TOWARDS THE SINTHESIS OF BLOCK COPOLYMERS USING OXOAMMONIO SALTS

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A new, simple and robust approach to functionalize polymers hydroxyl terminated with nitroxide moieties using oxoammonium salts (Br-TEMPO) under mild conditions is addressed. A reaction mechanism is proposed. The formation of peroxidic bonds was confirmed and quantified by titration finding moderate functionalization efficiencies (~50%). Functionalized polymers were used like macroalkoxyamines to produce block copolymers (PDMS-b-PSt). ^{1}H-NMR and TEM analyses support our findings.

Introduction Great interest has been focused on end-functional polymers as prepolymer for the synthesis of block and graft copolymers, polymer networks, and chain-extended polymers[1]. Particularly, few works[2] have explored the synthesis of block copolymers of polydimethylsiloxane-*block*-polystyrene (PDMS-b-PSt), or polyethylenglycol-*block*-polystyrene (PEG-b-PSt) using prepolymer of PDMS or PEG as a macroinitiator in the presence of nitroxide radicals and styrene monomer (St). On the other hand, considerable efforts have been committed for the synthesis of this kind of block copolymers: i) some approaches involve first the chemical modification of PDMS[3] or PEG[4] with azo-initiator moieties obtaining thus a macroinitiator, in order to form PDMS-b-PSt or PEG-b-PSt in the presence of MTEMPO (4-methoxy-2,2,6,6,tetramethylpiperidine-1-oxyl) and St; ii) anionic ring-opening polymerization in combination with nitroxide chemistry have been used in the synthesis of hexamethylciclotrisiloxane-styrene diblocks[5]; iii) The modification of a PDMS (previously synthesized by anionic polymerization) with a difunctional allyl ether[6], derivative of a difunctional initiator developed by Hawker[7]. These macroalkoxyamines in the presence of St leads to PDMS-b-PSt, in which the growth to the PSt block was controlled by nitroxide radicals. All these efforts involve both ingenious structures and numerous synthesis pathways.

On the other hand, nitroxides are free stable radicals that in presence of the judicious choice of a counter-ion could lead to oxoammonium salts (OS). This kind of salts, are powerful, selective and nonmetallic oxidants used extensively used for the oxidation of primary and secondary alcohols to aldehydes and ketones, respectively[8]. Amines, phosphines, phenols, and anilines have also been oxidized using OS[9]. Several scientific studies using OS as oxidants have been developed until our days[10] since Golubev et al.[11] reported for the first time the use of these salts as oxidant agents. However, we have found that not only are OS excellent oxidant agents but that, in the presence of a basis (triethylamine, Et_3N), the chemistry of oxidation radically changes towards chemistry of functionalization, which is not a trivial result. Thus, on this basis, in principle, any substrate, molecule or chemical compound containing hydroxyl groups could be functionalized with nitroxide moieties.

In summary, few strategies of synthesis have been developed in order to obtain block copolymers to PDMS-b-PSt or PEG-b-PSt, using macroinitiators containing nitroxide moieties however, these novel approaches involves numerous synthetic pathways and sophisticated methods of purification. In this work, we show a simple, robust and general approach about to the functionalization of polymers hydroxyl terminated, (PDMS, PEG) using for first time OS (Br-TEMPO) in the presence of Et_3N in solution. The functionalization processes was carried out using only one synthetic pathway, finding modest levels of functionalization measured by titration. Notice that as far we know the OS has not been used before for this end in polymers. Also, we demonstrated the chain extension polymerizing St towards the synthesis of block copolymers (PDMS-*b*-PSt) controlling the length to the second block by the nitroxide radical.

Experimental Part. Poly(dimethylsiloxane) hydroxy terminated (PDMS-OH, Mn = 15407 Da, PDI = 2), 2,2,6,6-tetramethylpiperidine-N-oxyl (TEMPO), carbon tetrachloride anhydrous (CCl_4), bromine, dichloromethane (CH_2Cl_2), triethylamine (Et_3N, 99.5%), deionized water, potassium iodide (KI), sodium thiosulfate, starch, sulphuric acid (H_2SO_4), styrene monomer (St, 99.9%) were purchased from Aldrich, and methanol from J. T. Baker. All the reagents were used as received except St which was distilled under vacuum before use.

Instrumentation. ^1H NMR spectroscopy was performed on a FT-NMR Jeol Eclipse 300 MHz Spectrometer at room temperature using $CDCl_3$. FT-IR spectra were measured with a Nexus 470 Spectrometer over 4000-400 cm^{-1} using 34 scans and 4 cm^{-1} of resolution. Gel permeation chromatography (GCP) was measured in an Alliance 2695 coupled to a Waters 2414 IR detector, with standard columns covering the range 1 310–3 114 000 Da, using thetrahydrofuran like eluent at a 1 $mL.min^{-1}$ flow rate.

Synthesis of 1-Oxo-2,2,6,6-tetramethylpiperidine Bromide (Br-T)

Synthesis of Br-T salt was reported by our group before[12]. In a typical experiment bromine (0.032 mol) was added slowly to a solution of TEMPO (0.032 mol in 100 mL of CCl_4). A dark red solid was formed almost instantaneously and was separated from the solution by filtration. The filtrate was exhaustively washed with CCl_4. The Br-T was dried over vacuum at room temperature for 24 h. ^1H NMR ($CDCl_3$): δ = 2.3–2.7 (m, 6H), 1.7–2.0 (s, methyl, 12H).

PDMS-OH functionalization with TEMPO using Br-T salt.

Polymers hydroxyl terminated were dissolved using a small amount of dichloromethane into a glass vial under inert atmosphere and magnetic stirring. After that, a solution of Br-TEMPO/dichloromethane was added. The functionalization reaction proceeded during 24h at 40°C. The functionalization reaction conditions are showed in Table 1.

Table 1. Functionalization of polymers hydroxyl terminated using Br-TEMPO salt. Reaction conditions

Tag	Substrate / (g)	Mn (Daltons)	-OH feasible (mol)	Br-TEMPO (mol)	Et_3N (mol)	CH_2Cl_2 (mL)
PDMS1-T	PDMS / 10	4000	0.0050	0.015	0.026	20
PDMS2-T	PDMS / 1	500	0.0036	0.007	0.008	2.6
PEG1-T	PEG / 1	600	0.0033	0.006	0.008	2.6
PEG2-T	PEG / 1	400	0.0033	0.010	0.012	2.3

For the first experiment, 10 g (see Table 1) of liquid sample (0.00064 mol of -OH groups corresponding to 0.00032 mol of chains) of PDMS were placed in a reactor equipped with magnetic stirred in the presence of Et_3N (0.026 mol). After that, a solution of Br-T (0.015 mol / 7 ml of CH_2Cl_2) was added dropwise. The functionalization reaction proceeded at room temperature during 24 h. The functionalized polymers with TEMPO were exhaustively washed with deionizer water (4 times, until the water does not present color) in order to remove the bromohydrate ($HBrEt_3N$) formed, which was dried and quantified. After that, the functional polymer was purified by silica gel chromatography (CH_2Cl_2) in order to remove water remains and non reacted Br-T salt. Finally, a light yellow product was recovered and dried to remove residual solvent using vacuum at room temperature for 24 h. All products were analyzed by ^1H NMR, TEM and SEM.

Peroxide groups titration

Qualitative test: 0.1 g of functionalized polymer was added at one solution of 0.1 g of KI in 5 mL of deionized water in acid media (1 drop of H_2SO_4) previously prepared in a glass baker. Instantaneously the clear solution changed to light yellow color, indicating the presence of ionide, due to the reaction between peroxide groups and KI. A control sample was prepared a similar way using PDMS, which does not present any coloration.

Quantitative test: The amount of peroxide groups per grams of sample was carried out by titration of iodine groups. 0.5 g of functional polymer was dissolved in a glass funnel in the presence of 20 mL of solution of acetic acid in chloroform (3:2) and 1 mL of saturated solution of KI under nitrogen stream under stirring during 1 min. After that, the stirring was stopped and the solution was protected to the light at room temperature during 15 min. Then, 25 mL of deionized water was added under stirring to dissolve the iodine formed in the aqueous phase. After that, five drops of solution of starch were added to the solution like indicator producing a dark color. The dark solution was titrated using a solution of sodium thiosulfate (0.01 N) until to obtain a solution colorless.

Results and Discussion. The new and simple synthetic route to obtain functionalized polymers with TEMPO moieties using Br-TEMPO salts is shown in Scheme 1.

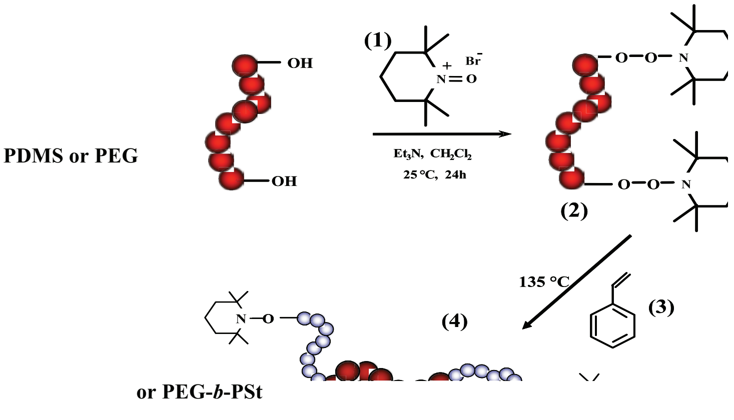
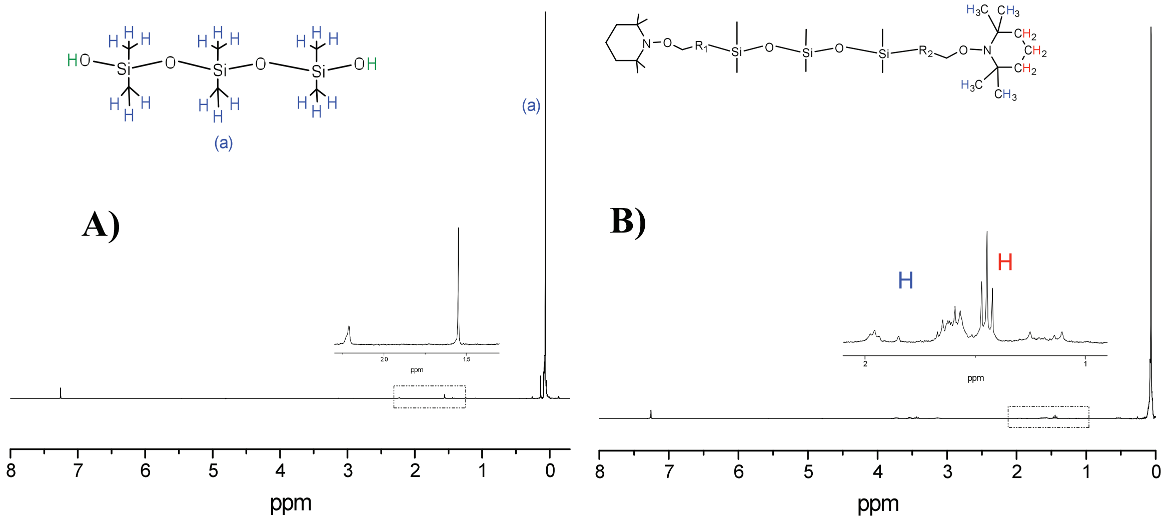


Figure 1. Schematic representation of the functionalization of polymers hydroxyl terminated (PDMS or PEG) with TEMPO mediated by oxoammonium bromide salt and their use like difunctional macroalcoxyamine in the synthesis of block copolymers (PDMS-b-PSt)

The reaction mechanism to obtain **(2)** involves a nucleophilic substitution mechanism by a free-radical process. In this reaction it is proposed that the hydroxyl groups at the end-chain of the polymer are potential sites for attack by a nucleophile such as bromine. This strategy takes advantage of the inherent existence of an equilibrium in **(1)** between the salt and radical species (bromine and TEMPO) which has been proposed previously.[12] In this way, a bromine radical is produced from **(1)**, which abstract a hydrogen atom from hydroxyl group to generate hydrobromic acid (HBr) and an oxygen-centered radical site[13] at the end of the chain, which is then quickly capped by the nitroxide radical to form **(2)**. The HBr formed during this synthesis is trapped by Et_3N to form triethylamine hydrobromide (Et_3NHBr). In a second stage, a block copolymer is formed using **(2)** in the presence of St in solution (toluene) at 135°C during 48h. Figure 2 shows ^{1}H-NMR spectra corresponding to: A) PDMS virgin (without modification); B) PDMS-T (PDMS functionalized with TEMPO), and C) PEG virgin and PEG1-T



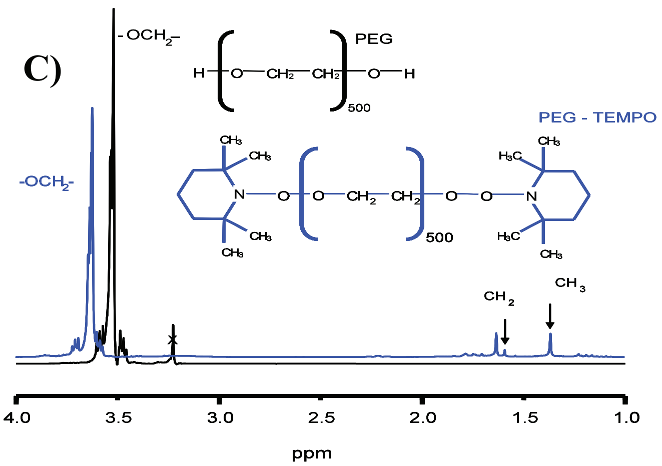


Figure 2. ^{1}H-NMR spectra corresponding to A) PDMS virgin and B) PDMS functionalized with TEMPO moieties, and C) Comparatives resonances of PEG virgin (Mn=600 Da) and PEG functionalized with TEMPO using oxoammonium bromide salt, PEG1-T)

Typical chemical shifts from PEG which exhibits centered resonances at 3.53 ppm attributable to two protons of -OC**H₂**- from PEG structure. New resonances (blue line) at 1.36 ppm and 1.63 ppm were attributed to $-CH_3$ and $-CH_2-$ from TEMPO, respectively. Resonances centered at 3.62 ppm were observed and attributed to -OC**H₂**- from PEG-TEMPO. Notice that this resonance corresponds to the backbone from PEG and is shifted due at the presence of a new covalent bond between TEMPO and PEG. Similar chemical shifts were observed in the functionalization of PDMS with TEMPO (not showed here) using OS. The efficiencies of functionalization obtained by titration with iodine, which is selective to peroxide groups, oscillated between 35 to 50%; for all cases showed in Figure 2, the efficiency obtained by titration was nearly to 50%, which suggest that at least one –OH group per each polymeric chain was functionalized with TEMPO moieties.

Chain extension (block copolymer) was carried out to confirm our findings. In this case, we used PDMS1-T (48% efficiency of functionalization) and St dissolved in toluene. The reaction of copolymerization was carried out at 135°C during 48h under inert atmosphere. Figure 3 shows the ^{1}H-NMR spectra corresponding to block copolymer of PDMS-b-PSt

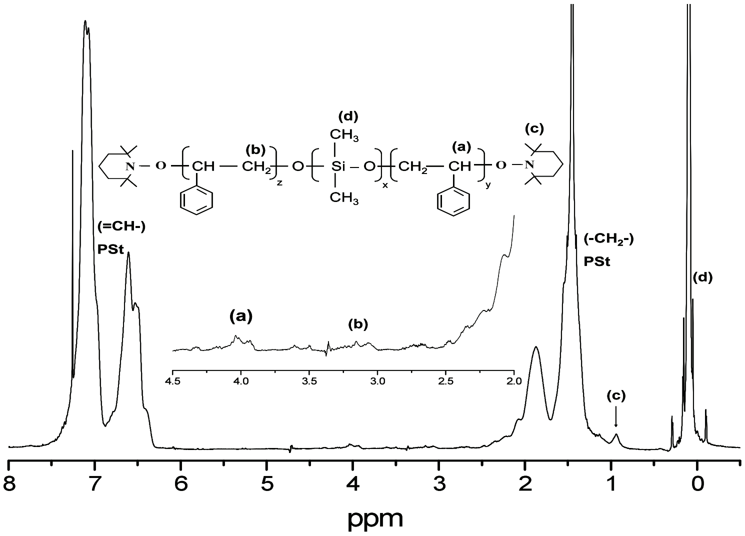


Figure 3. ^{1}H-NMR spectra corresponding to PDMS-b-PSt

Resonances centered at 4 ppm **(a)** were attributed to the proton of the carbon were the nitroxide is attached at the PSt chain. Chemical shifts at 3.1 ppm **(b)** were attributed to -CH_2- from PSt block, which are bonded to PDMS block. Resonances at 0.9 ppm **(c)** were attributed to –CH_3 from TEMPO. All new resonances are consistent according to the literature[6].

TEM Analysis. Figure 4 shows TEM micrographs.

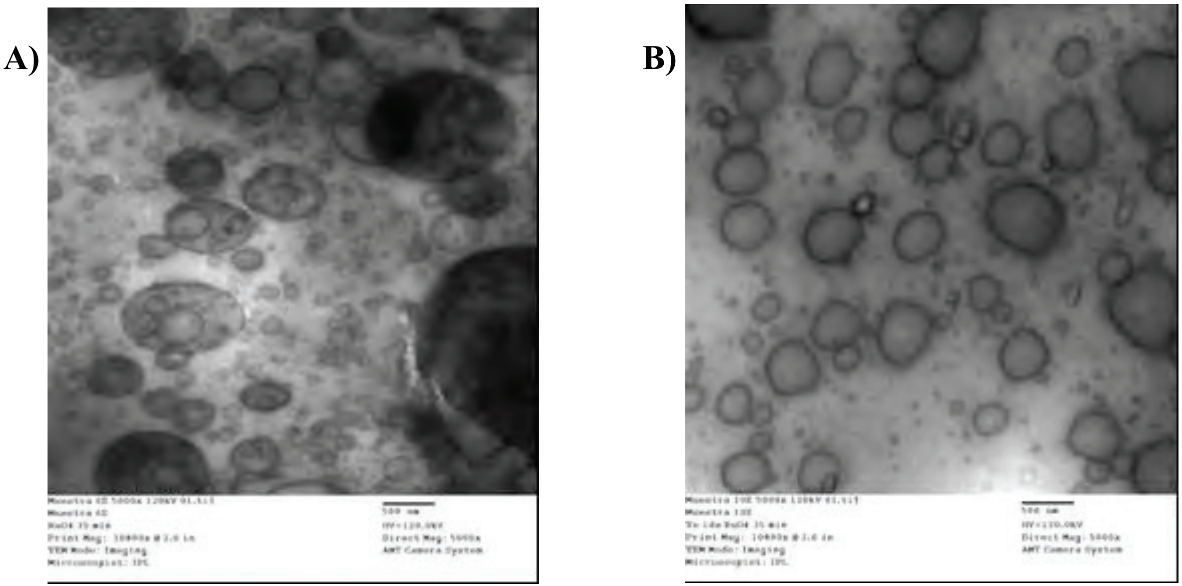


Figure 4. PDMS-*b*-PSt Vesicles. A) Sample disolved in $CHCl_3$ and exposed at toluene vapors, B) Sample disolved in $CHCl_3$. All samples were staining with RuO_4.

Block copolymer vesicles can be prepared in solution, in this case using organic solvents. Speculatively, TEM results suggest the formation of micelles or vesicles. The dark face corresponds to PSt block stained with RuO4 and the white face corresponds to PDMS block. More detail about this analysis will be offered during the congress.

Conclusion

In summary, the use of the chemistry of oxoammonium halogen salts in the functionalization of polymers has not been reported before. In this work, for the first time, we functionalized polymers with TEMPO moieties using OS (Br-TEMPO). The results suggest that: i) the OS are strong candidates for the functionalization of polymers containing hydroxyl groups. This new approach of synthesis opens up several possibilities of potential applications in the generation of novel materials (copolymers) following a facile chemistry pathway. ii) the efficiency of functionalization was significantly improved: 1) with temperature (40°C), and 2) using 200 mol.-% of Br-TEMPO, finding modest to high efficiencies of functionalization, iii) we provide spectroscopic evidences by ^{1}H-NMR to the functionalization of PEG with TEMPO and was quantified the presence to the peroxidic bond by titration; iv) it was confirm by ^{1}H-NMR and TEM the possibility of synthesize block copolymers using OS.

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