Effects of Substituted Aryloxyaminopropanols on Photosynthesis and Photosynthesizing Organisms

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Abstract. The inhibitory activity of 22 substituted aryloxyaminopropanols having beta-lytic and local anaesthetic properties was studied from the viewpoint of their influences on photosynthesis in plant chloroplasts as well as growth and synthesis of chlorophyll in algae and wheat plants. The inhibitory activity increased significantly with the increasing length of alkyl-substituents of the aryloxyaminopropanol molecule. Less pronounced dependences were found with respect to the position of the substituent chain on benzene ring. The inhibitory activity was found to correlate well with the lipophilicity of the compounds studied.

Key words: Aryloxyaminopropanols — Photosynthesis — Growth inhibition — *Chlorella vulgaris* — Wheat

Introduction

The amphiphilic molecules of aryloxyaminopropanols (AOAP) studied show typical beta-blocker characteristics as well as local anaesthetic properties (Béderová 1981). Bonds within complexes formed between the tertiary amine of a local anaesthetic in its ionized form and peptide were found to be considerably stronger than interpeptidic hydrogen bonds; thus these molecules are able to damage protein structures by destructing intramolecular hydrogen bonds (Remko and Scheiner 1988). As a result, key enzymatic systems of cells may be affected with subsequent changes in the biochemical as well as energy-related processes (Bendriss et al. 1988; Laasch and Weis 1988).

Amphiphilic molecules also strongly interact with the hydrophobic lipidic parts of membranes. They can penetrate the lipid molecules resulting in an expansion of the bilayer, and they introduce electric charge to the membranes. Hence, their function as proton carriers through lipid bilayers (Seelig et al.

1988), decreases the phase transition temperature of model membranes (Račanský et al. 1988), and changes both the electric properties and the fluidity of model membranes (Ondriaš 1987). Principally, the widespread interaction range of the amphiphilic molecules of local anesthetics in biological systems may affect the function of living systems at low stages of development (Ondriaš 1987; Brown and Vanlerberghe 1985; Abdelaziz and El-Nakeeb 1987; Semin et al. 1988).

The present work has been aimed at studing the influences of a group of synthetic aryloxyaminopropanols on photosynthesis and certain representatives of photosynthesizing organism (green algae and plants).

Materials and Methods

The substituted aryloxyaminopropanols were synthesized at the Pharmaceutical Faculty, Comenius University (Csöllei et al. 1982).

Determination of photosynthesis inhibition: ESR signal intensities were measured using a chloroplast preparation obtained from leaves of horsebean following homogenization in a phosphate buffer solution (containing sucrose, potassium and magnesium chlorides as well as sodium ascorbate), filtration and centrifugation; all operation were carried out at 0—4°C. The chloroplast sediment was suspended in the buffer to contain approx. 4—5 mg chlorophyll a per ml sample.

Instrumental conditions: ERS-230 (ZWG AdW., Berlin, G. D. R.), measurements at 25°C, with a microwave power of 5 mW, modulation 5.10^{-4}T. This instrument operates in the X band. The compounds studied were added to the chloroplast suspension to the final concentration of 5.10^{-2} mol.dm^{-3}, immediately before the measurements.

Determination of algae-induced inhibition: *Chlorella vulgaris* algae were stationary-cultivated at 25 ± 1°C under following light conditions: 16 hours illuminated, 8 hours in the dark in Šetlík' s culture medium (Šetlík 1968). After 7 days of cultivation distilled water was added to compensate for evaporation losses, and the absorbance of the cell suspension (corresponding to the algal cell numbers) was measured at 660 nm, along with the determination of the chlorophyll content following extraction from the centrifuged algal cells with N,N-dimethylformamide. The total chlorophyll contents of the algae in the culture medium was assessed according to Inskeep and Bloom 1985. The values obtained were compared to those obtained for simultaneously cultured control samples, and expressed as percentages of the controls.

Inhibitory effects on wheat growth: Wheat grains were soaked in aqueous solutions of the compounds studied (1.10^{-3} and 2.10^{-4} mol.dm^{-3}). Next, the grains were positioned on cotton wool pads moistened with the same solutions, and left to germinate for 72 hours in the dark. The germinating seeds were subsequently grown in a cultivation box at 14 hours light/10 hours dark cycle. After 3 days of cultivation, the green portions of the seedlings were weighed and the content of chlorophyll synthesized determined after extraction with N,N-dimethylformamide.
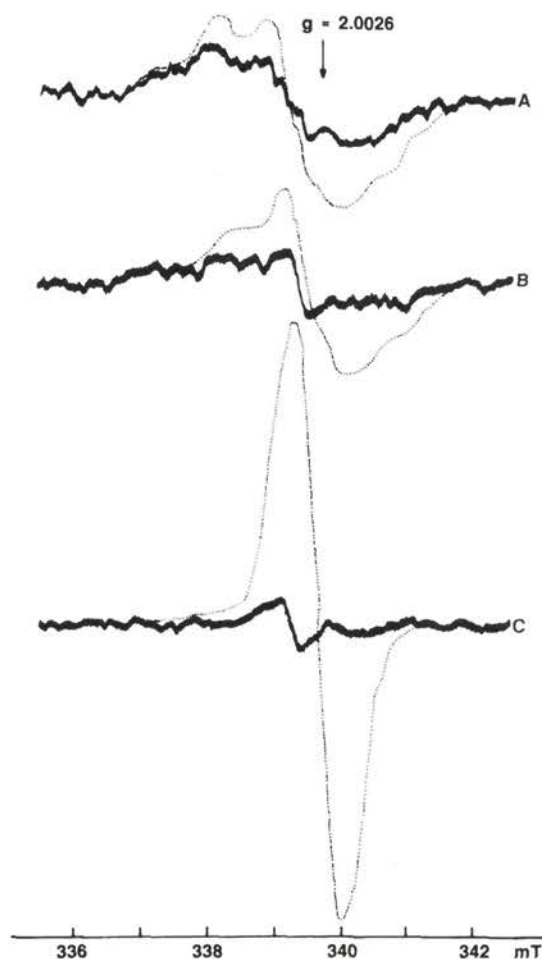
Fig. 1 ESR spectra of chloroplasts in the dark (full line) and in the light (broken line); *A*. Control sample; *B*. Chloroplasts in the presence of 0.05 mol . dm^{-3} AOAP 4—13; *C*. Chloroplasts in the presence of 0.05 mol . dm^{-3} AOAP 4—53.
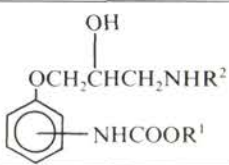
Results

Effect of substituted aryloxyaminopropanols on photosynthesis

It has been shown using electron spin resonance (ESR) that AOAP are able to inhibit the activity of photosystem II (PS II) of the photosynthesizing apparatus. In plant chloroplasts at laboratory temperature and in the dark, the ESR

Table 1. Inhibition of photosystem II of plant chloroplasts by substituted aryloxyaminopropanols; changes of ESR parameter P

$$\text{OH}$$
$$\text{OCH}_2\text{CHCH}_2\text{NHR}^2 \qquad . \text{HCl}$$
—NHCOOR^1 (phenyl ring)

Parameter P

Compound	Substituent position	R^1	R^2	
2—13	2	CH$_3$	CH(CH$_3$)$_2$	3.89
2—23	2	C$_2$H$_5$	CH(CH$_3$)$_2$	3.72
2—33	2	C$_3$H$_7$	CH(CH$_3$)$_2$	8.20
2—43	2	C$_4$H$_9$	CH(CH$_3$)$_2$	9.20
2—53	2	C$_5$H$_{11}$	CH(CH$_3$)$_2$	14.23
2—i33	2	CH(CH$_3$)$_2$	CH(CH$_3$)$_2$	2.36
2—55	2	C$_5$H$_{11}$	C(CH$_3$)$_3$	18.10
3—13	3	CH$_3$	CH(CH$_3$)$_2$	1.27
3—23	3	C$_2$H$_5$	CH(CH$_3$)$_2$	3.05
3—33	3	C$_3$H$_7$	CH(CH$_3$)$_2$	3.64
3—43	3	C$_4$H$_9$	CH(CH$_3$)$_2$	5.27
3—53	3	C$_5$H$_{11}$	CH(CH$_3$)$_2$	17.99
3 i33	3	CH(CH$_3$)$_2$	CH(CH$_3$)$_2$	1.69
3—25.	3	C$_2$H$_5$	C(CH$_3$)$_3$	1.60
3—45	3	C$_4$H$_9$	C(CH$_3$)$_3$	3.17
3—55	3	C$_5$H$_{11}$	C(CH$_3$)$_3$	5.11
4—13	4	CH$_3$	CH(CH$_3$)$_2$	1.27
4—23	4	C$_2$H$_5$	CH(CH$_3$)$_2$	1.59
4—33	4	C$_3$H$_7$	CH(CH$_3$)$_2$	8.71
4—43	4	C$_4$H$_9$	CH(CH$_3$)$_2$	16.41
4—53	4	C$_5$H$_{11}$	CH(CH$_3$)$_2$	30.65
4—i33	4	CH(CH$_3$)$_2$	CH(CH$_3$)$_2$	1.27

Parameter $P = [(I_{light}^{AOAP} : I_{dark}^{AOAP})/(I_{light} : I_{dark})] \cdot [\text{mg Ch}]^{-1}$

signal can be observed in the g $\sim$ 2 zone. It contains two patrial signals: 1/signal II at g = 2.0045 and ΔB = 2 mT attributed to the semiquinone radical cation of the donor side of the PS II photosynthetic centre (Hoff 1987; Govindjee 1986); and 2/signal I at g = 2.0026 and ΔB = 0.72 mT belonging to photosystem I (PS I) photosynthetic centre in particular to the dimeric chlorophyll a cation radical (Hoff 1987; Hoff 1979). Upon illumination, the signal I and II intensities of normal untreated chloroplasts increased 1.5 to 2-fold. When electron flow from PS II to PS I is damaged, the ratio of ESR signals of the photosystem measured in the dark and upon illumination increases.

Fig. 1 shows ESR spectra with superimposed signals I and II. The intensity

Table 2. Inhibitory effects of substituted aryloxyaminopropanols on *Chlorella vulgaris* algae

| Compound | IC_{50} | MIC | IC_{50} |
| | Algal Chlorophyll | | Algal Growth |
	10^{-5}mol.dm^{-3}		
2—13	23.2	134.9	67.0
2—23	13.6	81.3	30.5
2—33	7.2	30.5	18.2
2—43	3.4	17.0	5.6
2—53	2.2	5.6	2.5
2—i33	20.4	46.8	30.2
2—55	1.5	5.1	1.8
3—13	32.4	133.4	58.9
3—23	22.4	91.2	33.1
3—33	11.2	36.3	17.4
3—43	6.7	17.4	9.0
3—53	2.3	7.8	4.4
3—i33	16.1	56.5	28.4
3—25	14.5	57.5	24.5
3—45	2.8	12.6	6.3
3—55	3.1	5.4	3.7
4—13	17.1	87.3	29.8
4—23	14.1	45.7	24.0
4—33	8.2	25.4	12.1
4—43	3.0	11.2	6.5
4—53	1.9	5.9	2.7
4—i33	5.9	21.6	10.1

IC_{50} is the concentration of an AOAP compound resulting in 50% inhibition of the parameter evaluated as compared to control;
MIC is the minimum compound concentration which caused total suppression of the parameter evaluated.

ratio of dark/light signals is approx. 1.7 for pure chloroplasts, whereas AOAP-treated chloroplasts give substantially higher ratios. The interaction with AOAP results in lower signal II intensities; in the presence of some AOAP compounds having strong inhibitory properties, signal II may completely dissapear. Thus, certain AOAP are able to fully inhibit PS II activity (total deactivation); PS II loses its ability to supply electrons to PS I resulting in increased signal I intensities. The extent of PS II inhibition by the individual AOAP compounds tested is represented by values P shown in Table 1.

All aryloxyaminopropanol derivatives studied have shown inhibitory effects on the PS II of the photosynthesiszing apparatus. An exponentially
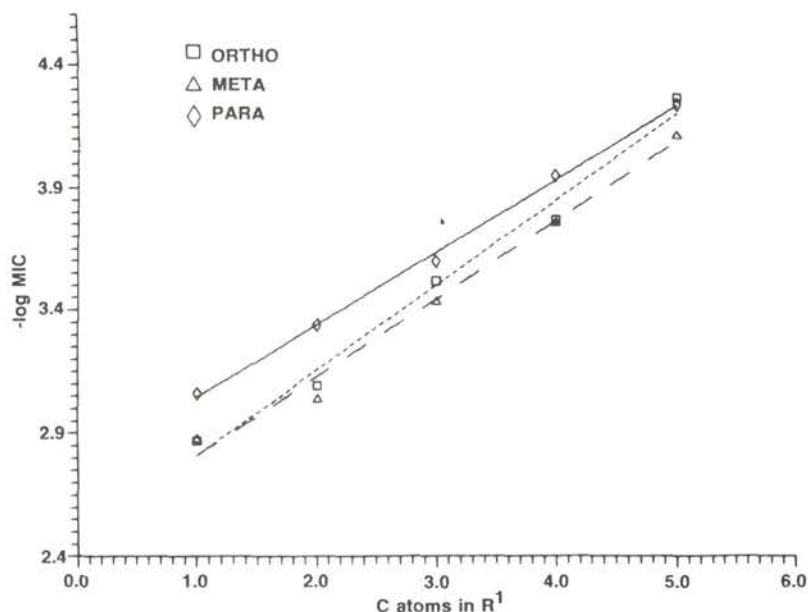
Fig. 2 The dependence of -log MIC chlorophyll synthesis in *Chlorella vulgaris* in the presence of aryloxyaminopropanols on the number of C-atoms of the alkylester substituent.

increasing inhibitory influence was observed for the range of R^1 substituent linear alkyl chain lengths tested $/C_1 - C_5/$. This effect was particularly pronounced in compounds with substituents in position *p* of the benzene ring. Branching of the esteric substituent alkyl group was associated with a decreased inhibitory activity in every case (samples 2-i33, 3-i33, 4-i33) as compared to the corresponding linear chain alkyls (samples 2-33, 3-33, 4-33). The inhibitory activity also decreased when the i-propyl group of amine nitrogen was replaced by i-butyl (R^2 substituent).

Effects of substituted aryloxyaminopropanols on growth and chlorophyll synthesis in green algae

All AOAP derivatives studied inhibited the growth and chlorophyll synthesis of green algae (*Chlorella vulgaris*). Algicidal effects occurred at 5.10^{-5} mol . dm^{-3} (i.e. 20 mg . dm^{-3}) and above. The concentrations of the individual AOAP derivatives causing 50% inhibition of algal growth or chlorophyll synthesis (IC_{50}) are shown in Table 2 along with values of minimum inhibitory concentrations (MIC) resulting in total algicidal effects, as determined by the chlorophyll
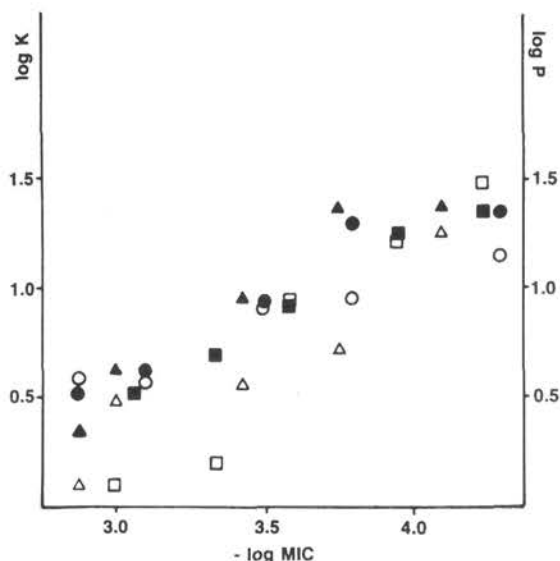
Fig. 3 Inhibition of photosystem II of plant chloroplasts (log. of parameter *P*) vs. inhibition of chlorophyll synthesis in algae (log. MIC) (empty symbols), and partition coefficients of AOAP compounds (log. K) vs. log. MIC (filled symbols). AOAP compounds with substituents in ortho-(circles), meta- (triangles) or para-(squares) position.

contents. The inhibitory efficiency of the AOAP compounds with respect to algae was shown to be strongly dependent on the length of the linear alkyl chain of R^1 esteric substituent. The position of the substituent on benzene ring is of only marginal significance with respect to this activity. The MIC logarithm is linearly dependent on the number of carbon atoms in the straight R^1 alkyl chain (Fig. 2).

However, contrary to the PS II inhibition, the inhibitory activity with respect to algae inscreased with the increasing hydrophobicity of the R^2 substituent (replacement of i-propyl by i-butyl). The inhibition of PS II of plant chloroplasts by AOAP compounds correlates fairly well with the inhibition of *Chlorella vulgaris* (Fig. 3).

Effects of substituted aryloxyaminopropanols on growth and chlorophyll synthesis of wheat

The AOAP derivatives studied had inhibitory effects on plants, predominantly with respect to weight increments of green matter and less as to the chlorophyll content synthesized by the plant. As can be seen from Table 3, this inhibitory

Table 3. Effects of substituted aryloxyaminopropanols on weight increments in the above-ground parts of wheat plants and on the contents of synthesized chlorophyll

Com-pound	Concentration 10^{-4} mol . dm^{-3}	% Controls $\pm \sigma$	
		Weight	Chlorophyll
2—13	10	67.1 ± 2.0	105.0 ± 2.2
	2	76.8 ± 1.1	96.0 ± 10.2
2—53	10	8.2 ± 0.2	21.1 ± 3.8
	2	34.3 ± 4.4	91.6 ± 1.8
3—13	10	82.1 ± 2.7	93.6 ± 5.7
	2	102.0 ± 1.8	98.2 ± 12.7
3—53	10	25.5 ± 2.5	70.0 ± 11.1
	2	42.5 ± 3.7	94.1 ± 6.0
4—13	10	93.7 ± 4.8	97.1 ± 4.5
	2	89.4 ± 3.7	94.1 ± 6.0
4—53	10	16.2 ± 1.8	68.7 ± 6.0
	2	64.0 ± 1.5	91.6 ± 2.0
2—55	10	15.6 ± 1.3	50.3 ± 4.7
	2	40.0 ± 2.9	57.2 ± 3.5
3—55	10	10.0 ± 2.7	50.9 ± 6.9
	2	62.8 ± 3.8	70.0 ± 6.9

effect is the more pronounced the longer the chain of the R^1 substituent. The strongest inhibition occurred with the derivatives substituted in position o of benzene ring.

Discussion

All AOAP derivatives studied had inhibitory effects on photosynthetic activity of isolated plant chloroplasts, growth and chlorophyll synthesis of *Chlorella vulgaris*, and on the growth of wheat plants. The algae were particularly sensitive to the presence of similar compounds, with algicidal effects observed at concentrations as low as 5.10^{-5} mol . dm^{-3}, i.e. 20 mg . dm^{-3}.

The inhibitory effects of substituted AOAP on photosynthesis and photosynthesizing organisms is assumed to result from non-specific interactions of these amphiphilic compounds with cell membrane components, with subse-

quent structural damage. Hydrophobic interactions of these molecules play a significant role in their inhibitory activity which showed marked increases, related to photosynthesis and photosynthesizing organisms, with the increasing length of the alkyl substituents in the AOAP molecule. This effect was explicitly present with both the inhibition of photosynthesis in plant chloroplasts and the inhibition of algal and plant growth. The substituent position in relation to benzene ring of the AOAP molecule was of less significance for the inhibitory process.

The important role of hydrophobic interactions in the inhibitory activity of these compounds is accentuated by the close correlation observed between inhibitory effect and the experimental partition coefficient between octanol and aqueous phosphate buffer, pH 7.2 (Bachratá et al. 1987). The correlation coefficients of the negative logarithm of MIC for algal inhibition, and of the logarithm of AOAP partition coefficients are 0.960 (ortho-), 0.967 (meta-), and 0.954 (para-substitution), respectively. The respective correlation coefficients of the logarithm of parameter P, characterizing the inhibition of photosynthesis, and the logarithm of partition coefficient, were 0.948 (o-), 0.881 (m-), and 0.916 (p-).

The close correlation between the inhibitory effects of AOAP compounds and the partition coefficients Fig. 3, stresses the important role of hydrophobic interactions in the biological effect.

Due to hydrophobic interactions, AOAP compounds can be incorporated into membranes of photosynthesizing organisms, resulting in the induction of conformational changes of biomolecules and in perturbations of membrane structure. Electron spin resonance study with AOAP compounds and with other analogous amphiphilic molecules (Šeršeň et al. 1990) showed that interactions of these compounds with biomolecules in plant chloroplasts can result in specific effects, such as changes of surface electrostatic potential with subsequent liberation of Ca^{2+} ions which are important constituents of the 18 and 24 kDa proteins of photosystem II. Similar results were reported by Semin et al. (1987, 1988) who have observed local anaesthetics of the dicaine group to inhibit in plant chloroplasts the electron transfer from water and hydroxylamine to 2,6-dichlorophenolindophenol.

The intensity of the interaction, and its consequences (the biological effects) are strongly determined also by the steric properties of the AOAP compounds. This could be confirmed by results obtained with compounds containing isomeric substituents, and by studies of the effects of a homologous series of analogous amphiphilic compounds on photosynthesizing organisms (Krempaská et al. 1989). These studies have shown that the correlation of the inhibitory effects of the amphiphilic compounds with the degree of their lipophilicity, as expressed by the partition coefficient, is only applicable within a certain interval of the

homologous series of substituents. Beyond this interval, a significant decrease of the inhibitory activity on photosynthesizing organisms has been found although the lipophilicity of these compounds increased.

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