Effects of chain transfer and recombination/disproportionation of inhibitor radicals on inhibited oxidation of lipids

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The kinetics of inhibited oxidation of lipids was studied by computer simulation to evaluate the contributions of the recombination/disproportionation of inhibitor radicals and chain transfer to retardation effects. The influence of inhibitor regeneration on the induction periods and inhibited oxidation rate was demonstrated.

Key words: inhibited oxidation, chain transfer, radical recombination, radical disproportionation, retardation effect, kinetics, inhibitor radicals, lipids.

The kinetics and mechanism of inhibited oxidation of hydrocarbons and lipids have sufficiently been studied both experimentally and theoretically.[1–5] Interrelations of the reactivity of inhibitors and substrates of oxidation with retardation effects and correlations between the structure of the inhibitor and its reactivity in reactions with radicals and peroxides have been studied for many inhibitors.[5–8] Many rate constants of elementary stages of inhibited oxidation have been determined and systematized.[5,7]

The interest in natural inhibitors, vegetable extracts, and concentrates with antioxidation properties increased in recent years. Great attention was paid to the specificity of the inhibition by α-tocopherol (vitamin E), one of the most abundant and efficient lipid antioxidants.[5–9] Testing of new antioxidation compositions usually includes overall kinetic effects: induction periods (τ),[10] decrease in the oxidation rate in the presence of an antioxidant (w_{inh}/w_o),[11] and dependence of τ and the rate of the process on the inhibitor concentration.[11–13] It has been found that at high concentrations the efficiency of many inhibitors decreases, and the contribution of side reactions involving inhibitors in the development of the oxidation process, including chain transfer reactions by the inhibitor radical, direct oxidation of the inhibitor by dioxygen and hydroperoxides, and participation of the products of inhibitor transformation in chain initiation, has been evaluated.[11–15] Diverse information on the synergistic effect of mixtures of inhibitors and various additives that enhance retardation effects is available.[16–20] Reactions resulting in the regeneration of a more efficient inhibitor and so-called multiple chain termination are often considered in terms of the mechanism of a synergistic effect.[5,7]

Regeneration of an inhibitor can occur in stages of disproportionation and chain transfer involving inhibitor radicals. The latter reaction has been discussed in detail.[1–8] Relatively high retardation effects in oxidation of highly unsaturated lipids in the presence of α-tocopherol are related sometimes with its efficient regeneration in this reaction.[12,32] The rate constants of the chain transfer reaction, especially for α-tocopherol, change within several orders of magnitude. In this work, using computer simulation, we studied the kinetics of inhibited oxidation of lipids to estimate the contribution of inhibitor regeneration in reactions of chain transfer and recombination of inhibitor radicals to retardation effects.

Choice of kinetic model

The kinetic model is based (Table 1) on the reactions and corresponding rate constants known for the oxidation of methyl linoleate,[3,22–24] because linoleic esters are easily oxidizable components of vegetable oils and many natural lipid systems, and their content determines, in many cases, the oxidizability of the lipid substrates.[4,21]

The kinetic scheme of liquid-phase oxidation of lipids (LH) includes reactions *1*—*12*.[1–8] In the presence of an initiator (I), the formation of radicals occurs with an almost constant initiation rate $w_i = 2k_1[I]$. Under autooxidation conditions ([I] = 0), the rates of radical formation in the reactions of LH with O_2 (*6*) and decomposition of hydroperoxides (LOOH) (reactions *7* and *8*) increase as LOOH is accumulated. The chain termination occurs due to recombination or disproportionation of radicals (reactions *9*, *11*, and *12*).

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Table 1. Kinetic model of inhibited oxidation of methyl linoleate

No.	Reaction	k/L mol^{-1} s^{-1}
1	I → I$^{\cdot}$ + I$^{\cdot}$	$5 \cdot 10^{-6}$
2	I$^{\cdot}$ + O_2 → $IO_2^{\cdot}$	$5 \cdot 10^{6}$
3	$IO_2^{\cdot}$ + LH → L$^{\cdot}$ + IOOH	$1 \cdot 10^{3}$
4	L$^{\cdot}$ + O_2 → $LO_2^{\cdot}$	$5 \cdot 10^{6}$
5	$LO_2^{\cdot}$ + LH → L$^{\cdot}$ + LOOH	90
6	2 LH + O_2 → L$^{\cdot}$ + $LO_2^{\cdot}$	$5.8 \cdot 10^{-11}$
7	LOOH + LH → LO$^{\cdot}$ + L$^{\cdot}$ + H_2O	$2.3 \cdot 10^{-7}$
8	LOOH + LOOH → $LO_2^{\cdot}$ + LO$^{\cdot}$ + H_2O	$2.4 \cdot 10^{-6}$
9	2 $LO_2^{\cdot}$ → Alc + Ket	$4.4 \cdot 10^{6}$
10	LO$^{\cdot}$ + LH → Alc + L$^{\cdot}$	$1 \cdot 10^{5}$
11	$LO_2^{\cdot}$ + LO$^{\cdot}$ → Ket + LOOH	$5 \cdot 10^{6}$
12	$LO_2^{\cdot}$ + $IO_2^{\cdot}$ → Alc + Ket	$5 \cdot 10^{6}$
13	PhOH + $LO_2^{\cdot}$ → LOOH + PhO$^{\cdot}$	$1.5 \cdot 10^{4}$—$1.5 \cdot 10^{6}$
14	PhOH + LO$^{\cdot}$ → Alc + PhO$^{\cdot}$	$1 \cdot 10^{7}$
15	PhOH + $IO_2^{\cdot}$ → IOOH + PhO$^{\cdot}$	$1.5 \cdot 10^{5}$
16	PhO$^{\cdot}$ + PhO$^{\cdot}$ → P_1 + (PhOH)	$3 \cdot 10^{3}$—$4 \cdot 10^{7}$
17	PhO$^{\cdot}$ + $LO_2^{\cdot}$ → P_2	$3 \cdot 10^{8}$
18	PhO$^{\cdot}$ + LO$^{\cdot}$ → P_3 + PhOH + Ket	$3 \cdot 10^{8}$
19	PhO$^{\cdot}$ + LH → L$^{\cdot}$ + (PhOH/P_4)	0—100

Note. The rate constants (k) correspond to the oxidation of methyl linoleate at 60 °C; in reactions *1*, *2*, and *4*, k are presented in s^{-1}. Initial concentrations: [LH] = 2.9 mol L^{-1}; $[LOOH]_0 = 1 \cdot 10^{-5}$ mol L^{-1}; [I] = $4 \cdot 10^{-3}$ mol L^{-1}; $[PhOH]_0 = 1 \cdot 10^{-4}$ mol L^{-1}; $[O_2] = 10^{-3}$ mol L^{-1} = const; oxidation usually occurs at a constant oxygen pressure; therefore, $[O_2]$ is included in the corresponding rate constants: $k_2 = k_4 = k_6 = k_i \cdot [O_2]$.

The scheme of inhibited oxidation includes, along with stages *1*—*12*, reactions *13*—*19*, which are known for phenol antioxidants (PhOH).[1—8] The calculation was performed for three groups of PhOH, which differ in their activity in reaction *13* with peroxyl radicals $LO_2^{\cdot}$: group I (of the type of α-tocopherol) with $k_{13} = 1.5 \cdot 10^{6}$ L mol^{-1} s^{-1}, group II (PhOH of the type of unhindered phenols, for example, hydroquinone) with $k_{13} = 1.5 \cdot 10^{5}$ L mol^{-1} s^{-1}, and group III (PhOH of the type of sterically hindered phenols, for example, ionol) with $k_{13} = 1.5 \cdot 10^{4}$ L mol^{-1} s^{-1}.

Reaction *16* is the bimolecular decay of phenoxyl radicals (PhO$^{\cdot}$), which can occur as either disproportionation with regeneration of the inhibitor (D) or recombination (R) without regeneration of PhOH. The effect of PhOH regeneration in reaction *16* was considered for rapidly ($k_{16} = 4 \cdot 10^{7}$) and slowly ($k_{16} = 3 \cdot 10^{3}$) reacting PhO$^{\cdot}$ radicals. The rate constant of the reaction of PhO$^{\cdot}$ with $LO_2^{\cdot}$ was accepted to be $k_{17} = 3 \cdot 10^{8}$ L mol^{-1} s^{-1}.[5]

Reaction *19* is the chain transfer by the inhibitor radical. It can be a hydrogen abstraction from the substrate molecule with regeneration of the inhibitor. Chain transfer can occur as the addition of PhO$^{\cdot}$ to unsaturated bonds of polyene compounds; in this case, the inhibitor is not regenerated.[25] We examined both cases; rate constants k_{19} were varied within the 0—10^{2} L mol^{-1} s^{-1} range (taking into account the published data). In this series of calculations, we accepted that reaction *16* occurs as disproportionation. Computer simulation was performed by the program presented in the previously published work.[26]

Influence of chain transfer reaction (19) by inhibitor radical

A. Initiated oxidation. Figure 1 presents the calculated kinetic curves of accumulation of hydroperoxides (LOOH) under the conditions of initiated oxidation of LH with $w_i = 4 \cdot 10^{-8}$ L mol^{-1} s^{-1} in the presence of inhibitors from groups I—III, which show the influence of chain transfer reaction (*19*) by the inhibitor radical on the induction periods. The curves for different k_{19} values in both variants were compared: when the inhibitor is regenerated in the chain transfer stage (+) PhO$^{\cdot}$ + LH → PhOH + L$^{\cdot}$ and when the reaction proceeds without regeneration PhOH (−): PhO$^{\cdot}$ + LH → L$^{\cdot}$ (+ P_4). It is seen in Fig. 1 that for all groups of PhOH, the chain transfer reaction with $k_{19} \leq 0.1$ L mol^{-1} s^{-1} virtually does not affect the induction periods (τ) if it is accompanied by the regeneration of PhOH (see Fig. 1, *a* and *c*, curves *1* and *2*; Fig. 1, *b*, curves *1*—*4*). When PhOH is not regenerated, the induction period becomes twofold shorter than that for the inhibitor of type I (see Fig. 1, *a*, curves *2* and *3*), is shortened by 7% in the case of inhibitor II (see Fig. 1, *b*, curves *4* and *5*), and remains almost unchanged for inhibitor III (see Fig. 1, *c*, curves *2* and *3*).

It follows from the kinetic analysis of inhibited oxidation made in the quasi-steady-state approximation[1—7] that the induction period when w_i = const is mainly determined by the amount of inhibitor and its stoichiometric coefficient f, which is an effective value that

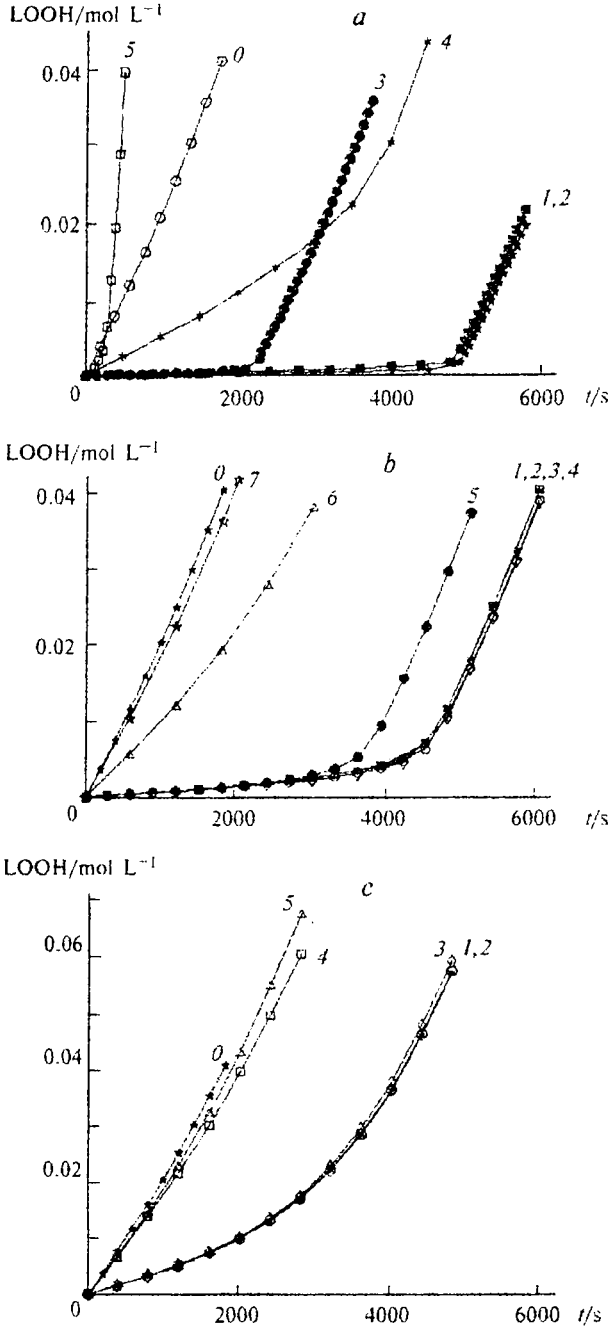

Fig. 1. Influence of the chain transfer rate constant on the accumulation of LOOH in initiated oxidation in the presence of PhOH ($1 \cdot 10^{-4}$ mol L^{-1}). *a*, PhOH of type I ($k_{13} = 1.5 \cdot 10^6$, $k_{16} = 3 \cdot 10^3$): *0*, noninhibited oxidation; *1*, $k_{19} = 0$; *2*, $k_{19} = 0.1$ (+); *3*, $k_{19} = 0.1$ (−); *4*, $k_{19} = 100$ (+); and *5*, $k_{19} = 100$ (−); *b*, PhOH of type II ($k_{13} = 1.5 \cdot 10^5$): *0*, noninhibited oxidation; *1*, $k_{19} = 0$, $k_{16} = 4 \cdot 10^7$ (+); *2*, $k_{19} = 10^{-3}$, $k_{16} = 4 \cdot 10^7$ (+); *3*, $k_{19} = 0.1$, $k_{16} = 4 \cdot 10^7$ (+); *4*, $k_{19} = 0.1$, $k_{16} = 3 \cdot 10^3$ (+); *5*, $k_{19} = 0.1$, $k_{16} = 3 \cdot 10^3$ (−); *6*, $k_{19} = 100$, $k_{16} = 4 \cdot 10^7$ (+); and *7*, $k_{19} = 100$, $k_{16} = 4 \cdot 10^7$ (−); and *c*, PhOH of type III ($k_{13} = 1.5 \cdot 10^4$, $k_{16} = 4 \cdot 10^7$): *0*, noninhibited oxidation; *1*, $k_{19} = 0$; *2*, $k_{19} = 0.1$ (+); *3*, $k_{19} = 0.1$ (−); *4*, $k_{19} = 100$ (+); and *5*, $k_{19} = 100$ (−).

characterizes the number of kinetic chains terminated by one inhibitor molecule[1]:

$$\tau = f[\mathrm{PhOH}]_0/w_i. \qquad (1)$$

For phenol inhibitors $f \leq 2$, because the chain termination involves PhOH (reaction *13* and at least in *14*, *15*) and PhO$^{\cdot}$ (reactions *17* and *18*) and depends on the ratio of rates of chain termination (*17*, *18*) and recombination of PhO$^{\cdot}$ (*16*). For $k_{19} \leq 0.1$ L mol^{-1} s^{-1} and inhibitor regeneration (+), the f value calculated by formula (1) from the data in Fig. 1 are the following: for PhOH of group I, $f = 2$; for PhOH of group II, $f = 1.81$; and for PhOH of group III, $f = 1.2$. It is seen that f decreases noticeably when k_{13} decreases and k_{16} increases. The chain transfer reaction virtually does not violate the stoichiometry of chain termination if the inhibitor is regenerated. If PhOH is not regenerated, reaction *13* results in a decrease in f.

The calculations show that the chain transfer reaction with $k_{19} \leq 0.1$ in both variants (with and without regeneration of the inhibitor) results in a relative increase in the initial rate of inhibited oxidation (w_{inh}) for all types of PhOH. However, absolute values of rate increments are low and can be undetectable experimentally, being within the measurement accuracy (see Fig. 1).

For $k_{19} = 100$ (see Fig. 1, *a*, curves 4 and 5; *b*, curves *6* and *7*; *c*, curves *4* and *5*) in all cases, a high initial rate is observed, which characterizes the combined oxidation of the inhibitor and substrate. It is remarkable that for PhOH from group I with slowly disproportionating PhO$^{\cdot}$ a weakly pronounced induction period is observed during regeneration of PhOH (see Fig. 1, *a*, curve *4*), and if the inhibitor is not regenerated, the process is accelerated (curve *5*).

B. Autooxidation. Under autooxidation conditions, the participation of the inhibitor radical in the chain transfer has a substantial effect on the kinetics of inhibited oxidation (Fig. 2). For PhOH of type I with $k_{19} = 0.1$, the induction period is halved if reaction *19* occurs with regeneration of PhOH, and it is shortened by 8 times if no regeneration occurs. For $k_{19} = 100$, only a relatively slight decrease in the rate without a noticeable induction period for variant (+) is observed (Fig. 2, *a*, curve *4*), and the oxidation is accelerated if the inhibitor is not regenerated (curve *5*).

In the case of the inhibitor of type II with $k_{19} = 0.1$, the induction perjod is also shortened, which is more pronounced for the inhibitor with slowly disproportionating radicals (see Fig. 2, *b*, curves *2* and *3*). In variant (+) with $k_{19} = 0.1$, the induction period is 1.7-fold higher than τ (−) (see Fig. 2, *b*, *cf.* curves *3* and *4*).

For $k_{19} = 100$, PhOH of group II has almost no effect on the oxidation rate if regeneration is absent (curve *6*), and it insignificantly decreases the oxidation rate if PhOH is regenerated (see Fig. 2, *b*, curve *5*).

For inhibitor of type III with $k_{19} = 0.1$, the induction periods in variants (+) and (−) differ within 10%, and for $k_{19} = 100$, PhOH has almost no effect on the oxidation kinetics.

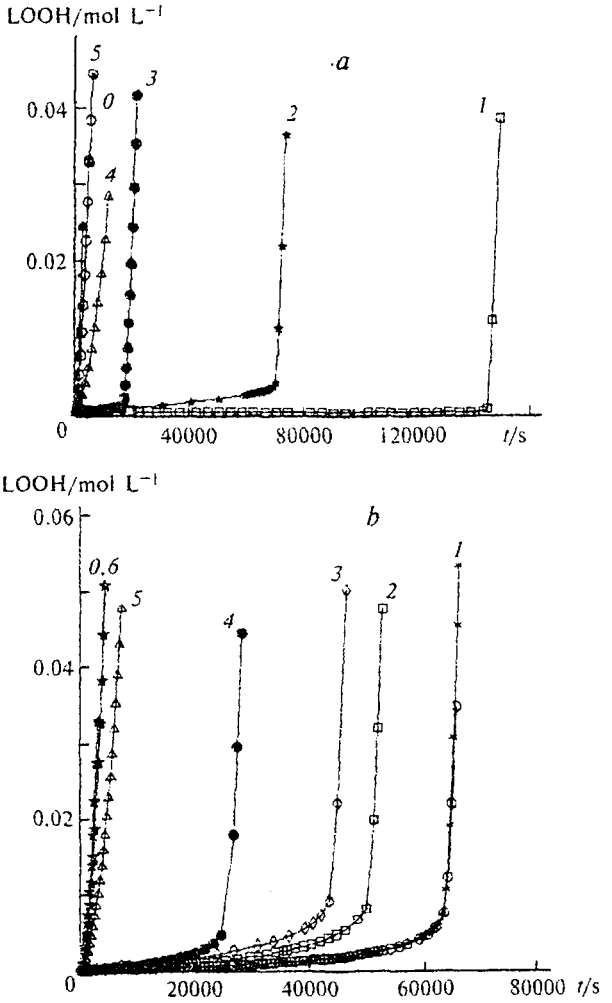

Fig. 2. Influence of the chain transfer reaction on the accumulation of LOOH during autooxidation in the presence of PhOH ($1 \cdot 10^{-4}$ mol L^{-1}). *a*, PhOH of type I ($k_{13} = 1.5 \cdot 10^6$, $k_{16} = 3 \cdot 10^3$): *0*, noninhibited oxidation; *1*, $k_{19} = 0$; *2*, $k_{19} = 0.1$ (+); *3*, $k_{19} = 0.1$ (−); *4*, $k_{19} = 100$ (+); *5*, $k_{19} = 100$ (−); *b*, PhOH of type II ($k_{13} = 1.5 \cdot 10^5$): *0*, noninhibited oxidation; *1*, $k_{19} = 0$; *2*, $k_{19} = 0.1$, $k_{16} = 4 \cdot 10^7$ (+); *3*, $k_{19} = 0.1$, $k_{16} = 3 \cdot 10^3$ (+); *4*, $k_{19} = 0.1$, $k_{16} = 3 \cdot 10^3$ (−); *5*, $k_{19} = 100$, $k_{16} = 4 \cdot 10^7$ (+); and *6*, $k_{19} = 100$, $k_{16} = 4 \cdot 10^7$ (−).

Influence of regeneration of inhibitor in reaction 16 on efficiency of retardation

The kinetic curves of accumulation of LOOH that demonstrate the influence of inhibitor regeneration in the reaction of bimolecular decay of PhO$^{\cdot}$ radicals on the induction periods are compared in Fig. 3. Under the conditions of initiated oxidation (see Fig. 3), the induction periods in the case of regeneration (τ_D) and without it (τ_R) differ noticeably only for inhibitors with rapidly recombining PhO$^{\cdot}$ ($k_{16} = 4 \cdot 10^7$): for PhOH of type I, $\tau_D/\tau_R = 1.5$ (see Fig. 3, *a*, curves *4* and *4′*); for PhOH

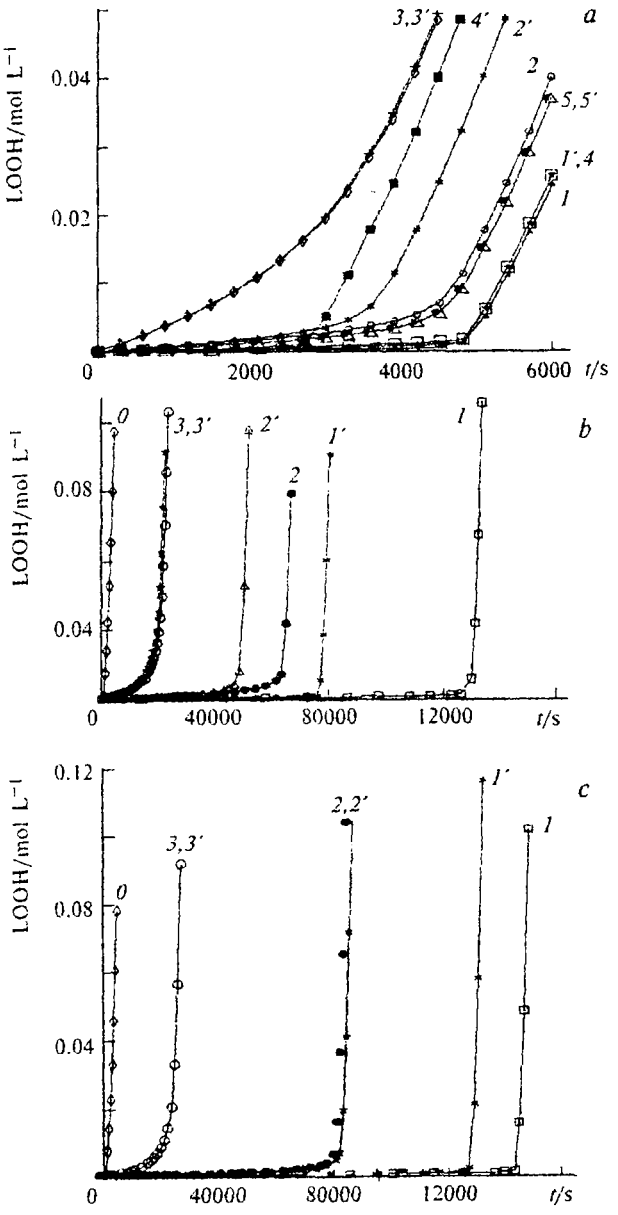

Fig. 3. Influence of the regeneration of PhOH in the bimolecular decay of PhO$^{\cdot}$ (reaction *16*, D is disproportionation, R is recombination) on the kinetics of accumulation of LOOH. *a*, in initiated oxidation: *1*, $k_{13} = 1.5 \cdot 10^6$, $k_{16} = 3 \cdot 10^3$ (D); *1′*, $k_{13} = 1.5 \cdot 10^6$, $k_{16} = 3 \cdot 10^3$ (R); *2*, $k_{13} = 1.5 \cdot 10^5$, $k_{16} = 4 \cdot 10^7$ (D); *2′*, $k_{13} = 1.5 \cdot 10^5$, $k_{16} = 4 \cdot 10^7$ (R); *3*, $k_{13} = 1.5 \cdot 10^4$, $k_{16} = 4 \cdot 10^7$ (D); *3′*, $k_{13} = 1.5 \cdot 10^4$, $k_{16} = 4 \cdot 10^7$ (R); *4*, $k_{13} = 1.5 \cdot 10^6$, $k_{16} = 4 \cdot 10^7$ (D); *4′*, $k_{13} = 1.5 \cdot 10^6$, $k_{16} = 4 \cdot 10^7$ (R); *5*, $k_{13} = 1.5 \cdot 10^5$, $k_{16} = 3 \cdot 10^3$ (D); *5′*, $k_{13} = 1.5 \cdot 10^5$, $k_{16} = 3 \cdot 10^3$ (R); $[PhOH]_0 = 1 \cdot 10^{-4}$ mol L^{-1}; *b*, in autooxidation with $k_{16} = 4 \cdot 10^7$: *0*, noninhibited oxidation; *1*, $k_{13} = 1.5 \cdot 10^6$ (D); *1′*, $k_{13} = 1.5 \cdot 10^6$ (R); *2*, $k_{13} = 1.5 \cdot 10^5$ (D); *2′*, $k_{13} = 1.5 \cdot 10^5$ (R); *3*, $k_{13} = 1.5 \cdot 10^4$ (D); *3′*, $k_{13} = 1.5 \cdot 10^4$ (R); $[PhOH]_0 = 1 \cdot 10^{-4}$ mol L^{-1}; *c*, in autooxidation with $k_{16} = 3 \cdot 10^3$: *0*, noninhibited oxidation; *1*, $k_{13} = 1.5 \cdot 10^6$ (D); *1′*, $k_{13} = 1.5 \cdot 10^6$ (R); *2*, $k_{13} = 1.5 \cdot 10^5$ (D); *2′*, $k_{13} = 1.5 \cdot 10^5$ (R); *3*, $k_{13} = 1.5 \cdot 10^4$ (D); *3′*, $k_{13} = 1.5 \cdot 10^4$ (R); $[PhOH]_0 = 1 \cdot 10^{-4}$ mol L^{-1}.

of type II, $\tau_D/\tau_R = 1.2$ (curves *2* and *2'*); and for PhOH of type III, $\tau_D \approx \tau_R$ (curves *3* and *3'*). If the recombination of PhO$^{\cdot}$ is relatively slow ($k_{16} = 3 \cdot 10^3$), τ_D and τ_R almost do not differ for all types of PhOH (see Fig. 3, *a*, *cf.* curves *1* and *1'*; *5* and *5'*).

Under autooxidation conditions, the differences between τ_D and τ_R are manifested to a greater extent and depend on the antiradical activity of PhOH. The induction periods for PhOH of all types with rapidly recombining PhO$^{\cdot}$ ($k_{16} = 4 \cdot 10^7$) are related as $\tau_{ID} : \tau_{IID} : \tau_{IIID} = 6.7 : 4 : 1$ and $\tau_{IR} : \tau_{IIR} : \tau_{IIIR} = 4 : 2.5 : 1$. In the case of PhOH of type I, $\tau_D/\tau_R = 1.7$; for PhOH of type II, $\tau_D/\tau_R = 1.3$; for PhOH of type III, $\tau_D \approx \tau_R$ (see Fig. 3, *b*).

It is shown in Fig. 3, *c* that in the case of PhOH of type I even with slowly recombining PhO$^{\cdot}$ ($k_{16} = 3 \cdot 10^3$), the induction periods differ: $\tau_D/\tau_R = 1.13$ (see Fig. 3, *c*, curves *1* and *1'*). The kinetic curves of τ_D and τ_R for inhibitors of types II and III (see Fig. 3, *c*, curves *3* and *4*, *5* and *6*) virtually coincide.

Results and Discussion

The calculated kinetic curves (see Figs. 1—3) are similar to experimental curves obtained by testing the inhibitors.[3,13—15,20] The data presented show that the differences in the reactivity of PhOH and PhO$^{\cdot}$ in reactions *13*, *16*, and *19* are more pronounced under conditions of autooxidation of the lipid substrate than for initiated oxidation. In the case of inhibitors of type III, which react relatively slowly with $LO_2^{\cdot}$, the chain transfer reaction and inhibitor regeneration in reactions *19* and *16* virtually do not affect the induction periods at $k_{13} < 0.1$. However, for inhibitors with a high antiradical activity, regeneration has a substantial effect on the induction periods and rate of inhibited oxidation. The reaction of phenoxyl radicals with an oxidized substrate is most often discussed in the literature for the mechanism of action of tocopherols.[3—8,12] The rate constants of reaction *19* for PhO$^{\cdot}$ from tocopherols differ (in different works) within several orders of magnitude ($0.01—10^3$ L mol^{-1} s^{-1}).[3—8,12,28—32] Therefore, it is noteworthy that for all types of PhOH, chain transfer (*19*) and recombination (*16*) involving inhibitor radicals decrease the efficiency of the inhibition effect, *i.e.*, result in a relative (as compared with $k_{19} = 0$ and $k_{16} = 0$) shortening of the induction periods and an increase in the inhibited oxidation rates, thus decreasing the stoichiometric coefficient of chain termination. The regeneration of the inhibitor in these reactions can be considered as a factor that "aligns" a decrease in the stoichiometric inhibition coefficient and the corresponding shortening of the induction period.

At high rate constants of chain transfer (already at $k_{19} = 100$ L mol^{-1} s^{-1}), compared in value with the rate constant of chain propagation ($k_5 = 90$ L mol^{-1} s^{-1}), the accumulation of LOOH occurs virtually without an induction period with a sufficiently high rate that can exceed the rate of the noninhibited process if PhOH is not regenerated in reaction *19* (see Fig. 1, *a*, curve *5* and Fig. 2, *a*, curve *5*). Since tocopherols are efficient antioxidants for unsaturated lipid systems, the chain transfer constants obtained by the kinetic and spectrophotometric methods, $k_{19} \leq 0.1$, for example, 0.082 L mol^{-1} s^{-1}, seem to be more reasonable.[31]

The results of calculations that characterize the influence of PhOH regeneration during bimolecular decay of PhO in induction periods are useful for interpretation of the experimental data on testing natural phenolic acids as oil antioxidants.[11,13,14,33] Under other equivalent conditions, the bimolecular decay of PhO by disproportionation in which PhOH is regenerated gives a considerable advantage in retardation effects as compared with the situation where no regeneration occurs (recombination of PhO$^{\cdot}$). Efficient disproportionation is possible when phenoxyl contains weakly bound H atoms, for example, when one of the substituents in positions 2, 4, or 6 contains β-H atoms, *e.g.*, —CHR_1R_2, —OH, —NHR, —SH, *etc.* It has previously been shown[33] that in a series of derivatives of *p*-hydroxybenzoic and *p*-hydroxycoumaric acids, dihydroxy-substituted derivatives in the aromatic ring of PhOH provide longer induction periods during autooxidation of different lipid substrates than their methoxy-substituted analogs, despite close antiradical activity (k_{13}). For example, the rate constants of the reactions with peroxy radicals (60 °C) of 3,4-dihydroxybenzoic and syringic (3,5-dimethoxy-4-hydroxybenzoic) acids are equal ($4.6 \cdot 10^4$ L mol^{-1} s^{-1}), and the induction periods (when 1 mmol L^{-1} of inhibitor is added to oxidized lard at 100 °C) are 9.0 and 3.0 h, respectively. It is possible that the bimolecular decay of phenoxyl radicals of 3,4-dihydroxybenzoic acid occurs by disproportionation with regeneration of PhOH, and in the case of syringic acid, without regeneration of PhOH. The presence of the second hydroxyl group in the aromatic ring results, as a rule, in higher k_{16}.[5,7] In this case, an increase in the induction period related to PhOH regeneration is probably most pronounced.

References

1. N. M. Emanuel', E. T. Denisov, and Z. K. Maizus, *Tsepnye reaktsii okisleniya uglevodorodov v zhidkoi faze* [*Chain Reactions of Hydrocarbon Oxidation in Liquid Phase*], Nauka, Moscow, 1965 (in Russian).
2. J. Scott, *Atmospheric Oxidation and Antioxidation*, Elsevier, Amsterdam, 1965.
3. A. Popov and N. Yanishlieva, *Avtookislenie i stabil'nost' na lipidite* [*Autooxidation and Stability on Lipid*], BAN, Sofiya, 1976 (in Bulgarian).
4. *Autoxidation of Unsaturated Lipids*, Ed. H. W.-S. Chan, Academic Press, London, 1987.
5. V. A. Roginskii, *Fenol'nye antioksidanty* [*Phenol Antioxidants*], Nauka, Moscow, 1988 (in Russian).
6. G. W. Burton, T. Doba, E. J. Gabe, L. Hughes, F. L. Lee, L. Prasad, and K. U. Ingold, *J. Am. Chem. Soc.*, 1985, **107**, 7053.

7. E. T. Denisov and V. V. Azatyan, *Ingibirovanie tsepnykh reaktsii* [*Inhibition of Chain Reactions*], Chernogolovka, 1997 (in Russian).
8. E. B. Burlakova, S. A. Krashakov, and N. G. Khrapova, *Khim. Fiz.*, 1995, **14**, 151 [*Russ. Chem. Phys.*, 1995, **14** (Engl. Transl.)].
9. R. Yamauchi, *Food Sci. Technol. Tokyo*, 1997, **3**, 301.
10. Le Tutour and D. Guedon, *Phytochemistry*, 1992, **31**, 1173.
11. E. M. Marinova and N. V. Yanishlieva, *J. Am. Oil Chem. Soc.*, 1994, **71**, 327.
12. E. B. Burlakova, S. A. Krashakov, and N. G. Khrapova, *Biologicheskie Membrany* [*Biological Membranes*], 1998, **15**, 137 (in Russian).
13. N. V. Yanishlieva and E. M. Marinova, *Recent Res. Dev. in Oil Chem.*, 1998, **2**, 1.
14. N. V. Yanishlieva and E. M. Marinova, *Food Chemistry*, 1995, **54**, 377.
15. E. Marinova and N. Yanishlieva, *Food Chemistry*, 1996, **56**, 139.
16. E. Niki, T. Saito, A. Kawakami, and Y. Kamiya, *J. Biol. Chem.*, 1984, **259**, 4177.
17. E. B. Burlakova, N. M. Storozhok, and N. G. Khrapova, *Voprosy pitaniya* [*Problems of Feeding*], 1990, No. 4, 53 (in Russian).
18. A. Nishida, *Agric. Biol. Chem.*, 1991, **55**, 1665.
19. E. M. Marinova and N. V. Yanishlieva, *Fat Sci. Technol.*, 1992, **94**, 448.
20. E. B. Burlakova, L. I. Mazaletskaya, N. I. Sheludchenko, and L. N. Shishkina, *Izv. Akad. Nauk, Ser. Khim.*, 1995, 1053 [*Russ. Chem. Bull.*, 1995, **44**, 1014 (Engl. Transl.)].
21. H. W.-S. Chan, in *Autoxidation of Unsaturated Lipids*, Ed. H. W.-S. Chan, Ch. 1, p. 1, Academic Press, London, 1987.
22. N. A. Porter, B. A. Weber, and H. Weenen, *J. Am. Chem. Soc.*, 1980, **102**, 5597.
23. H. Weenen and N. A. Porter, *J. Am. Chem. Soc.*, 1982, **104**, 5216.
24. W. A. Pryor, T. Strickland, and D. F. Church, *J. Am. Chem. Soc.*, 1988, **110**, 2224.
25. A. B. Gagarina, O. T. Kasaikina, and N. M. Emanuel', *Izv. Akad. Nauk SSSR, Ser. Khim.*, 1975, 2426 [*Bull. Acad. Sci. USSR, Div. Chem. Sci.*, 1975, **24** (Engl. Transl.)].
26. E. F. Brin and S. O. Travin, *Khim. Fiz.*, 1991, **10**, 630 [*Russ. Chem. Phys.*, 1991, **10** (Engl. Transl.)].
27. H. Tsuchiashi, M. Kigoshi, M. Iwatsuki, and E. Niki, *Arch. Biochem. Biophys.*, 1995, **323**, 137.
28. E. N. Kukhtina, N. G. Khrapova, E. B. Burlakova, I. K. Sarycheva, and R. P. Evstigneeva, *Dokl. Akad. Nauk SSSR*, 1983, **272**, 729 [*Dokl. Chem.*, 1983 (Engl. Transl.)].
29. K. Mukai and Y. Okauchi, *Lipids*, 1989, **24**, 936.
30. S. I. Nagaoka, Y. Okauchi, S. Urano, U. Nagashima, and K. Mukai, *J. Am. Chem. Soc.*, 1990, **112**, 8921.
31. A. A. Remorova and V. A. Roginskii, *Kinet. Katal.*, 1991, **32**, 808 [*Kinet. Catal.*, 1991, **32** (Engl. Transl.)].
32. H. G. Storozhok, R. O. Pirogov, S. A. Krashakov, N. G. Khrapova, and E. B. Burlakova, *Kinet. Katal.*, 1995, **36**, 818 [*Kinet. Catal.*, 1995, **36** (Engl. Transl.)].
33. O. T. Kasaikina, V. D. Kortenska, E. M. Marinova, I. F. Rusina, and N. V. Yanishlieva, *Izv. Akad. Nauk, Ser. Khim.*, 1997, 1119 [*Russ. Chem. Bull.*, 1997, **46**, 1070 (Engl. Transl.)].

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