*c*) MPP–MMA copolymers. Conversion of MPP–MMA copolymers, (*b*) 2 and (*c*) 30%.

The EPR spectrum of solid MPP (Figure 3) exhibits a strong simple signal with $\Delta H = 14.0$ G and a g-factor of 2.0031, which is close to that of free radicals.[20] It is known[21] that porphyrins can produce stable radical cations with an unpaired electron delocalized in the π-orbit of porphyrin. The EPR spectra of solid MPP–MMA copolymers synthesized at different conversions have similar basic shapes as in the case of MPP. $\Delta H = 13.5$ G and $g = 2.0026$ for 2% conversion MPP–MMA copolymer and $\Delta H = 13.5$ G and $g = 2.0022$ for 30% conversion MPP–MMA copolymer were obtained.

To compare the activities of monomeric MPP and polymer attached MPP photoinduced generations of singlet oxygen $^1O_2$ by these samples in chloroform solution were studied.

$$\text{R}_{\text{polymer}}\text{–MPP} \xrightarrow[\lambda_{\max} = 630\ \text{nm}]{h\nu} \text{R}_{\text{polymer}}\text{–MPP*}$$

$$\text{R}_{\text{polymer}}\text{–MPP*} + {}^3\text{O}_2 \longrightarrow \text{R}_{\text{polymer}}\text{–MPP} + {}^1\text{O}_2$$

$${}^1\text{O}_2 \longrightarrow {}^3\text{O}_2 + h\nu\ (\lambda_{\max} = 1274\ \text{nm})$$

It was found that, in the solutions of MPP and MPP–MMA copolymer, which are equimolar in porphyrin content, the relative intensities of $^1O_2$ luminescence signals are equal. Equally diluted solutions exhibit equal decreases in relative intensities of $^1O_2$ luminescence signals. Thus, the MPP molecule attached to a polymer chain retains its property as a photosensitizer.

Thus, the porphyrin-containing copolymers with maximum concentrations of methyl pheophorbide units were synthesized at a higher initial concentration of methyl pheophorbide A in the reacting mixture, a lower initiator concentration and lower synthesis temperatures. The specific solvation interaction of porphyrin molecules with an aromatic solvent affects the activity of particles participating in copolymerization. The optical characteristics of the synthesized porphyrin-containing copolymers are similar to those of monomeric methyl pheophorbide A.

This work was supported by the Federal Target Programme ‘Scientific and Scientific-Pedagogical Personnel of Innovative Russia’ in 2009–2013 (agreement no. 8458).

Online Supplementary Materials

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.mencom.2013.09.014.

References

1 *Porfiriny: spektroskopiya, elektrokhimiya, primenenie (Porphyrins: Spectroscopy, Electrochemistry, Application)*, ed. N. S. Enikolopyan, Nauka, Moscow, 1987, p. 384 (in Russian).

2 T. Asano, P.-C. Wang and A. Iwasaki, *Spectrochim. Acta, Part A*, 2010, **75**, 305.

3 I. J. Macdonald and Th. J. Dougherty, *J. Porphyrins Phthalocyanines*, 2001, **5**, 105.

4 B. Li, L. Lin, H. Lin and Sh. Xie, *J. Innovative Optical Health Sci.*, 2008, **1**, 141.

5 I. S. Lonin, M. A. Grin, A. A. Lakhina and A. F. Mironov, *Mendeleev Commun.*, 2012, **22**, 157.

6 K. A. Formirovsky, N. A. Bragina, A. F. Mironov, G. A. Anan’eva, V. V. Bykova and N. V. Usol’tseva, *Mendeleev Commun.*, 2012, **22**, 278.

7 K. Aramata, A. Kajiwara and A. Hashidzume, *Polym. J.*, 1998, **30**, 702.

8 M. Kamachi, X. S. Cheng, T. Kida, A. Kajiwara, M. Shibasaka and S. Nagata, *Macromolecules*, 1987, **20**, 2665.

9 R. M. Islamova, O. I. Golovochesova, S. V. Nazarova, M. A. Kiskin and I. L. Eremenko, *Mendeleev Commun.*, 2012, **22**, 52.

10 P. Natarajan and C. Raja, *Eur. Polym. J.*, 2004, **40**, 2291.

11 A. D. Pomogailo, V. F. Razumov and I. S. Voloshanovskii, *J. Porphyrins Phthalocyanines*, 2000, **4**, 45.

12 N. E. Nifantiev and D. V. Yashunsky, *US Patent*, 6777402, 2004.

13 M. Yu. Ovchinnikov, *PhD Thesis*, Ufa, 2010.

14 A. J. Gordon and R. A. Ford, *The Chemist’s Companion*, Wiley, New York, 1972, p. 537.

15 T. Alfrey, J. Bohrer and H. Mark, *Copolymerization*, Interscience Publishers, New York, 1952, p. 269.

16 C. H. Bamford, W. G. Barb, A. D. Jenkins and P. F. Onyon, *The Kinetics of Vinyl Polymerization by Radical Mechanisms*, Academic Press, New York, 1958, p. 318.

17 B. D. Berezin and N. S. Enikolopyan, in *Porfiriny: struktura, svoistva, sintez (Porphyrins: Structure, Properties, Synthesis)*, ed. N. S. Enikolopyan, Nauka, Moscow, 1985, p. 333 (in Russian).

18 A. I. Vyugin, M. B. Berezin and E. V. Antina, in *Biologicheski aktivnye veshchestva v rastvorakh: struktura, termodinamika, reaktsionnaya sposobnost (Biologically Active Substances in Solutions: Structure, Thermodynamics, Reactivity)*, ed. A. M. Kutepov, Nauka, Moscow, 2001, p. 403 (in Russian).

19 N. Sh. Lebedeva, N. A. Pavlycheva, A. I. Vyugin, O. I. Davydova and S. P. Yakubov, *Russ. Chem. Bull., Int. Ed.*, 2004, **53**, 330 (*Izv. Akad. Nauk, Ser. Khim.*, 2004, 159).

20 R. Drago, *Physical Methods in Chemistry*, W. B. Saunders Company, Philadelphia, 1977, p. 660.

21 *Handbook of Porphyrin Science with Applications to Chemistry, Physics, Materials Science, Engineering, Biology and Medicine. Volume 6. NMR and EPR Techniques*, eds. K. M. Kadish, K. M. Smith and R. Guilard, World Scientific, New Jersey, 2010, p. 466.

Received: 15th March 2013; Com. 13/4086