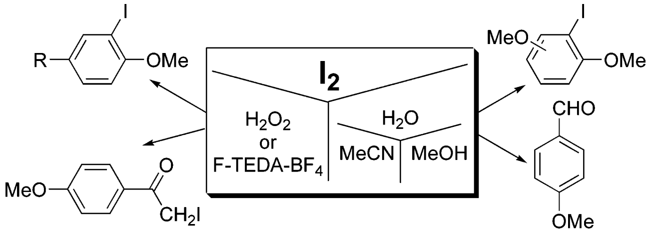
Effect of Water on the Functionalization of Substituted Anisoles with Iodine in the Presence of F−TEDA−BF_4 or Hydrogen Peroxide

Jasminka Pavlinac,† Marko Zupan,‡ and Stojan Stavber*,†

Laboratory for Organic and Bioorganic Chemistry, "Jozef Stefan" Institute, Jamova 39, 1000 Ljubljana, Slovenia, and Department of Chemistry at the Faculty for Chemistry and Chemical Technology, University of Ljubljana, Aškerčeva 5, 1000 Ljubljana, Slovenia

stojan.stavber@ijs.si

Received September 27, 2005



Water was found to be a convenient reaction medium for functionalization of substituted anisoles using iodine in the presence of Selectfluor F−TEDA−BF_4 or hydrogen peroxide as mediators and oxidizers. Two types of functionalization were observed: iodination or oxidation. In the iodination process, two reaction routes were established. In the case of the first route, a high iodine atom economy was achieved for selective and effective iodo functionalization with a stoichiometric ratio of substrate/iodine/(mediator/oxidizer) = 2:1:1.2. An electrophilic iodination reaction process was suggested for this route, with the oxidizer converting the liberated iodide anion to iodine. For the second reaction route, a stoichiometric ratio of substrate/iodine/(mediator/oxidizer) = 1:1:1 and a lower iodine atom economy were observed; in this case, ion radical formation in the first step of the reaction was suggested. Iodine was found to be an effective catalyst for the oxidation of a hydroxy benzyl functional group to benzaldehyde using F−TEDA−BF_4. Water is an effective medium for functionalization of anisole, *p*-methoxy benzyl alcohol, 1-(4-methoxyphenyl)ethanone, *o*-dimethoxy benzene, *m*-dimethoxy benzene, and *p*-dimethoxy benzene, whereas F−TEDA−BF_4 as a mediator/oxidizer could be replaced by hydrogen peroxide in the case of the functionalization of 1-(4-methoxyphenyl)ethanone, *o*-dimethoxy benzene, *m*-dimethoxy benzene, and *p*-dimethoxy benzene. Water changes the type of transformation of *p*-methoxy benzyl alcohol.

Introduction

Water, one of the most abundant molecules in the universe, with its unique properties, plays an important role in the formation of the so-called "chemistry of life". Its importance in chemistry has decreased in the last century because of the introduction of organic solvents as more convenient reaction media for the preparation of new organic molecules. However, the demands of recent decades for sustainable and ecologically more friendly procedures have again put water at the frontier of organic chemistry.[1] Nowadays, it is no longer surprising to conduct organometallic chemistry[2] or free-radical functionalization[3] of organic molecules in an aqueous medium. The solubility of substrates and reagents in water is of crucial importance if one tries to run reactions in the presence of water. Phase-transfer catalysis has been developed for systems where

---

† "Jozef Stefan" Institute.
‡ University of Ljubljana.

(1) (a) Li, C.-J.; Chan, T.-H. *Organic Reactions in Aqueous Media*; J. Wiley & Sons: New York, 1997. (b) Adams, D. J.; Dyson, P. J.; Tavener, S. J. *Chemistry In Alternative Reaction Media*; Wiley: New York, 2004. (c) Lubineau, A.; Augé, J.; Queneau, Y. *Synthesis* **1994**, 741−760. (d) Lindström, U. M. *Chem. Rev.* **2002**, *102*, 2751−2772. (e) Manabe, K.; Kobayashi, S. *Chem.−Eur. J.* **2002**, *8*, 18, 4095−4101. (f) Otto, S.; Engeberts, B. F. N. *Org. Biol. Chem.* **2003**, *1*, 2809−2820.

(2) (a) Li, C.-J. *Tetrahedron* **1996**, *52*, 16, 5643−5668. (b) Li, C.-J.; Chan, T.-H. *Tetrahedron* **1999**, *55*, 11149−11176. (c) Li, C.-J. *Green Chem.* **2002**, *4* (1), 1−4. (d) Kobayashi, S.; Manabe, K. *Acc. Chem. Res.* **2002**, *35*, 209−217. (e) Okuhara, T. *Chem. Rev.* **2002**, *102*, 3641−3666. (f) Miyabe, H.; Naito, T. *Org. Biomol. Chem.* **2004**, *2*, 1267−1270. (g) Li, C.-J. *Chem. Rev.* **2005**, *105*, 3095−3165.

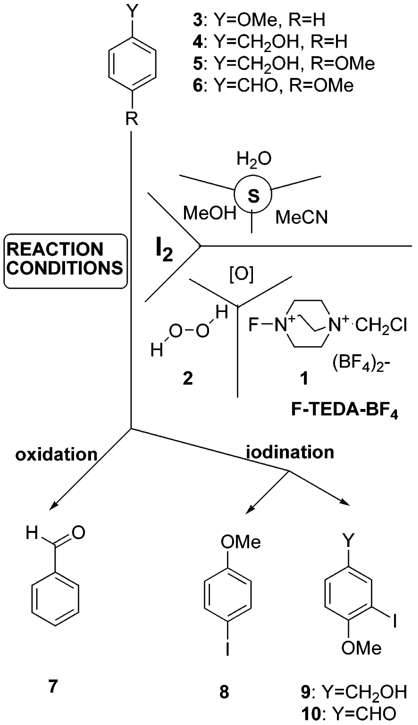
(3) Yorimitsu, H.; Shinokubo, H.; Oshima, K. *Synlett* **2002**, *5*, 674−686.

10.1021/jo052021n CCC: $33.50

one substrate is soluble in water and the other is completely insoluble. Breslow and co-workers used water in combination with antihydrophobic additives as a mechanistic tool for obtaining information about the nature and structure of transition states in transformations of molecules that are almost completely soluble in water.[4] Mayr and co-workers have recently found an important influence of water on the reactivity of organic molecules, enabling alkylation of aromatic molecules with benzyl halides in a water−acetonitrile mixture without the use of a Friedel−Crafts catalyst.[5] Very recently, Sharpless and co-workers[6] reported the important observation that some organic molecules can react on the surface of water, and in some cases, a very strong enhancement in reaction rates was noticed in comparison to reactions without the solvent. This is particularly the case when at least one molecule bears a polar group enabling some degree of solubility (carboxylic ether, amine, etc.). The authors also suggested that water could be a useful reaction medium for reactions where no acceleration of rate was observed, especially in cases of exothermic reactions because of the high heat capacity of water. This concept of organic reactions on water has been recently confirmed by Bose et al. as well.[7]

Water as a reaction medium has not been extensively used in connection with the introduction of halogens into organic molecules. However, we recently reported that fluorination[8] with F−TEDA−BF_4 and iodination[9] with the I_2/H_2O_2 tandem of various types of organic compounds could be effectively performed in water. To obtain some additional information about the role of water in these functionalizations, we decided to study reactions of substituted anisoles with iodine in the presence of F−TEDA−BF_4[10,11] or hydrogen peroxide (H_2O_2) as an environmentally more convenient oxidant.[12] The basic model compound was chosen because of the known fact that the activated aromatic ring in such molecules can readily form ion radicals with various oxidizing reagents.[13] The hydroxymethyl (*p*-methoxy benzyl alcohol (**5**)) and aldehyde (*p*-methoxy benzaldehyde (**6**)) functionalities were additionally introduced into the aromatic ring because of their sensitivity toward oxidants, and the acetyl group (1-(4-methoxyphenyl)ethanone (**11**)) or the propan-2-onyl functional moiety (1-(4-methoxyphenyl)propan-2-one (**12**)) was introduced to obtain some information about the regioselectivity of such functionalizations.

SCHEME 1



Results and Discussion

In studying the effect of water on the functionalization of organic molecules in or on water, one must carefully analyze where the reactions take place. For this reason, we chose a rather complex reaction system, where the oxidant (F−TEDA−BF_4, **1**, or H_2O_2, **2**) is completely soluble in water, the organic substrates are partially soluble, and solubility is dependent on the temperature; iodine is partly soluble both in water and in organic substrates (Scheme 1). Finally, we also used the anionic surface active compound sodium lauryl ether sulfate (Genapol LRO), which can enhance the solubility of the substrate or partly mycellize the substrate in the water. Benzyl alcohols are soluble in water, whereas other substrates form emulsions with various degrees of solubility.

As we studied the functionalization of anisole (**3**), we found that neither F−TEDA−BF_4 nor iodine by itself reacts with it in acetonitrile or methanol at room temperature. The triad anisole/iodine/F−TEDA−BF_4 readily exchanged electrons at room temperature, and after 3 h in acetonitrile, almost complete conversion to 4-iodo anisole (**8**) occurred (entry 1, Table 1). The molar ratio of substrate to iodine to mediator/oxidant plays an important role, and almost quantitative conversion was achieved at the ratio 2:1:1.2, respectively, which means that F−TEDA−BF_4, besides activating the reaction system, also oxidized the iodide anion to iodine. The introduction of a more hydrophilic solvent (MeOH or H_2O) demanded the prolongation of the reaction time to 17 h for comparable efficiency of the transformation (entries 3 and 4), with methanol being the worse choice (entry 2).

A typical experiment in water was carried out in the following way: to a mixture of 1 mmol of substrate in 10 mL of water

---

[4] (a) Breslow, R. *Acc. Chem. Res.* **1991**, *24*, 159−164. (b) Breslow, R. *Acc. Chem. Res.* **2004**, *37*, 471−478. (c) Breslow, R.; Groves, K.; Mayer, M. U. *J. Am. Chem. Soc.* **2002**, *124*, 3622−3635.

[5] (a) Hofmann, M.; Hampel, N.; Kanzian, T.; Mayr, H. *Angew. Chem., Int. Ed.* **2004**, *43*, 5402−5405. (b) Minegishi, S.; Kobayashi, S.; Mayr, H. *J. Am. Chem. Soc.* **2004**, *126*, 5174−5181. For further reading on the role of the acceptor and donor on the reactivity of organic molecules, see: (c) Mayr, H. *Angew. Chem.* **1990**, *102*, 1415−1428. (d) Mayr, H.; Patz, M. *Angew. Chem.* **1994**, *106*, 990−1010. (e) Mayr, H.; Kempf, B.; Ofial, A. R. *Acc. Chem. Res.* **2003**, *36*, 66−77.

[6] Narayan, S.; Muldoon, J.; Finn, M. G.; Fokin, V. V.; Kolb, H. C.; Sharpless, K. B. *Angew. Chem., Int. Ed.* **2005**, *44*, 3275−3279.

[7] (a) Bose, A. K.; Manhas, M. S.; Ganguly, S. N.; Pednekar, S.; Mandadi, A. *Tetrahedron Lett.* **2005**, *46*, 3011−3013. (b) Bose, A. K.; Manhas, M. S.; Pednekar, S.; Ganguly, S. N.; Dang, H.; He, W.; Mundadi, A. *Tetrahedron Lett.* **2005**, *46*, 1901−1903.

[8] Stavber, G.; Zupan, M.; Jereb, M.; Stavber, S. *Org. Lett.* **2004**, *6*, 26, 4973−4976 and references therein.

[9] Jereb, M.; Zupan, M.; Stavber, S. *Chem. Commun.* **2004**, 2614−2615.

[10] (a) Singh, R. P.; Shreeve, J. M. *Acc. Chem. Res.* **2004**, *37*, 31−44. (b) Nyffeler, P. T.; Gonzalez Durón, S.; Burkart, M. D.; Vincent, S. P.; Wong, C.-H. *Angew. Chem., Int. Ed.* **2005**, *44*, 192−212.

[11] Stavber, S.; Zupan, M. *Acta Chim. Slov.* **2005**, *52*, 13−26.

[12] Noyori, R.; Aoki, M.; Sato, K. *Chem. Commun.* **2003**, 1977−1986.

[13] (a) Kochi, J. K. *Angew. Chem.* **1988**, *100*, 1331−1372. (b) Bockman, T. M.; Kochi, J. K. *J. Phys. Org. Chem.* **1994**, *7*, 325−351. (c) Hubig, S. M.; Jung, W.; Kochi, J. K. *J. Org. Chem.* **1994**, *59*, 6233−6244. (d) Eberson, L.; Hartshorn, M. P.; Radner, F.; Persson, O. *J. Chem. Soc., Perkin Trans. 2* **1998**, 59−70.

TABLE 1. Effect of Reaction Conditions on the Functionalization of Anisoles and Benzyl Alcohols

		reaction conditions[a]					
entry	substrate	[O]	solvent	*T*/*t*	ratio of reactants	product	yield[b] (%)
1	**3**	**1**	MeCN	20/3	A	**8**	95 (74)
2	**3**	**1**	MeOH	20/17	A	**8**	94 (44)
3	**3**	**1**	H_2O/SAC[c]	20/17	A	**8**	92 (71)
4	**3**	**1**	H_2O	20/17	A	**8**	100 (83)
5	**3**	**2**	MeCN	50/16	A	**8**	80 (45)
6	**4**	**1**	MeCN	80/2	C	**7**	100 (69)
7	**5**	**1**	MeCN	20/18	A	**6**	100 (97)
8	**5**	**1**	H_2O/SAC	20/18	B	**9**	100 (82)
9	**5**	**1**	H_2O	20/18	B	**9**	94 (76)
10	**5**	**1**	H_2O	80/3	C	**6**	62 (44)
11	**6**	**1**	MeCN	20/17	A	**10**	75(68)
12	**6**	**1**	MeOH	50/21	A	**10**	95 (87)

[a] [O] oxidizer (**1**) F−TEDA−BF_4, (**2**) H_2O_2; *T*, temperature in °C; *t*, reaction time in hours. Ratio of substrate/I_2/oxidizer: A = 2:1:1.2; B = 1:1:1; C = 1:0.05:1. [b] The first value is the conversion of starting material, and the values in parentheses represent the yield of product in the isolated crude reaction mixtures and that calcd on the basis of starting material. [c] SAC (surface active compound) Genapol LRO present in 0.02% concentration.

was added 0.5 mmol of iodine, and after a few minutes of stirring, 0.6 mmol of F−TEDA−BF_4 was admixed and dissolved in the water layer. The reaction suspension was vigorously stirred at room temperature. In the experiments where SAC was present, a 0.02% aqueous solution was used as the reaction medium and, as evident (entries 3 and 8), its presence had little effect; indeed, conversion of the starting material and the yield of product was slightly lower in some cases (entry 3). In these reactions, F−TEDA−BF_4 could not be effectively replaced by hydrogen peroxide because very low yields of products were established at room temperature or at 50 °C in all solvents used, except in the case of anisole (entry 5).

Banks et al.[14] already demonstrated that an acetonitrile solution of benzyl alcohol is rather stable in the presence of F−TEDA−BF_4; nevertheless, 43% of benzaldehyde was obtained after 18 h of heating at reflux. We established that benzyl alcohol (**4**) becomes much more reactive when a catalytic amount (0.05 mmol) of iodine is introduced into the reaction mixture in acetonitrile (entry 6). Under these conditions, benzyl alcohol could be quantitatively converted to benzaldehyde (**7**) after 2 h at reflux temperature (entry 6). Unfortunately, water as the reaction medium failed in this case and only a trace amount of benzaldehyde was observed when either F−TEDA−BF_4 or hydrogen peroxide was used as the oxidizer (80 °C, 22 h). Banks also demonstrated that F−TEDA−BF_4 is able to convert benzaldehyde to benzoic acid[14] after 31 h at reflux in acetonitrile, where conversion of benzaldehyde to benzoic acid required 1.2 mmol of reagent. We found that quantitative conversion of benzyl alcohol to benzoic acid could be achieved in the presence of a catalytic amount of iodine with 1 mmol of F−TEDA−BF_4 and in the presence of air (reflux, 19 h). A similar modulation of alcohol oxidation assisted with a halogen anion in water with iodosyl benzene has already been reported.[15]

To clarify the role of iodine as the catalyst in the oxidation of benzyl alcohol to benzoic acid, the following additional experiments have been performed: After 2 h of heating under reflux of 10 mL of MeCN solution of benzyl alcohol (1 mmol) and F−TEDA−BF_4 (1 mmol) in the presence of a catalytic amount of iodine, the reaction solution was divided into two equal parts. One part was degassed with the flow of argon, and the reaction vessel was hermetically sealed and stirred at 80 °C for 19 h. Benzaldehyde was the only product isolated after this protocol. The second part continued to be stirred under reflux in the presence of air, and after 19 h, quantitative formation of benzoic acid was established. By independent experiments, we further established that benzaldehyde in MeCN solution remained stable even after 19 h of reflux with or without the presence of a catalytic amount of iodine. Even more, in a sealed vessel, benzaldehyde also remained unchanged after 19 h of heating at 80 °C of its degassed MeCN solution in the presence of an equimolar amount of F−TEDA−BF_4 and a catalytic amount of iodine. The catalytic role of iodine in the F−TEDA−BF_4-mediated formation of benzaldehyde from benzyl alcohol is thus obvious, and further oxidation to benzoic acid takes place only under reaction conditions characteristic for the first step of the reaction, with the essential presence of air oxygen.

Introduction of a methoxy group into the aromatic ring (**5**) resulted in a more selective course of reaction. After 18 h in acetonitrile (ratio of substrate/iodine/oxidizer 2:1:1.2), only oxidation took place and a quantitative amount of *p*-methoxy benzaldehyde (**6**) was isolated (entry 7). Also, in this case, water proved to be a very convenient reaction media, but the type of functionalization changed. After 18 h at room-temperature iodination, resulting in the formation of 3-iodo-4-methoxy benzyl alcohol (**9**) was the predominant reaction route (entry 9), and the addition of SAC even enhanced the conversion of **5** and the formation of **9** (entry 8). However, it is interesting that effective ring functionalization was achieved at a different ratio of reactants; namely, the amount of iodine had to be doubled (1:1:1). Hydrogen peroxide could not replace F−TEDA−F_4 as an oxidant in the transformation of *p*-methoxy benzyl alcohol. In acetonitrile, no reaction was observed even at 50 °C after 19 h, and in water, a complex reaction mixture was obtained. In contrast to the behavior of benzyl alcohol, water proved to be a suitable medium for the transformation of *para*-methoxy benzyl alcohol (**5**) to *para*-methoxy benzaldehyde (**6**) with **1** in the presence of a catalytic amount of iodine (entry 10). Functionalization of *p*-methoxy benzaldehyde (**6**) in acetonitrile with F−TEDA−BF_4 at room temperature for 17 h gave 75% conversion to 3-iodo-4-methoxy benzaldehyde (**10**, entry 11). In methanol, at higher temperature, 95% conversion to **10** was achieved (entry 12). The reaction in water failed, and less than 10% of iodinated product was obtained. Also, in this case, hydrogen peroxide proved to be an inappropriate oxidizer in the functionalization of **6**.

We already demonstrated that the regioselectivity of functionalization of various aryl methyl ketones can be directed by the solvent. In acetonitrile, ring fluorination or iodination took place, and side-chain functionalization was observed in methanol.[16] Functionalization of 1-(4-methoxyphenyl)ethanone (**11**, Scheme 2) with the iodine/F−TEDA−BF_4 tandem in acetonitrile gave almost quantitatively 1-(3-iodo-4-methoxyphenyl)ethanone (**13**, entry 1, Table 2), and in methanol, side-chain iodination took place and formed 2-iodo-1-(4-methoxyphenyl)ethanone (**15**) in high yield.[16b] In both cases, the molar ratio of reactants

---

[14] Banks, R. E.; Lawrence, N. J.; Popplewell, A. L. *Synlett* **1994**, 831−832.

[15] Tohma, H.; Takizawa, S.; Maegawa, T.; Kita, Y. *Angew. Chem., Int. Ed.* **2000**, *39* (7), 1306−1308.

[16] (a) Stavber, S.; Jereb, M.; Zupan, M. *Chem. Commun.* **2000**, 1323−1324. (b) Stavber, S.; Jereb, M.; Zupan, M. *Chem. Commun.* **2002**, 488−489.

SCHEME 2

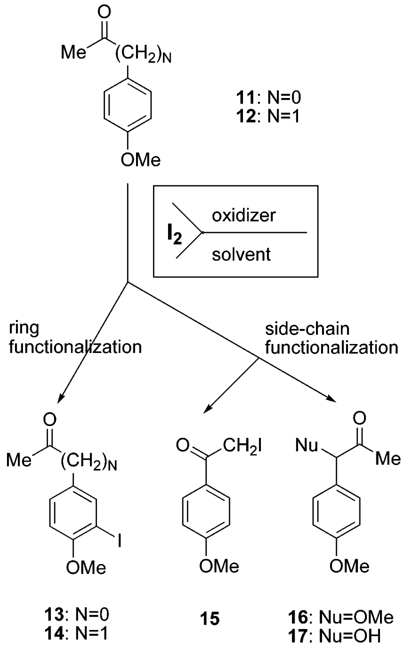


TABLE 2. Effect of Reaction Conditions on the Functionalization of 1-(4-Methoxyphenyl)ethanone (11) and 1-(4-Methoxyphenyl)propan-2-one (12)

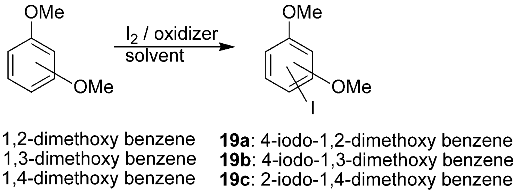
		reaction conditions[a]				
entry	substrate	[O]	solvent	T/t	product	yield[b]
1	**11**	**1**	MeCN	20/17	**13**	100 (75)
2	**11**	**2**	MeCN	50/5	**15**	89 (57)
3	**11**	**2**	H_2O	30/22	**15**	82 (71)
4	**12**	**1**	MeCN	50/4.5	**14**	85 (65)
5	**12**	**1**	MeOH	50/4.5	**16**	82 (63)
6	**12**	**2**	H_2O	50/19	**17**	90 (72)

[a] [O] oxidizer (**1**) F−TEDA−BF$_4$, (**2**) H_2O_2; T, temperature in °C; t, reaction time in hours. Ratio of substrate/I$_2$/**1** is 2:1:1 and ratio of substrate/I$_2$/**2** is 2:1:1.2. [b] The first value is the conversion of starting material, and the values in parentheses represent the yield of product in the isolated crude reaction mixtures and that calcd on the basis of starting material.

of substrate/I$_2$/**1** of 2:1:1 was sufficient for the transformation of the starting material. In water, the reaction failed and low conversion of substrate, as well as low selectivity, was observed. On the other hand, when hydrogen peroxide was used as the oxidizer, the side-chain iodination took place regioselectively thus forming **15** in acetonitrile (entry 2) and in methanol,[17] as well as in water (entry 3).

1-(4-Methoxyphenyl)propan-2-one as a model molecule (**12**, Scheme 2) offers the further possibility of studying the effect of the structure of the reagent and of the reaction conditions on the regioselectivity of functionalization. In acetonitrile, ring iodination took place with the I$_2$/**1** tandem (entry 4, Table 2), and in methanol, exclusive side-chain methoxy functionalization at the benzylic position took place, forming 1-methoxy-1-(4-methoxyphenyl)propan-2-one (**16**) (entry 5). When water was used as the reaction medium, the course of transformation became more complex because after 19 h at 50 °C up to three products, namely, 1-(3-iodo-4-methoxyphenyl)propan-2-one (**14**), 1-hydroxy-1-(4-methoxyphenyl)propan-2-one (**17**), and 1-hydroxy-1-(3-iodo-4-methoxyphenyl)propan-2-one, were present in the crude reaction mixture. The replacement of F−TEDA−BF$_4$ with H_2O_2 could be effectively performed only in an aqueous reaction medium, where 90% conversion to 1-hydroxy-1-(4-methoxyphenyl)propan-2-one (**17**) was achieved (entry 6), whereas in acetonitrile and methanol, a much lower conversion of starting material and low yield formation of 1-iodo-1-(4-methoxyphenyl)propan-2-one were observed.

TABLE 3. F−TEDA−BF$_4$- or H_2O_2-Mediated Iodo Functionalization of Dimethoxy Benzenes in Acetonitrile, Methanol, or Water



		reaction conditions[a]					yield[b]
entry	substrate	[O]	solvent	T/t	ratio	product	(%)
1	**18a**	**1**	CH_3CN	20/4	B1	**19a**	100 (46)
2			CH_3OH	20/18	B		100 (96)
3			H_2O/SAC[c]	20/22	B		0
4			H_2O	20/18	B		32 (5)
5		**2**	CH_3CN	50/18	A		70 (53)
6			CH_3OH	50/20	B		67 (56)
7			H_2O/SAC	50/23	B		90 (66)
8			H_2O	50/18	B		88 (68)
9	**18b**	**1**	CH_3CN	20/2	A	**19b**	100 (89)
10			CH_3OH	20/3	A		100 (71)
11			H_2O/SAC	20/3	A		100 (80)
12			H_2O	20/3	A		86 (72)
13		**2**	CH_3CN	50/2	A		100 (95)
14			CH_3OH	50/7	A		89 (75)
15			H_2O/SAC	50/2	A		100 (84)
16			H_2O	50/2	A		85 (75)
17	**18c**	**1**	CH_3CN	35/3	B	**19c**	0
18			CH_3OH	20/18	B		60 (38)
19			H_2O/SAC	50/27	B		100 (21)
20			H_2O	50/27	B		93 (17)
21		**2**	CH_3CN	50/20	B		83 (49)
22			CH_3OH	50/27	B		100 (74)
23			H_2O/SAC	50/27	B		86 (67)
24			H_2O	50/27	B		94 (67)

[a] [O] oxidizer (**1**) F−TEDA−BF$_4$, (**2**) H_2O_2; T, temperature in °C; t, reaction time in hours. Ratio of substrate/I$_2$/oxidizer: A = 2:1:1.2; B = 1:1:1; B1 = 1:0.9:0.9. [b] The first value is the conversion of starting material, and the values in parentheses represent the yield of product in the isolated crude reaction mixtures and that calcd on the basis of starting material.. [c] SAC (surface active compound) Genapol LRO present in 0.02% concentration.

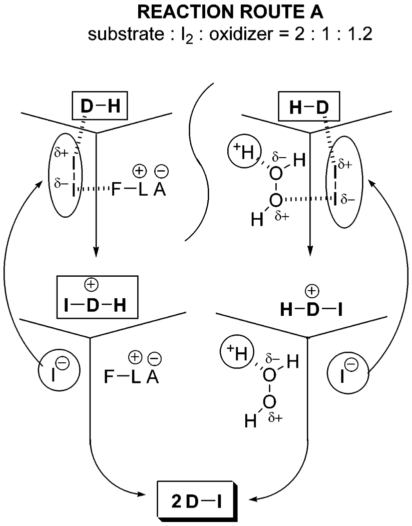
Introduction of a second methoxy group into the aromatic ring significantly enhances the electron-donor properties of the molecule, and its position importantly modulates reactivity. Differences in reactivities could be illustrated with the values for the halfway potentials ($E_{1/2}$(1,2-dimethoxy benzene **18a**) = 1.44 V, $E_{1/2}$(1,3-dimethoxy benzene **18b**) = 1.58 V, and $E_{1/2}$ (1,4-dimethoxy benzene **18c**) = 1.30 V),[18] and the stability of the cation radicals importantly directs further transformation.[13] The effects of the solvent and oxidizer on functionalization of the isomeric dimethoxy benzenes (**18a−c**) are presented in Table 3. It is evident that in these cases both F−TEDA−BF$_4$ and

---

(17) Jereb, M.; Iskra, J.; Zupan, M.; Stavber, S. *Lett. Org. Chem.* **2005**, *2*, 465−468.

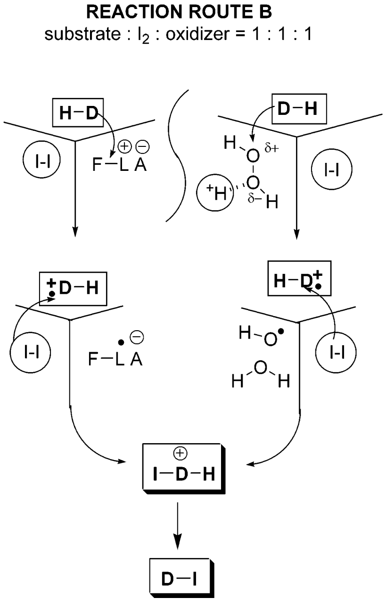
(18) (a) Bietti, M.; Capone, A. *J. Org. Chem.* **2004**, *69*, 482−486. (b) Jonsson, M.; Lind, J.; Reitberger, T.; Eriksen, T. E. *J. Phys. Chem.* **1993**, *97*, 11278−11282.

SCHEME 3



REACTION ROUTE A
substrate : I_2 : oxidizer = 2 : 1 : 1.2

SCHEME 4



REACTION ROUTE B
substrate : I_2 : oxidizer = 1 : 1 : 1

hydrogen peroxide are appropriate activators and/or oxidizers for these iodo functionalizations, but the solvent significantly influenced their effectiveness. It is also evident that the amount of iodine required to achieve effective iodination significantly differs, indicating that at least two different reaction routes leading to iodo products are involved. A reactant's ratio of substrate/iodine/oxidant = 2:1:1.2 was observed in all functionalizations of 1,3-dimethoxy benzene (**18b**, entries 9−16) and in the case of the 1,2-dimethoxy isomer (**18a**) when H_2O_2 was used in acetonitrile (entry 5). Almost double the amount of iodine as that used in the previous cases was required for effective iodination of the 1,2-dimethoxy isomer (**18a**) and the 1,4-dimethoxy isomer (**18c**), and a 1:1:1 ratio gave much higher conversions of starting materials (as a slight modification to improve yields, a 1:0.9:0.9 ratio was used to prevent the formation of the diiodo product; entry 1). Mediation of iodo functionalization with F−TEDA−BF_4 failed in the case of reactions of the 1,4-dimethoxy isomer (**18c**) in acetonitrile (entry 17) and the 1,2-dimethoxy isomer (**18a**) in water in the presence of SAC (entry 3).

The results presented demonstrate the important role of the structure of the organic molecule, the mediator/oxidizer, and the capability of the solvent to modulate the type of transformation of the tested compounds with iodine. Two types of functionalization are evident: oxidation and iodination. The first process is catalyzed by iodine, and two different reaction routes are evident for the iodo functionalization process. The dual role of F−TEDA−BF_4 or hydrogen peroxide is evident from the experiments conducted under condition A, where the substrate/iodine/oxidizer ratio is 2:1:1.2. The triad presented in Scheme 3 should be taken into account because of the fact that iodine by itself, F−TEDA−BF_4, or hydrogen peroxide does not cause significant transformation of substituted anisoles, whereas progressive electron exchange took place in various solvents when all three partners were present. The second role of F−TEDA−BF_4 or hydrogen peroxide, besides activation of the system, is oxidation of the iodide liberated during the iodination process, enabling a high atom economy of iodine introduction. In the first step of this reaction route, electrophilic attack of iodine on the ring or enolized form of the ketone as an electron donor (D−H) takes place. The second step is the regeneration of iodine, and finally, the third step is a second electrophilic addition to the substrate. However, the roles of the oxidizer and solvent on the course of iodination are not predictable, whereas water is a very convenient solvent in the iodination of anisole (**3**), 1,3-dimethoxy benzene (**18b**) mediated by F−TEDA−BF_4, and 1-(4-methoxyphenyl)ethanone (**11**) and 1,3-dimethoxy benzene (**18b**) mediated by hydrogen peroxide.

The second reaction route (route B, Scheme 4) does not obey the atom economy rule for iodine, and twice the amount of iodine is necessary for effective iodination, comparable to the transformation through route A. In this functionalization, the oxidizer and iodine play different roles. Iodine is the activator of electron transfer from the aromatic ring to the oxidizer in the first step, and in the second step, iodine quenches the cation-radical intermediate, thus forming an iodonium cation. It has been confirmed several times that iodine is a convenient quencher for the cation radical.[13] This type of functionalization is possible in/on water and was present in F−TEDA−BF_4-mediated functionalization for **5** and **18c** and hydrogen peroxide-mediated functionalization of **18a** and **18c**.

In the oxidation-type transformation, iodine plays the role of the catalyst and, acting as a weak Lewis acid, enhances the electron flow between the hydroxy methyl group and F−TEDA−BF_4, thus converting hydroxyl to the aldehyde functionality. A selective oxidation process with **1**, catalyzed by iodine, occurred in the case of benzyl alcohol in acetonitrile, and the *p*-methoxy substituted derivative (**5**) could also be oxidized in water.

Experimental Section

F−TEDA−BF_4- or H_2O_2-Mediated Reactions of Iodine with Aromatic Molecules. To 10 mL of solvent (MeCN, MeOH, H_2O, or a 0.02% aqueous solution of Genapol LRO) were added iodine (0.5, 0.6, or 1 mmol) and 1 mmol of substrate (**3**−**6**, **11**, **12**, **18a**−**c**), and the mixture was stirred at a given temperature (20 °C, 50 °C, 60 °C, or under reflux) for 5 min. Various amounts of oxidizer (F−TEDA−BF_4: 0.5, 0.6, 0.9, or 1.0 mmol; H_2O_2: 30% water solution of hydrogen peroxide containing 0.6 or 1.0 mmol of active compound and a drop of 40% aqueous H_2SO_4) were then added, and the reaction mixture was stirred further at the given temperature for various times (2−27 h). The progress of transformations was monitored by TLC or by checking the oxidation properties of the reaction mixtures. The workup procedure depended on the solvent used. In the case of MeCN or MeOH, the solvent was evaporated in a vacuum and methylene chloride (20 mL) was added to the crude residue. Then, the insoluble material was filtered off, and the methylene chloride fraction was washed with a water solution of sodium thiosulfate (10%, 20 mL) and water (20 mL) and dried over anhydrous sodium sulfate. Methylene chloride was then evaporated in a vacuum. In the case of water as the reaction medium, products were extracted with methylene chloride from the reaction mixture and extracts were treated as mentioned. The crude reaction mixtures were analyzed by TLC, GLC, and ^{1}H and ^{19}F NMR spectroscopy, and pure samples of products were isolated either by column chromatography or by TLC and were identified on the basis of comparison of their spectroscopic data with the literature or characterized by standard methods.

4-Iodo Anisole (8).[19] **3** was transformed (reaction conditions: 0.5 mmol I_2; 0.6 mmol F−TEDA−BF_4; water; 20 °C; 17 h) to 200 mg of crude reaction mixture. Column chromatography (SiO_2, CH_2Cl_2) gave 138 mg (59%) of pure solid product (**8**): mp = 43−45 °C (mp[19] = 46−48 °C). In the case of hydrogen peroxide as the oxidizer in acetonitrile, 45% of **8** was obtained.

1-(3-Iodo-4-methoxyphenyl)propan-2-one (14). 12 was transformed (reaction conditions: 0.5 mmol I_2, 0.5 mmol F−TEDA−BF_4, acetonitrile, 50 °C, 4.5 h) to 216 mg of crude reaction mixture. TLC (1% EtOH in CH_2Cl_2) gave 177 mg (61%) of pure oily product (**14**).

^{1}H NMR: δ 2.18 (s, 3H), 3.60 (s, 2H), 3.85 (s, 3H), 6.78 (d, $^3J_{H-H} = 8.4$ Hz, 1H), 7.15 (dd, $^3J_{H-H} = 8.4$ Hz, $^4J_{H-H} = 2.2$ Hz, 1H), 7.60 (d, $^4J_{H-H} = 2.2$ Hz, 1H). ^{13}C NMR: δ 29.3 (s), 49.2 (s), 56.3 (s), 86.3 (s), 110.9 (s), 128.3 (s), 130.4 (s), 140.2 (s), 157.2 (s), 205.9 (s). MS m/z 290 (M^+, 33), 247 (90), 121 (34), 117 (100), 84 (53), 77 (24). IR ν [cm^{-1}] 3000, 2930, 2815, 1715, 1600, 1565, 1490, 1355, 1280, 1250, 1150, 1050, 1020, 890, 820, 790, 760, 660. Elemental analysis: calcd for $C_{10}H_{12}O_2$, C 41.40, H 3.82; found, C 41.51, H 3.97.

Acknowledgment. We thank the Slovenian Research Agency for financial support.

Supporting Information Available: Experimental details of isolated products. This material is available free of charge via the Internet at http://pubs.acs.org.

JO052021N

---

[19] Iskra, J.; Stavber, S.; Zupan, M. *Synthesis* **2004**, 1869−1873.