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Reactions of Arylamine and Aminophenol Derivatives, and Riboflavin with Organic Radicals

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Based on product yield data on radiolysis of hexane, ethanol and 3 M aqueous ethylene glycol solutions, the ability of a number of arylamine, aminophenol and quinonimine derivatives to affect processes involving peroxyl, alkyl or α-hydroxyalkyl radicals was assessed. It has been shown that the introduction of a hydroxyl group into aromatic amine structure enhances its antioxidant performance and makes it significantly more reactive with respect to carbon-centered organic radicals. Replacement of the hydrogen atom of a hydroxyl group by a methyl group decreases the anti-radical activity of aminophenols drastically. Compounds containing (or capable of forming) a quinonimine moiety interact with alkyl or α-hydroxyalkyl radicals most effectively, suppressing recombination and fragmentation reactions of the latter. In the sequence: aromatic amines—aminophenols—quinonimines, a trend towards enhancement of the ability of the compounds studied to react with carbon-centered radicals was noted. Also, this study presents for the first time evidence of riboflavin reactivity with respect to organic radicals.

Keywords: Radicals; Arylamines; Aminophenols; Quinonimines; Oxidation; Recombination

Abbreviations: G: Radiation chemical yield

INTRODUCTION

The ability of arylamines to enhance the stability of organic materials, discovered earlier, was used for creation of the first industrial antioxidants.[1] The stabilizing action of arylamines is achieved in many respects by their inhibiting effects on oxidation processes, through the reduction of peroxyl organic radicals according to reaction:

$$Ar_2NH + ROO^{\cdot} \longrightarrow ROOH + Ar_2N^{\cdot} \qquad (1)$$

Subsequently, this knowledge became an incentive to perform investigations concerning the effects of structure of amino-containing organic compounds on their antioxidant properties. Details of work on development of industrial stabilizers have been published in Ref. [1].

Interest in studying antioxidant properties of substances based on aromatic amines is also due to the presence of pharmacological activity in some of them, which can be associated with their capability of regulating free-radical processes in an organism.[2] Structure-dependent changes in bioantioxidant properties of aromatic amine derivatives have been the subject of a number of publications.[3–7] Introduction of a hydroxyl or an additional amino group into the arylamine structure was found to considerably increase their efficiency in suppressing oxidation of unsaturated fatty acid moieties. Authors of the publications cited explain these effects in terms of the influence of inductive and resonance factors on the rate of reaction (1).

In some studies,[5–8] attempts have been made to find out correlation between either bond dissociation energies (N–H, O–H) or ionization potentials of various aminophenols and their antioxidant activity. At the same time, in spite of the fact that oxidation processes of organic substances begin, as a rule, from the formation of alkyl radicals, only single publications can be found

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in the literature reporting on studies of reactivity of aromatic amines and their derivatives towards carbon-centered organic radicals.[8,9]

Our study is based on the experimentally established evidence of an important role of free-radical fragmentation reactions in damage to biologically important molecules caused by various factors.[10–13] Such reactions occur with participation of α-hydroxyl-containing carbon-centered radicals. The effectiveness of fragmentation reactions and other homolytic processes involving carbon-centered radicals is significantly affected by diphenol and quinone derivatives.[14,15] Whether aromatic amines and aminophenols, as well as their derivatives, are able to affect these processes is addressed in this work.

In the approach adopted, we investigated the effects of aniline (I), diphenylamine (VI), aminophenols (III–V) and their derivatives (XI–XVI), as well as N-phenyl-1,4-benzoquinonemonoimine (X) and riboflavin (XVII) (see Table I) on product yields in radiolysis of hexane, ethanol and aqueous solutions of ethylene glycol.

MATERIALS AND METHODS

Ethylene glycol from Merk, hexane (99%) from Baker Analyzed and riboflavin from Aldrich were used without further purification. Ethanol was purified by means of Wolfen Zeosorb LA zeolite and distilled using a 3 m rectifying column.

Commercial aniline, phenol, diphenylamine, *o*-, *m*- and *p*-aminophenols were purified before use by recrystallization, vacuum sublimation and vacuum distillation. Physico-chemical and spectral parameters of the samples agreed with the data from the literature.

Other compounds needed for the study—2-hydroxy-diphenylamine, 4-hydroxy-diphenylamine, 4-methoxy-diphenylamine, N-phenyl-1,4-benzoquinonemonoimine, 2-hydroxy-3,5-di-tert-butylphenylaniline, N-(2-methoxy-3,5-di-tert-butylphenyl)aniline, 4,6-di-tert-butyl-2-[(4-methylphenyl)amino]-phenol, 4,6-di-tert-butyl-2-[(4-methoxyphenyl)-amino]phenol, 4,6-di-tert-butyl-2-aminophenol, N-(2-methoxy-3,5-di-tert-butyl-phenyl)dimethylamine—were synthesized according to known procedures.[16–21] Structures of all the compounds synthesized have been confirmed by ^{1}H NMR and mass spectral data.

Preparation of Solutions

Solutions of ethylene glycol (concentration 3 M) were prepared using twice-distilled water. To prepare deaerated solutions high-purity argon (99.9%) was blown through the sample before use for 1.5 h. Preparation of solutions containing the compounds studied was performed by dissolving accurately weighted amounts of the latter in aqueous ethylene glycol, ethanol or hexane under argon flow. Concentrations of compounds under study were generally 10^{-3} M.

Radiation Experiments

Initiation of free-radical transformations in model systems was performed by means of γ-radiation. The solutions in question were placed in glass ampoules, blown through with argon, sealed, and irradiated in a γ-unit using ^{137}Cs source. Absorbed dose rate was (0.32 ± 0.01) Gy/s, and the absorbed dose range used in this study was 0.2–4 kGy.

Determination of Molecular Products of Radical Transformations

The analysis of recombination products of *n*-hexyl radicals (dodecane isomers) was performed by gas chromatography using a quartz capillary column DB-5 ($l = 30$ m; 0.54 mm ID; 1.5 μm df) with a GC-17AAF/APC chromatograph (Shimadzu). Chromatography conditions: starting temperature 100°C; temperature increase rate up to 200°C: 8°C/min; temperature increase rate up to 270°C: 10°C/min; evaporator temperature: 250°C; flame ionization detector; detector temperature: 230°C; carrier gas nitrogen, 30 cm/s.

The analysis of free-radical oxidation products of *n*-hexane (hexanol-2, hexanol-3, hexanone-2, hexanone-3) was performed by gas chromatography using quartz capillary column RTX-Wax ($l = 30$ m; 0.32 mm ID; 0.5 μm df) with a GC-17AAF/APC chromatograph (Shimadzu). Chromatography conditions: starting temperature 60°C; temperature increase rate up to 180°C: 8°C/min; evaporator temperature: 250°C; flame ionization detector; detector temperature: 220°C; carrier gas nitrogen, 30 cm/s.

The analysis of free-radical transformation products of ethanol (acetaldehyde, 2,3-butanediol) was performed by gas chromatography using a quartz capillary column RTX-Wax ($l = 30$ m; 0.32 mm ID; 0.5 μm df) with a GC-17AAF/APC chromatograph (Shimadzu). Chromatography conditions: starting temperature 40°C; temperature increase rate up to 200°C: 8°C/min; isothermal conditions for 3 min; evaporator temperature: 250°C; flame ionization detector; detector temperature: 220°C; carrier gas nitrogen, 30 cm/s.

The analysis of free-radical transformation products of 3 M aqueous ethylene glycol (acetaldehyde, glycol aldehyde) was performed by gas chromatography using a quartz capillary column Stabilax-DA (Zebron) ($l = 30$ m; 0.53 mm ID; 1 μm df) with a GC-17AAF/APC chromatograph (Shimadzu). Chromatography conditions:

TABLE I Compounds examined in this study

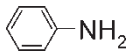
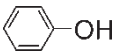
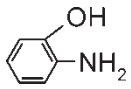
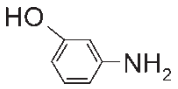
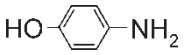
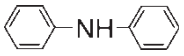
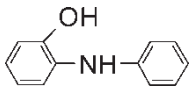
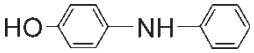
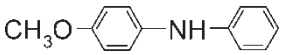
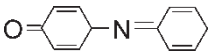
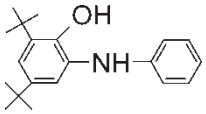
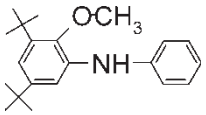
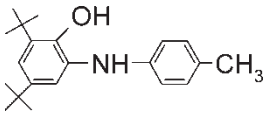
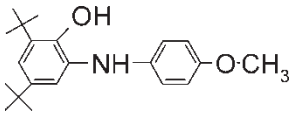
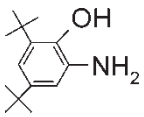
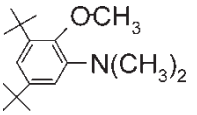
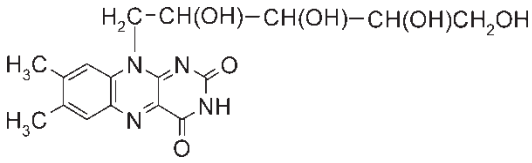
Compound No.	Name	Structure
I	Aniline	
II	Phenol	
III	*o*-Aminophenol	
IV	*m*-Aminophenol	
V	*p*-Aminophenol	
VI	Diphenylamine	
VII	2-Hydroxy-diphenylamine	
VIII	4-Hydroxy-diphenylamine	
IX	4-Methoxy-diphenylamine	
X	N-Phenyl-1,4-benzoquinonemonoimine	
XI	2-Hydroxy-3,5-di-tert-butylphenylaniline	
XII	N-(2-Methoxy-3,5-di-tert-butylphenyl)aniline	
XIII	4,6-di-tert-Butyl-2-[(4-methylphenyl)amino]-phenol	
XIV	4,6-di-tert-Butyl-2-[(4-methoxyphenyl)-amino]phenol	
XV	4,6-di-tert-Butyl-2-aminophenol	

TABLE I – *continued*

Compound No.	Name	Structure
XVI	N-(2-Methoxy-3,5-di-tert-butyl-phenyl)dimethyl-amine	
XVII	Riboflavin	

starting temperature 50°C; isothermal conditions for 2 min; temperature increase rate up to 230°C: 10°C/min; isothermal conditions for 5 min; evaporator temperature: 260°C; flame ionization detector; detector temperature: 240°C; carrier gas nitrogen, 30 cm/s.

RESULTS

To investigate the reactivity of aromatic amine, aminophenol derivatives and riboflavin with various organic radicals we studied their influence on molecular product yields (G) in radiolysis of *n*-hexane, ethanol and aqueous 3 M solution of ethylene glycol.

Interaction of Compounds under Study with Alkyl Radicals

A convenient method for generation of various alkyl radicals is radiolysis of the appropriate hydrocarbons. Thus, on γ-irradiation of deaerated hexane, the following processes occur:[22]

$$C_6H_{14} \rightsquigarrow C_6H_{14}^{\bullet+}, e^-, C_6H_{14}^{**} \quad (2)$$

$$C_6H_{14}^{\bullet+} + e^- \longrightarrow C_6H_{14}^{**} \quad (3)$$

$$C_6H_{14}^{**} \longrightarrow H_2 + C_6H_{12} \quad (4)$$

$$C_6H_{14}^{**} \longrightarrow H + C_6H_{13}^{\bullet} \quad (5)$$

$$H + C_6H_{14} \longrightarrow C_6H_{13}^{\bullet} + H_2 \quad (6)$$

$$2\,C_6H_{13}^{\bullet} \longrightarrow C_6H_{14} + C_6H_{12} \quad (7)$$

$$2\,C_6H_{13}^{\bullet} \longrightarrow C_{12}H_{26} \quad (8)$$

Dodecane isomers are formed as the main radiolysis products due to recombination of hexyl radicals (8). Hence, by measuring total dodecane yields ($\Sigma G(C_{12}H_{26})$) in the presence of various substances, relative ability of the latter to interact with alkyl radicals can be evaluated.

In Fig. 1, data are shown illustrating the dependence of accumulation of dodecanes resulting from recombination of C(2)- or C(3)-centered hexyl radicals on the dose absorbed in the absence and in the presence of compounds studied. Based on these data, the values of $\Sigma G(C_{12}H_{26})$ presented in the Table II were calculated.

As follows from the data obtained, the yields of recombination products of hexyl radicals were most markedly decreased in the presence of quinonimine (X) and all arylamine derivatives having a hydroxyl group in their structures (VII, VIII, XI, XIII, XIV, XV).

Interaction of Compounds under Study with Peroxyl ($ROO^{\bullet}$) Radicals

On radiolysis of hexane in the presence of oxygen, the main products are the corresponding hexanols and hexanones.[23] In their formation, reactions of hexyl radical generation (2–6) and subsequent oxidation (9) are involved.

$$C_6H_{13}^{\bullet} \xrightarrow{O_2} C_6H_{13}OO^{\bullet} \longrightarrow\longrightarrow\longrightarrow \text{hexanol}-2, \text{hexanol}-3, \text{hexanone}-2, \text{hexanone}-3 \quad (9)$$

By measuring total yield of hexanones and hexanones ($\Sigma G(Ox)$) under various conditions, relative reactivity of additives towards the $C_6H_{13}OO^{\bullet}$ species can be evaluated. The ΣG (Ox) values are given in Table II. It follows from these data that the highest efficiency in suppressing the liquid-phase oxidation of hydrocarbons was manifested by derivatives of diphenylamine (VI–IX) and compound (XIV).

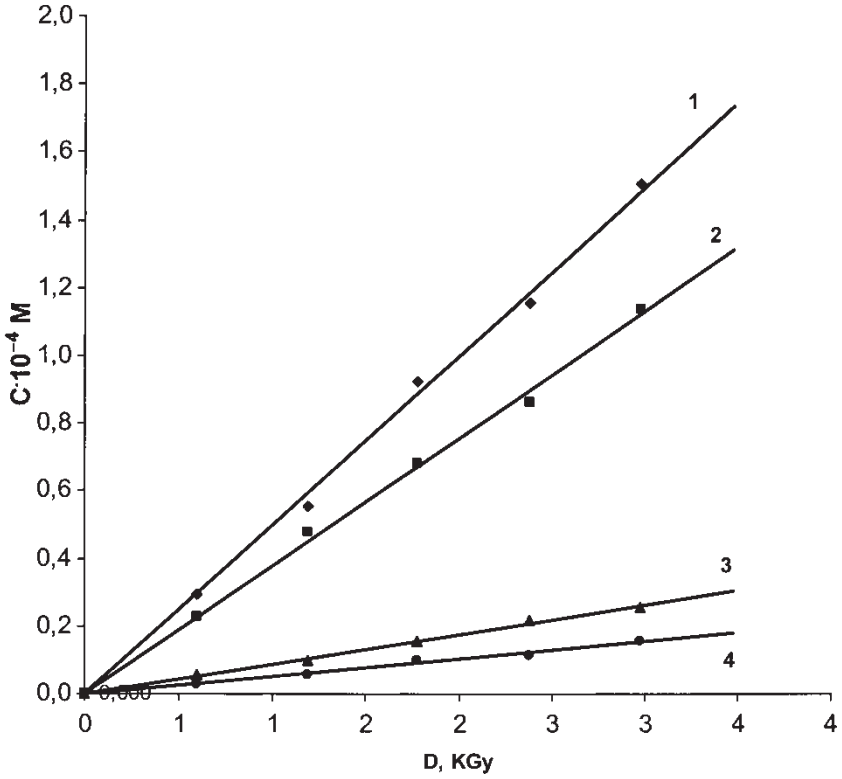


FIGURE 1 Concentration (C) of recombination products of C(2)- and C(3)-hexyl radicals (total values) as function of radiation dose absorbed (D, in kGy). 1, deaerated hexane without additives; 2, 3, 4—deaerated hexane in the presence of 1×10^{-3} M of compounds IX, VIII and X, respectively.

Interaction of Compounds under Study with α-hydroxyalkyl Radicals

It is known that the prevailing organic radicals generated in radiolysis of aliphatic alcohols are RC·HOH species.[24] Thus, formation and consumption of α-hydroxyethyl radicals on γ-radiolysis of ethanol occurs due to the following reactions:

$$C_2H_5OH \longrightarrow C_2H_5OH^{\bullet+} + e^- \quad (10)$$

$$C_2H_5OH^{\bullet+} + C_2H_5OH \longrightarrow C_2H_5OH_2^{+} + CH_3\dot{C}HOH \quad (11)$$

$$2\ CH_3\dot{C}HOH \longrightarrow CH_3CHO + C_2H_5OH \quad (12)$$

$$2\ CH_3\dot{C}HOH \longrightarrow CH_3CH(OH)CH(OH)CH_3 \quad (13)$$

The main radiolysis products of deaerated ethanol are acetaldehyde and 2,3-butanediol formed in reactions (12,13) of α-hydroxyalkyl radicals.[24,25] The yields of acetaldehyde can be affected by its reactions with solvated electrons formed in the course of radiolysis of ethanol. In that way, reactivity of compounds studied towards α-hydroxyalkyl radicals was evaluated according to changes in yields of 2,3-butanediol, the recombination product of $CH_3C^{\cdot}HOH$ species.

Values of 2,3-butanediol yields in radiolysis of ethanol are given in Table III. Quinonimine (X), riboflavin (XVII) and *p*-aminophenol (V) were found to be the most effective agents in decreasing the yields of 2,3-butanediol formation.

Interaction of Compounds under Study with Radicals of α-Diols

Ethylene glycol belongs to the simplest representatives of organic compounds, whose radicals are prone to fragmentation with rupture of two

TABLE II Effects of compounds under study on yields (G) of hexane radiolysis products formed as a result of recombination of hexyl radicals ($\Sigma G(C_{12}H_{26})$) or transformations of $C_6H_{13}OO^{\cdot}$ radicals (ΣG (Ox))

	$G \times 10^7$ mol/J	
Compound studied	$\Sigma G(C_{12}H_{26})$	ΣG(Ox)
–	0.48 ± 0.03	2.04 ± 0.11
VI	0.46 ± 0.03	1.21 ± 0.11
VII	0.066 ± 0.004	1.22 ± 0.10
VIII	0.085 ± 0.003	0.78 ± 0.07
IX	0.37 ± 0.01	0.89 ± 0.06
X	0.050 ± 0.003	1.72 ± 0.07
XI	0.11 ± 0.01	1.36 ± 0.09
XII	0.47 ± 0.02	2.02 ± 0.08
XIII	0.087 ± 0.004	1.70 ± 0.13
XIV	0.075 ± 0.005	0.87 ± 0.05
XV	0.087 ± 0.006	1.46 ± 0.11
XVI	0.47 ± 0.02	2.02 ± 0.08

TABLE III Effects of compounds under study on yields (G) of 2,3-butanediol—the product of ethanol radiolysis resulting from recombination of $CH_3\dot{C}HOH$ radicals

Compound studied	$G \times 10^7$ mol/J $CH_3CH(OH)CH(OH)CH_3$
–	1.29 ± 0.04
I	1.24 ± 0.06
II	1.23 ± 0.08
III	0.81 ± 0.03
IV	0.76 ± 0.04
V	0.19 ± 0.02
VI	0.99 ± 0.05
VII	0.92 ± 0.05
VIII	0.76 ± 0.03
X	0.059 ± 0.004
XVII*	0.32 ± 0.03*

*Concentration $= 10^{-4}$ M.

TABLE IV Effects of compounds under study on product yields (G) in radiolysis of aqueous 3M ethylene glycol solutions: CH_3CHO—fragmentation product and $HOCH_2CHO$—oxidation product

Compound studied	$G \times 10^7$ mol/J CH_3CHO	$HOCH_2CHO$
–	11.54 ± 0.92	0.79 ± 0.07
I	10.98 ± 0.98	0.61 ± 0.05
II	10.99 ± 0.98	0.81 ± 0.07
III	2.79 ± 0.22	0.71 ± 0.06
IV	3.97 ± 0.28	0.80 ± 0.06
V	3.30 ± 0.16	1.11 ± 0.11
VII	2.89 ± 0.14	0.77 ± 0.07
VIII	1.86 ± 0.13	1.43 ± 0.13
X	0.10 ± 0.01	5.69 ± 0.51
XVII	0.23 ± 0.02	9.01 ± 0.63

β-bonds.[26] Therefore, using ethylene glycol as an example, information can be obtained on the ability of compounds being tested to block homolytic fragmentation reactions that are quite common for more complex objects of study as well.[27]

It has been found that the main molecular products of radiation-chemical transformations taking place in aqueous ethylene glycol solutions are acetaldehyde and glycol aldehyde, formed due to reactions of ethylene glycol radicals.[28] The overall scheme of radiolysis includes the following reactions:

$$H_2O \longrightarrow H,\ OH,\ e_{aq} \quad (14)$$

$$HOCH_2CH_2OH \xrightarrow[-H_2,\ H_2O]{H,\ OH} HOCH_2\dot{C}HOH \quad (15)$$

$$HOCH_2\dot{C}HOH \longrightarrow \dot{C}H_2CHO + H_2O \quad (16)$$

$$2\ HOCH_2\dot{C}HOH \longrightarrow HOCH_2CHO + HOCH_2CH_2OH \quad (17)$$

$$HOCH_2\dot{C}HOH + \dot{C}H_2CHO \longrightarrow CH_3CHO + HOCH_2CHO \quad (18)$$

As seen from the scheme, acetaldehyde is formed as a result of disintegration of ethylene glycol radical via rupture of two β-bonds in reaction (16) and subsequent radical disproportionation stage in reaction (18). The formation of CH_3CHO can also occur by interaction of $\dot{C}H_2CHO$ radicals with ethylene glycol molecules in reaction (19):

$$\dot{C}H_2CHO + HOCH_2CH_2OH \longrightarrow CH_3CHO + HOCH_2\dot{C}HOH \quad (19)$$

The occurrence of the reaction (19) provides a possibility for CH_3CHO to be formed according to a chain reaction mechanism, when its yield is increased depending on concentration of the starting substance.

The reactivity of compounds under study towards ethylene glycol radicals was assessed according to their effects on yields of acetaldehyde and glycol aldehyde. In Table IV, values of product yields obtained in radiolysis of aqueous 3 M solutions of ethylene glycol are given. The acetaldehyde yield values exceed significantly the sum of the initiator yields $(G_H + G_{OH}) \approx 3.2$, corroborating the occurrence of a chain mechanism in ethylene glycol dehydration through reactions (14–19).

Quinonimine (X) and riboflavin (XVII) effectively suppressed the yield of acetaldehyde (fragmentation product), while increasing the yield of glycol aldehyde (oxidation product). Aminophenols (III–V) and hydroxydiarylamines (VII, VIII) also decreased the yield of acetaldehyde, the product of ethylene glycol fragmentation.

DISCUSSION

As pointed out in the introduction, investigation of reactivity of aromatic amines and various derivatives towards organic radicals is a topical task, whose realization will allow the identification of efficient antioxidants, with promising application in medicine and industry. At the same time, while comparing the available data concerning establishment of structure–reactivity relationships for various antioxidants, some contradictions and unresolved problems become apparent. It has been shown in Ref. [8,9] that the rate constants for reactions of primary alkyl radicals with diphenylamine and its derivatives are of the order of $10^6 \times M^{-1} s^{-1}$, exceeding almost 100 times the respective values for peroxyl radicals. An inverse trend was observed in reactions of R· and ROO· radicals with phenolic antioxidants,[8,29] and an adequate explanation of these facts has not been found. There are no data in the literature on reactivity of aminophenol derivatives with respect to various organic radicals, although statements are made that aminophenols are more effective antioxidants than arylamines.[3,5]

The results we have obtained demonstrate that diarylamine additions (VI, IX) to deaerated hexane do not alter dodecane yields while decreasing about two times the total yields of hexane oxidation products on radiolysis of systems containing air (cf. Table II). This points to a lower reactivity of diarylamines (VI, IX) towards alkyl radicals as compared to peroxyl radicals. Introduction of a hydroxyl group into diarylamine structure leads to an increase in the ability to inhibit the process of radiation-induced oxidation of hexane (cf. Table II). Thus, minimum total yields of hexanols and hexanones were obtained in the presence of compounds VIII, IX and XIV, more than two times lower than the respective values in the case of hexane without additives. It should be noted that, in the test system used, we did not observe such a marked dependence of changes in antioxidant properties on structure of the compounds tested as that reported by the authors of other publications.[3,5] At the same time, aminophenol derivatives suppressed recombination reactions of hexyl radicals considerably more effectively than diphenylamine (VI) and compounds IX, XII and XVI, which have no free hydroxyl groups available (Table II). Of the compounds studied, the highest reactivity towards alkyl radicals was displayed by quinonimine (X). It has been noted by Ref. [3] that the highest antioxidant activity was manifested by those compounds among the derivatives of aromatic amines that are capable of forming conjugated 1,4-cyclohexadiene structures. Our results (Table II) indicate that this conclusion is valid as far as reactions of arylamine derivatives with alkyl radicals are concerned. Suppression of oxidation processes is known to be the result of both reduction of ROO· radicals and capture of alkyl radicals. The latter is possible under conditions when concentration of oxygen and that of the oxidized form of an antioxidant are comparable.[1] The authors of publications[3,5] studied oxidation processes of linoleic acid and of methyl linoleate in aqueous and acetonitrile solutions, where oxygen concentration is significantly lower than in hexane. They therefore observed such a marked increase of the antioxidant effect on changing from arylamines to aminophenols. This effect is apparently due to not only reaction (1), but also to removal of alkyl radicals by quinonimines formed in the system. Hence, introduction of a hydroxyl into aromatic amine structure imparts new properties to compounds of this type, making them reactive towards alkyl radicals. Replacement of the hydrogen atom by a methyl group (compounds IX, XII, XVI) brings down the anti-radical activity of aminophenols drastically, while changing to quinonimine (X) enhances the inhibitory activity, as shown in the data on dodecane formation (Table II). We observed a similar trend also in a series of sterically-hindered aminophenols (XI–XVI). These facts may serve as a confirmation of importance of the role that quinonimine structures play in reactions with carbon-centered radicals.

This conclusion is corroborated also by the data that we have obtained in radiolysis studies of ethanol (Table III). Adding aniline or phenol to the starting substrate, ethanol, produced no changes in yields of 2,3-butanediol—the recombination product of α-hydroxyethyl radicals. At the same time, aminophenols, particularly *p*-aminophenol (V), as well as quinonimine (X) and riboflavin (XVII) effectively suppressed the recombination process of $CH_3C{\cdot}HOH$ species. Hence, the presence of both hydroxyl and amino groups in the aromatic ring makes aminophenols more reactive towards alcohol radicals than their respective monofunctional analogues.

Earlier,[15] in comparative studies concerning reactions of phenol, diphenols, quinones and their derivatives with various radicals, a view was formulated that the difference in the effects between diphenols and phenol is associated with the ability of the former to build up semiquinone and quinone structures, which are more reactive than the starting substances with respect to carbon-centered radicals. A similar tendency is observed in the sequence: aromatic amines—aminophenols—quinonimines, which interact with alkyl and α-hydroxyalkyl radicals more effectively. Also in the case of aminophenols, the formation of quinoid structures effective in reactions with alkyl and hydroxyalkyl radicals is possible. One can suggest that substances of natural origin containing quinonimine structures should be able to affect significantly free-radical processes occurring with participation of carbon-centered radicals. The data that we have obtained concerning the effects of riboflavin (Vitamin B2) on product formation in radiolysis of ethanol (Table III) and aqueous 3 M solution of ethylene glycol (Table IV) confirm this hypothesis.

While studying the effects of compounds tested on radiolysis of aqueous 3 M solution of ethylene glycol, we have made an attempt to find out whether aminophenols and their derivatives are able to influence free-radical fragmentation processes of organic compounds. The data obtained (see Table IV) clearly demonstrate differences between aminophenols, on the one hand, and phenol or aniline, on the other hand, in their influence on the course of fragmentation process [reactions (14)–(19)].

Comparison of the data on formation of glycol aldehyde and acetaldehyde (Table IV) indicates that quinonimine (X) and riboflavin (XVII) terminate the chain process of acetaldehyde formation owing to oxidation of the initial ethylene glycol radicals according to reaction

$$HOCH_2\dot{C}HOH + Q \longrightarrow HOCH_2CHO + \dot{Q}H \qquad (20)$$

Q = X, XVII,

while increasing the yield of glycol aldehyde. In this case, riboflavin (XVII) and quinonimine (X) behave like chain-breaking acceptors. Aminophenols, except for compound V, suppress the formation of CH_3CHO without increasing the yield of $HOCH_2CHO$. This is possible because of the participation of aminophenol oxidation products in reaction (20) and reduction by aminophenols of ethylene glycol radicals according to reaction (21):

$$HOCH_2\dot{C}HOH + QH_2 \longrightarrow HOCH_2CH_2OH + \dot{Q}H \qquad (21)$$

QH_2 = III, IV, VII, VIII, XI, XIII, XIV, XV.

Simultaneous occurrence of processes (20) and (21) leads to a decrease in acetaldehyde yields caused by aminophenols, and to a more complex influence of the latter on formation of glycol aldehyde.

The results obtained in this work together with literature data allows the conclusion that aminophenols, unlike arylamines, effectively interact with carbon-centered radicals due to their capability of forming quinoid structures. This indicates the possibility of creating efficient inhibitors of free-radical processes of various types based on aminophenols and quinonimines, with promising potential for using them as biosystem protectors.

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References

[1] Grassi, N. and Scott, D. (1988) *Destruction and Stabilization of Polymers* (Mir Publication, Moscow), in Russian.
[2] Halliwell, B. and Gutteridge, J.M.C. (1999) *Free Radicals in Biology and Medicine*, 3th ed. (Clarendon Press, Oxford).
[3] Iwatsuki, M., Komuro, E. and Niki, E. (1995) "Antioxidant activities of aminophenols against oxidation of methyl linoleate in solution", *Bull. Chem. Soc. Jpn.* **68**, 620–624.
[4] Mareyuki, T., Jyunichi, T. and Niki, E. (1989) "Oxidation of lipids. XVI. Inhibition of autoxidation of methyl linoleate by diarylamines", *Bull. Chem. Soc. Jpn.* **62**, 1880–1884.
[5] Yamamura, T., Suzuki, K., Yamaguchi, T. and Nishiyama, T. (1997) "Antioxidant activities of phenothiazines and related compounds: correlation between the antioxidant activities and dissociation energies of O–H or N–H bonds", *Bull. Chem. Soc. Jpn.* **70**, 413–419.
[6] Wright, J.S., Carpenter, D.J., McKay, D.J. and Ingold, K.U. (1997) "Theoretical calculation of substituent effects on the O–H bond strength of phenolic antioxidants related to vitamin E", *J. Am. Chem. Soc.* **119**, 4245–4252.
[7] Wright, J.S., Johnson, E.R. and DiLabio, G.A. (2001) "Predicting the activity of phenolic antioxidants: theoretical method, analysis of substituent effects, and application to major families of antioxidants", *J. Am. Chem. Soc.* **123**, 1173–1183.
[8] Lucarini, M., Pedrielli, P., Pedulli, G.F., Valgimigli, L., Gigmes, D. and Tordo, P.J. (1999) "Bond dissociation energies of the N–H bond and rate constants for the reaction with alkyl, alkoxyl, and peroxyl radicals of phenothiazines and related compounds", *J. Am. Chem. Soc.* **121**, 11546–11553.
[9] Burton, A., Ingold, K.U. and Walton, J.C. (1996) "Absolute rate constants for the reactions of primary alkyl radicals with aromatic amines", *J. Org. Chem.* **61**, 3778–3782.
[10] Muller, S.N., Batra, R., Senn, M., Giese, B., Kisel, M. and Shadyro, O. (1997) "Chemistry of C-2 glyceryl radicals: indications for a new mechanism of lipid damage", *J. Am. Chem. Soc.* **119**, 2795–2803.
[11] Edimecheva, I.P., Kisel, M.A., Shadyro, O.I., Vlasov, A.P. and Yurkova, I.L. (1997) "The damage to phospholipids caused by free radical attack on glycerol and sphingosine backbone", *Int. J. Radiat. Biol.* **71**, 555–560.
[12] Shadyro, O.I., Yurkova, I.L. and Kisel, M.A. (2002) "Radiation-induced peroxidation and fragmentation of lipids in a model membrane", *Int. J. Radiat. Biol.* **78**, 211–217.
[13] Shadyro, O.I. (1997) "Radiation-induced free radical fragmentation of cell membrane components and the respective model compounds", In: Minisci, F., ed., *Free Radicals in Biology and Environment* (Kluwer Academic Publishers, Dordrecht), pp 317–329.
[14] Shadyro, O.I., Glushonok, G.K., Glushonok, T.G., Edimecheva, I.P., Moroz, A.G., Sosnovskaya, A.A., Yurkova, I.L. and Polozov, G.I. (2002) "Quinones as free-radical fragmentation inhibitors in biologically important molecules", *Free Radic. Res.* **36**, 859–867.
[15] Shadyro, O.I., Edimecheva, I.P., Glushonok, G.K., Ostrovskaya, N.I., Polozov, G.I., Murase, H. and Kagiya, T. (2003) "Effects of phenolic compounds on reactions involving various organic radicals", *Free Radic. Res.* **37**, 1087–1097.
[16] Shenberg, A. (1963) *Preparative Organic Photochemistry* (Izdatinlit Publication, Moscow), in Russian.
[17] Shadyro, O.I., Sorokin, V.L., Ksendzova, G.A., Polozov, G.I., Nikolaeva, S.N., Pavlova, N.I., Savinova, O.V. and Boreko, E.I. (2003) "Synthesis and antiviral activity of 2,4-di-tert-butylphenol-2-aminophenol", *Khim-pharm.zhurnal* **37**(5–7), Russian.
[18] Weyl, Houben (1979) *Methoden der organischen chemie* (George Thieme Verlag, Stuttgart).
[19] Vol'eva, V.B., Prokof'eva, T.N. and Prokof'ev, A.M. (1965) *Izv. AN SSSR, ser. Khim.* **9**, 1789–1792, Russian.
[20] Lober, F. and Ley, K. (1959) Ger. Patent 1104522.
[21] Hardman, A.F. and Ohio, A. (1941) USA Patent 2238320.
[22] Gäumann, T. and Hoigne, I., eds (1968) *Aspects of Hydrocarbon Radiolysis* (Academic Press, London).
[23] Kunjappu, I.T. and Rao, K.N. (1979) "The radiation-induced oxidation of *n*-heptane", *Radiat. Phys. Chem.* **13**, 97–100.
[24] Freeman, G.R. (1982) "Labile species and fast processes in liquid alcohol radiolysis", In: Baxendale, I.H. and Busi, F., eds, *The Study of Fast Processes and Transient Species by Pulse Electron Radiolysis* (Reidel Publishing, Dordrecht), pp 399–416.
[25] Freeman, G.R. (1988) "The radiolysis of alcohols", In: Freeman, G.F., ed., *Kinetics of Nonhogenneous Processes: A Practical Introduction for Chemists, Biologists, Physicists, and Material Scientists* (Willey-Interscience, New York), pp 73–101.
[26] Gilbert, B.C., Larkin, J.P. and Norman, R.O.C. (1972) "Electron spin resonance studies. Evidence for heterolytic and homolytic transformations of radicals from α-diols and related compounds", *J. Chem. Soc. Perkin Trans.* **2**, 794–802.
[27] Davies, M.J. and Gilbert, B.C. (1991) "Free radical reactions: fragmentation and rearrangement in aqueous solutions", In: Coxon, J.M.M., ed., *Advances in Detailed Reaction Mechanisms: Single Electron Transfers and Concerted Reactions* (Jai Press Inc., USA), Vol. 1, pp 36–81.
[28] Petryaev, E.P. and Shadyro, O.I. (1986) *Radiation Chemistry of Bifunctional Compounds* (Universitetskoye, Minsk), in Russian.
[29] Roginskii, V.A. (1988) *Phenolic Antioxidants: Reactivity and Efficiency* (Nauka Publishing House, Moscow), in Russian.