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Synthesis and properties of PS–PEO core–shell amphiphilic dendrigrafts

J. Bernard[a], M. Schappacher[a], P. Viville[b], R. Lazzaroni[b], A. Deffieux[a,*]

[a]Laboratoire de Chimie des Polymères Organiques, UMR 5629 CNRS-ENSCPB, Université Bordeaux 1, 16 Avenue Pey Berland, 33607 Pessac Cedex, France
[b]Service de Chimie des Matériaux Nouveaux, Université de Mons-Hainaut/Materia Nova, 20, Place du Parc, 7000 Mons, Belgium

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Abstract

Water-soluble amphiphilic dendrigrafts constituted of a hydrophobic polystyrene core and a hydrophilic poly(ethylene oxide) shell have been prepared via a 'grafting onto' procedure from polystyrene dendrigraft precursors. The introduction of the surrounding hydrophilic shell was achieved through cyclic *trans*-acetalization between ω-acetal functionalized branches of the polystyrene precursor and PEO grafts bearing a α-bis(hydroxymethyl) chain end (A_2-PEO). Yields of grafting are strongly affected by the increase of the degree of polymerization of the reactive PEO grafts (respectively, 100, 87, and 38% with A_2-PEO20, A_2-PEO100 and A_2-PEO150). However, paradoxically, only the use of A_2-PEO100 or A_2-PEO150 as reactive grafts affords water-soluble dendrigrafts due to higher PEO weight content (respectively, 41 and 36%). The dimensions and the shape of the PS_{core}–PEO_{shell} polymers were investigated in solution (THF and water) by dynamic light scattering and in the dry state by TEM and AFM.

Keywords: Core–shell; Dendrigraft; PEO

1. Introduction

Since poly(ethylene oxide) (PEO) is a water-soluble non-toxic polymer widely used in biomedical applications, the preparation of branched amphiphilic core–shell materials constituted of a hydrophobic core and a hydrophilic PEO shell has been extensively investigated.

Grafting PEO chains onto a hydrophobic polymer core or backbone chain can typically be achieved via two different approaches: (1) The 'grafting from' procedure, which consists in growing PEO blocks directly from the core (or backbone) and (2) the 'grafting onto' procedure, which is based on the covalent binding of preformed linear PEO chains to the core.

Following the first approach, graft copolymers with peripheral PEO branches have been prepared from poly(1,3-diisopropenylbenzene) (PDIB) or poly(divinylbenzene) (PDVB) microgel cores [1–3]. The remaining pendant unsaturations were reacted with a stoichiometric amount of cumyl potassium (PDIB cores) or naphthalene potassium (PDVB cores) giving birth to anionic initiating sites for ethylene oxide polymerization. P(1,3-DIB), which exhibits one pendant unsaturated group per repeat unit, was proven to provide a far better control of the functionality compared to PDVB. Elaboration of PS-*b*-PEO amphiphilic arborescent copolymers from hydroxyl-functionalized polystyrene dendrigrafts has also been reported by Gauthier et al. [4]. After activation of the hydroxyl functions with potassium naphthalide, a PEO shell surrounding the hydrophobic PS core was grown. Amphiphilic arborescent copolymers with PEO content ranging from 19 to 66 wt% were thus prepared.

Gnanou et al. described the preparation of dendritic poly(ethylene oxide)s [5] by anionic ring opening polymerization initiated from a trifunctional initiator (trimethylolpropane) activated with diphenylmethylpotassium. The two-step strategy consisted first in growing PEO arms from branching points located at the chain ends, followed by adding a cyclic ketal as functional desactivating agent in order to introduce reactive termini capable after deprotection to reinitiate the polymerization of EO. The synthesis of dendritic PS_6-*b*-PEO_6 and PS_6-*b*-PEO_{12} [6] from hexa-armed hydroxyl-functionalized PS star has also been reported by the same group.

One main drawback of the 'grafting from' procedure lies in the impossibility to characterize precisely the structure of

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* Corresponding author. Tel.: +33 540 00 84 85; fax: +33 540 00 84 87.
E-mail address: deffieux@enscpb.fr (A. Deffieux).

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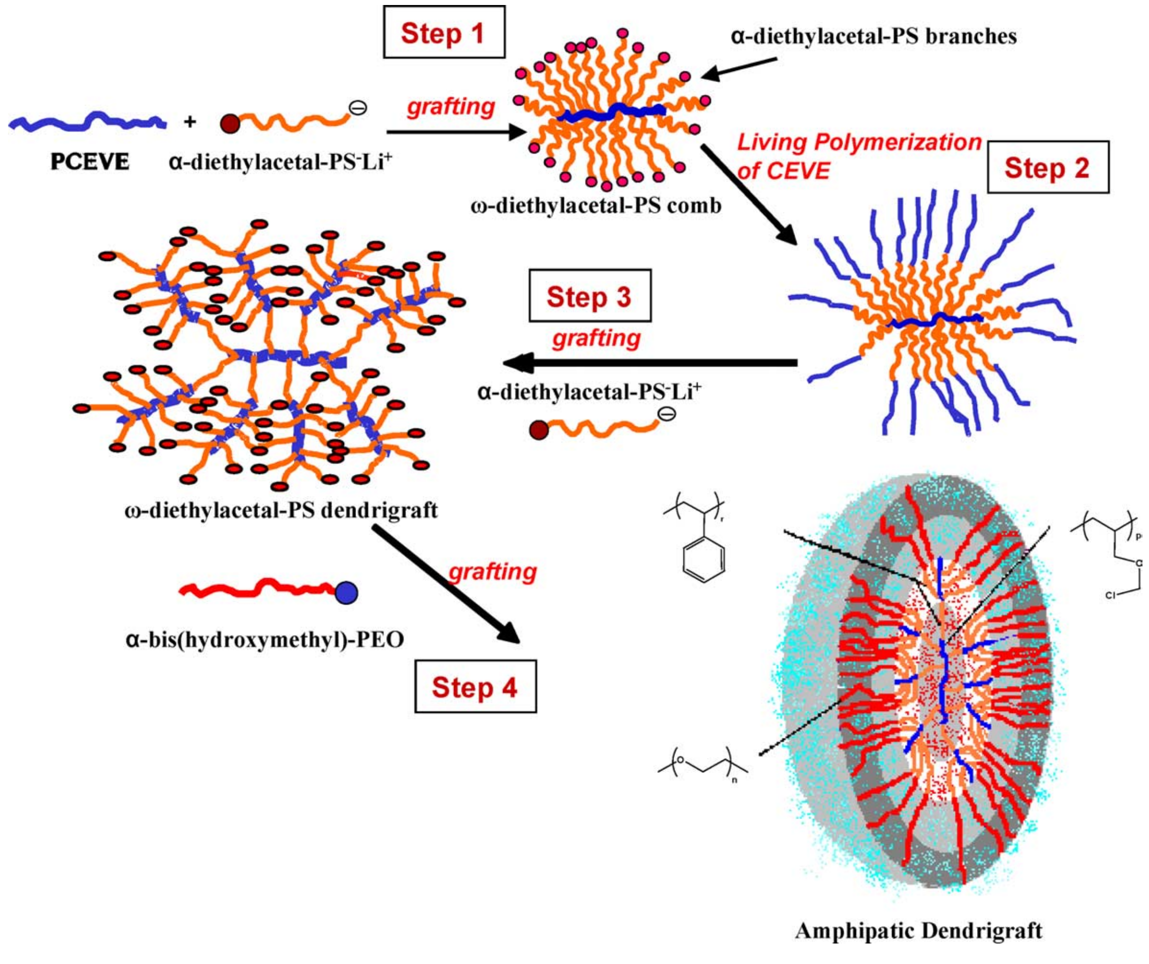
the resulting copolymers since neither the exact number of branches added nor their molar mass can be accurately determined.

Another route to amphiphilic branched polymers containing PEO branches consists in grafting living anionic PEO chains onto reactive functions located on the hydrophobic cores. Compared to the 'grafting from' procedure, this strategy based on the linking of elementary macromolecular blocks allows a more accurate characterization of the resulting copolymers since the building blocks can be characterized separately. Typically, chloromethylated units of polystyrene blocks were used as electrophilic sites for deactivation of living monofunctional poly(ethylene oxide) chains, leading to PS-*g*-PEO combs with a modulable number of PEO branches [7]. The 'grafting onto' procedure can also be carried out via the Decker–Forster reaction by anchoring Schiff's base functionalized PEO onto partially chloromethylated PS [8]. However, in this case the yield of PEO grafting onto PS backbone is not quantitative.

In recent publications, we described a multi-step synthetic procedure (Scheme 1, steps 1–3) that takes advantage of living anionic and cationic polymerizations for the preparation of monodisperse polystyrene dendrigrafts exhibiting well-controlled structural characteristics, dimensions, and shape [9,10] and bearing peripheral reactive groups [11] such as alcohol, acetal,… located at the extremity of PS branches. The presence of acetal termini has been previously exploited to initiate the growth of polyvinyl ether (PVE) blocks, yielding, after deprotection of the vinyl ether units, amphiphilic dendrigrafts constituted of a highly branched hydrophobic PS core surrounded by a hydrophilic PVE shell [12–15]. These dendrigrafts are readily soluble into water and adopt in the solid state a complex internal organization into hard and soft domains corresponding to phase segregation between polystyrene and poly(vinyl ether) blocks. However, the low availability of methyl vinyl ether and other hydrophilic vinyl ethers (hydroxyethyl vinyl ether…) as well as the biocompability and physico-chemical characteristics of PEO encouraged us to investigate the possibility to prepare water-soluble PS-*b*-PEO dendrigrafts from ω-diethyl acetal functionalized PS dendrigrafts.

In this paper, we report a methodology that affords



Scheme 1. Route to amphiphilic dendrigrafts bearing external PS-*b*-PEO chains.

well-defined water-soluble PS-*b*-PEO dendrigrafts via cyclic acetalization of ω-diethyl acetal functionalized PS branches with PEO grafts bearing a α-bis(hydroxymethyl) chain end. The study stresses the influence of the PEO graft length on the grafting yield and the solubility into water of the final amphiphilic dendrigrafts. Molecular characteristics, dimensions, shape, and organization of these PS-*b*-PEO dendrigrafts in solution and in the solid state are also reported.

2. Experimental part

2.1. Materials

Benzene and toluene (99.5%, J. T. Baker, Deventer, The Netherlands) were purified by distillation over calcium hydride and stored over polystyryllithium seeds. Tetrahydrofuran (99%, J. T. Baker, Deventer, The Netherlands) was purified by distillation over calcium hydride, stored over potassium/benzophenone and redistilled under vacuum just before use. Methylene dichloride (99.5%, J. T. Baker, The Netherlands, stabilized with amylene) was used as received.

CEVE (99%, Sigma Aldrich Chimie, St Quentin Fallavier, France) was washed with an aqueous NaOH solution (1 N), distilled twice over calcium hydride and stored under nitrogen in glass flask until use. Styrene (99%, Sigma Aldrich Chimie, St Quentin Fallavier, France) was purified by distillation over calcium hydride at reduced pressure. Chloropropionaldehyde diethyl acetal (95%, Sigma Aldrich Chimie, St Quentin Fallavier, France) and ethylene oxide (99.5%, Sigma Aldrich Chimie, St Quentin Fallavier, France) were purified and stored under nitrogen over calcium hydride.

Potassium (98%, Sigma Aldrich Chimie, St Quentin Fallavier, France) and 1,1,1-tris(hydroxymethyl)propane (97%, Sigma Aldrich Chimie, Steinheim, Germany) were used as received.

2.2. Synthesis

2.2.1. Functional initiators

3-Lithiopropionaldehyde diethyl acetal was prepared from 3-chloropropionaldehyde diethyl acetal as previously described [16].

Isopropylidene-1,1-bis(hydroxymethyl)-1-hydroxymethylpropane (A_2) was synthesized from tris(hydroxymethyl)propane as previously reported [17]. The corresponding potassium alcoolate $A_2^-K^+$ was prepared by addition to A_2 (440 mg of A_2, 2.5×10^{-3} mol) of an excess of potassium (0.2 g, 5×10^{-3}, 2 equiv) in 150 ml of THF. After 24 h at 20 °C, the slightly yellow colored alkoxide ($A_2^-K^+$) solution was filtered in order to eliminate residual potassium and then used as EO polymerization initiator.

2.2.2. Preparation of A_2-functionalized PEO

In a typical example, the α-isopropylidene-1,1-bis(hydroxymethyl)-1-(hydroxymethyl)-propane functionalized PEO grafts were obtained by addition of 11 g of ethylene oxide (0.25 mol) in the $A_2^-K^+$ alkoxide solution (2.5×10^{-3} mol of potassium salt in 150 ml of THF) at 20 °C. After 24 h of polymerization, the PEO chains were deactivated with dry methanol. The resulting polymer A_2-PEO100 was finally recovered by partial solvent evaporation followed by precipitation of the concentrated polymer solution into diethyl ether, dried and finally characterized: 11 g of A_2-PEO100; Yield: 100%; $\bar{M}_\mathrm{n} = 4270\ \mathrm{g\ mol^{-1}}$; $\bar{M}_\mathrm{w}/\bar{M}_\mathrm{n} = 1.06$, $\overline{\mathrm{DP}}_n = 93$.

The hydrophobic core PCEVE$_1$-*g*-(PS$_1$-*b*-(PCEVE$_2$-*g*-(A$_1$-PS$_2$))) 200/50/50/A$_1$-50 ($\overline{\mathrm{DP}}_{n\mathrm{PCEVE1}}/\overline{\mathrm{DP}}_{n\mathrm{PS1}}/\overline{\mathrm{DP}}_{n\mathrm{PCEVE2}}/\overline{\mathrm{DP}}_{n\mathrm{A1-PS2}}$, $A_1 = \alpha$-acetal groups; PCEVE$_1$: $\bar{M}_\mathrm{n} = 21{,}300\ \mathrm{g\ mol^{-1}}$, PDI = 1.09; PS$_1$: $\bar{M}_\mathrm{n} = 5200\ \mathrm{g\ mol^{-1}}$, PDI = 1.03; PCEVE2: $\overline{\mathrm{DP}}_n = 50$; PS2: $\bar{M}_\mathrm{n} = 5200\ \mathrm{g\ mol^{-1}}$, PDI = 1.03) was prepared according to a procedure recently described in detail [11]. The molecular characteristics and dimensions of the hyperbranched polymer used in this study are collected in Table 1.

2.2.3. Poly(ethylene oxide) grafting procedure

A_2-terminated PEOs were grafted to the PS dendrigraft through cyclic *trans*-acetalization [18].

Typically, 5 g of isopropylidene-1,1-bis(hydroxymethyl)-1-(hydroxymethyl)-propane functionalized PEO chains A_2-PEO100 (1.2 mmol) and 2.85 g of hyperbranched 200/50/50/A$_1$50 (0.6 mmol of acetal functions) were dissolved in 150 ml of methylene dichloride. 2 g of $MgSO_4$ and three drops of HCl (12 N) were added to the solution in order to regenerate the α-bis(hydroxymethyl) end groups and promote cyclic acetalization between the functionalized PS branches and the PEO polymer blocks. The mixture was vigorously stirred at room temperature for two days, then filtered and neutralized with NaOH solution. The organic phase was washed twice with 200 ml water and finally dried. After solvent evaporation, the crude polymer was recovered by precipitation into diethyl ether and solubilized in ethanol. The pure PS-*b*-PEO branched dendrigraft was obtained by selective precipitation of residual PEO grafts. This was achieved by progressive addition of butanol in the polymer solution at 4 °C. The procedure was repeated twice.

The pure dendrigraft was dissolved in THF and then dialyzed against pure water (Spectra/Por 7, molecular cut off ca. 1000) for a week.

2.2.4. Polymer characterization

^{1}H NMR spectra were recorded in $CDCl_3$ on a Bruker AC 200 FT apparatus. As the PS$_1$ blocks represent less than 5% wt of the PS dendrigrafts, the yield of PEO grafting was calculated by ^{1}H NMR from the respective proportions of PS$_2$ and PEO blocks.

Size exclusion chromatography (SEC) measurements of

Table 1
Characteristics of the polystyrene dendrigraft (200/50/50/$A_1$50) used as core precursor

Structure	$\bar{M}_w \times 10^{-6}$[a] (g mol^{-1})	$\bar{M}_n \times 10^{-6}$[a] (g mol^{-1})	$\bar{M}_w/\bar{M}_n$	Nber of acetal sites	R_g[a] (nm)	R_h[b] (nm)
Dendrigraft 200/50/50/$A_1$50	38	36	1.05	7600	34.5	34

[a] Measured by static light scattering in THF (d*n*/d*c* = 0.177).

[b] Measured by dynamic light scattering in THF.

PS and PS-*b*-PEO dendrigrafts were performed in tetrahydrofuran (THF) at 25 °C (flow rate 0.7 ml/min) on a Varian apparatus equipped with refractive index (Varian) and laser light scattering (Wyatt Technology) dual detection, and fitted with four TSK gel HXL columns (250, 1500, 10^4 and 10^5 Å). In order to perform light scattering measurements, the d*n*/d*c* of the different arborescent polymers (PS and PS-*b*-PEO dendrigrafts) were determined in THF at 25 °C with a laser source operating at 633 nm. d*n*/d*c* (PS dendrigrafts) = 0.177; d*n*/d*c* (PS-*b*-PEO dendrigrafts = 0.120).

SEC analysis of PS-*b*-PEO dendrigrafts was performed at 25 °C in a water/methanol mixture (v/v 80/20) containing $NaNO_3$ (1.27 g/l) on a Varian apparatus equipped with a refractive index detector and fitted with four TSK PWXL columns (300×7.7 mm^2, 250, 1500, 10^4 and 10^5 Å) at a flow rate of 1 ml/min.

Dynamic light scattering measurements in THF and in water (PS-*b*-PEO dendrigrafts) were performed at 25 °C on a Malvern apparatus (Zetasizer 3000HS) equipped with a laser source (633 nm). Correlation functions were analyzed by the Contin method (number average measurement). Latex particles were used as calibration standards. VPO measurements were performed on a Gonotec Osmomat 090 in toluene.

Samples for atomic force microscopy analysis (AFM) were prepared by solvent casting at ambient conditions starting from solutions of PS-*b*-PEO branched dendrigrafts in MeOH. Typically, 20 μl of a dilute solution (0.2 wt%) was cast on a 1×1 cm^2 freshly cleaved mica or highly oriented pyrolytic graphite (HOPG) substrate. Samples were analyzed after complete evaporation of the solvent at room temperature. All AFM images were recorded in air with a Nanoscope IIIa microscope operated in tapping mode (TM). The probes were commercially available silicon tips with a spring constant of 24–52 N/m, a resonance frequency lying in the 264–339 kHz range, and a typical radius of curvature in the 10–15 nm range. Both the topography and the phase signal images were recorded with the highest sampling resolution available, i.e. 512×512 data points.

Concerning transmission electron microscopy (TEM), a solution (0.5 mg/ml) of core–shell polymer (PS-*b*-PEO dendrigraft) in THF was deposited by spray onto a carbon-coated grid (Pelco). Samples were analyzed after complete evaporation of the solvent at room temperature. All samples were observed using a JEOL-JM-2000FX.

3. Results and discussion

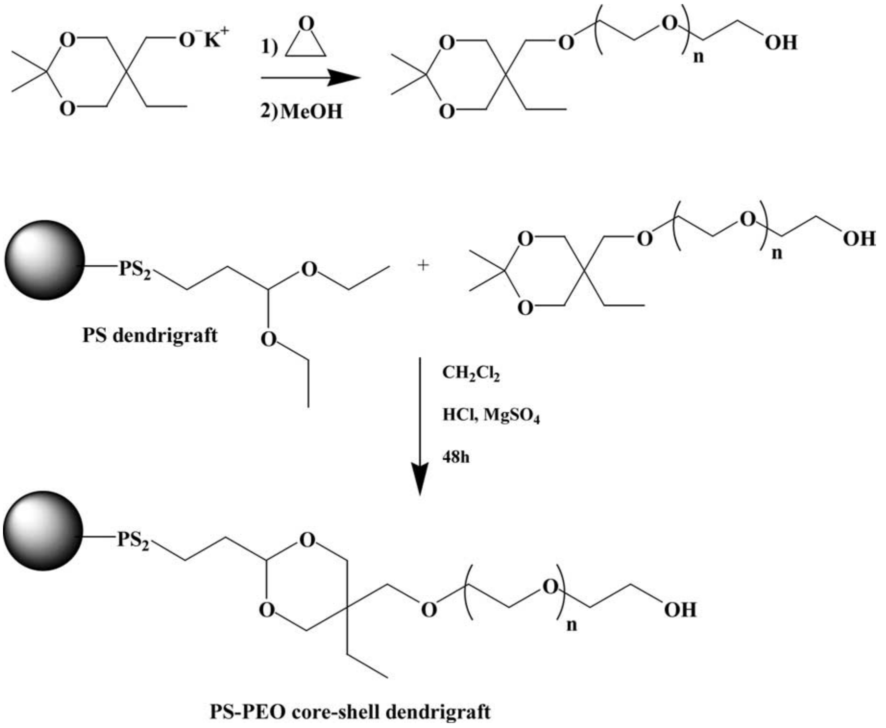
3.1. Synthesis of the amphiphilic dendrigrafts

The synthesis of monodisperse peripherally functionalized arborescent PS bearing α-bis(hydroxymethyl) or acetal terminal groups has been reported in a recent paper [11]. The method is based on the repeated grafting of anionically prepared living α-functionalized polystyryl–lithium chains onto reactive PCEVE blocks (linear or comb-like PCEVE) as described, see Scheme 1 (steps 1–3).

In the present study, a first generation acetal-functionalized dendrigraft PCEVE$_1$-*g*-(PS$_1$-*b*-(PCEVE$_2$-*g*-(A$_1$-PS$_2$))) 200/50/50/A$_1$50 ($\bar{M}_w = 38 \times 10^6$ g mol^{-1}; $\bar{M}_w/\bar{M}_n = 1.05$), see Table 1, has been used as hydrophobic precursor to prepare amphiphilic core–shell PCEVE$_1$-*g*-(PS$_1$-*b*-(PCEVE$_2$-*g*-(PS$_2$-*b*-PEO))) dendrigrafts. PEO blocks were introduced at the periphery of the dendrigrafts by formation of a cyclic acetal linkage between α-bis(hydroxymethyl) functionalized PEO chains and the ω-acetal terminated branches (cyclic *trans*-acetalization) of the PS core, Scheme 2.

In order to preserve the control on the dimensions of the amphiphilic dendrigrafts, α-bis(hydroxymethyl) functionalized poly(ethylene oxide) grafts were prepared by living anionic polymerization using the potassium salt of isopropylidene-1,1-bis(hydroxymethyl)-1-hydroxymethylpropane (A_2') as protected functional initiator, see Scheme 2. EO polymerization was performed in THF at room temperature for 24 h. A series of α-A_2-functionalized PEO grafts with polymerization degree ranging from 20 to 150 were prepared with the aim of evaluating the influence of the PEO graft length on the dimensions and characteristics of the resulting PS$_{core}$–PEO$_{shell}$ dendrigrafts.

The characteristics of the α-functionalized PEO are indicated in Table 2. The molar masses of the functionalized PEO chains were evaluated by SEC in a mixture of water and methanol (80/20, v/v) and by ^{1}H NMR (Fig. 1) from the relative integration of the protons of the PEO backbone (–OCH$_2$–, $\delta = 3.64$ ppm) and the α-isopropylidene-1,1-



Scheme 2. Route to PS–PEO core–shell dendrigraft through cyclic trans-acetalization.

bis(hydroxymethyl)-1-(hydroxymethyl)-propane chain ends (–CH_3–CH_2–, peak f).

As expected for a living anionic process, experimental molar masses evaluated from these two techniques are in good agreement with the theoretical molar masses and the molecular weight distribution of the PEO chains is narrow ($PDI \leq 1.2$).

Anchorage of the PEO grafts (A_2-PEO20, A_2-PEO100 or A_2-PEO150) on the PS core (200/50/50/$A_1$50) was carried out in one step under acidic conditions (HCl) by addition of an excess of α-A_2-functionalized PEO (2 equiv per acetal group) in a methylene dichloride solution containing the PS dendrigraft (Scheme 1, step 4), leading to the formation of amphiphilic dendrigrafts (D = **I**, **II** and **III**). The excess of α-A_2-functionalized PEO grafts was finally removed by selective precipitation in a cold ethanol/butanol mixture until complete purification of the dendrigraft copolymer. The SEC chromatograms of the crude and purified dendrigrafts confirmed the unimodal distribution and narrow molar mass distribution of the PS_{core}–PEO_{shell} dendrigrafts ($PDI \leq 1.15$ for **I** and **II**), see Fig. 2. Surprisingly, contrary to **I** and **II**, the PDI of **III** was found to be quite broad ($PDI = 1.62$) likely due to aggregation phenomena.

The introduction of a surrounding hydrophilic PEO shell by this ‘grafting onto’ procedure was confirmed by the increase of the hydrodynamic radius from 34 nm (for the 200/50/50/A_1-50 core) to 42 and 43 nm (respectively, for dendrigrafts **II** and **III**), observed by dynamic light scattering in THF.

The main characteristics of PS_{core}-*b*-PEO_{shell} amphiphilic dendrigrafts are given in Table 3. On the basis of the PS precursor ($\bar{M}_w$, $\overline{DP}_{nPS_2}$, number of external branches) and PEO grafts characteristics determined separately ($\overline{DP}_{nPEO}$),

Table 2
Characteristics of the α-A_2-functional PEO blocks

Reference	A_2-PEO20	A_2-PEO100	A_2-PEO150
$\overline{DP}_{n\,th}$	20	100	150
$\overline{DP}_{n\,exp}$ (^{1}H NMR)[a]	22	95	166
$\overline{DP}_{n\,exp}$ (SEC)[b]	18	93	153
$\overline{DP}_{n\,exp}$ (VPO)[c]	Not determined	Not determined	145
PDI[b]	1.22	1.06	1.13

[a] ^{1}H NMR analysis performed in $CDCl_3$.

[b] Determined by SEC in Water/MeOH (80/20, v/v).

[c] VPO analysis performed in toluene.

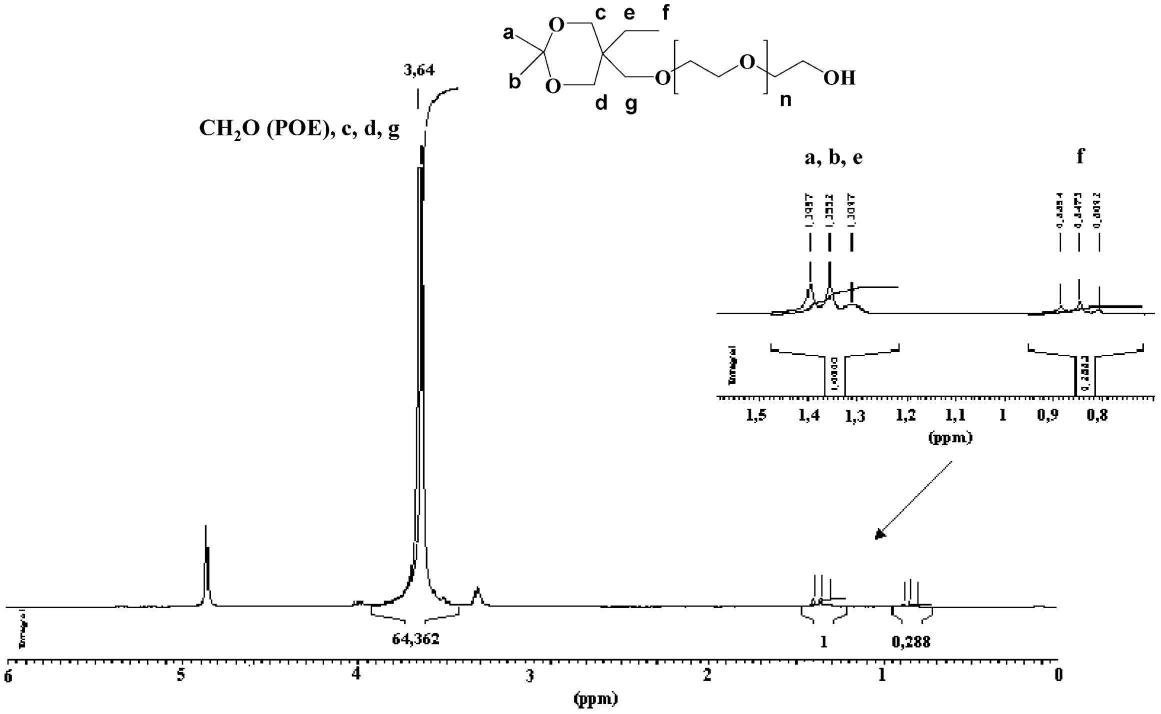


Fig. 1. 200 MHz ^{1}H NMR spectrum of α-isopropylidene-1,1-bis(hydroxymethyl)-1-(hydroxymethyl)-propane–PEO (A$_2$-PEO150; $\overline{DP}_{n\exp} = 166$) in CDCl$_3$.

an estimate of the PEO grafting yield was determined by ^{1}H NMR from the relative integration of PS aromatic (5H) and –OCH$_2$– PEO protons (4H), see Fig. 3. It also enabled to evaluate the average molar mass of the core–shell dendrigrafts. Knowing the molar mass of the PS core precursor and assuming that the contribution of vinyl ether units is negligible, we can write

$$\bar{M}_n(\mathrm{D})_{\mathrm{NMR}} = \bar{M}_{\mathrm{nPS_{core}}} \times \left(1 + r \times \frac{m_{\mathrm{EO}}}{m_{\mathrm{S}}}\right)$$

with $r = (I_{\mathrm{OCH_2}}/4)(I_{\mathrm{Ph}}/5)$, I_{OCH2} ^{1}H NMR integration of –OCH$_2$– groups and I_{Ph} ^{1}H NMR integration of PS aromatic protons, m_{EO} and m_{S}, molar masses of EO and styrene units.

The calculated molar masses of the PS-*b*-PEO dendrigrafts ($\bar{M}_n(\mathrm{D})_{\mathrm{NMR}}$) are in relatively good agreement with those measured by static light scattering in THF. The yield of PEO grafting was finally determined from the relation:

$$\text{Grafting yield} = \frac{\bar{M}_{\mathrm{w}}(\mathrm{D}) - \bar{M}_{\mathrm{w}}(\mathrm{PS_{core}})}{\bar{M}_{\mathrm{w\ th}}(\mathrm{D}) - \bar{M}_{\mathrm{w}}(\mathrm{PS_{core}})} \times 100$$

where $\bar{M}_{\mathrm{w\ th}}(\mathrm{D})$ and $\bar{M}_{\mathrm{w}}(\mathrm{D})$ are, respectively, the theoretical molar mass, assuming quantitative PEO grafting, and the experimental molar mass of dendrigrafts (D).

The coupling efficiency of the α-functionalized PEO chains to ω-terminated PS branches was found to strongly depend on the polymerization degree of the A$_2$-PEO grafts. Indeed, while the introduction of short PEO blocks ($\overline{DP}_{n\exp} = 22$) allowed quantitative trans-acetalization of A$_1$ acetal groups (100%) of the PS precursor, the yield of PEO grafting dropped to 87 and 38% (with respect to PS acetal groups) in the presence of A$_2$-PEO100 and A$_2$-PEO150, likely due to the increasing steric hindrance and lower accessibility of the reactive functions. However, increasing the peripheral density of hydrophilic grafts by grafting shorter PEO chains does not seem to be a successful

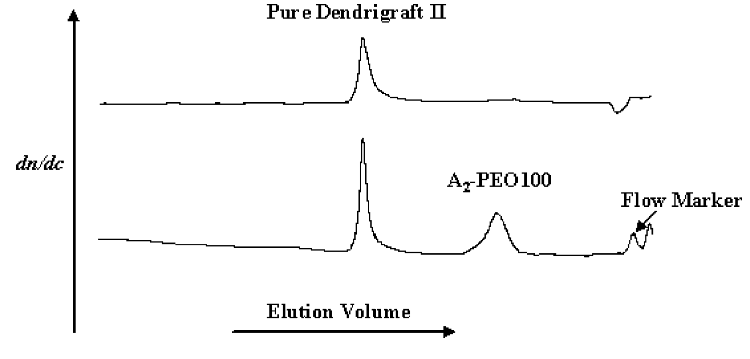


Fig. 2. SEC in water/methanol solvent mixture of dendrigraft **II** before (bottom) and after selective precipitation (top) of the excess A$_2$-PEO100 chains.

Table 3
Dimensions and solution characteristics of $\mathrm{PS_{core}}$–$\mathrm{POE_{shell}}$ amphiphilic dendrigrafts

Reference	I	II	III
Precursor	200/50/50/$\mathrm{A_1}$/50	200/50/50/$\mathrm{A_1}$/50	200/50/50/$\mathrm{A_1}$/50
PEO graft	$\mathrm{A_2}$-PEO20	$\mathrm{A_2}$-PEO100	$\mathrm{A_2}$-PEO150
$\bar{M}_{\mathrm{n\ NMR}} \times 10^{-6}$ (g mol^{-1})[a]	45	65	59
$\bar{M}_{\mathrm{w\ SLS}} \times 10^{-6}$ (g mol^{-1})[b]	Not measured	60	67
$\bar{M}_{\mathrm{w\ th}} \times 10^{-6}$ (g mol^{-1})[c]	45	71	94
$\bar{M}_{\mathrm{w}}/\bar{M}_{\mathrm{n}}$[d]	1.10	1.13	1.62
% of acetal modified functions (^{1}H NMR)[e]	100	87	38
% of acetal modified functions (SLS)[f]	Not measured	81	51
PEO content (wt%)[a]	16	41	36
R_{h} in THF (nm)[g]	33	42	43
Water solubility[h]	No	Yes	Yes
R_{h} in water (nm)[i]	Not measured	31	30

[a] Calculated from the relative integration of PS and PEO protons by ^{1}H NMR measurements in $\mathrm{CDCl_3}$.

[b] SLS measurements performed in THF.

[c] Calculated with the hypothesis of quantitative PEO grafting from the relation $\bar{M}_{\mathrm{w\ th}} = \bar{M}_{\mathrm{w}}(200/50/50/\mathrm{A_1}50) + [(\bar{M}_{\mathrm{n\ PEO}}/M_{\mathrm{n\ PS2}}) \times (M_{\mathrm{w}}(200/50/50/\mathrm{A_1}50) - M_{\mathrm{w}}(200/50/50))]$.

[d] Measured by SEC in a mixture MeOH/water (80/20, v/v).

[e] Measured by ^{1}H NMR in $\mathrm{CDCl_3}$.

[f] Calculated from the relation: $\% = [\bar{M}_{\mathrm{w}}(\mathrm{D}) - \bar{M}_{\mathrm{w}}(\mathrm{PS\ Core})]/[\bar{M}_{\mathrm{w\ th}}(\mathrm{D}) - \bar{M}_{\mathrm{w}}(\mathrm{PS\ Core})] \times 100$.

[g] Measured by dynamic light scattering (DLS) in THF.

[h] Dialysis against pure water.

[i] Measured by dynamic light scattering in water.

approach to preparing water-soluble dendrigrafts. As can be seen in Table 3, although dendrigrafts **I** (obtained with $\mathrm{A_2}$-PEO20) exhibited quantitative introduction of peripheral hydrophilic blocks, the resulting PEO weight content appears to be too low (about 16% in weight of the total dendrigraft) to balance the hydrophobicity of the PS core, leading consequently to a very poor solubility of **I** in water. On the contrary, the use of longer PEO grafts ($\mathrm{A_2}$-PEO100 or $\mathrm{A_2}$-PEO150), which resulted in an incomplete cyclic acetalization of the aldehyde groups (respectively, 87 and 38%), affords core–shell dendrigrafts (**II** and **III**) with higher PEO weight content (about 40%). As a consequence, both core–shell polymers were soluble in common organic solvents and in water. The stabilization of amphiphilic PS-*b*-PEO dendrigrafts exhibiting only 40% PEO weight content (60% of hydrophobic PS or PCEVE) in water can be

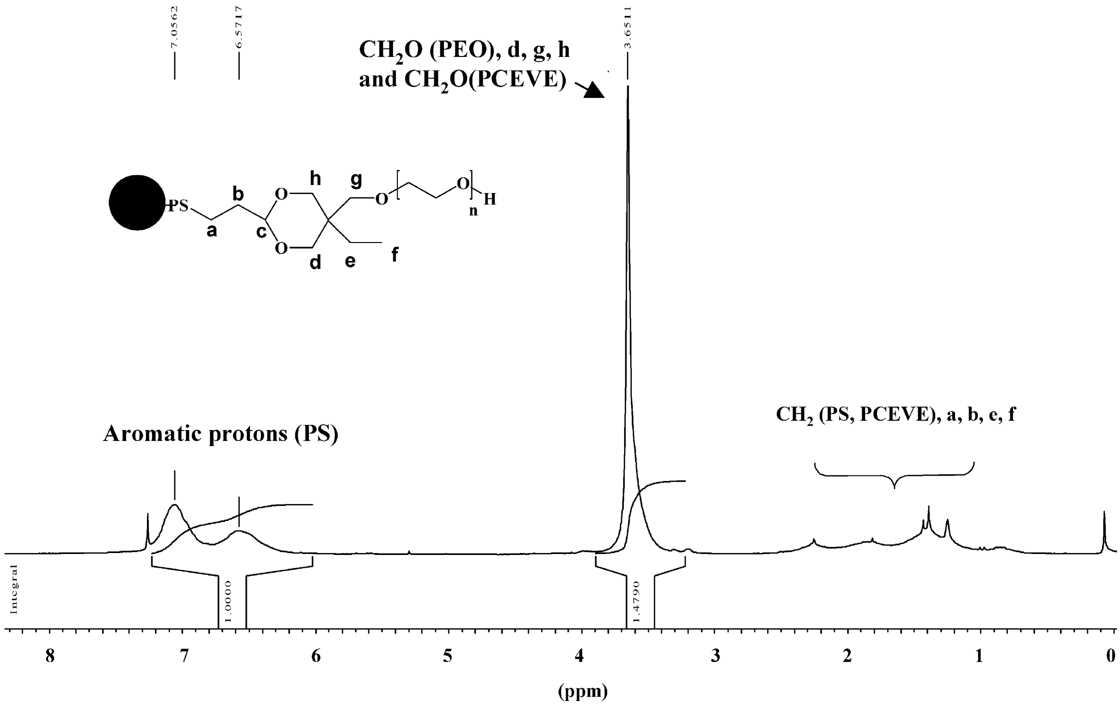


Fig. 3. 200 MHz ^{1}H NMR spectrum of dendrigraft **II** in $\mathrm{CDCl_3}$.

related to the core–shell structure of the dendrigrafts. Due to the amphiphilic core–shell structure of the polymers, solubilizing **II** or **III** in water significantly affected their dimensions in solution (R_h). In spite of the solvation of the PEO blocks, which ensures the water solubility of the amphiphilic dendrigrafts, the R_h values of the two water-soluble dendrigrafts drastically decreased from 42 to 43 nm (**II** and **III**) in THF to 31 and 30 nm (**II** and **III**) in water, as shown in Fig. 4. This can be explained by an extreme contraction of the PS core in water and possibly by a lower expansion of the PEO shell in water than in THF.

3.2. Microscopy analysis (TEM, TMAFM)

The shape and the size distribution of the dendrigrafts (**II** and **III**) were further investigated in the solid state by transmission electron microscopy (TEM). As shown in Fig. 5, dendrigrafts were relatively monodisperse in size confirming the SEC results. The average dendrigraft size (Φ_n) determined by TEM were on the order of 45–50 and 50–60 nm for **II** and **III**, respectively. One has to stress the lower values observed by TEM compared to DLS data ($\Phi_h = 84$ and 62 nm (**II**) and 86 and 60 nm (**III**) in THF and in water, respectively), which is likely due to the fact that microscopic analysis are performed in the dry state on non-swollen objects.

The nanoscale organization of the dendrigrafts **II** in thin solid deposits was further studied by tapping-mode atomic force microscopy (TMAFM). Two different substrates, mica (hydrophilic) and graphite (hydrophobic) were used to investigate how the interactions between the substrate and the core–shell polymer affect the surface organization of the macromolecules.

Deposits on mica from dilute solutions of **II** generated a homogeneous morphology consisting of a single layer of densely-packed molecules, which locally assemble in a hexagonal arrangement (Fig. 6). Dendrigrafts **II** appeared as almost spherical structures exhibiting a narrow size distribution, in agreement with TEM pictures and the low polydispersity index measured in solution by SEC. The average diameter size ($\Phi_n = 40$ nm) of **II** measured by AFM is consistent with the values obtained by TEM (45–50 nm). From a cross-section analysis, the measured height of the monolayer ($h = 31$ nm, not shown here) revealed a slight flattening of the dendrigrafts on the mica, likely due to the strong affinity of the PEO shell towards the hydrophilic mica surface. The diameter values obtained from TEM and AFM microscopy are in very good agreement with data calculated from experimental molar masses assuming an average specific density of 1 g/cm^3 for the polymer ($\Phi \approx 40$ nm).

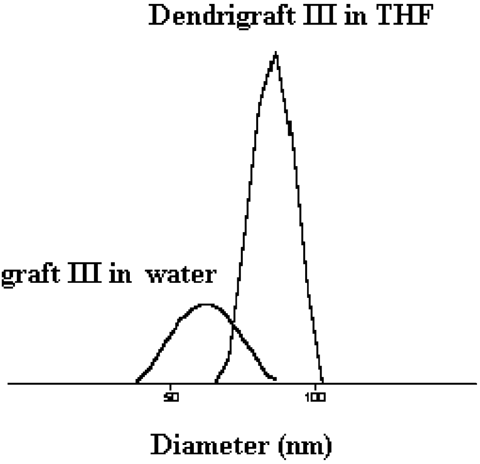


Fig. 4. Influence of the solvent on the hydrodynamic radii of amphiphilic dendrigraft **III** determined by DLS.

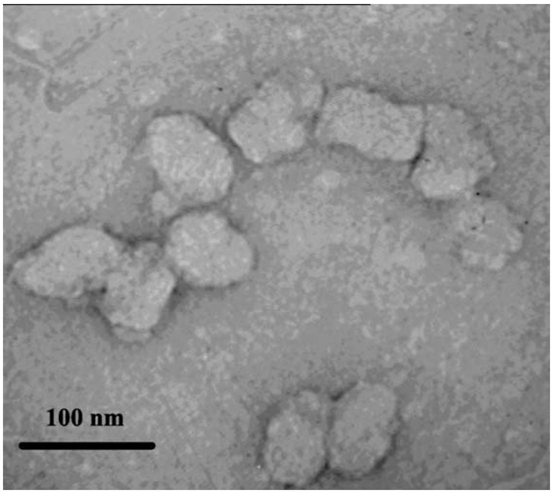


Fig. 5. TEM pictures of **III** on C/Cu grids.

Compared to the deposits on mica, casting the amphiphilic dendrigrafts on hydrophobic substrate (HOPG) led to the formation of a much more heterogeneous multilayered organization (Fig. 7), which is probably a direct consequence of the very poor affinity of the dendrigraft periphery towards the hydrophobic graphite surface and confirms indirectly the presence of the external PEO hydrophilic shell. In this case, the molecules are indeed poorly organized and no hexagonal packing could be found. The height of individual molecules could be measured at the periphery of the multilayer deposit (for instance, the molecules pointed by the white arrows in Fig. 7). Their profile ($h = \sim 40$ nm) indicates that, contrarily to the deposits on mica, the molecules are not flattened. This is also a good indication of the poor affinity of these molecules towards the graphite surface.

In both cases (mica and graphite), contrarily to PS–PVE-based water-soluble amphiphilic dendrigrafts [12] described in a previous paper, no internal organization in distinct subdomains (which may result from segregation of PS and PEO blocks inside each molecule), could be observed here. As an example, the right inset in Fig. 6 shows a high

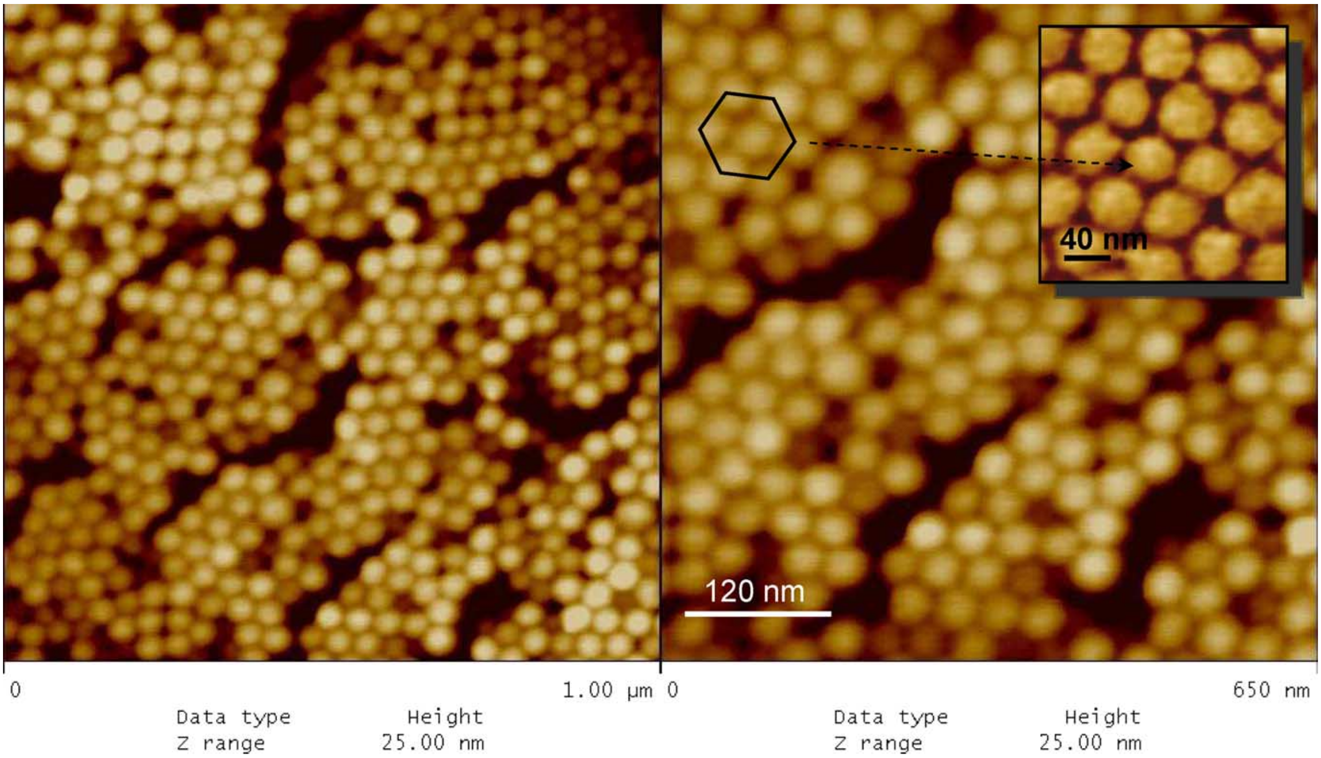


Fig. 6. Tapping mode AFM height images (1×1 µm^2, left) and (650×650 nm^2, right) of a monolayer of the dendrigraft **II** obtained from a 0.2 wt% methanol solution deposited on mica. The right (200×200 nm^2) inset is a phase image of the molecules that shows the absence of internal phase separation within the molecules.

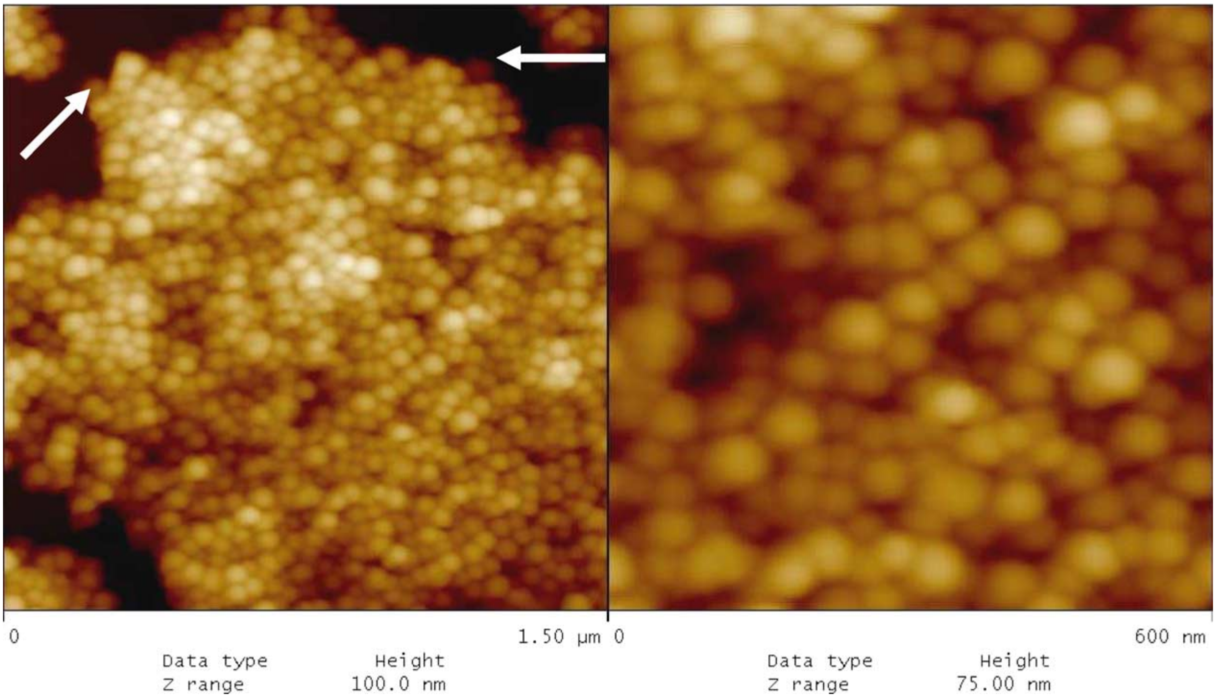


Fig. 7. Tapping mode AFM height images (1.5×1.5 µm^2, left) and (600×600 nm^2, right) of the multilayer morphology obtained from a 0.2 wt% methanol solution of dendrigraft **II** deposited on graphite.

resolution phase image of individual molecules of dendrigraft **II**. This can be attributed to the fact that the length of POE chains and their density is not sufficient for the formation of separated domains.

4. Conclusions

A series of core–shell amphiphilic dendrigrafts constituted of a hydrophobic polystyrene core and a hydrophilic poly(ethylene oxide) shell have been synthesized through a 'grafting onto' procedure involving a cyclic trans-acetalization reaction between ω-acetal functionalized branches of a hyperbranched polystyrene core precursor and PEO grafts bearing a α-bis(hydroxymethyl) chain end (A_2-PEO).

The degree of polymerization of the reactive PEO grafts (A_2-PEO20, A_2-PEO100 and A_2-PEO150) has a strong impact on the grafting yield, the PEO weight content of resulting dendrigrafts and consequently their solubility in water.

The characterization of dendrigrafts **II** and **III** both in organic solvent and in water confirms the synthesis of monodisperse nanometer-sized water-soluble dendrigrafts. The ability of these amphiphilic core–shell polymers to complex and transport active hydrophobic molecules in aqueous media will now be evaluated.

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