Organometallic derivatives of 2,6-di-*tert*-butylphenols as specific inhibitors of methyl oleate oxidation

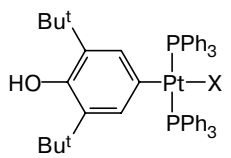
E. R. Milaeva,[a] D. B. Shpakovsky,[a] Yu. A. Gracheva,[a] N. T. Berberova,[b] and M. P. Egorov[c]*

[a]*Department of Chemistry, M. V. Lomonosov Moscow State University, Leninskie Gory, 119899 Moscow, Russian Federation. Fax: +7 (095) 939 5546. E-mail: milaeva@org.chem.msu.su*
[b]*Astrakhan´ State Technical University, 16 ul.Tatishcheva, 414025 Astrakhan´, Russian Federation. Fax: +7 (851 2) 25 6427. E-mail: berberova@astu.astranet.ru*
[c]*N. D. Zelinsky Institute of Organic Chemistry, Russian Academy of Sciences, 47 Leninsky prosp., 119991 Moscow, Russian Federation. Fax: +7 (095) 135 5328. E-mail: mpe@cacr.ac.ru*

2,6-Di-*tert*-butylphenols containing the Pt—$SnCl_3$ and Pt—$GeCl_3$ groups in the *para* position exert a dual effect on the oxidation of methyl oleate by molecular oxygen. Initially, these compounds act as antioxidants producing the corresponding phenoxyl radicals whose decomposition is accompanied by elimination of $SnCl_2$ and $GeCl_2$, which are oxidation promoters.

Key words: 2,6-di-*tert*-butylphenols, phenoxyl radicals, organometallic compounds, oxidation of olefins, antioxidants, methyl oleate, hydroperoxides.

Organic derivatives of sterically hindered phenols are widely used in industry as antioxidants.[1] The efficiency of 2,6-di-*tert*-butylphenols as inhibitors of oxidative destruction of hydrocarbons is determined by the nature of the group located in the *para* position with respect to the OH group.[2] On the other hand, metal salts and complexes are known to catalyze oxidation of organic substrates.[3] Previously, we have demonstrated[4—8] that the systems obtained by introduction of sterically hindered phenol into the ligand environment of metal complexes, which exhibit catalytic activity in oxidation of different organic compounds by molecular oxygen, possess polyfunctional properties. For example, metallophthalocyanines containing the 2,6-di-*tert*-butylphenol fragments in the macroring act as either catalysts or inhibitors of oxidation depending on the nature of the metal atom, the solvent, pH, and the concentration of the catalyst. At the same time, their synthetic precursors, *viz.*, (3,5-di-*tert*-butyl-4-hydroxyphenyl)phthalonitriles, are efficient antioxidants in thermooxidative destruction of polyethylene and an oligohexene oil. Properties of 2,6-di-*tert*-butylphenols, which contain metal atoms in the *para* position, as antioxidants (or as catalysts of oxidation) are as yet virtually unknown.



1a—c

X = Cl (**a**), $SnCl_3$ (**b**), $GeCl_3$ (**c**)

In the present work, we studied the effect of organometallic derivatives of 2,6-di-*tert*-butylphenol of general formula **1** on the oxidation of methyl oleate by molecular oxygen and compared them with 2,6-di-*tert*-butylphenol.

We chose methyl oleate as the substrate for, at least, two reasons. First, this compound, being a representative of unsaturated fatty acids, serves as a model in studies of *in vitro* oxidative destruction of food oils and pharmacological preparations. Second, methyl oleate is used in studies of the oxidative stress caused by *in vivo* lipid peroxidation.[9,10] In this connection, a search for stabilizers (antioxidants) with nontrivial molecular structures possessing a combination of inhibiting and promoting properties could serve as the basis for the construction of systems with the variable controlled action effect.

Experimental

Methyl oleate (Sigma, 99%), 2,6-di-*tert*-butylphenol (Merck), and $SnCl_2$ (Aldrich) were used without additional purification. Compounds **1a—c** [11,12] and $GeCl_2$ (the complex with dioxane)[13] were prepared according to procedures described previously. Methyl oleate was oxidized by oxygen at 50 °C with continuous air supply using a temperature-controlled apparatus protected against light. Since the reaction was carried out as autooxidation without the addition of initiators, air was bubbled through methyl oleate placed in the temperature-controlled apparatus for 2 h prior to the addition of compounds and the mixtures under investigation. In all cases, the concentrations of the additives were $1 \cdot 10^{-3}$ mol L^{-1}. The concentrations of hydroperoxides were determined (the accuracy was ± 0.01 mmol L^{-1}) by iodometric titration according to

Published in Russian in *Izvestiya Akademii Nauk. Seriya Khimicheskaya,* No. 6, pp. 1049—1052, June, 2001.

1066-5285/01/5006-1097 $25.00

a standard procedure.[14] The reactions were carried out for 5 h, and the samples were withdrawn every 1 h. The rate constants of hydroperoxide accumulation were determined from the logarithmic anamorphoses of the kinetic curves of product accumulation constructed by the least-squares method. The approximation coefficients of the linear dependences were 0.978—0.998.

Results and Discussion

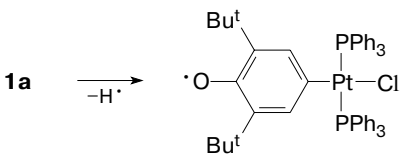
Oxidation of oleic acid and its methyl ester by molecular oxygen follows the general regularities of liquid-phase oxidation of hydrocarbons[15] and belongs to chain radical processes.

The mechanism of oxidation of methyl oleate (RH) by molecular oxygen has been studied in sufficient detail.[16] It involves generation of the corresponding substituted allylic radical followed by the formation of *cis* and *trans* isomers of hydroperoxides (ROOH) containing the hydroperoxide groups at positions 8, 9, 10, and 11, respectively. The addition of efficient proton donors, for example, of 2,6-di-*tert*-butylphenols, can lead to a change in the ratio between isomeric products,[17] but does not prevent determination of their overall concentrations.

In the present work, the activities of compounds **1a—c** as antioxidants, which differ substantially from the known inhibitors based on 2,6-di-*tert*-butylphenol in that the former contain metal atoms, were studied for the first time using oxidation of methyl oleate as an example. The concentration of methyl oleate hydroperoxides was used as the criterion for the efficiency of the compounds under study.

The kinetic curves of ROOH accumulation over 5 h in the absence of additives (curve *1*) and in the presence of compound **1a** and 2,6-di-*tert*-butylphenol (curves *2* and *3*, respectively) are shown in Fig. 1, *a*. It can be seen that the activity of **1a** virtually coincides with that of 2,6-di-*tert*-butylphenol. This fact is attributable to the characteristics of the inhibitors InH responsible for their efficiency among which are, in the general case, the energy of the In—H bond and the stability of the resulting In$^{\cdot}$ radicals.[1,2] The dissociation energies of the O—H bonds in 4-substituted 2,6-di-*tert*-butylphenols are in the range 330—360 kJ mol^{-1} and increase in the presence of electron-withdrawing substituents.[2] The $Pt(PPh_3)_2Cl$ group exhibits weak π-acceptor properties,[18] which are comparable with the effect of the phenyl ring (the energy of the O—H bond in 2,6-di-*tert*-butyl-4-phenylphenol[2] is 337.7 kJ mol^{-1}). Consequently, the extremely high stability of the corresponding phenoxyl radical **2a** generated from compound **1a** (Scheme 1) is the significant factor.[11]

Scheme 1



2a

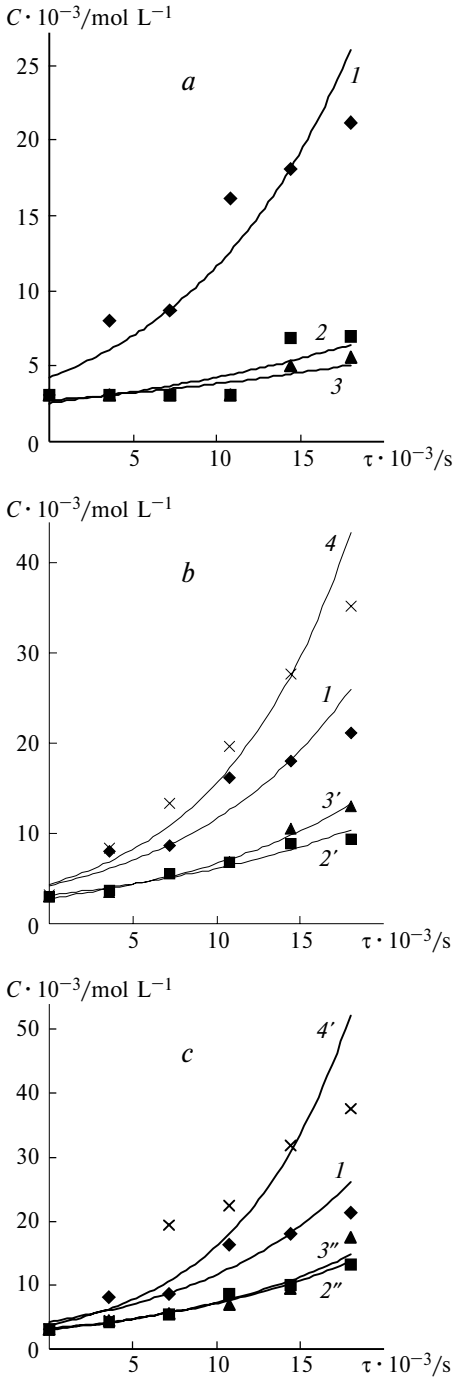
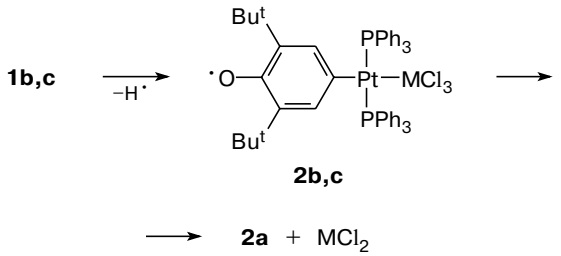


Fig. 1. Kinetic curves of accumulation of methyl oleate hydroperoxides without additives (*1*) and in the presence of: *a*, **1a** (*2*) and 2,6-di-*tert*-butylphenol (*3*); *b*, **1b** (*2′*) and equimolar mixtures of **1a** with $SnCl_2$ (*3′*) and $SnCl_2$ (*4*); *c*, **1c** (*2″*) and equimolar mixtures of **1a** with $GeCl_2$ (*3″*) and $GeCl_2$ (*4′*).

Unlike radical **2a** formed upon H abstraction from phenols **1b,c**, phenoxyl radicals **2b,c** are unstable and,

as we have demonstrated previously,[12] eliminate $SnCl_2$ and $GeCl_2$ to give radical **2a** (Scheme 2).

Scheme 2



M = Sn (**b**), Ge (**c**)

In this case, the presence of metal compounds, which promote oxidation of the substrate,[3] in the reaction medium is the critical factor.

The kinetic curves of accumulation of methyl oleate hydroperoxides in the presence of compounds **1b,c** in comparison with $SnCl_2$ and $GeCl_2 \cdot C_4H_4O_2$ as additives are shown in Figs. 1, *b* and *c*, respectively. It can be seen that these additives actually catalyze oxidation of methyl oleate, which is manifested in the increase in the concentration of ROOH compared to that obtained in the control experiment without additives.

In all cases, the kinetic curves of accumulation of primary oxidation products of methyl oleate (see Figs. 1, *a*—*c*) follow the exponential law, whereas their logarithmic anamorphoses are well described by linear functions, which made it possible to calculate the rate constants of the first-order total accumulation of hydroperoxides (Table 1). Based on these data, compounds **1b,c** containing the Pt—Sn and Pt—Ge bonds can be assigned to inhibitors whose activity is lower than that of compound **1a**. In our opinion, a decrease in the inhibiting activity of **1b,c** can be explained not only by the lower stability of radicals **2b,c**, but also by accumulation of $SnCl_2$ and $GeCl_2$ in the medium as the antioxidants are consumed (see Scheme 2). This conclusion was also confirmed by the data obtained with the use of equimolar **1a** + $SnCl_2$ or **1a** + $GeCl_2 \cdot C_4H_4O_2$ mixtures because in these cases the catalytically active salts were added at the beginning of the reaction, which led to the concurrent action of inhibitor **1a** and the catalysts and to the increase in the concentration of hydroperoxides (see Figs. 1, *b* and *c*).

Table 1. Rate constants of accumulation of methyl oleate hydroperoxides in the presence of different additives (50 °C, the concentration of the additives was $1 \cdot 10^{-3}$ mol L^{-1})

Additive	$k \cdot 10^{-4}/s^{-1}$
—	1.25±0.12
2,6-di-*tert*-Butylphenol	0.25±0.06
1a	0.37±0.09
1b	0.68±0.03
1c	0.83±0.03
1a + $SnCl_2$*	0.81±0.04
1a + $GeCl_2 \cdot C_4H_4O_2$*	0.85±0.04
$SnCl_2$	1.53±0.11
$GeCl_2 \cdot C_4H_4O_2$	1.59±0.14

* Equimolar mixtures were used.

Previously, we have demonstrated[12] that the rate of decomposition of radicals **2b,c** was ~10^3 s^{-1} and, hence, this was several orders of magnitude higher than the rate of formation of hydroperoxides. In this case, no insertion of MCl_2 at the Pt—Cl bond in radical species **1a** was also observed.[12] Consequently, the high rate of decomposition of radicals **2b,c** is responsible for the rapid appearance of the antioxidant and the catalyst in the reaction mixture. In this case, the effects of compounds **1b,c** would be expected to be comparable with those of mixtures of **1a** with $SnCl_2$ and $GeCl_2 \cdot C_4H_4O_2$, respectively. The data presented in Figs. 1, *b* and *c* and in Table 1 demonstrate that the rate constants of formation of hydroperoxides (*i.e.*, the efficiency of the inhibiting activity) are somewhat different for the above-mentioned pairs of the additives. Thus compounds **1b,c** exhibit higher antioxidating activity than the above-mentioned mixtures. Apparently, this difference can be explained by the competition of two processes, *viz.*, the promotion of peroxidation of methyl oleate in the presence of MCl_2 (M = Sn or Ge) and the establishment of the equilibrium between the antioxidant and the corresponding phenoxyl radical.

In the case of compounds **1b,c**, the additives change the effect from the inhibitory to catalytic one, which is clearly seen from comparison of the concentrations of the hydroperoxides within 1 and 5 h after their addition (Fig. 2). In the case of compounds **1a—c**, the inhibiting properties were manifested during the first hour due to the fact the H atom was readily transferred to the

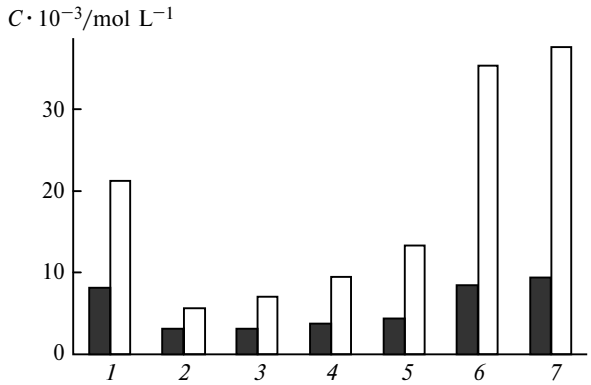


Fig. 2. Accumulation of methyl oleate hydroperoxides without additives (*1*) and in the presence of 2,6-di-*tert*-butylphenol (*2*), compounds **1a** (*3*), **1b** (*4*), **1c** (*5*), $SnCl_2$ (*6*), and $GeCl_2$ (*7*); the concentrations of ROOH after 1 h are shown by hatching, the concentrations after 5 h are not hatched (the initial concentrations of hydroperoxides were in the range of $3.07—3.12 \cdot 10^{-3}$ mol L^{-1}).

peroxide ROO$^{\bullet}$ radicals resulting in chain termination. However, further consumption of the functionally active inhibitor (**1b,c**) was accompanied by an increase in the concentration of the catalyst ($SnCl_2$ or $GeCl_2$), which led to a change in the mechanism of action of species involved in this process, and, as a consequence, to a change in the overall effect of the above-mentioned compounds. Due to the inhibitor—catalyst transformation, the concentrations of hydroperoxides in the presence of inhibitors **1b,c** were 1.5—2 times higher than those in the presence of **1a**.

Thus, the results of the present study provide evidence that organometallic derivatives of 2,6-di-*tert*-butylphenols are promising nontrivial agents in oxidation of organic substrates. These compounds are characterized by the inversion of the inhibitor—catalyst effect.

This work was financially supported by the Russian Foundation for Basic Research (Project No. 99-03-33052), by INTAS (Grant 97-30344), and by the Russian State Program (the Program "Fundamental Problems of Modern Chemistry," Project No. 9.3.03).

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Received December 28, 2000