DOI 10.5012/bkcs.2011.32.2.472

The Use of Sodium Chlorate/Hydrochloric Acid Mixtures as a Novel and Selective Chlorination Agent

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Received September 20, 2010, Accepted November 29, 2010

Sodium chlorate/hydrochloric acid mixtures were used to chlorinate activated arenes and the α-position of ketones. This chlorination method was used to produce selectively mono-, di-, and trichlorinated compounds by controlling the molarity of sodium chlorate. This reagent proved to be much more efficient and easier to handle than chlorine gas.

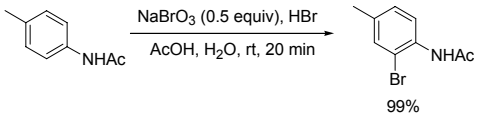
Key Words: Sodium chlorate, Chlorination agent, Sodium chlorate/HCl, Chlorination of aromatics, Chlorination of ketones

Introduction

The chlorinations of aromatic compounds and ketones at their α-positions constitute an important synthetic method, because chloro-substituted organic materials are key intermediates for the synthesis of a wide variety of fine chemicals and pharmaceuticals.[1] Chlorine gas is usually used for this purpose in industrial chlorination processes targeting the rings of arenes and the α-chlorinations of ketones.[2] However, chlorination with chlorine is hazardous, requires special apparatus, and is difficult to control. Various oxidative chlorination agents such as sulfuryl chloride,[3] *N*-chlorosuccinimide,[4] copper(II) chloride,[5] titanium tetrachloride,[6] trifluoromethanesulfonyl chloride,[7] *para*-toluenesulfonyl chloride[8] and acetyl chloride,[9] have been reported in this context. In addition, combination systems based on mixtures of diverse oxidants, i.e., perchloric acid, manganese(III) acetate, hydrogen peroxide, LDA, sulfuric acid, oxone® and dimethylsulfoxide with chlorine sources have been developed to generate chlorine.[3-9,10] The utilities of these systems indicate that oxidative chlorinations appear to offer a better means of synthesizing chloro-substituted organic intermediates than chlorine. To increase the selectivity, recently, chlorination has been achieved using ionic complexes of trichlorosulfonium, phenyldichlorosulfonium, and bis(*p*-chlorophenyl)chloro-sulfonium hexachloroantimonates and chlorine in the presence of the catalytic systems $SbCl_5$-sulfur-containing compounds (SCl_2, Ph_2S, Ph_2S_2).[11]

Unexpectedly, we found that bromine was generated in the presence of sodium bromate and hydrobromic acid during a study of the direct oxidative bromination of hydrobenzoquinone.[12] However, in this case the bromate/hydrobromic acid combination offered no advantage in terms of bromination *versus* bromine, because bromine allows mono-, di-, and tribrominated compounds to be controllably produced (Scheme 1).

On the other hand, the chlorinations of activated aromatics and ketones (α-position) using sodium chlorate/hydrochloric acid has many advantages compared with chlorine, because this combination is easier to handle and store, less hazardous, and does not need special equipment to control the selective formations of mono-, di- and trichlorinated compounds. Here, we describe a new selective chlorination process based on the use of sodium chlorate and hydrochloric acid for the chlorination of various activated arenes and for the alpha chlorination of ketones, such as, phenol, anisole, aniline, 4-nitroaniline, various acetanilides, 5- or 8-methoxyquinaldine, 1-indanone, and 3-nitroacetophenone.



Scheme 1

Results and Discussion

Chlorinations were performed using sodium chlorate and hydrochloric acid in aqueous glacial acetic acid. As shown in Table 1, most acetanilides **1a-d** were chlorinated in high yields. In case of acetanilide (**1a**), the *para*-position was chlorinated more rapidly than *ortho*-position. Although acetanilide (**1a**) has three positions, we obtained 4% of monochlinated and 88% of only one dichlorinated compound in the *para*- and *ortho*-positions (**2e**) without detecting of 2,6-dichloro products (entry 2). This could be attributed to the prevention of second chlorination on *ortho*-position by the steric effect of the acetyl group of **1e**.

Entries 1 and 2 show the possibility of mono- or dichlorination by controlling the amounts of sodium chlorate. Excess chlorate helps to accelerate the reaction rate, but this was accompanied by the oxidations of acetanilides **1a** and **1d** to the quinone (**6**) (entries 2, and 5).

Chlorinations of anilines (Table 2) did not proceed well even in longer reaction time and using larger amounts of chlorate, consequently giving poor yield. However, in the case of aniline (**7a**), chlorinated products were not obtained in acetic acid,

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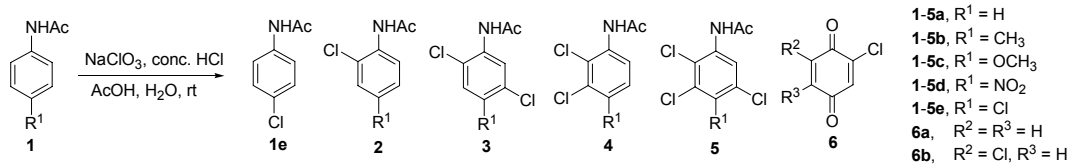
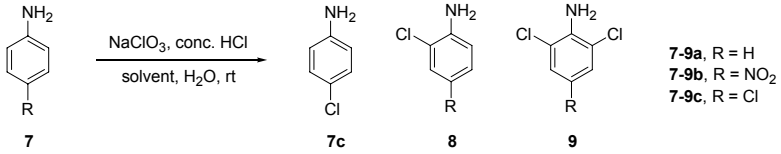
Table 1. Chlorination of acetanilides **1a-d**



Entry	Reactant[a]	$NaClO_3$ (mol %)	Time (h)	Yield (%)[b]										Total yield (%)
				1e	**2a**	**2b**	**2d**	**2e**	**3b**	**3c**	**4c**	**5c**	**6b**	
1	**1a**	35	8	64	32	-	-	-	-	-	-	-	-	96
2	**1a**	100	5	4	-	-	-	88	-	-	-	-	7	99
3	**1b**	50	1	-	-	88	-	-	9	-	-	-	-	97
4	**1c**	100	20	-	-	-	-	-	-	55	14	6	1	76
5	**1d**	200	20	-	-	-	58	-	-	-	-	-	17	75

[a]0.5 g scale using general method. [b]Isolated yields.

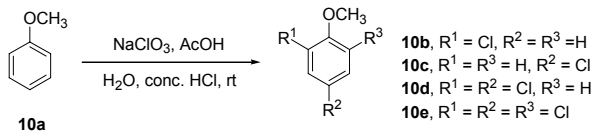
Table 2. Chlorination of anilines **7a-b**



Entry[a]	Reactant	Solvent	$NaClO_3$ (mol %)	Time (h)	Yield (%)[b]						Total yield (%)
					7b	**7c**	**8b**	**8c**	**9b**	**9c**	
1	**7a**	THF	70	20	-	30	-	9	-	9	48
2	**7a**	THF	100	20	-	4	-	6	-	31	41
3	**7b**	AcOH	85	40	14	-	32	-	9	-	41
4	**7b**	AcOH	140	40	-	-	-	-	72	-	72

[a]0.5 g scale using general method. [b]Isolated yields.

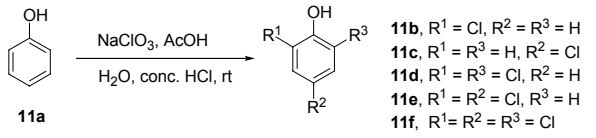
Table 3. Chlorination of anisole (**10a**)



Entry[a]	$NaClO_3$ (mol %)	Time (h)	Yield (%)[b]						Total yield (%)
			10b	**10c**	**10d**	**10e**	**6a**	**6b**	
1	35	12	19	38	-	-	-	-	57[c]
2	70	12	-	15	68	-	4	1	88
3	100	12	-	-	53	24	-	13	91
4	100	1	-	-	86	4	-	3	92
5	200	1	-	-	-	51	-	29	80

[a]0.5 g scale using general method. [b]Isolated yield. [c]Low yields were obtained because of volatility of **10a** and **10c**.

Table 4. Chlorination of phenol (**11a**)



Entry[a]	$NaClO_3$ (equiv)	Time (h)	Yield (%)[b]							Total yield (%)
			11b	**11c**	**11d**	**11e**	**11f**	**6b**	**6c**	
1	0.35	20	13	37	-	-	-	-	-	50[c]
2	0.7	72	-	16	4	65	-	-	-	85
3	1.0	26	-	-	-	6	60	-	-	66
4	1.5	3	-	-	-	-	-	35	34	69

[a]0.5 g scale using general method. [b]Isolated yield. [c]Low yields were obtained because of volatility of **11b** and **11c**.

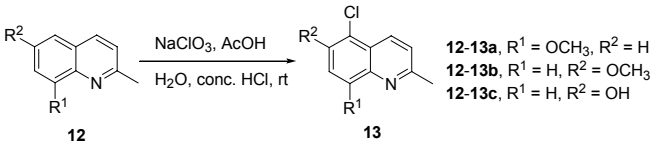
presumably because aniline is protonated under these conditions, and hence, protected from chlorination.

The chlorination of anisole is summarized in Table 3, and provided mono-, di- and trichloroanisoles as major products, which was controlled by adjusting amounts of sodium chlorate and reaction times.

Dichloroanisole **10d** was obtained in high yield (entry 4), but trichloroanisole **10e** was obtained in only moderate yield because of the presence of a competitive oxidation reaction to form 2,6-dichloro-1,4-benzoquinone (**6b**) (entry 5). Mono- or dichlorinated **10b** and **10c** were isolated in low yields due to their volatilities.

The results in Table 4 demonstrate that the formation of chlorinated products can be controlled well by changing the

Table 5. Chlorination of quinolines **12a-b**

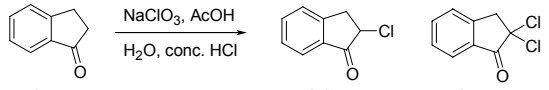


12 **13**

Entry[a]	Reactant	$NaClO_3$ (equiv)	Time (h)	Yield (%)[b]			Total yield (%)
				13a	**13b**	**13c**	
1	**12a**	0.5	2	67	-	-	67
2	**12b**	0.35	2	-	55	26	81

[a]1.0 g scale using general method. [b]Isolated yields.

Table 6. Chlorination of 1-indanone (**14a**)



14a **14b** **14c**

Entry[a]	$NaClO_3$ (equiv)	Temp.	Time (h)	Yield (%)[b]			Total yield (%)
				14a	**14b**	**14c**	
1	0.75	rt	3	27	68	4	72
2	3.0	120 °C	1	-	-	95	95

[a]0.1 g scale using general method. [b]The yields were calculated from NMR spectra of reaction mixtures containing acetanilide, because it was difficult to isolate the desired products by column chromatography.

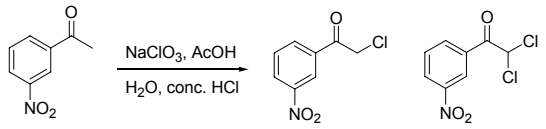
amounts of chlorate. Also from Table 4, it is clear that one equivalent of chlorate can produce three equivalents of chlorinating molecules. When excessive chlorate was used, only oxidized compounds (**6b-c**) were obtained. In addition, when chlorate was used at under one equivalent, the oxidized 1,4-benzoquinone could not be isolated, as shown in entries 1-4. These results indicate that the chlorination of phenol by sodium chlorate/HCl proceeds faster than its oxidation. Mono- or dichlorinated **11b** and **11c** were also obtained in low yields because of the volatility of compounds (entry 1), as were observed for **10b** and **10c**.

In chlorination of 8-methoxyquinaldine which has two activated positions for chlorination, monochlorinated 5-chloro-8-methoxyquinaldine (**13a**) was achieved at an yield of 67% in the absence of 7-chloro-8-methoxyquinaldine, as shown in Table 5. In the case of **12b**, only 5-chloro-6-methoxyquinaldine (**13b**) was obtained in 55% yield without 7-chloro-6-methoxyquinaldine but with the demethylated by-product **13c** in 26% yield by some unknown process.

The chlorinations of the α-position in two aromatic ketones are summarized in Tables 6 and 7. Optimizing of the amounts of chlorate, time and temperature allowed selective chlorination at high yields. Chlorination of the aromatic ring was not detected because of its deactivation by carbonyl or nitro groups. These results indicate that the chlorate/HCl system could be used to chlorinate activated aromatic compounds and α-positions of ketones.

In this study, the real chlorinating molecules are presumably HOCl, AcOCl, and Cl_2, formed by disproportion between chlorate and chloride, as shown in Figure 1. Theoretically, one equivalent of chlorate generates three equivalents of chlorinating agents; however, this was not matched precisely by experimental results.

Table 7. Chlorination of *m*-nitroacetophenone (**15a**)



15a **15b** **15c**

Entry[a]	$NaClO_3$ (equiv)	Temp.	Time (h)	Yield (%)[b]			Total yield (%)
				15a	**15b**	**15c**	
1	0.7	60 °C	15	-	11	87	98
2	1.0	rt	17	6	78	13	91

[a]0.1 g scale using general method. [b]The yields were calculated from NMR spectra of reaction mixtures containing acetanilide, because it was difficult to isolate the desired products by column chromatography.

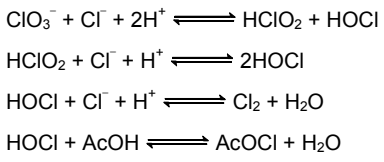


Figure 1. Disproportion reactions between chlorate and chloride.

Conclusion

In conclusion, the described chlorination method based on the use of sodium chlorate/hydrochloric acid as a novel and selective chlorination agent was found to provide a means of preparing used of mono-, di-, or trichlorinated compounds by controlling the amounts of sodium chlorate. As this sodium chlorate/hydrochloric acid mixture would be an efficient reagent for chlorination, it is expected that one can use this reagent easily compared to the use of chlorine gas at laboratory.

Experimental Section

Bromination of 4-Methylacetanilide (2-Bromo-4-methylacetanilide). *p*-Toluidine (1.5 g, 14.0 mmol) was added in acetic acid (30 mL). After the reaction mixture was stirred for 10 min at room temperature, sodium bromate dissolved in H_2O (5 mL) and conc. hydrobromic acid (5 mL) was added. After stirring for 20 min at room temperature, the reaction mixture was extracted with dichloromethane (80 mL × 3) and water (150 mL) containing sodium sulfite. The combined organic layer was evaporated and the crude mixture was purified by flash column chromatography (60% EtOAc/hexane) to give 2-bromo-4-methylacetanilide (3.16 g, 99%) as a white powder: ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.11 (d, J = 8.8 Hz, 1H), 7.50 (bs, 1H), 7.31 (s, 1H), 7.07 (d, J = 8.8 Hz, 1H), 2.26 (s, 3H), 2.19 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 168.1, 135.2, 133.0, 132.4, 128.9, 121.9, 113.2, 24.7, 20.5; MS (CI) *m/z* 230 (M^++1), 228 (M^++1, 100),

150, 148. CAS Registry No.: 614-83-5.

General Procedure of Chlorination. To a solution of a reactant (0.5 g) in glacial acetic acid (10 mL), $NaClO_3$ dissolved in H_2O (6 mL) and conc. HCl (2 mL) was added. After stirring for described time and temperature in table, the reaction mixture was extracted with EtOAc (× 3). The organic layer was dried with Na_2SO_4 and concentrated. The residue was purified by flash column chromatography to give desire product.

4-Chloroacetanilide (1e): ^{1}H NMR (200 MHz, DMSO-d_6) δ 10.0 (bs, 1H), 7.58 (d, J = 8.8 Hz, 1H), 7.27 (d, J = 8.8 Hz, 1H), 2.02 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 167.3, 137.2, 127.4, 125.5, 119.4, 22.9; MS (EI) *m/z* 171 (M^+), 169 (M^+), 129, 127 (100). CAS Registry No.: 539-03-7.

2-Chloroacetanilide (2a): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.35 (d, J = 8.0 Hz, 1H), 7.63 (bs, 1H), 7.36 (dd, J = 7.5, 1.4 Hz, 1H), 7.27 (td, J = 8.0, 1.4 Hz, 1H), 7.03 (td, J = 7.5, 1.6 Hz, 1H), 2.24 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 166.8, 132.9, 127.3, 125.9, 123.1, 120.5, 22.9; MS (EI) *m/z* 171 (M^+), 169 (M^+), 134, 129, 127 (100). CAS Registry No.: 533-17-5.

2-Chloro-4-methylacetanilide (2b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.20 (d, J = 8.4 Hz, 1H), 7.55 (bs, 1H), 7.19 (s, 1H), 7.08 (d, J = 8.4 Hz, 1H), 2.31 (s, 3H), 2.24 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 168.3, 134.7, 131.8, 129.1, 128.0, 122.8, 122.0, 24.4, 20.4; MS (CI) *m/z* 186 (M^++1), 184 (M^++1), 141. CAS Registry No.: 16634-82-5.

2-Chloro-4-nitroacetanilide (2d): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.66 (d, J = 9.4 Hz, 1H), 8.27 (d, J = 2.6 Hz, 1H), 8.14 (dd, J = 9.2, 2.6 Hz, 1H), 7.96 (bs, 1H), 2.33 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 167.0, 141.2, 138.7, 123.0, 121.8, 120.4, 118.6, 23.4; MS (EI) *m/z* 174 (M^+), 172 (M^+), 144, 142, 128, 126, 63, 43 (100). CAS Registry No.: 881-87-8.

2,4-Dichloroacetanilide (2e): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.31 (d, J = 8.8 Hz, 1H), 7.60 (bs, 1H), 7.37 (d, J = 2.2 Hz, 1H), 7.24 (dd, J = 8.8, 2.2 Hz, 1H), 2.24 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 166.6, 131.7, 127.4, 127.0, 126.1, 120.8, 23.0. CAS Registry No.: 6975-29-7.

2,5-Dichloro-4-methylacetanilide (3b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.38 (s, 1H), 7.57 (bs, 1H), 7.21 (s, 1H), 2.30 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 168.2, 133.2, 132.9, 132.5, 130.3, 121.8, 120.4, 24.7, 19.4; MS (CI) *m/z* 222 (M^++1), 220 (M^++1), 218 (M^++1, 100), 198, 182.

2,5-Dichloro-4-methoxyacetanilide (3c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.37 (s, 1H), 7.42 (bs, 1H), 6.93 (s, 1H), 3.88 (s, 3H), 2.23 (s, 3H); ^{13}C NMR (50 MHz, DMSO-d_6 + $CDCl_3$) δ 169.6, 152.6, 128.8, 127.4, 126.1, 120.6, 113.2, 56.9, 23.9; MS (EI) *m/z* 237 (M^+), 235 (M^+), 233 (M^+), 200, 198, 193, 191, 180, 178, 176 (100). CAS Registry No.: 13066-09-6.

2,3-Dichloro-4-methoxyacetanilide (4c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.06 (d, J = 9.2 Hz, 1H), 7.56 (bs, 1H), 6.83 (d, J = 9.6 Hz, 1H), 3.87 (s, 3H), 2.21 (s, 3H); ^{13}C NMR (50 MHz, DMSO-d_6 + $CDCl_3$) δ 169.5, 153.3, 129.2, 126.5, 123.4, 121.5, 110.2, 56.8, 24.3; MS (EI) *m/z* 237 (M^+), 235 (M^+), 233 (M^+), 200, 198, 193, 191, 180, 178, 176 (100).

2,3,6-Trichloro-4-methoxyacetanilide (5c): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.37 (s, 1H), 7.54 (bs, 1H), 3.84 (s, 3H), 2.20 (s, 3H); ^{13}C NMR (50 MHz, DMSO-d_6 + $CDCl_3$) δ 169.7, 149.9, 133.3, 128.8, 127.2, 124.7, 124.5, 61.0, 24.2; MS (EI) *m/z* 273 (M^+), 271 (M^+), 269 (M^+), 267 (M^+), 236, 234, 232, 227, 225, 216, 214, 212, 210 (100). CAS Registry No.: 128207-16-9.

2-Chloro-1,4-hydroquinone (6a): ^{1}H NMR (300 MHz, DMSO-d_6) δ 9.26 (s, 1H), 9.04 (s, 1H), 6.75 (d, J = 8.7 Hz, 1H), 6.69 (d, J = 3.0 Hz, 1H), 6.55-6.52 (m, 1H); ^{13}C NMR (75 MHz, DMSO-d_6) δ 150.7, 146.0, 119.9, 117.6, 116.4, 115.2. CAS Registry No.: 615-67-8.

2,6-Dichloro-1,4-hydroquinone (6b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.04 (s, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 180.8, 171.0, 141.9, 132.2; MS (EI) 180 (M^+), 178 (M^+), 176 (M^+, 100), 141, 120, 88, 60, 53. CAS Registry No.: 697-91-6.

2,5-Dichloro-1,4-hydroquinone (6c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.31 (s, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 168.7, 139.9, 128.9; MS (EI) *m/z* 180 (M^+), 178 (M^+), 176 (M^+), 150, 148, 122, 120, 87, 85, 60, 53. CAS Registry No.: 824-69-1.

4-Chloroaniline (7c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.10 (d, J = 8.4 Hz, 2H), 6.59 (d, J = 8.4Hz, 2H), 3.36 (bs, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 143.4, 127.4, 121.4, 114.6; MS (EI) *m/z* 129 (M^+), 127 (M^+, 100), 100, 92, 65, 45. CAS Registry No.: 106-47-8.

2-Chloro-4-nitroaniline (8b): ^{1}H NMR (200 MHz, DMSO-d_6) δ 7.89 (d, J = 2.6 Hz, 1H), 7.77 (dd, J = 9.2, 2.6 Hz, 1H), 7.73 (d, J = 9.0 Hz, 1H), 3.93 (bs, 2H); ^{13}C NMR (50 MHz, DMSO-d_6) δ 150.2, 134.9, 124.5, 123.5, 114.5, 112.5. CAS Registry No.: 121-87-9.

2,4-Dichloroaniline (8c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.23 (d, J = 2.2 Hz, 1H), 7.60 (bs, 1H), 7.02 (dd, J = 8.4, 2.2 Hz, 1H), 6.65 (d, J = 8.4 Hz, 1H), 3.99 (bs, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 140.0, 127.2, 126.0, 121.1, 117.9, 114.8; MS (EI) *m/z* 207 (M^+), 205 (M^+), 203 (M^+), 170, 168, 165, 163, 161 (100). CAS Registry No.: 554-00-7.

2,6-Dichloro-4-nitroaniline (9b): ^{1}H NMR (200 MHz, DMSO-d_6) δ 8.09 (s, 2H), 7.01 (bs, 2H): ^{13}C NMR (50 MHz, DMSO-d_6) δ 146.6, 134.4, 123.2, 115.6. CAS Registry No.: 99-30-9.

2,4,6-Trichloroaniline (9c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.18 (s, 2H), 4.42 (bs, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 137.4, 125.9, 120.2, 118.0; MS (EI) *m/z* 201 (M^+), 199 (M^+), 197 (M^+), 195 (M^+, 100), 159, 124, 97, 62. CAS Registry No.: 634-93-5.

2-Chloroanisole (10b): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.36 (dd, J = 7.8, 1.5 Hz, 1H), 7.25-7.20 (m, 1H), 6.94-6.87 (m, 2H), 3.90 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 155.0, 130.3, 127.8, 122.4, 121.3, 112.1, 56.1. CAS Registry No.: 766-51-8.

4-Chloroanisole (10c): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.24 (d, J = 9.0 Hz, 2H), 6.83 (d, J = 9.0 Hz, 2H), 3.78 (s, 3H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 158.2, 129.3, 125.5, 115.2, 55.5. CAS Registry No.: 623-12-1.

2,4-Dichloroanisole (10d): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.37 (d, J = 2.6 Hz, 1H), 7.19 (dd, J = 8.8, 2.4 Hz, 1H), 6.85 (d, J = 8.8 Hz, 1H), 3.89 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 152.2, 128.3, 125.9, 123.9, 121.6, 111.1, 54.7; MS (EI) *m/z* 180 (M^+), 178 (M^+), 176 (M^+), 165, 163, 161 (100), 137, 135, 133, 109, 63. CAS Registry No.: 553-82-2.

2,4,6-Trichloroanisole (10e): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.30 (s, 2H), 3.88 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 149.7, 128.3, 127.9, 127.1, 59.1; MS (EI) *m/z* 216 (M^+), 214 (M^+), 212 (M^+), 210 (M^+), 201, 199, 197 (100), 195, 171, 169, 167, 109, 97. CAS Registry No.: 87-40-1.

2-Chlorophenol (11b): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.31 (dd, J = 8.1, 1.8 Hz, 1H), 7.21-7.16 (m, 1H), 7.02 (dd, J = 8.1,

1.5 Hz, 1H), 6.90-6.84 (m, 1H), 5.56 (brs, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 151.4, 129.0, 128.4, 121.4, 116.3. CAS Registry No.: 95-57-8.

4-Chlorophenol (11c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.18 (d, J = 8.8 Hz, 2H), 6.76 (d, J = 8.8 Hz, 2H), 5.51 (bs, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 152.3, 127.9, 124.1, 115.0; MS (EI) m/z 130 (M^+), 128 (M^+, 100), 100, 65. CAS Registry No.: 106-48-9.

2,6-Dichlorophenol (11d): ^{1}H NMR (300 MHz, $CDCl_3$) δ 7.25 (d, J = 8.1 Hz, 2H), 6.81 (t, J = 8.1 Hz, 1H), 5.82 (bs, 1H); ^{13}C NMR (75 MHz, $CDCl_3$) δ 147.9, 128.3, 121.2. CAS Registry No.: 87-65-0.

2,4-Dichlorophenol (11e): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.32 (d, J = 2.2 Hz, 1H), 7.15 (dd, J = 8.8, 2.2Hz, 1H), 6.95 (d, J = 8.8 Hz, 1H), 5.54 (bs, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 148.5, 126.9, 126.8, 123.9, 118.8, 115.5; MS (EI) m/z 166 (M^+), 164 (M^+), 162 (M^+), 98, 63. CAS Registry No.: 120-83-2.

2,4,6-Trichlorophenol (11f): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.25 (s, 2H), 5.87 (bs, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 145.2, 126.4, 123.7, 119.9; MS (EI) m/z 202 (M^+), 200 (M^+), 198 (M^+), 196 (M^+, 100), 164, 162, 160, 99, 97. CAS Registry No.: 88-06-2.

5-Chloro-8-methoxyquinaldine (13a): ^{1}H NMR (400 MHz, $CDCl_3$) δ 8.38 (d, J = 8.8 Hz, 1H), 7.43 (d, J = 8.4 Hz, 1H), 7.40 (d, J = 8.8 Hz, 1H), 6.92 (d, J = 8.4 Hz, 1H), 4.06 (s, 3H), 2.81 (s, 3H); ^{13}C NMR (100 MHz, $CDCl_3$) δ 158.7, 153.8, 140.0, 133.0, 125.3, 125.0, 123.2, 122.0, 107.3, 56.0, 25.5; MS (CI) m/z 210 (M^++1), 208 (M^++1, 100), 188. CAS Registry No.: 34171-47-6.

5-Chloro-6-methoxyquinaldine (13b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.34 (d, J = 8.8 Hz, 1H), 7.94 (d, J = 9.0 Hz, 1H), 7.44 (d, J = 9.2 Hz, 1H), 7.29 (d, J = 8.8 Hz, 1H), 4.00 (s, 3H), 2.71 (s, 3H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 156.2, 152.1, 140.6, 132.9, 126.3, 124.9, 122.8, 116.5, 115.2, 56.4, 23.4; MS (CI) m/z 210 (M^++1), 208 (M^++1, 100). CAS Registry No.: 882159-11-7.

5-Chloro-6-hydroxyquinaldine (13c): ^{1}H NMR (200 MHz, DMSO-d_6 + $CDCl_3$) δ 10.14 (bs, 1H), 8.24 (d, J = 8.8 Hz, 1H), 7.70 (d, J = 9.0 Hz, 1H), 7.40 (d, J = 9.2 Hz, 1H), 7.27 (d, J = 8.8 Hz, 1H), 2.61 (s, 3H); ^{13}C NMR (50 MHz, DMSO-d_6 + $CDCl_3$) δ 156.2, 151.1, 143.4, 131.8, 128.4, 125.9, 123.2, 121.9, 112.9, 25.0; MS (EI) m/z 195(M^+), 193 (M^+, 100), 158, 129, 102, 97.

2-Chloro-1-indanone (14b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.81 (d, J = 7.4 Hz, 1H), 7.69-7.65 (m, 1H), 7.45-7.43 (m, 2H), 4.56 (ddd, J = 7.6, 4.0, 1.2, 1H), 3.79 (dd, J = 17.6, 7.6, 1H), 3.29 (dd, J = 17.6, 4.0, 1H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 197.5, 149.1, 134.4, 132.1, 126.6, 124.7, 123.3, 54.1, 35.9; MS (EI) m/z 168 (M^+), 166 (M^+), 131 (100), 103, 77, 51. CAS Registry No.: 1579-14-2.

2-Dichloroindanone (14c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 7.95 (d, J = 7.6 Hz, 1H), 7.74 (t, J = 7.6 Hz, 1H), 7.49-7.45 (m, 2H), 4.05 (s, 4.0 Hz); ^{13}C NMR (50 MHz, $CDCl_3$) δ 190.1, 145.5, 135.4, 128.6, 127.4, 124.9, 124.5, 79.9, 48.5; MS (EI) m/z 204 (M^+), 202 (M^+), 200 (M^+), 167, 165 (100), 129, 101, 75, 68, 51. CAS Registry No.: 17215-77-9.

2-Chloro-1-(3-nitrophenyl)ethanone (15b): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.77 (s, 1H), 8.48 (d, J = 8.0 Hz, 1H), 8.34 (d, J = 7.8 Hz, 1H), 7.79 (t, J = 8.0 Hz, 1H), 4.84 (s, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 187.8, 146.8, 133.7, 128.6, 126.5, 21.7, 43.9; MS (CI) m/z 202 (M^++1), 200 (M^++1), 136 (100), 94, 41. CAS Registry No.: 99-47-8.

2,2-Dichloro-1-(3-nitrophenyl)ethanone (15c): ^{1}H NMR (200 MHz, $CDCl_3$) δ 8.94 (s, 1H), 8.51-8.48 (m, 2H), 7.81 (t, J = 8.0 Hz, 1H), 6.72 (s, 1H), 4.84 (s, 2H); ^{13}C NMR (50 MHz, $CDCl_3$) δ 182.5, 146.7, 133.6, 130.8, 128.6, 126.9, 123.0, 66.0; MS (CI) m/z 238 (M^++1), 236 (M^++1), 234 (M^++1, 100), 200, 170, 150. CAS Registry No.: 27700-44-3.

Acknowledgments. This work was supported by the Converging Research Program (2010K001050) and the Real-Time Molecular Imaging Project (NRF, 2009-0065588) through the Ministry of Education, Science and Technology and by Korea Health 21 R&D Project, Ministry of Health & Welfare

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