

Effect of Functionalized Multi-walled Carbon Nanotubes with Poly(*N*-vinyl pyrrolidone-*co*-2-acrylamido-2-methyl-1-propanesulfonic acid) on the Release of Tramadol Hydrochloride

Ahmed Awadallah-F^{a*} and Tahia B. Mostafa^b

^a National Center for Radiation Research and Technology, P.O. Box 29, Nasr City, Cairo, Egypt

^b Chemistry Department, University College for Women, Ain Shams University, Heliopolis, Cairo, Egypt

Abstract Multi-walled carbon nanotubes (MWCNTs) were grafted with poly(*N*-vinyl-2-pyrrolidone) and with poly(2-acrylamido-2-methyl-1-propanesulfonic acid) at different compositions by using γ -rays technique as initiator. The MWCNTs, MWCNT-graft-PNVP, MWCNT-graft-PAMPS and MWCNTs-graft-P(NVP-*co*-AMPS) were characterized by Fourier transform infra red (FTIR) spectroscopy, X-ray diffraction (XRD), thermal gravimetric analysis (TGA), elemental analysis and high-resolution transmission electron microscopy (HR-TEM). The results indicated that the grafting processes of PNVP, PAMPS and P(NVP-*co*-AMPS) occurred on to the surfaces of MWCNTs without destroying the framework of MWCNTs. Tramadol hydrochloride (TH) was loaded as model drug and its release behavior was analyzed *via* various kinetic models. Release of the loaded TH was studied in simulated gastric fluid (SGF, pH = 1.2) and simulated intestinal fluid (SIF, pH = 7.4) at 37 °C. Controlled release of TH from grafted MWCNTs was investigated. The outcome results suggest that the grafted MWCNTs could be used as a promising matrix candidate for oral drug delivery system by harmonization between the composition and pH level of the simulated biological fluids.

Keywords: Polymer grafting; Gamma irradiation; Multi-walled carbon nanotubes; Controlled release; Tramadol hydrochloride.

INTRODUCTION

The branch of polymer grafting is considered the one of cornerstone of technology development in numerous fields and represents the criteria of progress for nations. Carbon nanotubes (CNTs) possess superlative mechanical, thermal and electrical properties that justify the steadily increasing attention being paid to them^[1–3]. These properties make the CNTs attractive for a wide range of applications such as conductive and high-strength polymer composites, energy storage and conversion devices, field emission displays, *etc*^[4,5]. Nevertheless, their insolubility in most solvents and matrices has limited their applications. To date, non-covalent and covalent modification methods have been developed to improve their solubility and surface functionality^[6–11]. Among them, a covalent reaction of CNTs with polymers is widely used because the long polymer chains help to disperse the nanotubes into a wide range of solvents even at a low degree of functionalization.

Recently, polymer grafted-CNTs have been synthesized through various types of polymerization methods such as anionic polymerization, ring-opening polymerization, atom transfer radical polymerization, reversible addition-fragmentation chain transfer polymerization and radiation induced-polymerization^[12]. Tramadol hydrochloride (TH) is widely used in clinical field to relieve physical pain caused by surgical operation or chronic diseases^[13]. Due to fast metabolism in human body, the working duration of TH lasts only 4 h. In order

* Corresponding author: Ahmed Awadallah-F, E-mail: elsheshengy@yahoo.co.uk

Received May 15, 2014; Revised August 6, 2014; Accepted August 14, 2014

doi: 10.1007/s10118-015-1591-5

to maintain the effective plasma concentration, TH has to be administered more than 5 times per day to achieve the expected therapeutic effect. One of the side effects of TH is the easiness of habit-forming. Therefore, it is necessary to develop a controlled release system for TH, which prolongs the effective therapeutic time by controlling its blood concentration. The motive of this study is to develop sustained drug delivery of TH using nanomaterials such as CNTs in order to minimize the degradation loss and cost by maintaining minimum effective concentration over a period of time.

Therefore, this work reports a recipe to modify MWCNTs with *N*-vinyl-2-pyrrolidone (NVP) and 2-acrylamido-2-methyl-1-propanesulfonic acid (AMPS) at different feeding compositions by using a simultaneous radiation-induced graft polymerization. Further, the novelty of this study is to graft two different monomers having different structure, different functional groups and different chemical behavior on to MWCNTs to produce the optimum carrier for drug exposed to external stimulus such as pH. The effect of irradiation dose on the grafting degree of PNVP, PAMPS and P(NVP-*co*-AMPS) on to MWCNTs will be investigated. Further, the effect of composition of binary monomers on the degree of grafting (%) on to MWCNTs will be studied. The grafted samples of MWCNTs could be exploited as a tunable drug carrier *via* using tramadol hydrochloride (TH) as a model drug.

EXPERIMENTAL

Materials

2-Acrylamido-2-methyl-1-propanesulfonic acid and *N*-vinyl-2-pyrrolidone were obtained from Merck, Germany. Potassium bromide (KBr) of FTIR grade was purchased from Fisher Scientific, UK. Multi-walled carbon nanotubes (MWCNTs) were purchased from Sigma Aldrich, USA, synthesized by the chemical vapor deposition method (purity > 98%, length 5–15 μm). Tramadol hydrochloride ($\text{C}_{16}\text{H}_{13}\text{NO}_2\cdot\text{HCl}$) was purchased from Sigma Aldrich, USA. All other chemicals were of analytical grade.

Functionalization of MWCNTs

The impurities were eliminated by refluxing the MWCNTs in 2.6 mol/L HNO_3 for 12 h and washed several times with deionized water and dried at 60 $^\circ\text{C}$. 0.1 g of purified MWCNTs and 60 mL of ethanol were mixed together in a glass tube. The mixture was sonicated for 20 min before irradiation and then subjected to γ -irradiation for 50 kGy at a fixed dose rate of 2.5 kGy/h. Then, the mixture was filtered through 0.2 μm microporous poly(ether sulfone) membrane and dried for 12 h at 60 $^\circ\text{C}$. The product is called hydroxyethylated multi walled carbon nanotubes and symbolized as HOEt-MWCNTs for brevity.

Radiation-induced graft polymerization and copolymerization were carried out by mixing HOEt-MWCNTs (0.1 g) with different ratios of comonomer compositions AMPS: NVP (100:0, 50:50, 0:100, mol/mol %) at total comonomer concentration 20 $\text{V/V}\%$ in deionized water. Each solution was poured into glass tube after sonicating for 20 min and bubbling N_2 gas to remove the air. The solutions were exposed to a total dose of 30 kGy at a fixed dose rate of 2.5 kGy/h. After irradiation step, the produced solutions were diluted with 600 mL of deionized water and centrifuged at 4500 r/min to sediment the grafted MWCNTs samples. The repeated centrifugation and re-suspension processes in deionized water were used to remove all of the non-grafted species of PAMPS, PNVP and poly(NVP-*co*-AMPS). The collected black powder samples were dried overnight in an oven at 50 $^\circ\text{C}$. The grafting percentage (GP) for the grafting of MWCNTs was determined by the following formula

$$\text{GP}\% = \left(\frac{W_g - W_0}{W_0} \right) \times 100$$

where W_0 and W_g denote the weights of MWCNTs samples before and after grafting process, respectively.

Tablet Preparation

The dried graft MWCNTs samples were finely powdered in a mortar, and sieved through mesh size: 150. In a typical tablet (~2.5 mm thickness and ~13 mm diameter) formulation exactly 200 mg of graft MWCNTs was

loaded with 35 mg of TH by mixing and grinding in a mortar to make sure the homogeneity, followed by compression using a hydraulic press (Atlas™ Manual 15T) at a load of 5 tons.

TH Release from Grafted MWCNTs

UV spectra of the pure drug solution and the drug released from the tablet in drug dissolution studies were recorded on a Perkin Elmer Lambda-40 ultraviolet-visible spectrophotometer (UVWINLAB software). The drug of TH was estimated in drug release study by measuring the absorbance at $\lambda_{\text{max}} = 271 \text{ nm}^{[14]}$.

The simulated gastric fluid (SGF, pH = 1.2) was made of HCl solution, and the simulated intestinal fluid (SIF, pH = 7.2) was a phosphate buffer. The drug release was performed by dispersing ~0.235 g of tablet (grafted MWCNTs and uploaded with drug of TH) in 100 mL SGF or SIF under continuous shaking at 37 °C. At different intervals, 5 mL of solution was withdrawn for concentration measurement, immediately followed by refilling 5 mL fresh solution; consequently the total volume was maintained at 100 mL. The experiments were made in triplicate and the results were recorded as an average values.

Characterization

For FTIR spectroscopy analyses pellets of multi wall carbon nanotubes and grafted multi wall carbon nanotubes powders mixed with KBr powders were formed. FTIR spectra measured at room temperature in a spectral range from 400 to 4000 cm^{-1} in transmittance mode, on a Nicolet 380 FTIR, Thermo Electron Corporation spectrometer. Elemental analyses were performed using a Thermo Flash EA 1112 Series CHNS-O elemental analyzer with an accepted tolerance of (± 0.4) units.

Thermal gravimetric analysis (TGA) was performed using a thermogravimetric analyzer (Perkin Elmer Pyris 6 TGA) from 25 to 1000 °C at a heating rate of 10 K/min under a nitrogen atmosphere. High-resolution transmission electron microscopy (HR-TEM) analysis was performed using a JEOL TEM-2100 electron microscope operating at an accelerating voltage of 200 kV. The TEM specimens were prepared by adding a few drops of a sample THF solution onto a carbon-coated copper grid and then subsequent evaporation of the solvent. X-ray diffraction investigations were conducted in a Philips PW1050 diffractometer using Cu K α radiation ($\lambda = 0.154 \text{ nm}$, 40 kV, 50 mA).

RESULTS AND DISCUSSION

Effect of Irradiation Dose on the Grafting

Figure 1 shows the impact of the irradiation dose on the grafting degree on MWCNTs at different compositions of NVP:AMPS (mol/mol%) (100:0, 50:50 and 0:100). From whole view, it was observed that the grafting degree increased with increasing irradiation dose and leveled off at 40 kGy. This increment in grafting degree is due to the formation of more cross-linking density at higher irradiation dose between MWCNTs and the grafted polymer or copolymer. Further, the grafting degree increased with increasing the concentration of NVP in the initial solutions of different compositions. Otherwise, the decrement of grafting degree occurred with increasing the concentration of AMPS in the initial solutions of grafting reaction. This phenomenon may be due to the affinity of NVP and the resistance of AMPS to generate more free radicals to be grafted on to MWCNTs. Therefore, the order of GP of MWCNTs was outlined as MWCNTs-graft-PNVP > MWCNTs-graft-P(NVP-co-AMPS) > MWCNTs-graft-PAMPS.

Morphology and Dispersion Stability

Figure 2 shows the HR-TEM images of the MWCNTs and MWCNTs-graft-P(NVP-co-AMPS) samples. It was observed that the average diameter of MWCNTs increased with increasing the grafting of P(NVP-co-AMPS) on to MWCNTs. Furthermore, it was seen that the wall surface of purified MWCNTs was smooth, without wrinkles or deformations. Figure 3 shows the histograms of diameter distribution of MWCNTs (curve a) and MWCNTs-graft-P(NVP-co-AMPS) (curve b). Each histogram was obtained by analyzing at least 300 objects on TEM images. It was seen that the diameter of MWCNTs-graft-P(NVP-co-AMPS) is bigger than the diameter of MWCNTs samples. Therefore, the grafting process has a clear effect on diameter of MWCNTs.

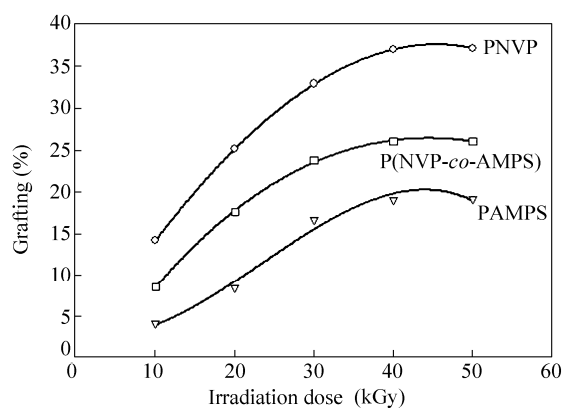


Fig. 1 Effect of irradiation dose on the grafting percentage of different compositions of NVP and AMPS at a total comonomer concentration 20 g/V%, and dose rate 2.5 kGy/h

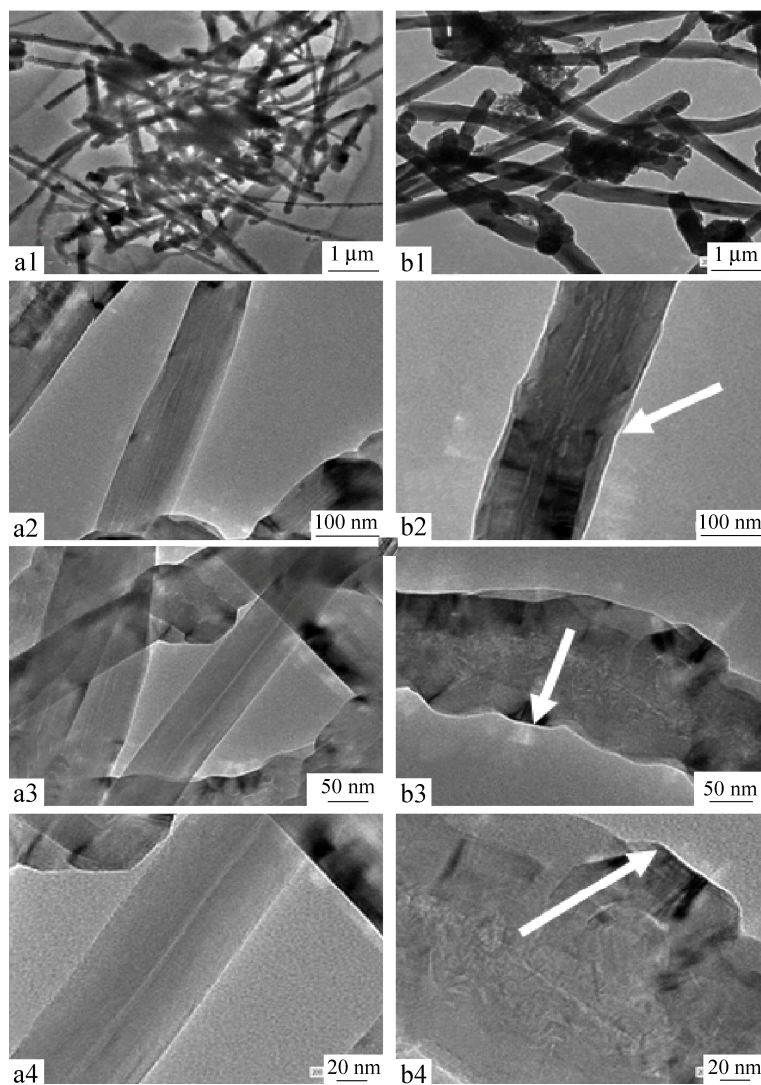


Fig. 2 HR-TEM images of samples: (a1–a4) MWCNTs and (b1–b4) MWCNTs-graft-P(NVP-co-AMPS) with grafting degree of 26% at different zoom levels

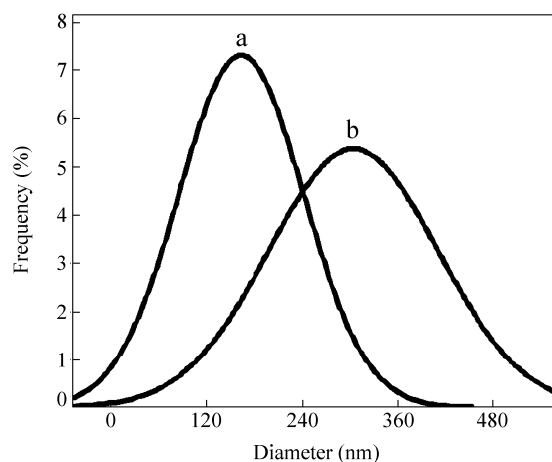


Fig. 3 Diameter size distributions of samples: (a) MWCNTs and (b) MWCNTs-graft-P(NVP-*co*-AMPS)

Figure 4 illustrates the stability of dispersions of MWCNTs (Fig. 4a) and MWCNTs-P(NVP-*co*-AMPS) with DP of 26% (Fig. 4b) in water after 5 months of storage at room temperature. MWCNTs-P(NVP-*co*-AMPS) was well dissolved in water, whereas MWCNTs could not be dispersed in water. This is assignable to that water is a good solvent for both of PNVP and PAMPS homopolymers or P(NVP-*co*-AMPS) copolymer.

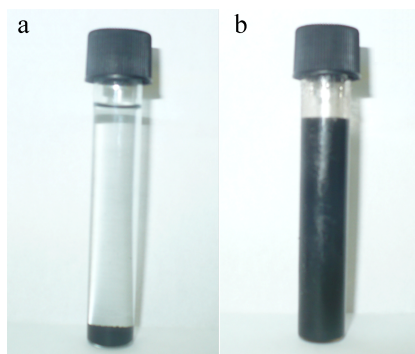


Fig. 4 Dispersibility of samples in water of (a) MWCNTs and (b) MWCNTs-graft-P(NVP-*co*-AMPS) with grafting degree of 26% at ambient temperature

FTIR Spectroscopy and Elemental Analysis

Figure 5(a) exhibits the FTIR spectrum of MWCNTs with characteristic absorption peaks at 3430 cm^{-1} (O—H stretching mode), 1635 cm^{-1} (C=O stretching mode), 1452 cm^{-1} (C=C stretching mode), 1385 cm^{-1} (O—H bending mode), 1046 and 1092 cm^{-1} (C—O stretching mode)^[15–17], which indicate that the surface of MWCNTs has a certain amount of oxygen-containing functional groups. Therefore, MWCNTs generates some reactive and anchoring sites^[18–20]. Figures 5(b), 5(c) and 5(d) show the IR spectra of MWCNTs-graft-PNVP, MWCNTs-graft-PAMPS and MWCNTs-graft-P(NVP-*co*-AMPS), respectively. The characteristic peaks of PNVP are illustrated in Fig. 5(b), the stretching vibration of C—N appears at 1286 cm^{-1} and the stretching vibration of C=O is observed at 1654 cm^{-1} ^[21]. The characteristic peaks of PAMPS are represented in Fig. 5(c), the stretching of O—H and N—H bonds are between 3600 and 3000 cm^{-1} . Moreover, C—H stretching vibration is observed at 2947 and 2850 cm^{-1} , C=O stretching vibration of amide group (amide I) appears at 1635 cm^{-1} . The bending of N—H bond appears at 1552 cm^{-1} (amide II). The peak at 1447 cm^{-1} is assigned to the stretching of C—N bond (amide III). The peaks at 1039 and 1221 cm^{-1} are due to the S—O stretching of sulfonic acid groups^[22–25]. The characteristic peaks of P(NVP-*co*-AMPS) are depicted in Fig. 5(d), the vibration absorption band of C=O stretching shifted towards high frequency at 1680 cm^{-1} as a result of the interaction between

PNVP and PAMPS and the hydrogen bond formation between C=O and OH inside grafted P(NVP-*co*-AMPS) on MWCNTs.

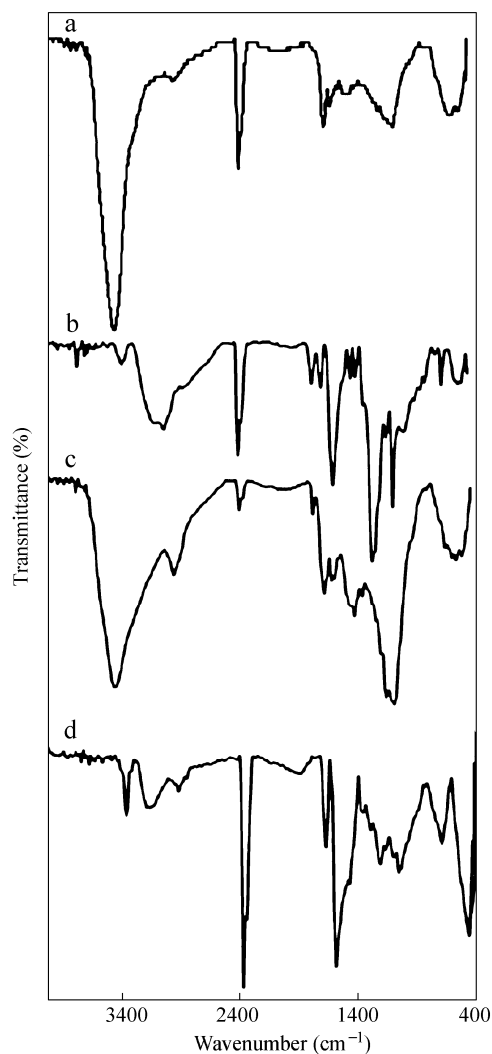


Fig. 5 FTIR spectra of (a) MWCNTs, (b) MWCNTs-graft-PNVP, (c) MWCNTs-graft-PAMPS and (d) MWCNTs-graft-P(NVP-*co*-AMPS) at a fixed comonomer composition of 50:50 mol/mol% (The degree of grafting is 16% for the grafted MWCNTs.)

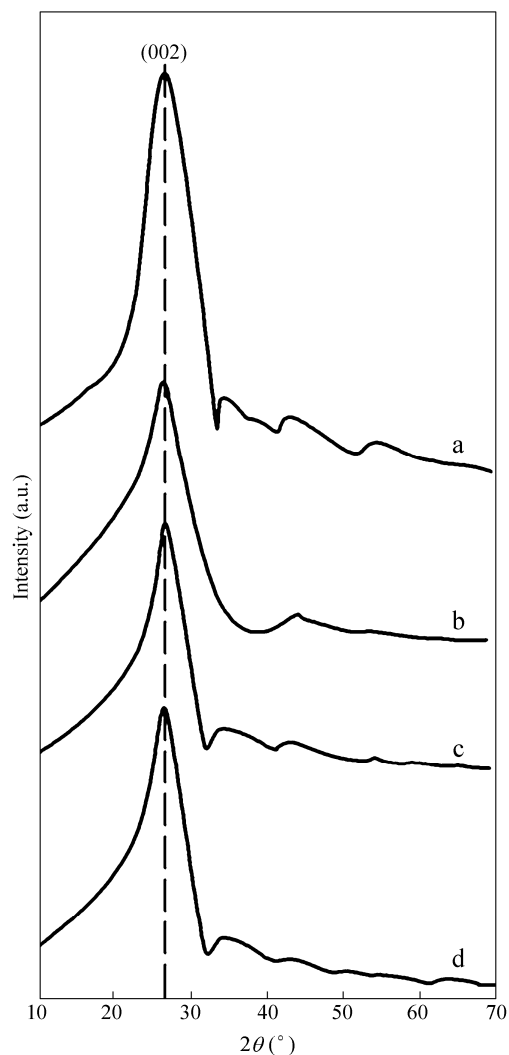


Fig. 6 X-ray diffractograms of (a) MWCNTs, (b) MWCNTs-graft-PNVP, (c) MWCNTs-graft-PAMPS and (d) MWCNTs-graft-P(NVP-*co*-AMPS) (The degree of grafting is 16% for the grafted MWCNTs.)

The elemental analyses of MWCNTs, MWCNTs-graft-PNVP, MWCNTs-graft-PAMPS and MWCNTs-graft-P(NVP-*co*-AMPS) samples are listed in Table 1. It can be seen that there are different values (%) in carbon, hydrogen, nitrogen, sulfur and oxygen contents of MWCNTs and the grafted MWCNTs samples.

Table 1. Elemental analyses of MWCNTs and functionalized MWCNTs samples

Sample	C (%)	H (%)	N (%)	S (%)	O (%)
MWCNTs	97.2	0.39	0	0	2.41
MWCNTs-graft-PNVP	88.0	3.40	5.17	0	3.43
MWCNTs-graft-PAMPS	86.5	4.71	0	4.25	4.54
MWCNTs-graft-P(NVP- <i>co</i> -AMPS)	84.0	3.93	4.38	3.46	4.23

XRD Patterns

Figure 6 shows the X-ray diffraction (XRD) patterns of MWCNTs, MWCNTs-graft-PNVP, MWCNTs-graft-PAMPS and MWCNTs-graft-P(NVP-co-AMPS), respectively. It is observed from Fig. 6(a) that MWCNTs, which exhibits a strong diffraction peak at $2\theta = 26.2^\circ$ and it could be indexed as the (002) reflection of the hexagonal graphite structure. Furthermore, the XRD patterns of MWCNTs, MWCNTs-graft-PNVP, MWCNTs-graft-PAMPS and MWCNTs-graft-P(NVP-co-AMPS) are similar, which indicates that there is no alteration in the structure of MWCNTs during the grafting process. Further, the irradiation grafting process occurred on to the surface of MWCNTs and their framework did not smash. These deduced results are consistent with the observations of HR-TEM images shown in Fig. 2.

Suggested Mechanism of Grafting Reaction

The grafting reaction of MWCNTs with PNVP and PAMPS was induced by γ -radiation suggested in Fig. 7. The samples of MWCNTs were irradiated in ethanol using γ -radiation. The tips and defects of MWCNTs could be destroyed under γ -radiation due to their high reactivity^[26]. Further, the radiolysis of ethanol generates various active species such as $\cdot\text{CH}_2\text{CH}_2\text{OH}$, and $\cdot\text{CH}(\text{CH}_3)\text{OH}$, which interact with the MWCNTs and attach on to the surface of MWCNTs. The functionalized hydroxyethyl groups of MWCNTs were designed as HOEt-MWCNT. Moreover, the hydroxyethyl groups onto MWCNTs improve the hydrophilicity of HOEt-MWCNTs. Therefore,

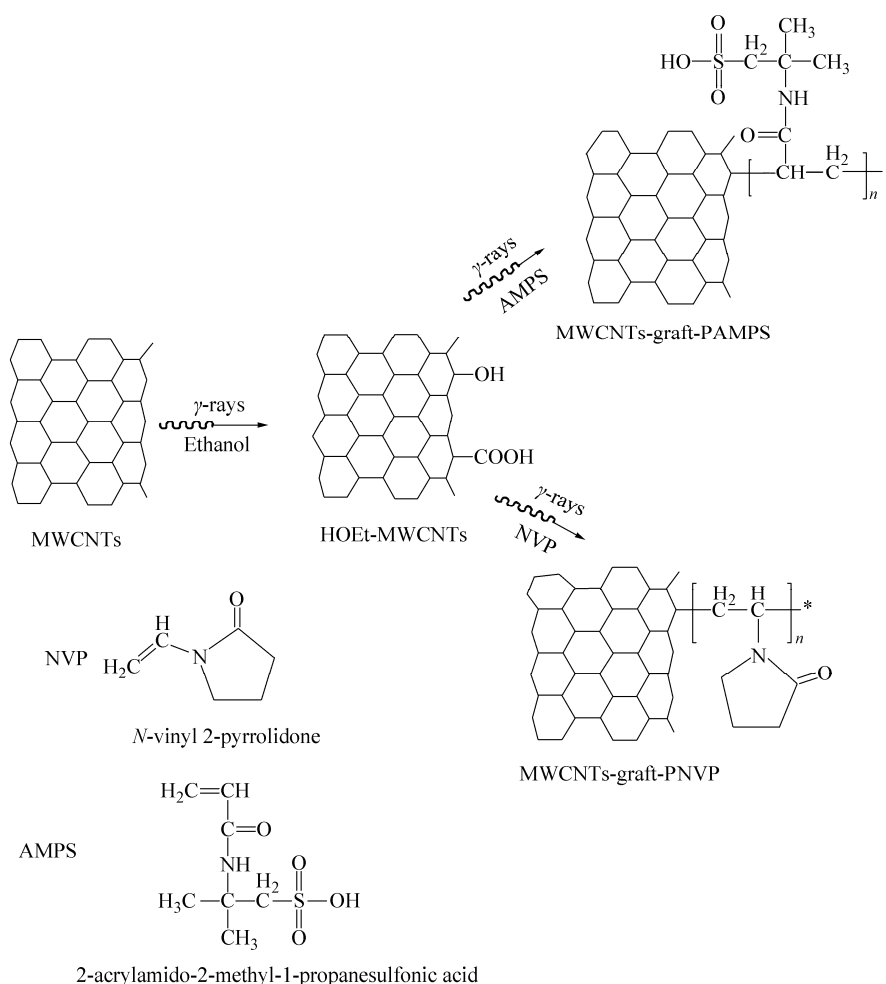


Fig. 7 The suggested reaction mechanism of grafting NVP and AMPS on to HOEt-MWCNTs

this step facilitates the adsorption of NVP or AMPS or NVP/AMPS on to the surface of HOEt-MWCNTs, which is a very important procedure for the radiation-induced graft polymerization and copolymerization of monomer (NVP and AMPS) and comonomer (NVP/AMPS), respectively. The functionalized hydroxyethyl groups on MWCNTs act as the initiating sites of the graft polymerization or copolymerization. Moreover, the grafting process does not occur on the skeleton of MWCNTs, but on the hydroxyethyl groups^[27–29].

TGA Analysis

Thermo gravimetric analysis (TGA) is considered the most important method for studying the material thermal stability. Thermal properties of MWCNT, MWCNTs-graft-PAMPS, MWNTs-graft-PNVP, and MWNTs-graft-P(NVP-co-AMPS) samples were investigated by TGA technique from 25 °C to 1000 °C under nitrogen gas as shown in Fig. 8. It was observed from the results that the weight loss of MWCNTs at 700 °C is ~7.2% (Fig. 8a). All of the functional groups and grafted PNVP, PAMPS and P(NVP-co-AMPS) chains are assumed to be lost at 700 °C^[30], and therefore almost all of the weight losses during fragmentations are due to the pyrolysis of side-chain groups. Further, it was seen that during the initial stage of the thermal diagram, from ambient temperature to ~150 °C, the weight loss is due to a dehydration process of the water contained in such hydrophilic grafted polymers or copolymers on MWCNTs. During the second stage, in the range of 150 °C to 580 °C and 150 °C to 650 °C for PNVP and PAMPS, respectively, the weight losses are due to the decomposition in the side chains. It was noticed that the ~36% weight change was resulted for grafted PNVP at 580 °C (Fig. 8d), whereas ~16% and ~14% weight losses were observed for MWCNTs grafted with PAMPS and P(NVP-co-AMPS), respectively. It could be concluded that the grafting of PNVP, PAMPS and P(NVP-co-AMPS) on to MWCNTs reduces the thermal stability of MMCNTs. Otherwise, the presence of PAMPS inside the matrix enhances the thermal stability of grafted PNVP on MWCNTs.

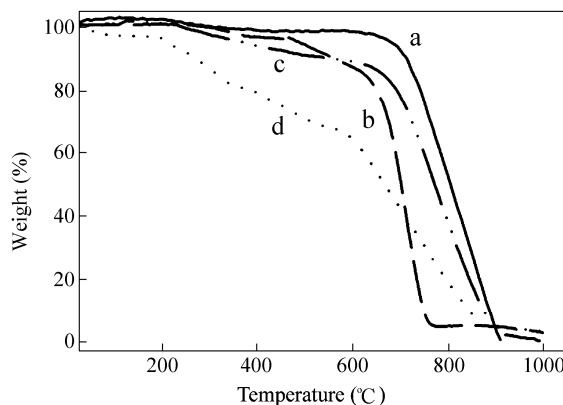


Fig. 8 TGA curves of (a) MWCNTs, (b) MWCNT-graft-PAMPS, (c) MWCNTs-graft-P(NVP-co-AMPS) and (d) MWCNTs-graft-PNVP at degree of grafting of 16%

Drug Release

The release profiles of TH from MWCNTs and MWCNTs-graft-P(NVP-co-AMPS) samples in SGF of pH = 1.2 and in SIF of pH = 7.4 at 37 °C are exhibited in Fig. 9. It was observed from Fig. 9(a) that at 300 min, ~80% and ~98% of TH were released from MWCNTs in SGF and SIF, respectively. Therefore, it could be said that the TH release behavior was affected by the pH level, and the drug release rate in SGF is lower than that in SIF. This is due to the grafted function groups on MWCNTs. Figure 9(b) shows the release profiles of TH from MWCNTs-graft-P(NVP-co-AMPS) in SGF of pH = 1.2 and in SIF of pH = 7.4, respectively at 37 °C as function of time. It is noticed that the release profile of TH at 300 min is ~73% and ~91% in SGF and SIF, respectively. If the release profile of TH from MWCNTs was compared to the release profile of TH from MWCNTs-graft-P(NVP-co-AMPS) at same duration, it could be deduced that the presence of grafting copolymer on MWCNTs delays the release of TH. The release process may consist of ion exchange between TH and ions in SGF and SIF.

Moreover, the modified MWCNTs are acting as better drug carriers characterized with different releasing rates at different pH levels than net MWCNTs. This is due to the synergetic effect of sulfonic and nitrogen groups in PAMPS and PNVP, respectively.

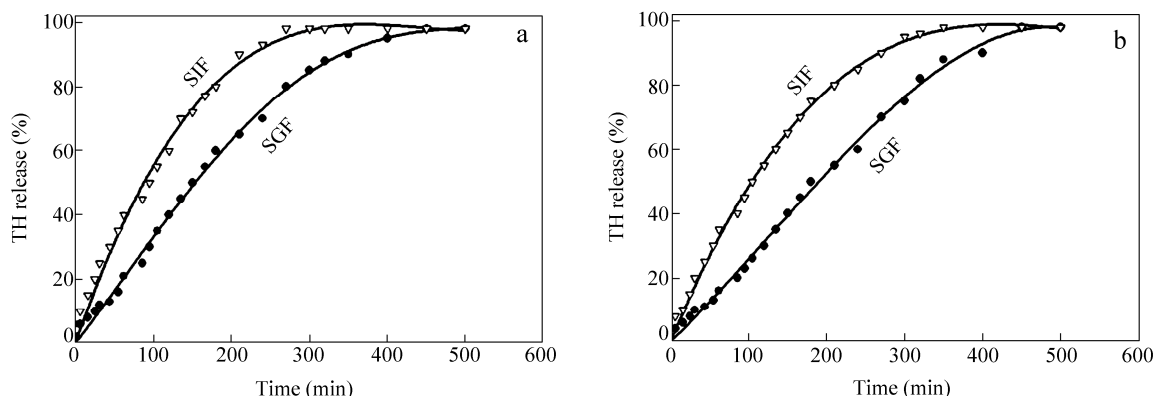


Fig. 9 Drug release of TH from (a) MWCNTs and from MWCNTs-graft-P(NVP-co-AMPS) in SGF and SIF at 37 °C (The grafting degree is 25%).

The release data of TH were fitted by Bhaskar equation, first-order kinetics equation, Higuchi equation and Korsmeyer-Peppas equation, and the results are listed in Table 2^[31, 32]. In SGF, the Korsmeyer-Peppas and first order equations produced the best representation of the release data, and the release mechanism seemed to be proliferation. In SIF, the release followed the first order kinetic equation as well as the Korsmeyer-Peppas equation. Thus, the release mechanism was described as the proliferation and non-Fickian proliferation. The concentration gradient of the drug was the main driving force for the release process both in SGF and SIF.

Table 2. Fitting data of release of TH from MWCNTs and MWCNTs-graft-P(NVP-co-AMPS) in SGF and SIF

Sample	Media	Korsmeyer-Peppas $F = k_1 t^n$			Higuchi $F = k_2 t^{0.5}$		First order $F = 1 - e^{-k_3 t}$		Bhaskar $\lg(1-F) = Bt^{0.65}$	
		$k_1 \times 10^{-2}$	n	R^2	$k_2 \times 10^{-2}$	R^2	$k_3 \times 10^{-2}$	R^2	B	R^2
^a S-1	SGF	3.71	0.70	0.97	1.11	0.93	2.28	0.98	0.11	0.81
	SIF	6.16	0.80	0.98	1.21	0.94	1.20	0.97	0.58	0.88
^b S-2	SGF	4.50	0.73	0.98	2.51	0.90	3.11	0.97	0.15	0.86
	SIF	2.56	0.60	0.98	1.84	0.92	1.46	0.99	0.70	0.90

Note that the symbols of ^aS-1 and ^bS-2 indicate MWCNTs and MWCNTs-graft-P(NVP-co-AMPS), respectively.

CONCLUSIONS

Different compositions of NVP and AMPS were grafted on to MWCNTs by using γ -radiation technique. The virgin and the grafted MWCNTs were characterized by Fourier transform infrared (FTIR), X-ray diffraction (XRD), thermal gravimetric analysis (TGA), elemental analysis and high-resolution transmission electron microscopy (HR-TEM). The outcome results indicated that the grafting (%) decreased the thermal stability of MWCNTs. Furthermore, the sequential order of thermal stability of samples is as MWCNTs > MWCNTs-graft-PAMPS > MWCNTs-graft-P(NVP-co-AMPS) > MWCNTs-graft-PNVP. From general overview of analyzing the histograms of diameter distribution, it was deduced that the grafting sample of MWCNTs has greater diameter than the ungrafted sample of MWCNTs. Tramadol hydrochloride (TH) was loaded as model drug and its release behavior was investigated. It was deduced that the drug release rate was greater in SIF than in SGF either in virgin or grafted MWCNTs. Further, the drug release of TH in grafted MWCNTs is smaller than the drug release of TH of virgin MWCNTs at same duration. The release behavior of TH from MWCNTs-graft-P(NVP-co-AMPS) sample was fitted by various kinetic models. The grafted MWCNTs showed the efficient controlled release in both SGF and SIF as well. Therefore, the grafted MWCNTs could be considered as a potential controlled drug release system.

REFERENCES

- 1 Tasis, D., Tagmatarchis, N., Bianco, A. and Prato, M., *Chem. Rev.*, 2006, 106(3): 1105
- 2 Moniruzzaman, M. and Winey, K.I., *Macromolecules*, 2006, 39(16): 5194
- 3 Coleman, J.N., Khan U., Blau, W.J. and Gun'ko, Y.K., *Carbon*, 2006, 44(9): 1624
- 4 Paradise, M. and Goswami, T., *Mater. Design*, 2007, 28(5): 1477
- 5 Hanzel, O., Sedláček, J. and Šajgalík, P., *J. Eur. Ceram. Soc.*, 2014, 34(7): 1845
- 6 Huang, W., Lin, Y., Taylor, S., Gaillard, J., Rao, A.M. and Sun, Y.P., *Nano Lett.*, 2002, 2(3): 231
- 7 Jin, J., Li, R., Wang, H., Chen, H., Liang, K. and Ma, J., *Chem. Commun.*, 2007, 4(4): 386
- 8 Tasis, D., Papagelis, D., Prato, M., Kallitsis, I. and Galiotis, C., *Macromol. Rapid Commun.*, 2007, 28(15): 1553
- 9 Hong, C.Y., You, Y.Z. and Pan, C.Y., *Chem. Mater.*, 2005, 17(19): 2247
- 10 Zhang, H., Li, H.X. and Cheng, H.M., *J. Phys. Chem. B*, 2006, 110(18): 9095
- 11 Wang, T., Zhao, G.C. and Wei, X.W., *Chem. Lett.*, 2005, 34(4): 518
- 12 Pei, X., Hu, L., Liu, W. and Hao, J., *Eur. Polym. J.*, 2008, 44(12): 2458
- 13 Lebitasy, M., Hecq, J.D., Vanbeckbergen, D., Jamart, J. and Galanti, L., *Ann. Pharm. Fran.*, 2009, 67(4): 272
- 14 Obaidat, A.A. and Obaidat, R.M., *Eur. J. Pharm. Biopharm.*, 2001, 52(2): 231
- 15 Tan, X.L., Fang, M., Chen, C.L., Yu, S.M. and Wang, X.K., *Carbon*, 2008, 46(13): 1741
- 16 Xie, X., Gao, L. and Sun, J., *Colloids Surf. A*, 2007, 308(1–3): 54
- 17 Chang, P.R., Zheng, P.W., Liu, B.X., Anderson, D.P., Yu, J.G. and Ma, X.F., *J. Hazard. Mater.*, 2011, 186(2–3): 2144
- 18 Mishra, A.K. and Ramaprabhu, S., *J. Phys. Chem. C*, 2010, 114(6): 2583
- 19 Jia, B.P. and Gao, L., *J. Phys. Chem. B*, 2007, 111(19): 5337
- 20 Kong, L.R., Lu, X.F. and Zhang, W.J., *J. Solid State Chem.*, 2008, 181(3): 628
- 21 Zhao, L., Xu, L., Mitomo, H. and Yoshii, F., *Carbohydr. Polym.*, 2006, 64(3): 473
- 22 Bozkurt, A., Ekinici, O. and Meyer, W.H., *J. Appl. Polym. Sci.*, 2003, 90(12): 3347
- 23 Rosa, F., Bordado, J. and Casquilho, M., *J. Appl. Polym. Sci.*, 2003, 87(2): 192
- 24 Travas-Sejdic, J. and Easteal, A., *J. Appl. Polym. Sci.*, 2000, 75(5): 619
- 25 Rivas, B.L., Pooley, S.A., Luna, M. and Geckeler, K.E., *J. Appl. Polym. Sci.*, 2001, 82(1): 22
- 26 Peng, J., Qu, X.X., Wei, G.S., Li, J.Q. and Qiao, J.L., *Carbon*, 2004, 42(47): 2741
- 27 Jiang, B. and Huang, G., *Radiat. Phys. Chem.*, 2004, 69(11): 433
- 28 Hong, K., Liu, N. and Sun, S., *Eur. Polym. J.*, 2009, 45(8): 2443
- 29 Shao, D., Jiang, Z., Wang, X., Li, J. and Meng, Y., *J. Phys. Chem. B*, 2009, 113(4): 860
- 30 Saini, R.K., Chiang, I.W., Peng, H., Smalley, R.E., Billups, W.E., Hauge, R.H. and Margrave, J.L., *J. Am. Chem. Soc.*, 2003, 125(12): 3617
- 31 Brophy, M.R. and Deasy, P.B., *Int. J. Pharm.*, 1987, 37(14): 41
- 32 Ritger, P.L. and Peppas, N.A., *J. Control. Release*, 1987, 5(1): 37