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The Grunwald-Winstein Relationship in the Solvolysis of β-Substituted Chloroformate Ester Derivatives: The Solvolysis of 2-Phenylethyl and 2,2-Diphenylethyl Chloroformates

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Solvolysis rate constants of 2-phenylethyl-(2-$PhCH_2CH_2OCOCl$, **1**) and 2,2-diphenylethyl chloroformate (2,2-Ph_2CHCH_2OCOCl, **2**), together with the previously studied solvolyses of α- and β-substituted chloroformate ester derivatives, are reported in pure and binary solvents at 40.0 °C. The linear free energy relationship (LFER) and sensitivities (l and m) to changes in solvent nucleophilicity (N_T) and solvent ionizing power (Y_{Cl}) of the solvolytic reactions are analyzed using the Grunwald-Winstein equation. The kinetic solvent isotope effects (KSIEs) in methanol and activation parameter values in various solvents are investigated for **1** and **2**. These results support well the bimolecular pathway with same aspects. Furthermore, the small negative values of the entropies of activation of solvolysis of **1** and **2** in the highly ionizing aqueous fluoroalcohols are consistent with the ionization character of the rate-determining step, and the KSIE values of 1.78 and 2.10 in methanol-*d* indicate that one molecule of solvent acts as a nucleophile and the other acts as a general-base catalyst. It is found that the β-substituents in alkyl chloroformate are not the important factor to decide the solvolysis reaction pathway.

Key Words : 2-Phenylethyl chloroformate, 2,2-Diphenylethyl chloroformate, Grunwald-Winstein equation, Solvolysis, Linear free energy relationship

Introduction

Alkyl and aryl chloroformate esters are often used to provide the information concerning a variety of protecting groups in organic synthesis.[1,2] Hence, it is very important to determine the relationship between their mechanistic pathways in solvolysis reactions.

During more than half a century, the Grunwald–Winstein (G-W) equations [eqns. (1)[3] and (2)[4]] have been considered one of the most useful mechanistic tools for the structure of the transition states of chemical reactions.

$$\log (k/k_o) = mY_X \quad (1)$$

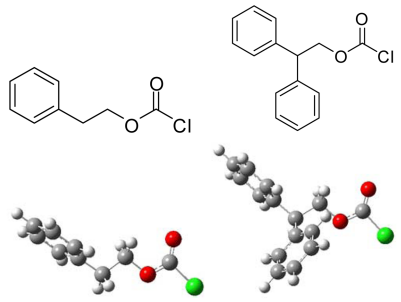
$$\log (k/k_o) = lN_T + mY_X \quad (2)$$

In Eqns. (1) and (2), k and k_o are the rate constants of solvolysis in a given solvent and in 80% ethanol-water ($EtOH-H_2O$), respectively; l is the sensitivity of substrate to the solvent nucleophilicity (N_T)[5,6] and m is the sensitivity to the solvent ionizing power (Y_X).[7-9] Accordingly, the determination of the l and m values is related to the extent of nucleophilic and electrophilic assistance of solvent in the rate determining step, with the structure of the transition state for corresponding solvolyses. In 1982, Bentley and co-workers defined Y_{Cl} scale by the solvolysis of the standard bridgehead compound, 1-adamantyl chloride (1-AdCl),[7] and in 1991, Kevill and Anderson developed N_T scale by the solvolysis of the *S*-methyl dibenzothiophenium ion as a nucleophilic standard compound.[5]

From the l and m values obtained using Eqns. (1) and (2), we previously reported that the results of primary, secondary and tertiary alkyl chloroformates (ROCOCl) in a wide range of solvent mixtures can follow bimolecular and/or unimolecular pathways.[10-17] Kevill and D'Souza[10] showed that, particularly in ethyl chloroformate (**4**, EtOCOCl) solvolysis, an addition-elimination mechanism dominates [$l = 1.56$, $m = 0.55$] in all except the highly ionizing solvents, and the major reaction channel in the least nucleophilic solvents involves ionization mechanism [$l = 0.69$, $m = 0.82$]. Bentley *et al.* also carried out a series studies of the solvolyses of acyl chloride and their derivatives using the G-W equation.[18] For the parent compound and several of the derivatives, a mechanism involving S_N2 character with bond breaking running ahead was proposed for highly aqueous solvents and a carbonyl addition mechanism in less aqueous solvents.

Although the solvolyses of acyl haloformate esters have been widely used in mechanistic studies of nucleophilic substitution reactions, still these compounds are not established the criterion of a definite reaction mechanism. Accordingly, it is necessary to investigate the solvolysis of acyl haloformate esters in a variety of pure and binary solvents for the reasonable reaction mechanisms.

The previously published kinetics for the solvolyses of several alkyl chloroformates, *i.e.*, methyl- (MeOCOCl, **3**),[12] ethyl- (EtOCOCl, **4**),[10] *n*-propyl- (*n*-PrOCOCl, **5**),[13] *sec*-butyl- (*sec*-BuOCOCl, **6**),[14] neopentyl- (NeopOCOCl, **7**),[15]



2-PhCH$_2$CH$_2$OCOCl (**1**) 2,2-PhCHCH$_2$OCOCl (**2**)

Scheme 1. The normal and ball-and-stick structures of substrates studied.

i-propyl- (*i*-PrOCOCl, **8**),[16] 1-adamantyl- (1-AdOCOCl, **9**),[17] and benzyl- (BnOCOCl, **10**),[18] are extended to 2-phenylethyl- (**1**) and 2,2,-diphenylethyl (**2**) chloroformates (Scheme 1). In the present study, we report the rate constants for the solvolyses of **1** and **2** at 40.0 °C in pure and binary solvents, together with the previously studied solvolyses of **4**, **5**, **6**, **7** (*i.e.*, as the branching β-alkyl- and phenyl groups adjacent to an oxygen atom in the ester structure), **8**, **9** and **10**, and also the relationship of the G-W equation [eqns. (1) and (2)]. Using these equations, we analyze the *l*- and *m*-values obtained for **1** and **2**, including a comparison with those previously observed for the solvolyses of alkyl chloroformates (**3-10**). In order to reveal the solvolysis mechanism of **1** and **2**, we also investigate the KSIEs in methanol-*d*, the product study and the activation parameters ($\Delta H^{\neq}$ and $\Delta S^{\neq}$).

Results and Discussion

The chosen substrates, **1** and **2** are basically a primary alkyl chloroformate which is connected alkyl group adjacent oxygen atom of alkoxy system. Previously, many alkyl chloroformates were studied and reported the reactivity and mechanism.[10,12-18] Some of results showed that the substituent at α-position of ester functional group is an important factor for deciding the solvolysis mechanism. In this phenomenon, substituent has the key role to affect the reaction center carbonyl carbon by a steric hindrance and/or electron effects. By the way, substrates, **1** and **2** have one or two phenyl substituents at β-position from ester functional group. In alkyl chloroformates, the reactivity of solvolysis can be considered to change by branched functional groups on the α- and β-positions which are connected to the oxygen atom adjacent the reaction center (O atom of alkoxy group, R_2^{β}-R_1^{α}-O-C-). In other words, the solvolysis rate can be affected by the steric and resonance effects due to branched functional groups. In this research, we investigated the effect of β-substituent, specifically phenyl group.

First of all, the optimized molecular energies were calculated for several alkyl chloroformates including **1** and **2** in order to confirm charges of atoms and bond distance between carbon and chlorine atoms by using the Gaussian 03, B3LYP/6-31(d) method [supporting information (SI) 1].[19,20] In this information, the remarkable point is that the charges of carbonyl carbon and bond distance are obtained very similar values in most substrates (including **1** and **2**) except tertiary and phenyl compounds. As we (in general) know, tertiary alkyl and phenyl groups have a little strong function of electronic effect, there are the corresponding results of the small increase of charge and distance, but phenyl substituted compound showed the small decrease of charge and distance due to the electron withdrawing effect. These are consistent with the previous reported results well.[21] Specifically, the charge of reaction center and bond distance are very similar values to other primary and secondary alkyl chloroformats including benzyl compound, but when they are compared with tertiary alkyl and phenyl chloroformates, values are different. This phenomenon can be expected that the reactivity and mechanism of **1** and **2** will be similar one with primary and secondary alkyl chloroformates.

The solvolysis rate constants measured in 24 solvent systems at 40.0 °C for substrates, **1** and **2**, and also rate constant ratios, k_2/k_1 and KSIE values of methanolysis together with solvent nucleophilicity and ionizing power respectively, are summarized in Table 1. The rate constant is increased by more water content in binary solvent systems. Also in EtOH-TFE mixtures, the rate constant is increased along the increase of EtOH content. In general, the aspect of solvolysis rate constants is very similar in substrates **1** and **2**, but the solvolysis of **2** is slightly faster than **1**. Also the rate constants ratios (k_2/k_1) are 1.25-1.87 in all solvent systems. This phenomenon is usually observed in case of similar reactivity essentially.

The rate constants of **1** and **2** obtained in this study and **3-9** obtained in previously reported, are summarized in Table 2. Substrates **1-7** are all primary alkyl chloroformats, **8** is a secondary alkyl chloroformate, and **9** is a tertiary alkyl chloroformate. Showing in Table 2, the rate order of primary, secondary, and tertiary alkyl chloroformats at α-position adjacent oxygen atom of alkoxy group, is $k_{primary} > k_{secondary} > k_{tertiary}$ only except in 70%TFE. The increase of alkyl group on α-carbon makes electronic effect and large steric hindrance by strong repulsion of lone pair electrons of alkoxy O atom, these effects result in the decrease of solvolysis rate because of the hard to attack by nucleophilic solvents. These aspects are known as a typical character of bimolecular reactions.

In spite of smaller electron charge (EC = 0.470(−0.394), SM 1) of electron withdrawing ability than the other substrates, the solvolysis of **3** has slightly fast rate constants in various solvents, because the reaction center is connected with the simple methoxy group which has small steric hindrance relatively. This phenomenon is reported previously in the results of alkyl halide's S_N2 reactions. By the way, the reaction rate order is reversed, $k_{primary} < k_{secondary} < k_{tertiary}$, in 70%TFE solvent system of the strong electrophilic character and ionizing power. In this solvent, the tertiary 1-adadmantyl chloroformate is too fast to measure the rate constants. When the rate constant of the above primary substrate is compared with a secondary *i*-propyl chloroformate, the latter is much faster than the former ($k_{i\text{-propyl}}/k_{ethyl} \approx 38$). Because

Table 1. The Rate Constants of **1**[a] and **2**[b] in Pure and Binary Solvents at 40.0 °C

No.	Solvent (%)[c]	**1**	**2**	k_2/k_1	N_T[e]	Y_{Cl}[f]
		10^4k, s^{-1}[d]	10^4k, s^{-1}[d]			
1	100MeOH	4.57 ± 0.02[g]	7.71 ± 0.07[h]	1.69	0.17	−1.17
2	90MeOH	9.35 ± 0.02	13.8 ± 0.09	1.48	−0.01	−0.18
3	80MeOH	12.6 ± 0.21	17.2 ± 0.07	1.37	−0.06	0.67
4	70MeOH	15.4 ± 0.25	23.6 ± 0.21	1.53	−0.4	1.46
5	100EtOH	1.33 ± 0.02	2.33 ± 0.02	1.75	0.37	−2.52
6	90EtOH	3.07 ± 0.02	4.76 ± 0.03	1.55	0.16	−0.94
7	80EtOH	4.17 ± 0.02	6.13 ± 0.03	1.47	0.00	0.00
8	70EtOH	5.35 ± 0.02	7.46 ± 0.06	1.39	−0.20	0.78
9	60EtOH	6.05 ± 0.03	9.21 ± 0.10	1.52	−0.38	1.38
10	90Acetone	0.123 ± 0.01	0.156 ± 0.003	1.27	−0.35	−2.22
11	80Acetone	0.426 ± 0.003	0.565 ± 0.002	1.33	−0.37	−0.83
12	70Acetone	0.827 ± 0.009	1.08 ± 0.009	1.31	−0.42	0.17
13	97TFE[i]	0.0104 ± 0.0034	0.0130 ± 0.0047	1.25	−3.30	2.83
14	90TFE[i]	0.0323 ± 0.0008	0.0456 ± 0.0001	1.41	−2.55	2.85
15	70TFE[i]	0.266 ± 0.003	0.407 ± 0.005	1.53	−1.98	2.96
16	50TFE[i]	0.853 ± 0.004	1.23 ± 0.06	1.44	−1.73	1.89
17	80T-20E[j]	0.0384 ± 0.0001	0.0673 ± 0.0001	1.75	−1.76	1.89
18	60T-40E[j]	0.175 ± 0.003	0.327 ± 0.005	1.87	−0.94	0.63
19	40T-60E[j]	0.495 ± 0.003	0.910 ± 0.006	1.84	−0.34	−0.48
20	20T-80E[j]	0.906 ± 0.003	1.66 ± 0.02	1.83	0.08	−1.42
21	97HFIP[i]	0.0564 ± 0.0232	0.0820 ± 0.0317	1.45	−5.26	5.17
22	90HFIP[i]	0.0330 ± 0.0145	0.0523 ± 0.0248	1.59	−3.84	4.31
23	70HFIP[i]	0.209 ± 0.002	0.315 ± 0.005	1.51	−2.94	3.83
24	50HFIP[i]	0.437 ± 0.008	0.680 ± 0.008	1.56	−2.49	3.80

[a]Substrate concentration of 6.515×10^{-3} mol dm^{-3}. [b]Substrate concentration of 4.817×10^{-3} mol dm^{-3}. [c]Unless otherwise indicated, on a volume/volume basis, at 25.0 °C, with the other component water. [d]The average of all integrated specific rates from duplicate runs, with associated standard deviation. [e]Based on the specific rate of the *S*-methyl dibenzothiophenium ion. [f]*Y* values of 1-admantyl chloride. [g]Value of $k_{MeOD} = (2.33 \pm 0.03) \times 10^{-4}\ s^{-1}$, and kinetic solvent isotope effect (k_{MeOH}/k_{MeOD}) of 1.78 ± 0.01. [h]Value of $k_{MeOD} = (3.66 \pm 0.02) \times 10^{-4}\ s^{-1}$, and kinetic solvent isotope effect (k_{MeOH}/k_{MeOD}) of 2.10 ± 0.01. [i]Solvent prepared on weight/weight basis. [j]T-E represents 2,2,2-trifluoroethanol–ethanol mixtures on a volume/volume basis, at 25.0 °C.

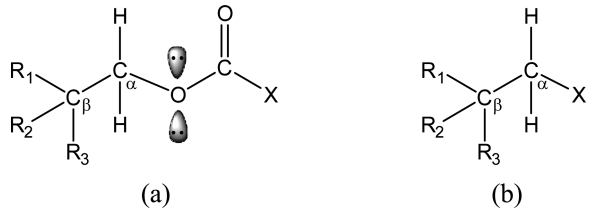
Table 2. A Comparison of the Rate Constants (10^4k, s^{-1})[a,b] of Solvolysis of Several Alkyl Chloroformates (ROCOCl) in Pure and Binary Solvents at 40.0 °C

Solvent[c]	**1**	**2**	**3**[e]	**4**[f]	**5**[g]	**6**[h]	**7**[i]	**8**[j]	**9**[k]	**10**[l]
MeOH	4.57	7.71	5.21	3.13	2.94	3.28	3.32	1.54	–	6.17
EtOH	1.33	2.33	1.32	0.806	0.773	0.848	0.989	0.541	0.255	1.77
80EtOH	4.17	6.13	5.27	2.53	2.49	2.65	2.59	1.86	–	5.56
70TFE[d]	0.266	0.407	0.398	0.311	0.285	0.263	–	11.7	Too fast	–

[a]Values obtained using Arrhenius plots with the specific rates reported at different temperatures. [b]Values in parentheses represent the specific rates of solvolysis of alkyl chloroformates at 40.0 °C. [c]Unless otherwise indicated, on a volume/volume basis, at 25.0 °C, with the other component water. [d]Solvent prepared on weight/weight basis. [e]From Ref. [12]. [f]From Ref. [10]. [g]From Ref. [13]. [h]From Ref. [14]. [i]From Ref. [15]. [j]From Ref. [16]. [k]From Ref. [17]. [l]From Ref. [18].

the solvolysis of secondary *i*-propyl chloroformates involves the fast reaction procedure forming the *i*-propyl cation which is more stable by the electrophilic influence of the strong ionizing TFE solvent than the primary alkyl chloroformates relatively. Therefore, the increase of polarity or/and ion-solvation ability of solvent makes the faster solvolysis reactions for the ionization pathway, for example, secondary and tertiary chloroformates in general.

By the way, the order of solvolytic rate constants is $k_{Et} \approx k_{n\text{-pr}} \approx k_{i\text{-Bu}} \approx k_{Neop} \leq k_{2\text{-Ph}} < k_{2,2\text{-diPh}}$ for the β-substituted alkyl chloroformates (**1**-**7**) which are all primary alkyl conpounds. Even though the ECs of the reaction center for **1** and **2** are same values (SI 1), specifically, the rates of **1** and **2** are slightly faster than the others that they have similar values generally. This aspect implies that the acyl carbon of the reaction center in the substrate is not affected by the β-alkyl or β-phenyl group due to the shielding effect of lone pair electrons on oxygen atom of alkoxy group, so the solvolysis rate of the above alkyl chloroformates is not considered to be affected by β-substituents adjacent oxygen atom (scheme 2(a)). However, Hughes and co-workers[22-24] reported previously that the solvolysis rate ratios of alkyl bromides are



Scheme 2. The steric influents due to the present of a branching β-alkyl group in the alkyl haloformate (a) and the alkyl halide (b).

showed the very large difference between substrates, ethyl k_{Et}/k_{Et} = 1.0, *n*-propyl $k_{n\text{-Pr}}/k_{Et}$ = 0.57, *i*-butyl $k_{i\text{-Bu}}/k_{Et}$ = 0.080 and neopentyl k_{neo}/k_{Et} = 0.0065. That reason is that the substrates do not have any like oxygen atom containing lone pair electrons to screen the β-alkyl group around the reaction center carbon atom in the solvolysis of alkyl bromides (Scheme 2(b)). The different structures of the above substrate's cases are showed in Scheme 2.

In primary alkyl chloroformates, **1** and **2** containing the phenyl substituent on β-carbon instead of one or two alkyl group, showed a little faster reaction rate than the others, because it can be considered the electronic effect of phenyl group on acyl carbon.

In order to analyze the co-relationship of the rates of alkyl chloroformates and solvent parameters of the ionizing power (Y_{Cl}) and the nucleophilicity (N_T), the simple and extended forms of G-W equation were applied to the rates in Table 1, and the results were summarized in Table 3. The analysis of simple G-W equation showed much dispersed plots for both substrates (for 1, R = 0.473 and for 2, R = 0.477, SI 2 and 5). In the analysis using the extended G-W equation considered nucleophilicity and ionizing power of solvent, the results were showed the satisfied co-relationships, but still some points of strong electrophilic solvents were dispersed from a linear relationship. So the remove of these points gave very good linear relationships (Figures 1 and 2). These aspects have been reported in the study of primary alkyl chloroformates[10,12,13] except secondary *i*-PrOCOCl (**8**) and tertiary 1-AdOCOCl, previously.

The sensitivities of solvent nucleophilicity and ionizing power in the extended G-W equation and their ratio (l/m) values have been a very useful tool to prospect the solvolysis reaction mechanism for a long time. The sensitivity ratios of alkyl chloroformates are separated two cases; (i) the sensitivity (l) of solvent nucleophilicity is larger than the one (m) of solvent ionizing power ($l > m$, l/m = 2.74-3.67), *i.e.*, bimolecular pathway dominant, (ii) m is larger than l ($m > l$, l/m = 0-0.84) or depending on only m, *i.e.*, unimolecular pathway dominant. In Table 3, the phenyl chloroformate (**11**)[21] in all range of solvents, and Me- (**3**), Et- (**4**), *n*-Pr- (**5**), *s*-Bu- (**6**), neopentyl- (**7**), and benzyl (**10**) chloroformates in all solvents except some of strong electrophilic aqueous fluoroalcohol solvents are affiliated with the category (i), the orther substrates are in (ii). As a result of this study, the sensitivity ratios of **1** and **2** are 2.88 and 2.86, respectively, which are the solvolysis mechanisms of these two substrates in all except some of strong electrophilic solvents are

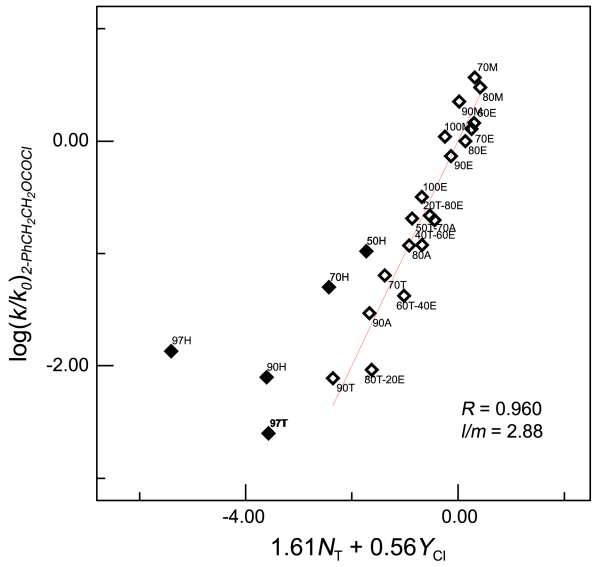


Figure 1. Plot of log (k/k_o) for solvolyses of 2-phenylethyl chloroformate (**1**) at 40.0 °C against ($1.61N_T + 0.56Y_{Cl}$). The data points for 97%TFE, and the HFIP-H_2O mixtures are not included in the correlation; they are added to show their considerable deviation from the correlation line.

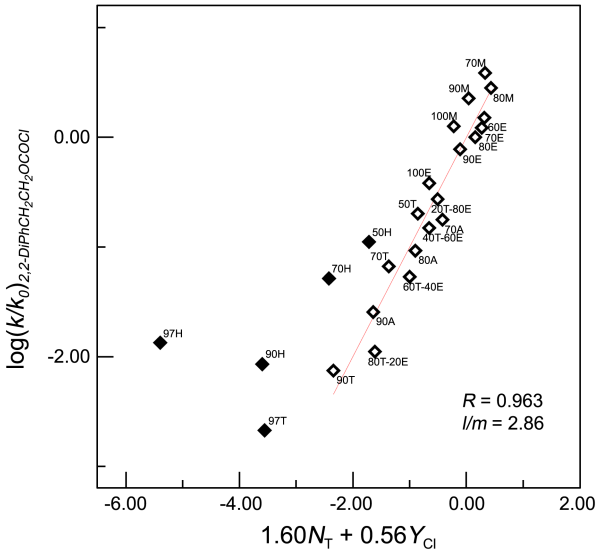


Figure 2. Plot of log (k/k_o) for solvolyses of 2,2-diphenylethyl chloroformate (**2**) at 40.0 °C against ($1.60N_T + 0.56Y_{Cl}$). The data points for 97%TFE, and the HFIP-H_2O mixtures are not included in the correlation; they are added to show their considerable deviation from the correlation line.

dominant to the bimolecular addition-elimination pathway consistently with previously reported other primary alkyl chloroformates. Also sensitivity ratios in the excepted solvents are obtained 0.85 and 0.87, which means ionization pathway is dominant with the priority bond-breaking. Summarizing the results in Table 3, substituents on β-position do not affect to the reactivity, while the mechanism of solvolysis is changed along the α-positioned substituents [*i.e.*, primary EtOCOCl (**4**), secondary *i*-PrOCOCl (**8**), tertiary 1-AdOCOCl (**9**)] like the solvolysis of acyl halides.[25-27] The

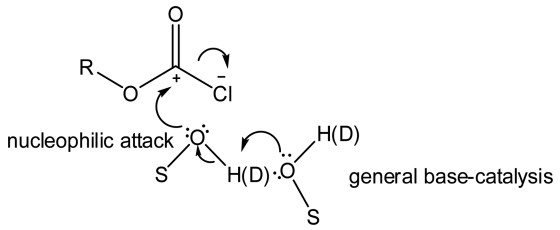
Table 3. Correlations of the Rate Constants of Solvolysis of Several Alkyl Chloroformate Esters, Using the Extended Grunwald–Winstein Equation

Substrate	n^a	l^b	m^b	c^b	l/m	R^c
1	19[d]	1.61 ± 0.12	0.56 ± 0.06	0.14 ± 0.08	2.88	0.960
	5[d]	0.81 ± 0.23	0.93 ± 0.29	−2.60 ± 0.79	0.87	0.931
2	19[d]	1.60 ± 0.12	0.56 ± 0.06	0.15 ± 0.07	2.86	0.963
	5[d]	0.85 ± 0.22	1.00 ± 0.27	−2.72 ± 0.74	0.85	0.945
3	19[e]	1.59 ± 0.09	0.58 ± 0.05	0.16 ± 0.07	2.74	0.977
4	28[f]	1.56 ± 0.09	0.55 ± 0.03	0.19 ± 0.24	2.84	0.967
	7[f]	0.69 ± 0.13	0.82 ± 0.16	−2.40 ± 0.27	0.84	0.946
5	22[g]	1.57 ± 0.12	0.56 ± 0.06	0.15 ± 0.08	2.80	0.947
	6[g]	0.40 ± 0.12	0.64 ± 0.13	−2.45 ± 0.47	0.63	0.942
6	18[h]	1.82 ± 0.15	0.53 ± 0.05	0.18 ± 0.07	3.43	0.957
7	13[i]	1.76 ± 0.14	0.48 ± 0.06	0.14 ± 0.08	3.67	0.977
	8[i]	0.36 ± 0.10	0.81 ± 0.14	−2.79 ± 0.33	0.44	0.938
8	20[j]	0.28 ± 0.05	0.52 ± 0.03	−0.12 ± 0.05	0.54	0.979
9	15[k]	–	0.47 ± 0.03	0.03 ± 0.05	–	0.985
10	15[l]	1.95 ± 0.16	0.57 ± 0.05	0.16 ± 0.15	3.42	0.966
	11[l]	0.25 ± 0.05	0.66 ± 0.06	−2.05 ± 0.11	0.38	0.976
11	21[m]	1.68 ± 0.10	0.57 ± 0.06	0.12 ± 0.41	2.95	0.973

[a]Number of solvent systems included in the correlation. [b]Using equation 15 and 18, with standard errors for *l* and *m* values and with standard errors of the estimate accompanying the *c* values. [c]Correlation coefficient. [d]The solvent systems divided into 97%TFE, 97, 90, 70, 50%HFIP (n = 5) and the remainder (n = 19). [e]From ref. [12]. [f]The solvent systems divided into HCOOH, 100% and 97%TFE, and 97-50%HFIP (n = 7) and the remainder (n = 28), from ref. [10]. [g]The solvent systems divided into 100%TFE, 97%TFE, 97, 90, 70, 50%HFIP (n = 6) and the remainder (n = 22), from ref. [13]. [h]From ref. [14]. [i]The solvent systems divided HFIP-H_2O and TFE-H_2O mixtures (n = 8) and the remainder (n = 13), from ref. [15]. [j]From ref. [16]. [k]From ref. [17]. [l]From ref. [18]. [m]From ref. [21].

other words, the bulkiness on β-position is not a main factor in decision of reaction mechanism. This aspect is consistent with the previously explained screening effect due to lone pair electrons of the oxygen atom adjacent the reaction center, acyl carbon.

Further information of the reaction mechanism, the reaction rate change in the isotope substitution reaction can be considered.[28] The solvolysis rates of **1** and **2** in the pure MeOH and MeOD (methanol-*d*) were determined and these rate ratio (k_{MeOH}/k_{MeOD}) were summarized in footnote section of Table 1 with corresponding values of several alkyl chloroformates. The k_{MeOH}/k_{MeOD} values of alkyl chloroformates are in the 1.70-2.42 ranges generally. These are large relatively; the meaning of this phenomenon is that the reaction rate is largely affected by the nucleophile of solvent in the rate determining step, the rate can be expected to decrease in case of the heavy isotopic substituted solvent. This aspect is known to the bimolecular reaction characters, specially, the large value of rate ratio (k_{MeOH}/k_{MeOD}) in the



Scheme 3. General base-catalysed reactions for nucleophilic attack on carbonyl cation.

kinetic solvent isotope effect (KSIE) of the methanolysis suggests that solvent has a role of the nucleophile to react with substrate firstly, and the general base catalyst to remove a hydrogen from the nucleophile (Scheme 3).[29-31]

The previous researchers[21] reported that the rate ratios of phenyl chloroformate (**11**) typically solvolyzed by bimolecular pathway are k_{MeOH}/k_{MeOD} = 2.3-2.5 in methanolysis[32] and k_{H_2O}/k_{D_2O} = 1.79 in hydrolysis,[33] while the rate ratio of chlorodiphenylmethane (Ph_2CHCl) generally solvolyzed by unimolecular pathway is k_{MeOH}/k_{MeOD} = 1.1 in methanolysis[34] and that of *i*-PrOCOCl (**8**) is k_{H_2O}/k_{D_2O} = 1.25 in hydrolysis,[16] respectively. Therefore, KSIE is considered that the a near unity or small value of the rate ratio is supported to be unimolecular reaction pathway and a larger value than 1.7 of the rate ratio is supported to be bimolecular reaction pathway.[35]

The solvolysis rate constants of **1** and **2** in pure and binary solvents at several temperatures were measured to calculate the enthalpies and entropies of activation, listed in Table 4. Values of enthalpy ($\Delta H^{\neq}$) and entropy ($\Delta S^{\neq}$) of activation for both **1** and **2** are similar to those of ethyl (**3**) and *n*-propyl chloroformate (**5**) studied previously. The values of enthalpies are 12.2-15.5 kcal·mol^{-1} and entropies are −34.1 ~ −22.8 cal·mol^{-1}·K^{-1} in 100%MeOH, 100%EtOH, 80%EtOH and 70%TFE, suggesting the typical bimolecular character. In a strong electrophilic solvents of 97%TFE, 90%, 97%HFIP, the values of enthalpy and entropy for **1** and **2** are 21.5-24.9 kcal·mol^{-1} and −14.3 ~ −3.3 cal·mol^{-1}·K^{-1}, respectively, implying the unimolecualr character.

Product study of solvolysis of **1** and **2** was performed for

Table 4. Enthalpies ($\Delta H^{\neq}$, kcal mol^{-1}) and Entropies ($\Delta S^{\neq}$, cal mol^{-1} K^{-1}) of Activation for Solvolysis of **1** and **2** at 40.0 °C

Solvent (%)[a]	**1**		**2**	
	$\Delta H^{\neq}$ [b]	$-\Delta S^{\neq}$ [b]	$\Delta H^{\neq}$ [b]	$-\Delta S^{\neq}$ [b]
100MeOH	14.2 ± 0.1	28.4 ± 0.2	12.2 ± 0.2	34.1 ± 0.5
100EtOH	15.5 ± 0.5	26.7 ± 1.6	14.0 ± 0.2	30.5 ± 0.7
80EtOH	13.6 ± 0.4	30.7 ± 1.4	15.2 ± 0.4	24.9 ± 1.1
70TFE	17.8 ± 0.1	22.8 ± 0.4	14.7 ± 0.2	31.6 ± 0.7
97TFE	24.9 ± 0.3	6.5 ± 0.8	23.1 ± 0.3	11.9 ± 1.0
90HFIP	24.4 ± 0.8	6.1 ± 2.3	21.5 ± 0.5	14.3 ± 1.7
97HFIP	24.9 ± 0.4	3.3 ± 1.3	24.4 ± 0.4	4.0 ± 1.1

[a]Volume/volume basis at 25.0 °C, except for TFE-H_2O, which are on a weight/weight basis. [b]With associated standard error.

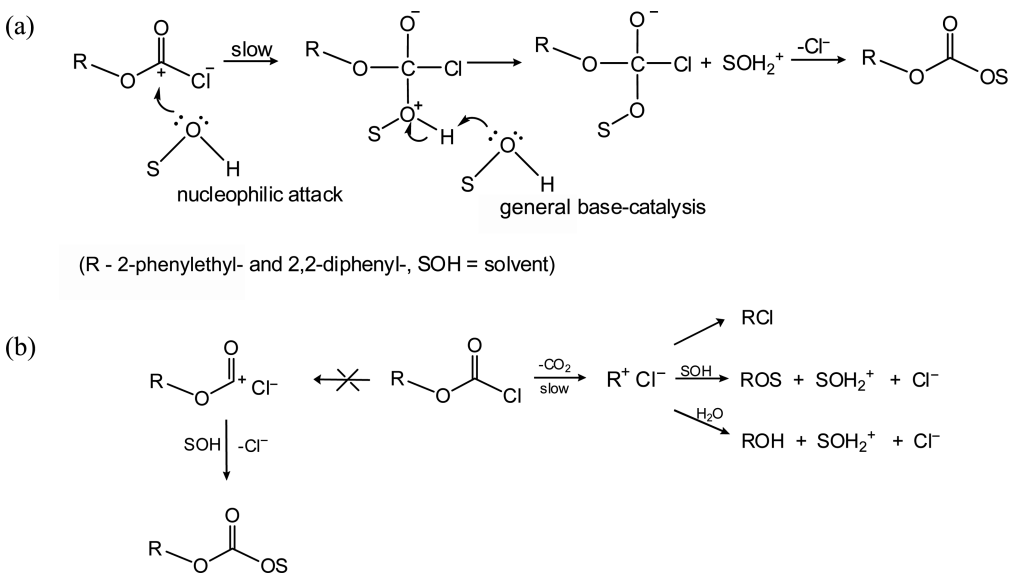
supporting the interpretation of mechanism additionally. In case of bimolecular pathways (addition-elimination pathway, specifically), an alkyl carbonate is produced by alcoholysis and an alcohol is produced by hydrolysis and carbon dioxide decomposition mainly. But, in case of unimolecular pathway (ionization pathway including the elimination of carbon dioxide) has alkyl halide, alkyl ether, and alcohol as possible products.

In this study, we have chosen 100%EtOH and 80%EtOH of nucleophilic solvents, 97%TFE and 50%TFE of electrophilic solvents, and 50% acetone for the product study. At first, the solvolysis of **1** was confirmed to obtain 2-phenylethyl ethylcarbonate mainly in 100%EtOH designed only ethanolysis, and in 80%EtOH including the hydrolysis additionally, 2-phenylethyl ethylcarbonate and 2-phenylethanol were obtained mainly. Also, 2-phenylethyl-2,2,2-trifluoroethyl ether, 2-phenylethyl chloride, and 2-phenyl ethanol were confirmed mainly in 97%TFE and 50%TFE. The special point is the portion of 2-phenylethyl-2,2,2-trifluoroethyl ether was decreased critically in 50%TFE, that is meaning that water of a small size molecule did key role to produce the products. Additionally, in 50% acetone, 2-phenyl ethanol was confirmed as a main product (SI 8).

Secondly, the product study of **2** was simpler than **1**, only 2,2-diphenylethyl ethylcarbonate in 100%EtOH, and 2,2-diphenylethyl ethylcarbonate and 2,2-diphenylethanol in 80%EtOH were confirmed mainly. 2,2-Diphenylethyl 2,2,2-trifluoroethyl ether, 2,2-diphenyl ethyl chloride, and 2,2-diphenylethanol were confirmed in 97%TFE, and 2,2-diphenylethyl 2,2,2-trifluoroethyl ether and 2,2-diphenylethanol were confirmed in 50%TFE. In addition, the hydrolysis in 50% acetone produced only 2,2-diphenylethanol in reaction. (SI 8)

In comparison of products of **1** and **2**, the most results were very similar each other, however, one difference found is that substrate **1** has the alkyl chloride while substrate **2** does not have. The possible route to generate 2-phenylethyl chloride is that substrate **1** can be solvolyzed by another substrate molecule at α-carbon. In detail, the chlorine atom of other substrate would be nucleophile and this chlorine atom can attack the α-carbon, because **1** is primary structure, so the α-carbon could be another reaction center to occur a simple chlorination reaction with small portion in all solvents. In case of 97%TFE, large portion of 2-phenylethanol were confirmed, this can be interpreted that the substrate **1** is decomposed in large portion in strong electrophilic solvent. Also in the case of 50%TFE, it could generate more 2-phenylethanol, but this product was converted to 2-phenylethyl chloride by a large content of water.

As shown in the above results, both **1** and **2** are solvolyzed by dual pathway consistently with other primary alkyl chloroformates. In the product study, the corresponding results were observed for both substrates. In strong nucleophilic solvents, 100%EtOH and 80%EtOH, a dialkyl carbonate was



Scheme 4. The possible mechanisms of current studied **1** and **2**. (a) The addition-elimination pathway of solvolysis of **1** and **2** in all the mixed solvents except for the more ionizing solvents. (b) The ionization pathway of solvolysis of **1** and **2** in the more ionizing solvents (mostly fluoroalcohols).

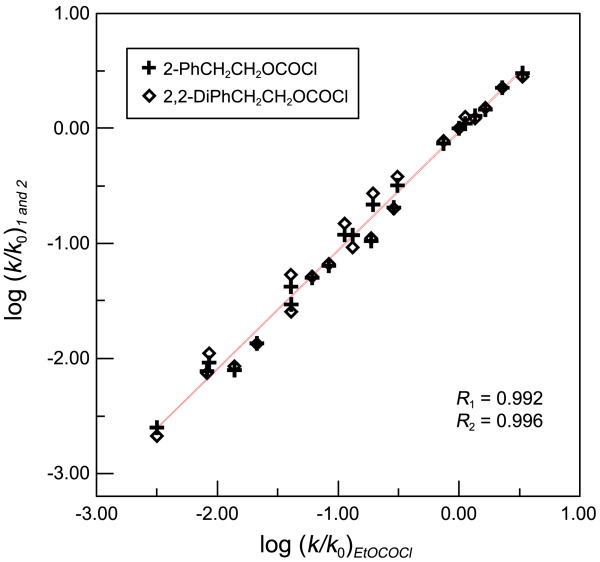


Figure 3. Plots of log (k/k_0) of EtOCOCl (**4**) *versus* log (k/k_0) of **1** and **2**.

observed mainly as a bimolecular reaction product (Scheme 3(a)), when the nucleophile is water (hydrolysis), an alcohol was observed after the elimination of carbon dioxide (CO_2) from an alkyl hydrogen carbonate and very little amount of an alkyl chloride was observed. In strong electrophilic solvents, 97%TFE and 50%TFE, however, a dialkyl carbonate was not observed, the products were dialkyl ether, alkyl chloride, and alcohol which are generated by the elimination of carbon dioxide (Scheme 3(b)).

For more justification of proposed mechanisms, the linear free energy relationship (LFER) was considered by plotting log (k/k_0) of EtOCOCl (**4**) *versus* log (k/k_0) of **1** and **2** (Figure 3). As results, these plots exhibit very good linear relationship which is known to solvolyze by the typical bimolecular addition-elimination mechanism in all except some of strong electrophilic fluoroalcohol solvents. These also support the preceding idea that both substrates **1** and **2** have similar reaction mechanisms of **4**.

Conclusions

The solvolyses of **1** and **2** showed a good relationship in the analysis of the extended G-W equation, and both substrates containing the phenyl groups on β-position proceed through dual pathways that the bimolecular addition-elimination mechanism is dominant (l/m values are 2.86 for **1** and 2.88 for **2**) in strong nuleophilic solvents and the unimolecular ionization mechanism is dominant (l/m values are 0.85 for **1** and 0.88 for **2**) in strong electrophilic solvents, similarly to the former studied primary alkyl chloroformtes (Table 3).

Also, KSIE's values of k_{MeOH}/k_{MeOD} = 1.78 (**1**) and 2.10 (**2**) are obtained similarly to primary alkyl chloroformates, indicating that the methanol molecule acts as a nucleophilic attacker and a general base-catalyst. Entropy values of activation for both substrates were large negative −34.1 ~ −22.8 cal·mol^{-1}·K^{-1}, these values are one of the typical bimolecular characters in all except strong electrophilic fluoroalcohol solvents, in contrast, small negative −14.4 (**1**) and −6.2 (**2**) cal·mol^{-1}·K^{-1} of entropy values of activation in excepted some of strong electrophilic aqueous fluoroalcohols are corresponded to unimolecular character. In also the product analysis, the corresponding compounds were confirmed *e.g.*, the dialkyl carbonate from the bimolecular pathway in the strong nucleophilic solvents and the dialkyl ether, alkyl chloride, and alcohol from the unimolecular pathway in the strong electrophilic solvents. Summarizing of the above results, the solvolysis studies of **1** and **2** revealed that β-substitued phenyl group does not affect the reactivity of substrates **1** and **2**, and their reactions proceed through a similar mechanism of other primary alkyl chloroformates.

Experiments

Substrates, **1** and **2**, were synthesized by the same method of 2-adamantyl chloroformate.[36] The triphosgene treated in toluene at 0-4 °C (ice bath) for 20 min. The mixture of 2-phenylethanol or 2,2-diphenylethanol with pyridine was prepared in toluene at room temperature. Then the latter mixture was added to the former solution slowly. After the stirring for 1 h, the organic mixture was washed with water and dried by magnesium sulfate. The solvent was removed by the evaporation, the colorless oil (**1**) or white solid (**2**) was obtained as a crude product. The substrate **1** was purified from vacuum distillation (120 °C and 18 torr) and the substrate **2** was recrystallized by using ligroin. Solvents were purified as described previously.[37,38]

The kinetic experiments of **1** and **2** were carried out as described previously.[39] The products from the reactions of **1** and **2** under solvolytic conditions were analyzed after 10 half-lives by GC-9A (Shimadzu) using a 2.1 m glass column containing 10% Carbowax 20M on Chromosorb WAW 80/100. The specific rates were obtained by averaging all of the values from, at least, duplicate runs.

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