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Kinetic study of hydrolysis of benzoates. Part XXIV—Variation of the *ortho* substituent effect with solvent in the alkaline hydrolysis of substituted phenyl benzoates

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ABSTRACT: The second-order rate constants k_2 ($\mathrm{M}^{-1}\,\mathrm{s}^{-1}$) for the alkaline hydrolysis of *meta*-, *para*- and *ortho*-substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in aqueous 0.5 M *n*-Bu_4NBr were measured spectrophotometrically. The dependence of substituent effects, especially *ortho* inductive, resonance and steric terms on different solvent parameters, was studied using the following equation:

$$\begin{aligned}\Delta\log k_{ortho} = {} & c_0 + c_{1(ortho)}\sigma_I + c_{2(ortho)}\sigma_R^0 + c_{3(ortho)}E_s^B + c_4\Delta E + c_5\Delta Y + c_6\Delta P + c_{7(ortho)}\Delta E\sigma_I \\ & + c_{8(ortho)}\Delta Y\sigma_I + c_{9(ortho)}\Delta P\sigma_I + c_{10(ortho)}\Delta E\sigma_R^0 + c_{11(ortho)}\Delta Y\sigma_R^0 + c_{12(ortho)}\Delta P\sigma_R^0\end{aligned}$$

where $\Delta\log k = \log k^X - \log k^H$, σ_I, σ_R^0 and $E_s{}^B$ are the inductive, resonance and steric substituent constants and E, Y and P are the solvent electrophilicity, polarity and polarizability parameters, respectively. In data treatment $\Delta E = E_S - E_{H_2O}$, $\Delta Y = Y_S - Y_{H_2O}$ and $\Delta P = P_S - P_{H_2O}$ were used. The solvent electrophilicity was found to be the main factor responsible for changes in the *ortho*, *para* and *meta* polar substituent effects with medium. The variation of the *ortho* inductive term with the solvent electrophilicity E_S was found to be ca threefold smaller than that for *para* substituents, whereas the *ortho* resonance term appeared to vary with solvent very similarly to that for *para* substituents. The steric term of *ortho* substituents was found to be approximately independent of solvent parameters. The *ortho* effect caused by the supplementary inductive effect from *ortho* position was found to disappear in a solvent whose electrophilic solvating power is comparable to that of 60% aqueous ethanol ($E \approx 13.3$). Copyright © 2005 John Wiley & Sons, Ltd.

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KEYWORDS: esters; phenyl benzoates; alkaline hydrolysis; substituent effects; *ortho* effects; solvent effects; kinetics

INTRODUCTION

The purpose of the present work was to study the dependence of substituent effects, especially *ortho* inductive, resonance and steric terms on solvent electrophilicity, polarity and polarizability parameters, in the alkaline hydrolysis of substituted phenyl benzoates. In previous papers, we studied the substituent effects, especially *ortho* effect, in the alkaline hydrolysis of *ortho*-, *meta*- and *para*-substituted phenyl benzoates, $C_6H_5CO_2$-C_6H_4X, and tosylates, 4-$CH_3C_6H_4SO_2OC_6H_4X$, in water, aqueous 2.25 M Bu_4NBr, 80% (v/v) DMSO and 5.3 M $NaClO_4$ (see Refs 1–4 and references cited therein). Recently, the study of substituents effects in the alkaline hydrolysis of *ortho*-, *meta*- and *para*-substituted phenyl tosylates was extended to aqueous 0.5 M Bu_4NBr.[5] In the present work the second-order rate constants for the alkaline hydrolysis of substituted phenyl benzoates [X = H, 4-NO_2, 4-CN, 4-Cl, 4-F, 4-CH_3, 4-OCH_3, 4-NH_2, 3-NO_2, 3-Cl, 3-CH_3, 3-NH_2, 2-NO_2, 2-CN, 2-CF_3, 2-F, 2-Cl, 2-I, 2-CH_3, 2-OCH_3, 2-$C(CH_3)_3$, 2-$N(CH_3)_2$] in aqueous 0.5 M Bu_4NBr at various temperatures are reported. The electrophilic solvating power of aqueous 0.5 M Bu_4NBr is reduced compared with pure water and 5.3 M $NaClO_4$. However, it is higher than that of aqueous 2.25 M Bu_4NBr and 80% (v/v) DMSO.

Lately, in order to study the significance of different solvent parameters for the substituent effects, in particular *ortho* effects, in the alkaline hydrolysis of *ortho*-, *meta*- and *para*-substituted phenyl tosylates, the $\log k$ values in various media have been analyzed[5] according to the modified Fujita and Nishioka[6] equation:

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$$\Delta\log k_{m,p,ortho} = c_0 + c_{1(m,p,ortho)}\sigma^0 + c_{2(ortho)}\sigma_{\mathrm{I}} + c_3\Delta E + c_4\Delta Y + c_5\Delta P + c_{6(m,p,ortho)}\Delta E\sigma^0 + c_{7(m,p,ortho)}\Delta Y\sigma^0 + c_{8(m,p,ortho)}\Delta P\sigma^0 + c_{9(ortho)}\Delta E\sigma_{\mathrm{I}} + c_{10(ortho)}\Delta Y\sigma_{\mathrm{I}} + c_{11(ortho)}\Delta P\sigma_{\mathrm{I}} \tag{1}$$

where $\Delta\log k = \log k^{\mathrm{X}} - \log k^{\mathrm{H}}, \sigma^0$ and σ_{I} are the Taft polar and inductive substituent constants, $\Delta E = E_{\mathrm{S}} - E_{\mathrm{H_2O}}, \Delta Y = Y_{\mathrm{S}} - Y_{\mathrm{H_2O}}, \Delta P = P_{\mathrm{S}} - P_{\mathrm{H_2O}}$ and E, Y and P are the solvent electrophilicity, polarity and polarizability parameters of the Koppel–Palm equation.[7,8]

In an earlier paper,[5] it was shown, that in the alkaline hydrolysis of substituted phenyl tosylates the solvent electrophilicity was the main factor responsible for changes in the *ortho*, *para* and *meta* polar substituent effects due to medium [$c_{6(m,p,ortho)} = -0.0856$]. The *ortho* inductive term appeared to vary with the solvent electrophilicity, E, nearly half as much as that for *para* substituents [$c_{9(ortho)} = 0.0480$] whereas the *ortho* resonance term was found to change with solvent at nearly the same rate as that for *para* substituents.[5]

On the basis of our earlier kinetic data for various media (Refs 1–4, 9 and references cited therein) and kinetic data reported in this work, it was interesting to check on the significance of different solvent parameters for the substituent effects, especially *ortho* inductive, resonance and steric terms, in the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, using a multilinear relationship similar to Eqn (1), including an additional steric term for *ortho* derivatives.

In the present paper, the substituent effects in alkaline hydrolysis of substituted phenyl benzoates for aqueous 0.5 M Bu_4NBr are also analyzed.

EXPERIMENTAL

The preparation procedure and characteristics of most substituted phenyl benzoates are described in Refs 1–5, 10–12 and references cited therein. In this work, nine new phenyl benzoates were synthesized. To synthesize the substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, three methods were used: the reaction of benzoyl chloride with the corresponding substituted phenol in 10% aqueous NaOH solution[13] (X = 4-CN, 2-CN, 4-Cl, 4-CH_3, 4-OCH_3, 2-I), the Einhorn method[14] (in pyridine) [X = 2-$C(CH_3)_3$, 2-CF_3] and reduction of 4-nitrophenyl benzoate (X = 4-NH_2).[15] Esters were recrystallized from aqueous ethanol, dried in a desiccator over P_2O_5 or purified by vacuum- distillation. The esters were identified by NMR chemical shifts [Table S1 (Tables S1–S6 are available in Wiley Interscience)] and by melting or boiling points: 4-cyanophenyl benzoate, m.p. 91 °C (lit.[16] 91–92 °C), 2-cyanophenyl benzoate, m.p. 105.5 °C (lit.[17] 105 °C), 4-chlorophenyl benzoate, m.p. 86.5–87.7 °C (lit.[18] 88–89 °C), 4-methylphenyl benzoate, m.p. 69.7 °C (lit.[18] 70.4–71.2 °C), 4-methoxyphenyl benzoate, m.p. 86.6–87.8 °C (lit.[19] 87–88 °C), 2-iodophenyl benzoate, b.p. 162 °C/0.9 mmHg, 2-*tert*-butylphenyl benzoate, m.p. 69.1–70.3 °C, 2-trifluoromethylphenyl benzoate, b.p. 125–126 °C/1.5 mmHg, 4-aminophenyl benzoate, m.p. 160.5–161.5 °C (lit.[20] 153–154 °C) tetrabutylammonium hydroxide (0.0184 M) was used as the reagent. The purification of Bu_4NOH and Bu_4NBr was described previously.[1–5]

The kinetics were measured spectrophotometrically as described.[1–5,10,11] The second-order rate constants, k ($\mathrm{M^{-1}\,s^{-1}}$), for the alkaline hydrolysis of substituted phenyl benzoates in aqueous 0.5 M Bu_4NBr at 15, 20, 25, 30 35, 40 50 and 55 °C and the wavelength λ used in spectrophotometric kinetic measurements are given in Table S2. The second-order rate constants, k ($\mathrm{M^{-1}\,s^{-1}}$), for 2-cyano- and 4-cyanophenyl and non-substituted phenyl benzoates in water at 25 °C are given in Table S3.

DATA PROCESSING

For the study of substituent effects at a single temperature, the $\log k$ values for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in aqueous 0.5 M Bu_4NBr were treated according to the Taft[21] equation, Eqn (2), and the modified Charton[22] equations, Eqns (3) and (4):

$$\log k_{m,p} = \log k_0 + (\rho^0)_{m,p}\sigma^0 \tag{2}$$

$$\log k_{m,p,ortho} = \log k_0 + (\rho^0)_{m,p}\sigma^0 + (\rho_{\mathrm{I}})_{ortho}\sigma_{\mathrm{I}} + (\rho_{\mathrm{R}})_{ortho}\sigma^0_{\mathrm{R}} + \delta E^{\mathrm{B}}_{\mathrm{s}} \tag{3}$$

$$\log k_{ortho} = \log k_0 + (\rho_{\mathrm{I}})_{ortho}\sigma_{\mathrm{I}} + (\rho_{\mathrm{R}})_{ortho}\sigma^0_{\mathrm{R}} + \delta E^{\mathrm{B}}_{\mathrm{s}} \tag{4}$$

In order to study the dependence of the substituent effects on different solvent parameters, the $\Delta\log k = \log k^{\mathrm{X}} - \log k^{\mathrm{H}}$ values for *ortho*-, *meta*- and *para*-substituted phenyl benzoates at 50 °C in various media were correlated with Eqn (5):

$$\Delta\log k_{m,p,ortho} = a_0 + a_{1(m,p)}\sigma^0 + a_{2(ortho)}\sigma_{\mathrm{I}} + a_{3(ortho)}\sigma^0_{\mathrm{R}} + a_{4(ortho)}E^{\mathrm{B}}_{\mathrm{s}} + a_5\Delta E + a_6\Delta Y + a_7\Delta P + a_{8(m,p)}\Delta E\sigma^0 + a_{9(m,p)}\Delta Y\sigma^0 + a_{10(m,p)}\Delta P\sigma^0 + a_{11(ortho)}\Delta E\sigma_{\mathrm{I}} + a_{12(ortho)}\Delta Y\sigma_{\mathrm{I}} + a_{13(ortho)}\Delta P\sigma_{\mathrm{I}} + a_{14(ortho)}\Delta E\sigma^0_{\mathrm{R}} + a_{15(ortho)}\Delta Y\sigma^0_{\mathrm{R}} + a_{16(ortho)}\Delta P\sigma^0_{\mathrm{R}} \tag{5}$$

The inductive effect from the *ortho* position, different from that from the *meta* and *para* positions, was assumed.[6,22–24] Similarly, in the case of *ortho* substituents, the variation of the inductive term with solvent parameters, different from that for *meta* and *para* derivatives, was assumed. The steric term of *ortho* substituents in the alkaline hydrolysis of phenyl benzoates was considered to be independent of the solvent[2,4] and the corresponding cross-terms with the solvent parameters (ΔE, ΔY, ΔP) were omitted. In the data processing including only *ortho*-substituted derivatives the log *k* value for unsubstituted derivative (X = H) as standard was included besides the *ortho*-substituted derivatives.

The Taft's polar σ^0 [25,26], inductive σ_I,[27] the resonance σ^0_R $[\sigma^0_\mathrm{R} = (\sigma^0)_{para} - \sigma_\mathrm{I}]$[28] scales were used in the data processing. E^B_s constants[2,4] ($E^\mathrm{B}_\mathrm{s} = \log k^\mathrm{X}_{\mathrm{H}^+} - \log k^\mathrm{H}_{\mathrm{H}^+}$, where $k^\mathrm{X}_{\mathrm{H}^+}$ and $k^\mathrm{H}_{\mathrm{H}^+}$ are the rate constants for the acidic hydrolysis of *ortho*-substituted and unsubstitued phenyl benzoates in water at 50 °C[29]) were used as the steric constants for *ortho* substituents (Table S4). The previous statistical data treatment[2,4] confirmed that there was no resonance in the case of 2-N(CH$_3$)$_2$ substituent and in the common data processing the correction $\rho^0\sigma^0_\mathrm{R}$ was added.

In the data processing according to Eqn (5), the $\log k$ values for the alkaline hydrolysis of *ortho*-, *meta*- and *para*-substituted phenyl benzoates at 50 °C in pure water, aqueous 0.5 M Bu$_4$NBr (present work, Table S2), aqueous 1 M Bu$_4$NBr, 2.25 M Bu$_4$NBr, 80% (v/v) DMSO, 5.3 M NaClO$_4$ and 4.8 M NaCl (Refs 1–4, 9 and references cited therein) were included. In Eqn (5) the values of ΔE, ΔY and ΔP are the differences in electrophilicities, polarities and polarizabilities on going from pure water to the corresponding aqueous binary solution, $\Delta E = E_\mathrm{s} - E_{\mathrm{H_2O}}, \Delta Y = Y_\mathrm{S} - Y_{\mathrm{H_2O}}, \Delta P = P_\mathrm{S} - P_{\mathrm{H_2O}}$, respectively. The standard medium, where ΔE, ΔY and ΔP are equal to zero, is pure water and the standard substituent is X = H. The electrophilicity *E* values of Koppel and Palm,[30–33] polarity *Y* calculated as a function of dielectric constant ε in the form $(\varepsilon - 1)/(\varepsilon + 2)$ and the polarizability *P* as a function of refractive index n_D in the form $(n^2 - 1)/(n^2 + 2)$ were used (see Table S5). The data processing was carried out using a multiple parameter linear least-squares (LLSQ) procedure.[34] Significantly deviating points were excluded using a Student criterion. The exclusion of the significantly deviating points was performed on different confidence levels of the *t*-test. Results of the data treatment in the present work are given mainly at the 0.99 confidence level.

The results of the data treatment with Eqns (2)–(5) are presented in Tables 1 and 2. The values of substituent constants σ^0, σ_I, σ^0_R and E^B_s used in the correlations and the values of $\log A$ and activation energies, *E* (kJ mol^{-1}), for the alkaline hydrolysis of substituted phenyl benzoates in aqueous 0.5 M Bu$_4$NBr, calculated with the Arrhenius equation ($\log k = \log A - E/2.3RT$), are listed in Table S4. The values of solvent characteristics used in data treatment with Eqn (5) are collected in Table S5.

DISCUSSION

Substituent effects in aqueous 0.5 M Bu$_4$NBr

For most substituted phenyl benzoates the transition from pure water to aqueous 0.5 M Bu$_4$NBr solution results in a decrease in the rate constants of the alkaline hydrolysis.

Table 1. Results of the correlation with Eqns (2)–(4) for alkaline hydrolysis of substituted phenyl benzoates, C$_6$H$_5$CO$_2$C$_6$H$_4$X, in aqueous 0.5 M Bu$_4$NBr and in pure water[a]

Temperature (°C)	Eqn No.	$\log k_0$	$\rho^0_{m,p}$	$(\rho_\mathrm{I})_{ortho}$	$(\rho_\mathrm{R})_{ortho}$	δ_{ortho}	*R*	*s*	*n*
0.5 M Bu$_4$NBr									
50	2	-0.084 ± 0.016	1.31 ± 0.05	—	—	—	0.995	0.049	11
	3	-0.074 ± 0.059	1.30 ± 0.06	1.46 ± 0.06	1.22 ± 0.08	1.30 ± 0.08	0.997	0.061	21
	4	-0.026 ± 0.061	—	1.41 ± 0.09	1.24 ± 0.10	1.38 ± 0.13	0.994	0.070	11
40	2	-0.324 ± 0.020	1.37 ± 0.06	—	—	—	0.994	0.061	12
	3	-0.316 ± 0.036	1.36 ± 0.05	1.50 ± 0.07	1.25 ± 0.09	1.33 ± 0.09	0.994	0.066	22
	4	-0.299 ± 0.065	—	1.49 ± 0.10	1.25 ± 0.11	1.36 ± 0.14	0.993	0.074	11
25	2	-0.754 ± 0.019	1.45 ± 0.05	—	—	—	0.994	0.059	11
	3	-0.748 ± 0.037	1.45 ± 0.06	1.63 ± 0.07	1.37 ± 0.09	1.34 ± 0.09	0.995	0.067	21
	4	-0.727 ± 0.066	—	1.61 ± 0.10	1.37 ± 0.11	$1.\ 38 \pm 0.14$	0.994	0.076	11
20	2	-0.923 ± 0.027	1.54 ± 0.06	—	—	—	0.995	0.056	8
	3	-0.903 ± 0.055	1.51 ± 0.07	1.72 ± 0.09	1.23 ± 0.12	1.53 ± 0.17	0.995	0.070	15
	4	-0.853 ± 0.085	—	1.66 ± 0.12	1.25 ± 0.14	1.62 ± 0.22	0.994	0.080	8
15	2	-1.044 ± 0.041	1.49 ± 0.07	—	—	—	0.992	0.077	9[b]
	3	-1.032 ± 0.045	1.47 ± 0.07	1.64 ± 0.08	1.26 ± 0.12	1.31 ± 0.10	0.994	0.071	18[c]
	4	-1.004 ± 0.061	—	1.61 ± 0.14	1.28 ± 0.16	1.36 ± 0.26	0.994	0.069	10[c]
Water									
25	2	-0.377 ± 0.025	1.11 ± 0.05	—	—	—	0.988	0.067	12
	3	-0.375 ± 0.034	1.11 ± 0.04	1.52 ± 0.06	0.92 ± 0.08	1.05 ± 0.11	0.994	0.055	22
	4	-0.377 ± 0.040	—	1.54 ± 0.05	0.95 ± 0.07	1.09 ± 0.11	0.997	0.047	13

[a] The log *k* values reported previously[2] and measured in the present work were included.

[b] The log *k* value for the unsubstitued derivative, calculated with the Arrhenius equation, was included.

[c] The log *k* value for 2-CH$_3$- and 2-OCH$_3$-subsituted and unsubstituted derivative, calculated with the Arrhenius equation, were included.

Table 2. Results of the correlation with Eqn (5) for kinetic data for alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in various media at 50 °C[a]

Reaction constant	*meta* and *para* derivatives	Weight	*ortho* derivatives	Weight	*ortho, meta* and *para* derivatives	Weight
Solvent electrophilicity parameter, ΔE, was included[b]						
a_0	-0.004 ± 0.017		0.014 ± 0.046		0.001 ± 0.033	
$a_{1(m,p)}$	1.075 ± 0.033	0.700	—		1.069 ± 0.040	0.357
$a_{2(ortho)}$	—		1.428 ± 0.059	0.538	1.437 ± 0.052	0.145
$a_{3(ortho)}$	—		0.838 ± 0.075	0.226	0.829 ± 0.068	0.145
$a_{4(ortho)}$	—		1.228 ± 0.090	0.067	1.199 ± 0.070	0.121
$a_{8(m,p)}$	-0.0646 ± 0.0038	0.300	—		-0.0645 ± 0.0046	0.146
$a_{11(ortho)}$	—		-0.0212 ± 0.0059	0.047	-0.0211 ± 0.0054	0.013
$a_{14(ortho)}$	—		-0.0685 ± 0.0089	0.122	-0.0685 ± 0.082	0.073
n/n_0	42/45		41/46		76/84	
R	0.992		0.988		0.991	
s	0.061		0.081		0.074	
s_0	0.126		0.153		0.136	
t	0.97		0.95		0.97	
Solvent electrophilicity, ΔE, and polarity, ΔY, parameters were included[c]						
a_0	-0.004 ± 0.017		0.014 ± 0.046		-0.044 ± 0.039	
$a_{1(m,p)}$	1.075 ± 0.033	0.700	—		0.993 ± 0.060	0.329
$a_{2(ortho)}$	—		1.428 ± 0.059	0.538	1.444 ± 0.051	0.128
$a_{3(ortho)}$	—		0.838 ± 0.075	0.226	0.822 ± 0.068	0.133
$a_{4(ortho)}$	—		1.228 ± 0.090	0.069	1.198 ± 0.063	0.145
$a_{8(m,p)}$	-0.0646 ± 0.0038	0.300	—		-0.0722 ± 0.0052	0.166
$a_{9(m,p)}$	—		—		-4.08 ± 1.87	0.021
$a_{11(ortho)}$	—		-0.0212 ± 0.0059	0.047	-0.0212 ± 0.0055	0.012
$a_{14(ortho)}$	—		-0.0685 ± 0.0089	0.122	-0.0689 ± 0.0083	0.067
n/n_0	42/45		41/46		77/84	
R	0.992		0.988		0.992	
s	0.061		0.081		0.075	
s_0	0.126		0.153		0.130	
t	0.97		0.95		0.99	

[a] A table containing the results of the correlations with Eqs (5) for kinetic data for alkaline hydrolysis of substituted phenyl benzoates in various media at 50 °C when three solvent parameters, the solvent electrophilicity, ΔE, the solvent polarity, ΔY, and the solvent polarizability, ΔP, were included, is available as supplementary material (Table S6). If the scale is not shown in the table, the corresponding argument scale is excluded as insignificant during the data processing ($a = 0$).

[b] In most cases exclusion of significantly deviating points performed before excluding insignificant argument scales and cross terms are formed from non-centered basic argument scales.[5,34]

In Eqn (5) the terms $a_6\Delta Y$, $a_7\Delta P$, $a_{9(m,p)}\Delta Y\sigma^0$, $a_{10(m,p)}\Delta P\sigma^0$, $a_{12(ortho)}\Delta Y\sigma_I$, $a_{13(ortho)}\Delta P\sigma_I$, $a_{15(ortho)}\ \Delta Y{\sigma^0}_R$ and $a_{16(ortho)}\Delta P\sigma^0_R$ were omitted before data processing.

[c] In Eqn (5) the terms $a_7\Delta P$, $a_{10(m,p)}\Delta P\sigma^0$, $a_{13(ortho)}\Delta P\sigma_I$, and $a_{16(ortho)}\Delta P\sigma^0_R$ were omitted before data processing.

The retardation is larger for esters with electron-donating substituents than that for esters with electron-withdrawing substituents (Table S2).

In the alkaline hydrolysis of of *meta*- and *para*-substituted phenyl benzoates in aqueous 0.5 M Bu_4NBr, the dependence of the reaction rates on the substituent effects is nicely described with σ^0 values [Eqn (2)]. As found earlier[1–4] for water, aqueous 2.25 M Bu_4NBr, aqueous 5.3 M $NaClO_4$ and aqueous 80% DMSO, the inductive, σ_I, resonance, σ^0_R, and steric, E^B_s, constants were used in the case of *ortho* substituents (Table 1). The values of reaction constants $(\rho_I)_{ortho}$, $(\rho_R)_{ortho}$ and δ calculated from Eqn (4) separately for *ortho*-substituted derivatives are approximately the same as those calculated simultaneouly with *ortho*-, *meta*- and *para*-substituted derivatives using Eqn (3) (see Table 1).

In the alkaline hydrolysis of substituted phenyl benzoates, the $(\rho^0)_{m,p}$ and $(\rho_I)_{ortho}$ values for aqueous 0.5 M Bu_4NBr for various temperatures are in the ranges 1.30–1.54 and 1.46–1.72, respectively. Earlier the $(\rho^0)_{m,p}$ and $(\rho_I)_{ortho}$ values for pure water were found to be in the ranges 0.90–1.15 and 1.26–1.72 respectively.[2] On going from pure water to aqueous 0.5 M Bu_4NBr the polar effect of *meta* and *para* substituents increases by ca 0.4 units of $(\rho^0)_{m,p}$. The change in the susceptibility to the *ortho* inductive effect, $(\rho_I)_{ortho}$, is essentially lower by ca 0.10 units of $(\rho_I)_{ortho}$. Earlier[5] it was found that the ${\rho^0}_{m,p}$ values in the alkaline hydrolysis of substituted phenyl tosylates on going from pure water to aqueous 0.5 M Bu_4NBr changed by nearly the same extent ($\rho^0_{m,p}$ by ca 0.5–0.6 units and $(\rho_I)_{ortho}$ by 0.15–0.20 units) as the $\rho^0_{m,p}$ and $(\rho_I)_{ortho}$ values in the alkaline hydrolysis of phenyl benzoates.

The analysis of the data for the alkaline hydrolysis of phenyl benzoates in aqueous 0.5 M Bu_4NBr demonstrates once again that the *ortho* inductive term varies with solvent less than the *para* inductive term. In water, the inductive influence from the *ortho* position was found to be 1.5 times stronger than that from the *para* and *meta* positions. Whereas the variation of the susceptibility of the *para* inductive term with solvent is nearly double the variation of the *ortho* inductive term, in aqueous 0.5 M Bu_4NBr solution the *para* inductive effect reaches nearly the level of the *ortho* inductive effect [in aqueous 0.5 M Bu_4NBr $(\rho_I)_{ortho}$ surpasses the $(\rho^0)_{m,p}$ value only by 0.1 units of ρ].

In the alkaline hydrolysis of substituted benzoates in aqueous 0.5 M Bu_4NBr solution, the susceptibility to the steric effect was ($\delta \approx 1.35$, Tables 1 and 2) nearly the same as we have found earlier[2–4] for water, aqueous 2.25 M Bu_4NBr, aqueous 5.3 M $NaClO_4$ and aqueous 80% DMSO (the δ values range from 1.0 to 1.4).

From the dependence of ρ on temperature, $\rho_T = c_0 + c_1(1/T)$, where $\beta = -c_1/c_0$,[35] the isokinetic temperatures β for the *ortho* inductive term and *meta* and *para* polar effect in the alkaline hydrolysis of substituted phenyl benzoates in aqueous 0.5 M Bu_4NBr were calculated. For aqueous 0.5 M Bu_4NBr $\beta_{I(ortho)} = 872$ K $[(\rho_{I(ortho)} = (-0.837) + 0.730(10^3/T)]$ and $\beta_{m,p} = 1355$ K $[(\rho_{m,p} = (-0.411) + 0.557(10^3/T)]$. For water $\beta_{I(ortho)} = 832$ K $[(\rho_{I(ortho)} = (-0.89) + 0.741(10^3/T)]$ and $\beta_{m,p} = \infty$ K. For aqueous 2.25 M Bu_4NBr $\beta_{I(ortho)} = 702$ K $[(\rho_{I(ortho)} = (-1.51) + 1.06(10^3/T)]$ and $\beta_{m,p} = 628$ K ($\beta_{m,p} = 628$ K[36]) $[(\rho_{m,p} = (-2.14) + 1.34(10^3/T)]$. The values of β for the alkaline hydrolysis of substituted phenyl benzoates in various media demonstrate that the isokinetic temperature $\beta_{I(ortho)}$ for the *ortho* inductive effect varies with solvent considerably less than the isokinetic temperature for polar effect of *meta* and *para* substituents, $\beta_{m,p}$.

In the alkaline hydrolysis of *ortho*-, *meta*- and *para*-substituted phenyl benzoates, the dependence of the activation energies E on the substituent effects in aqueous 0.5 M Bu_4NBr is entirely caused by polar effects of substituents (Table S4), whereas electron-withdrawing substituents decrease and electron-donating substituents increase it. The activation energy for *ortho*-substituted derivatives with electronegative substituents was found to be lower than those for *para*-substitued derivatives owing to the additional inductive influence from *ortho* position. The influence of the *ortho*, *meta* and *para* substituent polar effects on the activation energy is greater in aqueous 0.5 M Bu_4NBr than in the pure water. However, in 0.5 M Bu_4NBr a decrease in the difference $E^X_{para} - E^X_{ortho}$ compared with that in pure water could be observed.

The steric factor of *ortho* substituents appeared to be independent of temperature and therefore influences the $\log A$ value. The $\log A$ values for *ortho*-substituted derivatives in aqueous 0.5 M Bu_4NBr were smaller than that for *para* derivatives (Table S4) owing to the steric influence from *ortho* position.

Influence of solvent on substituent effects

To study the influence of the solvent parameters on the substituent effects in the alkaline hydrolysis of substituted phenyl benzoates, the $\Delta\log k$ values at 50 °C for various media were subjected to the multilinear regression analysis according to Eqn (5) in three different ways: (i) only the solvent electrophilicity, ΔE, was included, (ii) both the solvent electrophilicity, ΔE, and the solvent polarity, ΔY, were included or (iii) all three solvent parameters, the solvent electrophilicity, ΔE, the solvent polarity, ΔY, and the solvent polarizability, ΔP, were included. For comparison, the data treatment is shown separately for *meta*- and *para*-substitued derivatives, *ortho*-substituted derivatives and simultaneously for *ortho*-, *meta*- and *para*-substituted derivatives [Eqn (5), Tables 2 and S6]. If the scale is not shown in the table, the corresponding argument scale is excluded during the data processing as insignificant.

The reaction constants a_0, $a_{1(m,p)}$, $a_{2(ortho)}$, $a_{3(ortho)}$ and $a_{4(ortho)}$ in pure water appeared to be fairly constant values that do not depend significantly on the method used for the data treatment: the data included are either only for *meta*- and *para*-substitued derivatives or for *ortho*-substitued derivatives, or the data set can embrace the data simultaneously for *ortho*-, *meta*- and *para*-substituted derivatives. The reaction constant $a_{1(m,p)}$ shows the susceptibility to the polar effect of *meta* and *para* substituents in standard solution, in water at 50 °C (Tables 2 and S6). The values of $a_{1(m,p)}$ found in different ways appeared to vary in a narrow range, from 0.99 to 1.10. Earlier the $(\rho^0)_{m,p}$ value for the alkaline hydrolysis of substituted benzoates in water at 50 °C was found to be in the range 0.96–1.01.[2] The calculated values of $a_{2(ortho)}$, $a_{3(ortho)}$ and $a_{4(ortho)}$ as the susceptibilities to the *ortho* inductive, resonance and steric effects in pure water, were in ranges 1.41–1.45, 0.83–0.86 and 1.15–1.20, respectively. Earlier, the corresponding values of $(\rho_I)_{ortho}$, $(\rho^0_R)_{ortho}$, and $(\delta)_{ortho}$ for pure water at 50 °C were found to be in the ranges 1.50–1.52, 0.94–1.01 and 0.97–1.20, respectively.[2]

The solvent electrophilicity parameter, ΔE, was the main factor responsible for the dependence of the substituent effects on medium as the contribution of cross terms $[a_{8(m,p)}\Delta E\sigma^0, a_{11(ortho)}\Delta E\sigma_I, a_{14(ortho)}\Delta E\sigma^0_R]$ containing the solvent electrophilicity parameter ΔE was significant when the $\Delta\log k$ values were processed according to Eqn (5) (Tables 2 and S6). Consequently, in the alkaline hydrolysis of substituted phenyl benzoates the variation of the *meta*, *para* polar effect, the *ortho* inductive and *ortho* resonance effects with solvent occurs mainly due to the change in electrophilicity of the medium considered.

The cross term containing the solvent polarity $a_{9(m,p)}\Delta Y\sigma^0$ was different from zero for the simultaneous data treatment with Eqn (5) for *ortho, meta* and *para* derivatives. However, the contribution of solvent polarity on the polar effect of substituents could be considered as almost insignificant owing to its very low relative weight. Further, in the separate data treatment for *meta* and *para* derivatives the term $a_{9(m,p)}\Delta Y\sigma^0$ was excluded as insignificant. The terms $a_{12(ortho)}\Delta Y\sigma_{\mathrm{I}}$ and $a_{13(ortho)}\Delta P\sigma_{\mathrm{I}}$, were significant when the data for *ortho* derivatives were processed with Eqn (5). Owing to very low weight, the term $a_{12(ortho)}\Delta Y\sigma_{\mathrm{I}}$ was excluded during the data processing when data for aqueous 80% DMSO were excluded before data treatment. Similarly, the term $a_{13(ortho)}\Delta P\sigma_{\mathrm{I}}$ was excluded as insignificant when Eqn (5) included only the solvent electrophilicity, ΔE, and the solvent polarizability, ΔP, and the corresponding cross terms.

The variation of the *meta* and *para* polar effects with the solvent electrophilicity is three times higher than that for the *ortho* inductive effect. The corresponding value for reaction constants $a_{8(m,p)}$ are in the range from -0.065 to -0.072. In the case of *ortho* substituents, the susceptibility of the inductive effect to variation of the solvent electrophilicity ranges from 0 to -0.023. Earlier, nearly the same values for reaction constants $a_{8(m,p)} = -0.0856$ and $a_{11(ortho)} = -0.0376$ were found for the alkaline hydrolysis of substituted phenyl tosylates.[5] The *ortho* resonance effect appears to vary with the solvent electrophilicity to nearly the same extent as the polar effect of *para* substituents, $a_{8(m,p)} \approx a_{14(ortho)}$.

The results of data treatment in Tables 2 and S6 confirm that the steric effect of *ortho* substituents could be really considered independently of solvent parameters as assumed in Eqn (5).

Therefore, in the alkaline hydrolysis of substituted phenyl benzoates, the polar effect of *meta* and *para* substituents, the *ortho* inductive and resonance effect vary with the solvent electrophilicity to the same extent as found earlier[5] for the alkaline hydrolysis of substituted phenyl tosylates, although the ratio of the susceptibilities to polar effect of substituents in water differs twofold, i.e. $(\rho^0_{m,p})_{\mathrm{Tos}}/(\rho^0_{m,p})_{\mathrm{Benz}} = (\rho_{\mathrm{I}(ortho)})_{\mathrm{Tos}}/(\rho_{\mathrm{I}(ortho)})_{\mathrm{Benz}} \approx 2.$[2]

It follows from Table 2 that in medium considered the total substituent effect in the alkaline hydrolysis of substituted phenyl benzoates could be expressed by Eqns (6) and (7):

$$\begin{aligned}\Delta\log k_{m,p(ortho)} &= \log k^{\mathrm{X}} - \log k^{\mathrm{H}} = 0.001 + (1.069\sigma^0)_{m,p} \\ &+ (1.437\sigma_{\mathrm{I}})_{ortho} + (0.829\sigma^0_{\mathrm{R}})_{ortho} + (1.199E^{\mathrm{B}}_{\mathrm{s}})_{ortho} \\ &- (0.0645\Delta E\sigma^0)_{m,p} - (0.0211\Delta E\sigma_{\mathrm{I}})_{ortho} \\ &- (0.0685\Delta E\sigma^0_{\mathrm{R}})_{ortho} \qquad (6)\end{aligned}$$

$$R = 0.991, s = 0.074, s_0 = 0.136, n/n_0 = 76/84$$

$$\begin{aligned}\Delta\log k_{(ortho)} &= \log k^{\mathrm{X}} - \log k^{\mathrm{H}} \\ &= 0.014 + 1.428\sigma_{\mathrm{I}} + 0.838\sigma^0_{\mathrm{R}} + 1.228E^{\mathrm{B}}_{\mathrm{s}} \\ &- 0.0212\Delta E\sigma_{\mathrm{I}} - 0.0685\Delta E\sigma^0_{\mathrm{R}} \qquad (7)\end{aligned}$$

$$R = 0.988, s = 0.081, s_0 = 0.153, n/n_0 = 41/46$$

An excellent fit between the experimental $\log k$ values at 50 °C (Tables S2 and S3, Refs 1–5 and references cited therein) and predicted $\log k$ values calculated with Eqns (6) and (7), was found:

$$\begin{aligned}(\Delta\log k_{\mathrm{obs}})_{m,p(ortho)} &= (0.057 \pm 0.008) + (0.997 \pm 0.015) \\ &\times (\Delta\log k_{\mathrm{cal}})_{m,p(ortho)} \qquad (8)\end{aligned}$$

$$R = 0.992, s = 0.069, s_0 = 0.126, n/n_0 = 76/84$$

$$\begin{aligned}(\Delta\log k_{\mathrm{obs}})_{ortho} &= -(0.002 \pm 0.012) \\ &+ (0.993 \pm 0.023)(\Delta\log k_{\mathrm{cal}})_{ortho} \qquad (9)\end{aligned}$$

$$R = 0.990, s = 0.076, s_0 = 0.144, n/n_0 = 41/46$$

In the alkaline hydrolysis of substituted phenyl benzoates, the induction factor from the *ortho* position, 1.5-fold higher than from the *para* position in water, varies nearly three times less than the polar effect from the *para* position with change in solvent. From Eqn (6) could be calculated the value of solvent electrophilicity at which the *ortho* effect caused by the additional inductive effect from *ortho* position, becomes zero:

$$\begin{aligned}(1.069\sigma_{\mathrm{I}})_p - (0.0645\Delta E\sigma_{\mathrm{I}})_p &= (1.437\sigma_{\mathrm{I}})_{ortho} \\ &- (0.0211\Delta E\sigma_{\mathrm{I}})_{ortho} \qquad (10)\end{aligned}$$

In the alkaline hydrolysis of substituted phenyl benzoates, the polar effects of *ortho* and *para* substituents become equals in a solvent with an electrophilic solvating power nearly the same as that of 60% aqueous ethanol and 1 M $\mathrm{Bu_4NBr}$ $[\Delta E_{(\rho\mathrm{I})_{ortho}=(\rho\mathrm{I})_{para}} = -8.48]$. Consequently, in 60% aqueous ethanol and aqueous 1 M $\mathrm{Bu_4NBr}$ the *ortho* effect, caused by the supplementary inductive effect from the *ortho* position, will disappear and the *ortho* effect is caused only by steric effect of *ortho* substituents.

The present work shows that in the alkaline hydrolysis of substituted phenyl benzoates, similarly to the alkaline hydrolysis of phenyl tosylates, the polar effects of *ortho*, *meta* and *para* substituents increase on going from water to aqueous solutions of organic salts (0.5 M $\mathrm{Bu_4NBr}$, 1.0 M $\mathrm{Bu_4NBr}$, 2.25 M $\mathrm{Bu_4NBr}$ and 80% DMSO) the electrophilic solvating power of which is reduced compared with water. On the other hand, the polar effects of *ortho*, *meta* and *para* substituents decreased on going from water to inorganic salt solutions (5.3 M $\mathrm{NaClO_4}$, 4.8 M NaCl) whose electrophilic solvating power is higher than that of water. In the alkaline hydrolysis of substituted phenyl benzoates, the variation of *ortho*, *para* and *meta* polar effects with solvent electrophilicity properties, ΔE, occurs to nearly the same extent as found earlier for the alkaline hydrolysis of substituted phenyl tosylates.[5]

Supplementary material

The following tables are available as supplementary material in Wiley Interscience:

Table S1, ^{1}NMR spectra of substituted phenyl benzoates, $C_6H_5COOC_6H_4X$; Table S2, second-order rate constants k for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in aqueous 0.5 M Bu_4NBr at various temperatures; Table S3, pseudo-first-order rate constants k_1 (s^{-1}) and the second-order rate constants k ($M^{-1}\,s^{-1}$) for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in water at 25 °C; Table S4, substituent constants used in the correlations and values of $\log A$ and activation energy, E (kJ mol^{-1}), for the alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in aqueous 0.5 M Bu_4NBr; Table S5, values of electrophilicity, E, dielectric permittivity, ε, refractive index, n_D, polarizability, $P = (n^2 - 1)/(n^2 + 2)$, and polarity, $Y = (\varepsilon - 1)/(\varepsilon + 2)$, at 25 °C for various aqueous solutions; Table S6, results of the correlation with Eqn (5) for kinetics of alkaline hydrolysis of substituted phenyl benzoates, $C_6H_5CO_2C_6H_4X$, in various media at 50 °C (solvent electrophilicity, ΔE, polarity, ΔY and polarizability, ΔP, parameters included).

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REFERENCES

1. Nummert V, Piirsalu M, Palm V. *Org. React.* 1996; **30**: 85–94.
2. Nummert V, Piirsalu M. *J. Chem. Soc., Perkin Trans. 2* 2000; 583–594.
3. Nummert V, Piirsalu M. *Org. React.* 1997; **31**: 101–109.
4. Nummert V, Piirsalu M. *Collect. Czech. Chem. Commun.* 2003; **67**: 1833–1857.
5. Nummert V, Piirsalu M, Lepp M, Mäemets V, Koppel I. *Collect. Czech. Chem. Commun.* 2005; **70**: 198–222.
6. Fujita T, Nishioka T. *Prog. Phys. Org. Chem.* 1976; **12**: 49–89.
7. Koppel IA, Palm VA. In *Advances in Linear Free Energy Relationships*, Chapman NB, Shorter J (eds). Plenum Press: London, 1972; Chapt. 5, 203.
8. Koppel IA, Palm VA. *Org. React.* 1971; **8**: 291–301.
9. Nummert V, Piirsalu M. *Org. React.* 1977; **14**: 263–279.
10. Püssa TO, Nummert (Maremäe) VM, Palm VA. *Org. React.* 1972; **9**: 697–728.
11. Nummert V, Eek M, Piirsalu M. *Org. React.* 1981; **18**: 363–374.
12. Nummert VM, Piirsalu MV. *Org. React.* 1975; **11**: 899–910.
13. Bauerova I, Ludvig M. *Collect. Czech. Chem. Commun.* 2000; **65**: 1777–1790.
14. Pirinccioglu N, Williams A. *J. Chem. Soc. Perkin Trans. 2* 1998; 37–40.
15. Uhlmann F, Meyer GM, Loewenthal O, Gilli E. *Liebigs Ann. Chem.* 1904; **332**: 38–81.
16. Correia VR, Cuccovia IM, Chaimovich H. *J. Phys. Org. Chem.* 1991; **4**: 13–18.
17. Auwers K, Walker AJ. *Chem. Ber.* 1899; **31**: 3037–3046.
18. Kirch JF, Clewell W, Simon A. *J. Org. Chem.* 1968; **33**: 127–132.
19. Neuvonen H, Neuvonen K, Pasanen P. *J. Org. Chem.* 2004; **69**: 3794–3800.
20. Hübner H. *Liebigs Ann. Chem.* 1881; **210**: 328–396.
21. Taft RW Jr. In *Steric Effects in Organic Chemistry*, Newman MS (ed). Wiley: New York, 1956; Chapt. 13, 556.
22. Charton M. *Prog. Phys. Org. Chem.* 1971; **8**: 235–317.
23. Charton M. *J. Am. Chem. Soc.* 1969; **91**: 624–628.
24. Böhm S, Fiedler P, Exner O. *New J. Chem.* 2004; **28**: 67–74.
25. Palm VA (ed). *Tables of Rate and Equilibrium Constants of Heterolytic Organic Reactions*, vol. 5(II). VINITI: Moscow, 1979.
26. Hansch C, Leo A, Taft RW. *Chem. Rev.* 1991; **91**: 165–195.
27. Taft RW Jr, Lewis IC. *J. Am. Chem. Soc.* 1958; **80**: 2436–2443.
28. Taft RW Jr, Ehrenson S, Lewis IC, Glick RE. *J. Am. Chem. Soc.* 1959; **81**: 5352–5361.
29. Nummert VM, Piirsalu MV. *Org. React.* 1975; **11**: 921–932.
30. Koppel IA, Paju AJ. *Org. React.* 1974; **11**: 137–140.
31. Palm VA. *Foundations of Quantitative Theory of Organic Reactions* (2nd edn). Khimya: Leningrad, 1977; Chapt. 1 (in Russian).
32. Koppel IA, Koppel JB. *Org. React.* 1984; **21**: 98–123.
33. Koppel IA, Koppel JB. *Org. React.* 1983; **20**: 523–546.
34. Palm VA. *J. Chem. Inf. Comput. Sci.* 1990; **30**: 409–412.
35. Exner O. *Collect. Czech. Chem. Commun.* 1974; **39**: 515–527.
36. Ruff F. *J. Mol. Struct.* 2003; **617**: 31–45.