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Preparation and Characterization of Persistent Maltose-Conjugated Triphenylmethyl Radicals

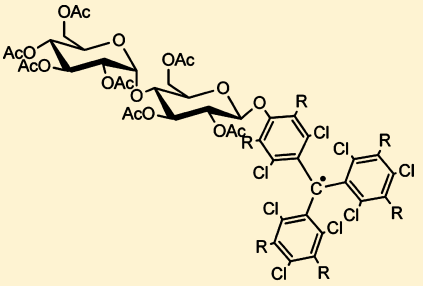
Juan Antonio Mesa,[†] Amado Velázquez-Palenzuela,[‡] Enric Brillas,[‡] Josep Coll,[†] Josep Lluís Torres,[†] and Luis Juliá*[,†]

[†]Departament de Química Biològica i Modelització Molecular, Institut de Química Avançada de Catalunya (CSIC), Jordi Girona 18-26, 08034 Barcelona, Spain

[‡]Departament de Química Física, Universitat de Barcelona, Martí i Franquès 1-11, 08028 Barcelona, Spain

Supporting Information

ABSTRACT: The condensation reaction of D-maltose to free radicals of the series of tris(2,4,6-trichlorophenyl)methyl (TTM) and tris(perchlorophenyl)methyl (PTM) has been described for the first time. The new persistent radicals **1** and **2** are very stable and have been characterized by EPR. Their cyclic voltammograms show a quasi-reversible process in the cathode, being reduced to the corresponding anions, with redox potentials a little lower than those of TTM and PTM, respectively. Their oxidant activity is in close relation with their reduction potentials. Therefore, while **2** is reduced by ascorbic acid, **1** remains unaltered.



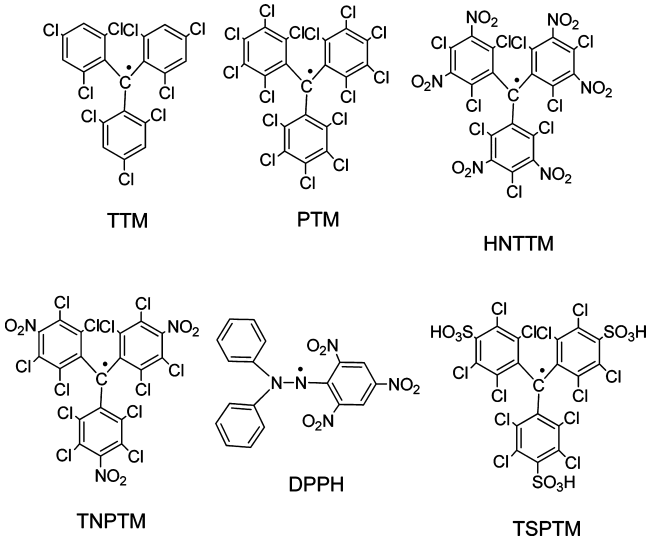
1: R = H
2: R = Cl

INTRODUCTION

Stable carbon-centered alkaromatic radicals have attracted considerable interest as chemical sensors of oxygen and reactive oxygen species in chemical and biological systems.[1] Some of them are radical derivatives of the PTM (perchlorotriphenylmethyl) series.[2] All these radical species show a characteristic and narrow band in the electron paramagnetic resonance (EPR) spectrum whose peak-to-peak line-width is very sensitive to the concentration of oxygen. Some of these radicals are easily reduced in the presence of superoxide by electron transfer reactions to the diamagnetic parent compounds.

Radicals of the TTM [tris(2,4,6-trichlorophenyl)methyl] and PTM series such as tris(2,4,6-trichloro-3,5-dinitrophenyl)-methyl (HNTTM)[3] and tris(2,3,5,6-tetrachloro-4-nitrophenyl)-methyl (TNPTM)[4] radicals (Scheme 1) have proven to be very useful chemical sensors of the antioxidant activity of simple or natural polyphenols, such as catechol and pyrogallol or flavanols.[5,6] All these triphenylmethyl radicals are far from being planar due to the bulky chlorine *ortho*-substituted phenyl rings around the central carbon. Thus, the phenyl rings are twisted substantially out of plane with the consequent conjugation decrease of the π-system, and the spin density is mainly localized on the sterically protected central carbon. The inefficiency of these triphenylmethyl radicals to abstract H-atoms from hydrogen-labile species, contrary to the general behavior of many free radicals, exemplified by 2,2-diphenyl-1-picrylhydrazyl radical (DPPH), is accounted for by the steric shielding, and therefore, they are not operative in these processes. However, they are very sensitive to electron-transfer reactions, being easily reduced to carbanions with stabilities

Scheme 1



comparable to their precursors and they are also electrochemically reduced by reversible processes. There are two major mechanisms to deactivate radicals, the hydrogen atom transfer (HAT) and the single electron transfer (SET). While DPPH and many other indicator radicals can act indistinctly by HAT or SET mechanisms depending mainly on the pH of the

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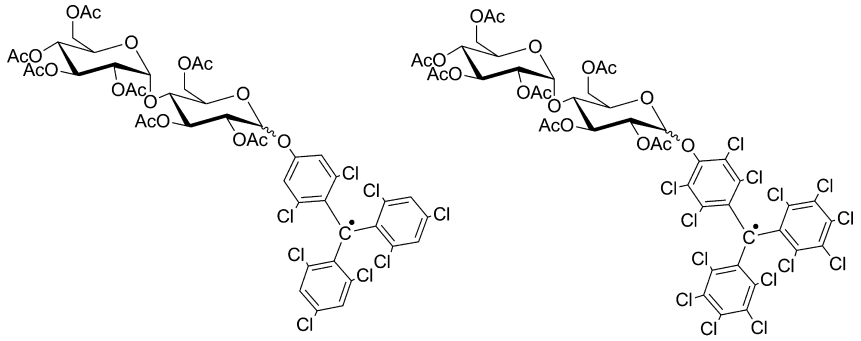
Scheme 2



1 ($C_{45}H_{41}Cl_8O_{18}$ MW: 1153.38) **2** ($C_{45}H_{35}Cl_{14}O_{18}$ MW: 1360.03)

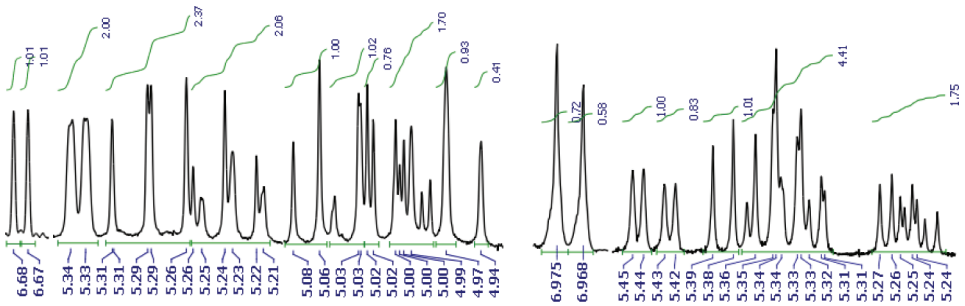


Figure 1. ^{1}H NMR spectra (400 MHz, in $CDCl_3$) of **1H** (left) and **2H** (right) showing expanded sections of the methyne proton signals of the triphenylmethyl moieties and the anomeric proton chemical shifts.

medium,[7] HNTTM and TNPTM radicals only act by SET reactions. As chemical sensors, these radicals measure the electron-donor capacity of polyphenols, which is in close relation with their oxidation potential measured by cyclic voltammetry.

Unfortunately, a disadvantage of HNTTM and TNPTM is their very poor solubility in hydroxylic solvents, and therefore, they cannot be used to measure the antioxidant activity of many natural polyphenolic oligomers soluble in aqueous and alcoholic media. One strategy to get water-soluble radicals has been developed by us and deals with the introduction of polar and ionizable groups in the PTM molecule. In this way, we have reported the synthesis of tris(tetrachloro-4-sulfophenyl)methyl radical (TSPTM) (Scheme 1), an oxidant radical highly soluble in water.[8] Another strategy is the incorporation of a big multipolar group.

In our efforts leading to new molecular sensors for antioxidants, we report the synthesis of new amphiphilic free radicals of the TTM and PTM series, possessing both hydrophilic and lipophilic groups, in which the radical moiety is grafted onto a disaccharide. These new stable maltose-conjugated triphenylmethyl radicals, **1** and **2** (Scheme 2), are covalently linked to the carbohydrate such as maltose, through the anomeric carbon, and have the particularity of being soluble in alcoholic solvents.

RESULTS AND DISCUSSION

One simple strategy in the glycosylation reactions of phenols is the use of glycosyl acetates as donors activated by Lewis acids.[9,10] Therefore, the glycosylation of the phenol radical of TTM, TTMOH,[11] was achieved with octa-*O*-acetyl-β-D-maltose in anhydrous CH_2Cl_2 in the presence of a strong Lewis acid (boron trifluoride diethyl etherate; $BF_3{\cdot}OEt_2$) at low temperature (−15 °C). The condensation reaction is very regioselective, affecting only the anomeric carbon, and proceeds without disturbing the initial radical character of the phenol. The glycosylated radical **1** was obtained with a moderate yield (57%) due to the partial anomerization of the starting material to octa-*O*-acetyl-α-D-maltose, which is inert in these particular reaction conditions. Compound **1** was characterized by IR, UV−vis, EPR spectroscopy, and HRMS. To go more deeply into its molecular structure, radical **1** was reduced by controlled-potential electrolysis to the corresponding diamagnetic compound **1H** and characterized by NMR spectra (expanded details of the 400 MHz ^{1}H NMR spectrum of **1H** are shown in Figure 1).

Two singlets are present in the chemical shift region characteristic of the α-hydrogens in polychlorotriphenylmethanes, at δ_H = 6.68 and 6.67 ppm, and reveal the presence of two isomeric forms, at a ratio of approximately 1. The ^{1}H and HSQC spectra of **1H** (Figures S6−S9, Supporting Information) contained two overlapping doublet signals (δ_H = 5.34 ppm J = 4.0 Hz), correlating with two ^{13}C chemical shifts at δ_C = 95.85 and 95.80 ppm. These doublets might be assigned to the H-1′ anomeric protons typical of maltose [α-D-Glc*p*-(1→4)-β-D-Glc*p*]. Two ^{13}C bands at δ_C = 98.0 and 98.1 ppm show correlation with δ_H = 5.065 and 5.035 ppm, respectively, assigned as H-1_{ax} protons (both display J_{1-2} = 7.5 Hz) in C-1β anomers of the glycosyl bond to the triphenylmethyl moiety. These results indicate the existence of two radical adduct conformers.

Attempts to obtain radical **2** by the same methodology from octa-*O*-acetyl-β-D-maltose and the phenol radical derivative of the PTM, PTM-OH,[12] under similar reaction conditions were

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unsuccessful. This *O*-glycosylation failure was attributed to the presence of chlorine atoms in the *ortho*-position of the phenol reducing its nucleophilicity and increasing steric hindrance. Glycosyl halides[9,10] are more reactive than glycosyl acetates as donors in the glycosylation reaction. Therefore, hepta-*O*-acetyl-α-D-maltosyl bromide and PTM-OH in a 1:1.5 molar ratio were stirred in acetone with a small excess of a saturated aqueous solution of $NaHCO_3$ at room temperature to give the radical adduct **2** in low yield (23%). Similarly as before, **2** was characterized by IR, UV−vis, EPR spectroscopy, and HRMS and chemically reduced to **2H** by ascorbic acid and, in turn, characterized by ^{1}H, ^{13}C, and HSQC NMR spectrometry (Figures S14−S20, Supporting Information). In the ^{1}H NMR spectra, the presence of two singlets, δ = 6.975 and 6.968 ppm, in the chemical shift region characteristic of the α-hydrogens in the perchlorotriphenylmethanes, reveal again the presence of two isomeric forms in **2H**, at a ratio of approximately 0.85. The anomeric proton α-D-Glc*p*-(1→4)-β-D-Glc*p* of **2H** displayed two signals at δ = 5.44 (d, $J_{1'\text{-}2'}$ = 4.0 Hz) and 5.42 (d, $J_{1'\text{-}2'}$ = 4.0 Hz) ppm, both correlated with one signal for ^{13}C at δ = 95.6 ppm. The glycosyl bond to the triphenylmethyl moiety displayed chemical shifts for ^{13}C at δ = 99.7 and 102.0, correlated with two doublet signals at δ = 5.38 (J = 7.6 Hz) and 5.32 (J = 7.6 Hz, overlapped) (Figure 1), assigned again as H-1_{ax} protons in β anomers of the glycosyl bond, pointing again to the existence of two radical adduct conformers.

X-band EPR spectra of the conjugated radicals **1** and **2** were recorded in CH_2Cl_2 solution (~10^{-3} M) at 298 ± 3 K and 180 ± 5 K and in EtOH solution (~10^{-3} M) at 298 ± 3 K (radical **1**, Figure 2 and Figures S3 and S12, Supporting Information, and radical **2**, Figures S10−S12, Supporting Information), and their spectral data in CH_2Cl_2 are reported in Table 1. *g*-Values of radicals **1** and **2** were similar to those of TTM (g = 2.0034)[13] and PTM (2.0026),[14] respectively, and very close to that of the free electron (g = 2.0023), in agreement with the expected small spin−orbit interaction. Both spectra at room temperature consisted of a broad and single line (**1**, ΔH_{pp} = 1.6 G; **2**, ΔH_{pp} = 3.8 G), next to a small and equidistant pair of lines on both sides of the main spectrum in **1**, and two equidistant pair of lines in **2**. The small pair in **1** and the most remote in **2** correspond to the strong coupling of the free electron with the α-^{13}C nucleus, and the coupling values are listed in Table 1. At low temperature, the spectrum of **1** showed an overlapped multiplet of very close 7 lines corresponding to the weak coupling with the six equivalent aromatic hydrogens in *meta*-positions, and two weak multiplets in both sides of the central multiplet attributed to the coupling with the three bridgehead-^{13}C nuclei adjacent to the α-carbon atom. The spectrum of **2** showed two overlapped pair of bands close to the central line attributed to the coupling with the three bridgehead-^{13}C nuclei adjacent to the α-carbon atom and with the six ortho-^{13}C nuclei. All the coupling values are also displayed in Table 1.

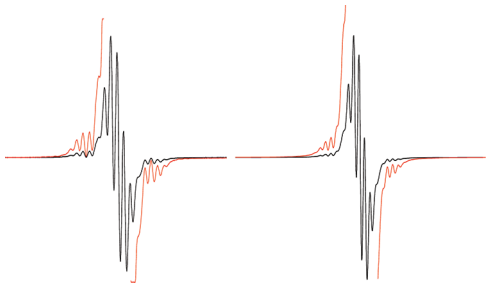

Figure 2. Left: experimental EPR spectrum of radical adduct **1** (~10^{-4} M) in CH_2Cl_2 at 180 K. Scan range: 60 G; ΔH_{pp} = 0.7 G; a(6H, arom) = 1.2 G; a(^{13}C bridge) = 12.8 G. Right: simulated spectrum with the parameters given in the text.[15] The red lines are *y*-axis expanded spectra.

Cyclic voltammograms of radicals **1** and **2** (~10^{-3} M) were recorded in THF/H_2O 10:1 (v/v) solution containing tetrabutylammonium perchlorate (0.1 M) as supporting electrolyte on a platinum disk as working electrode at 25 °C and scan rates between 20 and 200 mV s^{-1} using a three-electrode two-compartment cell with a saturated calomel electrode (SCE) as reference electrode and a platinum wire as counter electrode. The voltammograms of each radical displayed one quasi-reversible redox pair corresponding to its reduction, which is attributed to the equilibrium reaction involving the addition of one electron to the trivalent central carbon atom to form a stable anion. These redox processes for radicals **1** and **2** are represented in Scheme 3, and values of the electrochemical parameters are shown in Table 2 together with the values for TTM and PTM in the same solvent (voltammograms are shown in Figures S5 and S14, Supporting Information). Each redox process in the cathodic region is quasi-reversible because the difference between their anodic and cathodic peak potentials is always higher than the theoretical value of 59.2 mV expected for a one-electron reversible process. Its standard potential ($E°$) was determined as the average of the anodic (E_p^a) and cathodic (E_p^c) peak potentials. An analysis of Table 2 indicates that the standard potentials for **1** and **2** are lower than those for their precursors, TTM and PTM radicals, respectively.

The oxidant power of radical adducts **1** and **2** was evaluated in the presence of ascorbic acid as a good radical scavenger. To make the kinetic measurements, reactions of **1** and **2** with ascorbic acid were carried out in THF/H_2O (10:1, v/v) and monitored by UV−vis spectroscopy, recording the decay of the maximum absorbance of **1** (λ = 373 nm) and **2** (λ = 384 nm). The experiments were performed with initial concentrations of radicals of ~10^{-4} M and with a radical/ascorbic acid molar ratio of ~5:1. The stoichiometric factor was calculated after the reactions were completed (48 h).

While radical **2** was slowly reduced with ascorbic acid to $\mathbf{2}^-$ and finally to **2H**, radical **1** was completely stable. This is

Table 1. *g*-Values and Hyperfine Coupling Constants in Gauss for Triphenylmethyl Radicals 1 and 2 in CH_2Cl_2 (~10^{-3} M)

radical	g^b	1H^a	^{13}C(α)^{a,c}	^{13}C(arom)^{a,c}	$\Delta H_{pp}{}^a$
1	2.0032 ± 0.0001	1.2	28.0	12.8	0.70
2	2.0024 ± 0.0001		30.1	12.66 (^{13}C bridge); 10.45 (^{13}C ortho)	1.0

^{a}The hfc constants for six 1H in meta and ^{13}C(arom) (adjacent to α-carbon) and values for ΔH_{pp} (peak to peak line width) were determined at 180 ± 5 K and checked by computer simulation. ^{b}*g*-values were measured against dpph (2.0037 ± 0.0002) at 298 K. ^{c}Natural abundance of ^{13}C isotope: 1.10%.

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Scheme 3

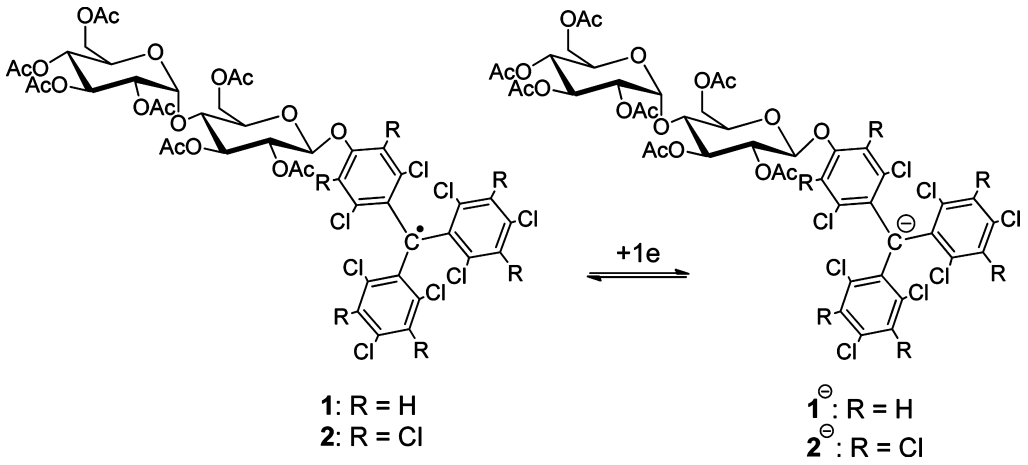

Table 2. Cathodic onset and Peak Potentials and Standard Potentials (E_{red}^0) for the Reduction of Triphenylmethyl Radicals 1 and 2 and Anodic Onset and Peak Potential for the Oxidation of Ascorbic Acid[a,b]

radical	E^c_{onset} / V	E_p^c / V	E_{red}^0 / V	E^a_{onset} / V	E_p^a / V
1	−0.33	−0.52	−0.47		−0.41
TTM	−0.18	−0.40	−0.35		−0.31
2	+0.24	−0.02	+0.02		+0.07
PTM	+0.22	+0.04	+0.10		+0.15
ascorbic acid				+0.11	+0.61

[a]Radicals (~10^{-3} M) in THF/H_2O 10:1 (v/v) solution with Bu_4NClO_4 (0.1 M) as background electrolyte on Pt electrode at 25 °C. [b]Potential values versus SCE (saturated calomel electrode). Scan rate of 100 mV s^{-1}.

consistent with the cathodic onset potentials of **1** and **2** and with the anodic onset potential of ascorbic acid (see Table 2). A redox reaction is thermodynamically allowed when there is a negative change in the Gibbs free energy of the reaction ($\Delta G = -F(E^c_{onset} - E^a_{onset})$, where F is the Faraday constant, 96487 C mol^{-1}). For the reaction between ascorbic acid and radical **1**, $\Delta G = -96487(-0.33 - 0.11) = 42454$ J mol^{-1}, and for ascorbic acid and radical **2**, $\Delta G = -96487(0.24 - 0.11) = -12543$ J mol^{-1}, indicating that only the latter is thermodynamically allowed. Figure 3 (left) shows the decrease with time of the intensity of the band (λ = 384 nm) of **2** in the UV−vis spectrum. The rate constant and stoichiometric factor for the reaction of **2** is given in Table 3 together with those values corresponding to the reaction of PTM with ascorbic acid under the same conditions. The reaction of PTM is slightly faster than that of radical **2**, with equal stoichiometric factors, consistent with the transfer of two electrons from ascorbic acid to reduce two molecules of radical (Table 3). (Graphics of the kinetics of the reaction between **2** and ascorbic acid are displayed in the Supporting Information, Figures S22 and S23).

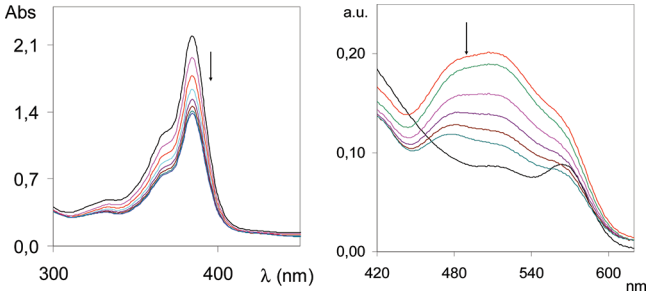

Figure 3. (Left) Evolution of the UV−vis spectrum of a solution of radical **2** (~10^{-4} M) and ascorbic acid (5:1) in THF−H_2O (10:1, v/v). (Right) Evolution of the lowest energy band intensity of the same solution at different times; the band in black corresponds to a blanck solution: radical **2** in THF−H_2O (10:1, v/v). The band in red corresponds to the reaction mixture after 10 min.

Table 3. Observed Rate Constants (k) and Stoichiometric Values (n) for the Reaction of Radicals 1, 2, and PTM with Ascorbic Acid in THF/H_2O (10:1 v/v)

compd	k (M^{-1} s^{-1})	n^a
1	~0	0
2	3.3	1.8−2.0
PTM	6.5	2.0

[a]Values measured after 48 h of reaction time.

This reaction leads to the generation of the charged species $\mathbf{2}^-$ in a first stage of the process and, finally, to the corresponding **2H** in acidic medium. Figure 3 (right) confirms the presence of the anion intermediate in the reduction of **2**. Initially, the wavelength interval where the lowest energy band of the radical **2** (black band) appears (λ, 450−600 nm), undergoes an increase in intensity (red band) due most probably to the broad absorbance band corresponding to the anion $\mathbf{2}^-$ (the anion of PTM shows a broad band with a maximum at λ = 510 nm).

CONCLUSIONS

In summary, we have described for the first time the condensation reaction of a disaccharide, D-maltose, to free radicals of the series of TTM and PTM. These reactions are regio- and enantioselective, affecting only the anomeric carbon of the carbohydrate molecule, and proceed without disturbing the radical character of the starting free radical. The presence of two different conformers in both diamagnetic compounds **1H** and **2H** is being investigated in our laboratory. The new triphenylmethyl radicals **1** and **2** are very stable, either in solid or in solution, are soluble in methanol and ethanol, and have been characterized by EPR. They are active in electron transfer reactions being reduced to their corresponding anions in polar

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solvents. Electrochemically, **1** and **2** show quasi-reversible processes in the cathode with redox potentials a little lower than those of TTM and PTM, respectively. Their activity as oxidant species is in close relation with their reduction potentials. Therefore, while **2** is reduced by ascorbic acid, **1** remains unaltered. The present paper proves that the incorporation of acetylated maltose to TTM and PTM does not alter significantly the redox behavior of the original radicals as a first step toward the preparation of electron transfer sensitive water-soluble free radicals to be used as chemical sensors of natural antioxidants in biological fluids.

EXPERIMENTAL SECTION

General Experimental Procedures. UV spectra were recorded in $CHCl_3$ with a single-cell UV−vis spectrophotometer. IR spectra (Figures S4 and S13, Supporting Information) were recorded in KBr tablets with a FT-IR spectrophotometer. NMR spectra (^{13}C NMR, ^1H NMR, COSY, TOCSY, ROESY, HSQC, and HMBC) were acquired in $CDCl_3$ at rt, on a 400 MHz spectrometer. Chemical shifts are reported in ppm (δ) relative to the $CHCl_3$ signal (7.26 ppm). X-band EPR spectra were recorded in CH_2Cl_2 solution at rt and 180 K with an EMX-Plus 10/12 spectrometer.

Column chromatography was performed on Kieselgel 60 A (35−70 mesh), and fractions were monitored by TLC on Kieselgel 60 F254. Detection was effected by charring with 5% H_2SO_4−methanol and UV lamp under 360 nm and natural light. Boron trifluoride/diethyl etherate was distilled before use. Evaporations were conducted under reduced pressure at 40 °C. Anhydrous CH_2Cl_2 was used for the synthetic procedures.

Kinetic Measurements. Kinetic parameters of the reactions between **1** or **2** and ascorbic acid in THF−H_2O (10:1, v/v) were estimated by UV−vis spectroscopy. Freshly prepared solutions of **1** or **2** (~86 μM) and ascorbic acid (~19 μM) were mixed (1:1, v/v, molar ratio 4−5:1), and the decay of the radical absorbance band of **1** (373 nm) or **2** (384 nm) was followed at room temperature under inert atmosphere. Spectra were recorded every 5 min during the first 2 h and every 15 min until the final of the reaction (36 h). The rate constants and the total number of electrons transferred per polyphenol (n_e) were estimated with a simple and general kinetic model reported by Dangles et al. defined by eq 1. The values for the rate constant, k were calculated from the integrated eq 2.

$$-\mathrm{d[radical]}/\mathrm{d}t = kn[\text{ascorbic acid}][\text{radical}] = k_1[\text{ascorbic acid}][\text{radical}] \quad (1)$$

$$\ln\frac{1 - A_f/A}{1 - A_f/A_0} = -\frac{k_1 c}{A_0/A_f - 1}t \quad (2)$$

In eqs 1 and 2: n represents the number of reduced moles of radical per mole of ascorbic acid; A_o is the initial intensity of the radical signal in the UV−vis spectra; A_f is the final visible intensity; and c is the initial concentration of ascorbic acid. The n values of the stoichiometry of the ascorbic acid were calculated using eq 3; ε is the molar absorptivity characteristic of the stable free radical.

$$n = \frac{A_0 - A_f}{\varepsilon c} \quad (3)$$

The curve-fittings of the decay of the maximum of the absorbance band of radical vs time plots were carried out using OriginPro 7. The experiments were repeated three times and the values reported are mean values. The curve-fitting procedure gave good correlation coefficients (>0.99).

Bis(2,4,6-trichlorophenyl)[2,6-dichloro-4-[2,3,4,6-tetra-*O*-acetyl-α-D-glucopyranosyl-(1→4)-2,3,6-tri-*O*-acetyl-β-D-glucopyranosyloxy]phenyl]methyl Radical (1). To a stirred solution of bis(2,4,6-trichlorophenyl)(2,6-dichloro-4-hydroxyphenyl)-methyl radical (TTM−OH) (1.0 g; 1.87 mmol) and octa-*O*-acetyl-β-D-maltose (1.90 g; 2.80 mmol) in anhydrous CH_2Cl_2 (15 mL), with activated powdered molecular sieves (4 Å) at low temperature (−30 °C), in Ar atmosphere, and protected from light, was added dropwise freshly distilled boron trifluoride diethyl etherate (0.47 mL). The reaction mixture was monitored by TLC (silica gel plates, hexane−ethyl acetate 5:3 v/v) and was further stirred (24 h) at −15 °C. After completion, CH_2Cl_2 (20 mL) was added and the mixture washed three times with saturated aqueous $NaHCO_3$ solution and three times with water, dried over anhydrous $MgSO_4$, and filtered. The residue after solvent evaporation at reduced pressure was chromatographed in silica gel eluting with hexane−ethyl acetate (5:2 v/v), to afford **1** as a red solid (1.12 g; 57%): R_f = 0.46; IR ν_{max} (KBr) (Figure S4, Supporting Information) 2959 (w), 1754 (s), 1582 (m), 1555 (m), 1526 (m), 1432 (m), 1370 (s), 1226 (s), 1339 (s), 858 (w), 825 (w), 601 (w) cm^{-1}; UV−vis ($CHCl_3$) $\lambda_{max}(\varepsilon)$ 373 (30 800), 490 (1000), 537 (1015) nm; ESIHRMS (+) calcd for $C_{45}H_{41}O_{18}Cl_8{\cdot}NH_4$ $(M{\cdot}NH_4)^+$ 1171.0093, found 1171.0083; calcd for $(M{\cdot}Na)^+$ 1175.9646, found 1175.9706.

Bis(2,4,6-trichlorophenyl)[2,6-dichloro-4-[2,3,4,6-tetra-*O*-acetyl-α-D-glucopyranosyl-(1→4)-2,3,6-tri-*O*-acetyl-β-D-glucopyranosyloxy]phenyl]methane (1H). A two-compartment three-electrode cell containing a Pt cathode (6 cm^2), a Pt wire as the anode and saturated calomelanes (SCE) as the reference electrode was used for the controlled-potential (−0.90 V vs SCE) electrolysis of **1** (60 mg) in CH_2Cl_2 (100 mL) with tetrabutylammonium perchlorate (TBAP) (3.42 g; 0.1 M) at room temperature. The anolyte was the same background electrolyte and was separated from the catholyte by glass frit. The catholyte (**1** and TBAP) was stirred and deaerated with Ar for 10 min. After adding the compound was pre-electrolyzed at the same cathodic potential. After 3 h of electrolysis the stoichiometric charge for one-electron reduction of the initial compound was passed and the electrolysis was finished. The solution was evaporated at reduced pressure, and the residue, dissolved in CH_2Cl_2, was washed three times with water and dried over anhydrous $MgSO_4$. The residue of solvent evaporation at reduced pressure was chromatographed with silica gel and hexane−ethyl acetate mixture (1:1 v/v) as eluent to give **1H** with some colored impurities. This solid was left (12 days) on the bench and chromatographed again with the above system to give pure **1H** (30 mg; 50%): R_f = 0.46; ^1H NMR (400 MHz, $CDCl_3$) δ 1.93 (2), 1.96 (4), 1.97 (2), 1.98 (1), 1.99 (1), 2.00 (1), 2.03 (2), 2.04 (1) (CH_3CO); 3.82−3.98 m (H-5, H-5′ and H-4); 4.005, 4.017 dd ($J_{6'A\text{-}6'B,6'A\text{-}5'}$ = 12.4, 2.2 Hz, H-6′A); 4.16 m (H-6′B, H-6A); 4.408, 4.414 dd, ($J_{6A\text{-}6B,6B\text{-}5}$ = 12.0, 2.5 Hz, H-6B); 4.795, 4.799 dd ($J_{2'\text{-}3',2'\text{-}1'}$ = 10.5, 4.0 Hz, H-2′); 4.97 dd ($J_{4'\text{-}3',4'\text{-}5'}$ = 9.9, 9.9 Hz, H-4′); 4.98−5.08 m (H1, H-2); 5.23, 5.24 dd ($J_{3-4,3-2}$ = 10.5, 10.5 Hz, H-3); 5.29 dd ($J_{3'\text{-}2',3'\text{-}4'}$ = 10.5, 9.6 Hz, H-3′); 5.34 d ($J_{1'\text{-}2'}$ = 4.0 Hz, H-1′); 6.67, 6.68 s (α-H); 6.88, 6.89 d (J_m = 2.6 Hz, H_{Ar}); 7.02, 7.02 d (J_m = 2.6 Hz, H_{Ar}); 7.22−7.23 m (H_{Ar}); 7.35−7.36 m (H_{Ar}). ^{13}C NMR (100 MHz, $CDCl_3$) δ 20.5−20.9 (CH_3−CO); 49.6, 49.7 (α-H); 61.7 (C6); 62.9, 63.0 (C-6′); 68.1 (C-4′); 68.8, 68.8 (C-5); 69.3 (C-3′); 70.0 (C-2′); 71.7, 71.7 (C-2); 72.6, 72.7 (C-5′); 72.9, 73.0 (C-4); 75.1 (C-3); 95.8, 95.9 (C-1′); 98.0, 98.1 (C-1); 117.2, 117.3 ($C\text{-}3_{ArO}$); 118.6, 118.8 ($C\text{-}5_{ArO}$); 128.4 ($C\text{-}3_{Ar}$); 129.9, 130.0 ($C\text{-}5_{Ar}$); 133.6 ($C\text{-}4_{Ar}$); 134.2, 134.2 ($C\text{-}1_{Ar}$); 137.1, 137.1 ($C\text{-}1_{ArO}$); 155.6, 155.7 ($C\text{-}4_{ArO}$); 169.4−170.5 (CH_3-CO).

Bis(2,3,4,5,6-pentachlorophenyl)[2,3,5,6-tetrachloro-4-[2,3,4,6-tetra-*O*-acetyl-α-D-glucopyranosyl-(1→4)-2,3,6-tri-*O*-acetyl-β-D-glucopyranosyloxy]phenyl]methyl Radical (2). Under Ar atmosphere, hepta-*O*-acetyl-α-D-maltopyranosyl bromide (0.314 g; 0.45 mmol) was added to a solution of bis(2,3,4,5,6-pentachlorophenyl)(2,3,5,6-tetrachloro-4-hydroxyphenyl)methyl radical (PTM-OH) (0.5 g; 0.67 mmol) in a mixture of acetone and saturated aqueous solution of $NaHCO_3$ (60 mL; 1:1, v/v) protected from the light. The mixture was stirred at room temperature (48 h) and the reaction progress monitored by TLC (silica gel plates, hexane−ethyl acetate 1:1 v/v). After completion, the solvent was evaporated under reduced pressure, and the residue in ethyl acetate was washed once with a saturated aqueous solution of $NaHCO_3$ and three times with water, dried over $MgSO_4$, and filtered. The solution was evaporated at reduced pressure to give a red residue. Chromatographic purification in silica gel eluting with hexane−ethyl acetate (2:1 v/v) gave **2** as a red solid (0.210 g, 23%): R_f = 0.63; IR

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(KBr) (Figure S13, Supporting Information) 2957 (w), 1755 (s), 1358 (m), 1339 (m), 1230 (s), 1035 (s), 898 (w), 810 (w), 712 (w) cm^{-1}; UV–vis ($CHCl_3$) λ_{max} (ε) 384 (38 600), 503 (1000), 562 (1160) nm; ESIHRMS calcd for $C_{45}H_{35}O_{18}Cl_{14}$ $(M)^+$ 1358.7391, found 1358.7403.

Bis(2,3,4,5,6-pentachlorophenyl)[2,3,5,6-tetrachloro-4-[2,3,4,6-tetra-*O*-acetyl-α-D-glucopyranosyl-(1→4)-2,3,6-tri-*O*-acetyl-β-D-glucopyranosyloxy]phenyl]methane (2H). To a solution of **2** (0.60 g; 0.37 mmol) in THF/water (10:1 v/v, 20 mL) was added ascorbic acid (1.30 g, 7.40 mmol). The reaction mixture was stirred at room temperature (3 h) and then evaporated at reduced pressure. The residue in CH_2Cl_2 was washed with water, dried with anhydrous $MgSO_4$, and filtered and the solvent evaporated under reduce pressure. The residue was chromatographed in silica gel with hexane–ethyl acetate mixture (2:1 v/v) as eluent to give **2H** (0.59 g; 98%): R_f = 0.63; IR (KBr) 2993–2952, 1756.4, 1368.9, 1339.1, 1229.2, 1034.9 cm^{-1}; ^{1}H NMR (400 MHz, $CDCl_3$) δ 1.94 s (2), 1.96 s (4), 1.97 s (2), 1.98 s (1), 1.99 s (1), 2.01 s (1), 2.03 s (2), 2.04 s (1) (CH_3CO); 3.65 m (0.55H, H-5A); 3.70 m (0.45H, H-5B); 3.93 m (1H, H-5′); 4.049, 4.054 dd ($J_{6'A\text{-}6'B,6'A\text{-}5'}$ = 12.5, 2.6 Hz, 1H, H-6′A); 4.07–4.15 m (1.57H, H-4B, H-$6A_A$, H-4A); 4.19–4.28 m (1.41H, H-$6B_A$, H-6′A); 4.38 dd ($J_{6BB\text{-}6BA,6BB\text{-}5B}$ = 12.0, 2.8 Hz, 0.41H, H-$6B_B$); 4.50 dd ($J_{6AB\text{-}6AA,6AB\text{-}5A}$ = 12.2, 2.7 Hz, 0.50H, H-$6A_B$); 4.85 dd ($J_{2'\text{-}3',2'\text{-}1'}$ = 10.6, 4.0 Hz, 1H, H-2′); 5.04, 5.05 dd, ($J_{4'\text{-}3',4'\text{-}5'}$ = 9.9, 9.9 Hz, 1H, H-4′); 5.24, 5.25 dd ($J_{2-3,2-1}$ = 9.2, 7.6 Hz, 1H, H-2); 5.30–5.37 m (2.41H, H-3, H-3′, H-1B); 5.38 d ($J_{1A\text{-}2}$ = 7.5, 0.52H, H-1A); 5.42 d ($J_{1'B\text{-}2'}$ = 4.0, 0.46H, H-1′B); 5.44 d ($J_{1'A\text{-}2'}$ = 4.0, 0.53H, H-1′A); 6.975, 6.978 s (0.54, 0.46H, α-H); ^{13}C NMR (100 MHz, $CDCl_3$) 20.59–20.31 (CH_3CO), 56.56 (αH), 61.5 (C-6), 61.7 (C-6′), 68.0 (C-4), 68.6 (C-5), 69.3 C-3), 72.7 (C-5′), 72.8 (C-4′), 75.1 (C-3′), 77.4 (C-2), 95.6, 95.7 (C-1′), 99.7, 102.0 (C-1), 129.5 (C-1_{ArO}), 133.3 (C-1_{Ar}), 168.7 (C-4_{ArO}) 169.7–170.4 (CH_3-CO)

■ ASSOCIATED CONTENT

Ⓢ Supporting Information

Infrared and EPR spectra and cyclic voltammograms for radicals **1** and **2**. ^{1}H and HSQC NMR spectra of diamagnetic compounds **1H** and **2H**. Graphics for kinetics of radical **2** with ascorbic acid. This material is available free of charge via the Internet at http://pubs.acs.org.

■ AUTHOR INFORMATION

Corresponding Author

*E-mail: ljbmoh@cid.csic.es.

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■ NOTE ADDED AFTER ASAP PUBLICATION

Scheme 2 was published with errors on January 4, 2012; it was corrected in the version reposted on January 6, 2012.