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Identification of Volatile Organic Compounds in Several Indoor Public Places in Korea

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ABSTRACT

A comprehensive profile of volatile organic compounds (VOCs) in public spaces is needed for interpreting indoor air measurements. Seasonal differences in profiles are critical for epidemiological study and risk assessment. The purposes of this study were to establish profiles for individual VOCs in 50 indoor public places in Korea and to determine seasonal variations in their concentrations. Air samples were taken during working hours. Seventy-two of the 91 targeted VOCs were identified using multiple standards. Six VOCs detected in all summer and winter samples were toluene, acetone, *m*,*p*-xylenes, ethylbenzene, benzene, and styrene. In summer, methyl ethyl ketone and 1-butanol were also found in all samples. In both seasons, the dominant indoor VOCs were toluene, *m*,*p*-xylenes, ethylbenzene, acetone, and isopropyl alcohol. Other chemicals associated with gasoline emissions were dominant in summer. Limonene was dominant only in winter due to the consumption of tangerines. The nine VOCs with the highest concentrations comprised 64.8% and 49.6% of the TVOC in summer and winter, respectively. Comparing two types of adsorbent tube, a single adsorbent tube with Tenax-TA had similar detection performance as a double adsorbent tube with Tenax and Carbotrap.

Key words: Individual VOC, Indoor air, Adsorbent tube, Seasonal variation, Source

1. INTRODUCTION

Volatile organic compounds (VOCs) are all organic compounds with a boiling point between 50°C and 250°C (WHO, 1989), although there is no clear and widely accepted definition. Although more than 900 VOCs have been identified at detectable levels in indoor air, about 250 chemicals have been recorded at concentrations higher than 1 ppb (Nathanson, 1993). The presence and magnitude of a wide variety of VOCs can be affected by different factors, which increase the complexity of indoor air quality. The VOCs most commonly detected in indoor air are benzene, ethylbenzene, tetrachloroethylene, trichloroethylene, toluene, *o*-xylene, and *m,p*-xylenes (Etkin, 1996).

Many researchers are currently using the concept of total volatile organic compounds (TVOC), since the identification and measurement of individual VOCs are expensive and time-consuming and some compounds are difficult to identify or measure because of their very low concentrations. Indoor TVOC and VOCs concentrations are often significantly higher than those outdoors (Salonen *et al*., 2009; Brown *et al*., 1994; Wallace *et al*., 1991). Many indoor VOC sources exist, including outdoor sources, human activities, building materials, furniture, and other indoor products (Nazaroff and Weschler, 2004; Ekberg, 2003; Edwards *et al*., 2001; Hodgson *et al*., 2000; Wolkoff, 1995). Due to various source strengths and ventilation conditions, estimation of indoor VOC concentrations is difficult.

TVOC levels are generally associated with general indoor air quality (Molhave *et al*., 1997). VOCs are frequently investigated when bad indoor air quality is suspected. Many VOCs are known to have acute and chronic adverse effects on human health and comfort (Molhave, 1991). Some VOCs are associated with the perception of odors. Adverse health impacts include the irritation of mucous membranes, mostly of the eyes, nose, and throat, and long-term toxic reactions of various kinds (ECA-IAQ, 1991). However, it is difficult to conclude that TVOC is a predictor of health risks as they represent only the sum of the mass concentrations of VOCs at the low exposure levels typically encountered in nonindustrial indoor air (Wolkoff and Nielson, 2001; Andersson *et al*., 1997; Molhave *et al*., 1997). The results of the few reported controlled human exposure studies and epidemiological studies have confirmed that health effects and outcomes were often inconsistent (Molhave *et al*., 1997).

Although the TVOC concept is widely used, information on the individual VOCs concentrations typically present in public spaces is needed for the interpretation of indoor air measurements. The purposes of our study were to establish profiles for 91 individual VOCs in indoor public places in Korea and to determine seasonal variations in their concentrations. In addition, statistical analyses were conducted to determine correlations between individual VOCs.

2. MATERIALS AND METHODS

2.1 Sampling Locations

VOC concentrations were measured in a total of 50 indoor public spaces, which consisted of 17 types of public space, as classified by Korean regulation. The 17 types were underground station (n=2), underground market (n=2), department store (n=7), public bath (n=5), funeral home (n=2), waiting room of a bus terminal (n=2), airport (n=1), waiting room of a port facility (n=1), waiting room of a train station (n=2), library (n=2), museum (n=2), art gallery (n=1), health care facility (n=5), preschool (n=6), elderly welfare facility (n=2), postpartum care facility (n=3), and indoor parking lot (n=5). VOCs were measured in all 50 locations between July and August 2008, and 49 locations were measured between January and February 2009. One preschool was not measured in winter.

2.2 Sampling Method

At each location, indoor air samples were collected at flow rate of 100 mL/min for 30 min. Two types of adsorbent tubes were used. VOCs at all 50 locations were measured using a Tenax-TA 300 mg with a stainless steel tube (6.35 mm × 9 cm, PerkinElmer, Cambridge, Cambridgeshire, UK). The tubes were treated by thermal conditioner (Markes Inc., Llantrisant, Rhondda Cynon Taff, UK) with ultrapure helium at 80 mL/min.

Table 1. Physical and chemical characteristics of 91 targeted VOCs.

No.	VOCs	CAS No.	STD①[1)]	STD②[2)]	STD③[3)]	Molecular form	MW	BP (°C)
1	Difluorodichloromethane	75-71-8		O		Cl_2CF_2	120.91	−30
2	Dichlorotetrafluoroethane	76-14-2		O		$F_2CClCClF_2$	170.92	4
3	1,3-Butadiene	106-99-0		O		$CH_2CHCHCH_2$	54.09	−5
4	Ethyl chloride	75-00-3		O		C_2H_5Cl	64.52	12
5	Acetone	67-64-1	O	O		$CH_3C(O)CH_3$	58.08	56
6	Isopropyl alcohol	67-63-0	O	O		$CH_3CH(OH)CH_3$	60.10	80-83
7	Trichlorofluoromethane	75-69-4		O		CCl_3F	137.37	24
8	1,1-Dichloroethene	75-35-4		O		$C_2H_2Cl_2$	96.94	57
9	Methylene chloride	75-09-2	O	O		CH_2Cl_2	84.93	40
10	1,1,2-Trichlorotrifluoroethane	76-13-1		O		CF_2ClCCl_2F	187.38	48
11	Carbon disulfide	75-15-0		O		CS_2	76.13	46
12	1-Propanol	71-23-8	O			C_3H_8O	60.10	97.2
13	trans-1,2-Dichloroethylene	156-60-5		O		$C_2H_2Cl_2$	96.94	48
14	Methyl tert-butyl ether	1634-04-4		O		$(CH_3)_3COCH_3$	88.15	55
15	1,1-Dichloroethane	75-34-3		O		CH_3CHCl_2	98.96	57
16	Vinyl acetate	108-05-4		O		$CH_3CO_2CHCH_2$	86.09	72
17	Methyl ethyl ketone	78-93-3	O	O		$CH_3CH_2COCH_3$	72.12	80
18	cis-1,2-Dichloroethylene	156-59-2		O		$C_2H_2Cl_2$	96.94	60
19	Ethyl acetate	141-78-6	O	O		$CH_3CO_2C_2H_5$	88.11	77
20	Hexane	110-54-3	O	O		$CH_3(CH_2)_4CH_3$	86.18	69
21	Chloroform	67-66-3	O	O		$CHCl_3$	119.38	62
22	Tetrahydrofuran	109-99-9		O		C_4H_8O	72.10	67
23	2,4-Dimethylpentane	108-08-7	O			C_7H_{16}	100.20	81
24	1,2-Dichloroethane	107-06-2	O	O		$ClCH_2CH_2Cl$	98.96	84
25	1,1,1-Trichloroethane	71-55-6	O	O		CH_3CCl_3	133.40	74
26	1-Butanol	71-36-3	O			$C_4H_{10}O$	74.12	117.6
27	Benzene	71-43-2	O	O	O	C_6H_6	78.11	80
28	Carbon tetrachloride	56-23-5	O	O		CCl_4	153.82	77
29	Cyclohexane	110-82-7		O		C_6H_{12}	84.18	81
30	1,2-Dichloropropane	78-87-5	O	O		$CH_3CH_2ClCH_2Cl$	112.99	96
31	1,4-Dioxane	123-91-1		O		$OCH_2CH_2OCH_2CH_2$	88.11	101
32	Bromodichloromethane	75-27-4	O	O		$CHBrCl_2$	163.83	90
33	2,2,4-Trimethylpentane	540-84-1	O			C_8H_{18}	114.23	99.2
34	Trichloroethylene	79-01-6	O	O		$ClCHCCl_2$	131.39	87

Table 1. Continued.

No.	VOCs	CAS No.	STD①[1)]	STD②[2)]	STD③[3)]	Molecular form	MW	BP (˚C)
35	Heptane	142-82-5	O	O		$CH_3(CH_2)_5CH_3$	100.21	98
36	Methyl isobutyl ketone	108-10-1	O	O		$(CH_3)_2CHCH_2C(O)CH_3$	100.16	117
37	cis-1,3-Dichloropropene	10061-01-5		O		$ClCH_2CHCHCl$	110.97	104
38	trans-1,3-Dichloropropene	10061-02-6		O		$ClCH_2CHCHCl$	110.97	112
39	1,1,2-Trichloroethane	79-00-5		O		$CH_2ClCHCl_2$	133.40	113-114
40	Toluene	108-88-3	O	O	O	$C_6H_5CH_3$	92.14	111
41	2-Hexanone	591-78-6		O		$C_6H_{12}O$	100.18	128
42	Dibromochloromethane	124-48-1	O	O		$ClCHBr_2$	208.28	119-120
43	Butyl acetate	123-86-4	O			$C_6H_{12}O_2$	116.16	126.1
44	1,2-Dibromoethane	106-93-4		O		$BrCH_2CH_2Br$	187.86	131
45	Octane	111-65-9	O			C_8H_{18}	114.23	126
46	Tetrachloroethylene	127-18-4	O	O		Cl_2CCCl_2	165.83	121
47	Chlorobenzene	108-90-7		O	O	C_6H_5Cl	112.56	132
48	Ethylbenzene	100-41-4	O	O	O	$CH_3CH_2C_6H_5$	106.17	136
49	*m*-Xylene	108-38-3	O	O	O	C_8H_{10}	106.17	138-139
50	*p*-Xylene	106-42-3	O	O	O	C_8H_{10}	106.17	138-139
51	Bromoform	75-25-2		O		$CHBr_3$	252.73	150
52	Styrene	100-42-5	O	O	O	C_8H_8	104.14	146
53	1,1,2,2-Tetrachloroethane	79-34-5		O		$CHCl_2CHCl_2$	167.85	146
54	*o*-Xylene	95-47-6	O	O	O	C_8H_{10}	106.17	144
55	Nonane	111-84-2	O			C_9H_{20}	128.26	150.8
56	Isopropylbenzene	98-82-8			O	C_9H_{12}	120.19	151
57	Bromobenzene	108-86-1			O	C_6H_5Br	157.01	155
58	α-Pinene	7785-26-4	O			$C_{10}H_{16}$	136.24	155-156
59	*n*-Propylbenzene	103-65-1			O	C_9H_{12}	120.19	159
60	4-Chlorotoluene	106-43-4			O	C_7H_7Cl	126.59	158.97
61	2-Chlorotoluene	95-49-8			O	C_7H_7Cl	126.59	161.9
62	3-Ethyltoluene	620-14-4	O			C_9H_{12}	120.19	158-159
63	4-Ethyltoluene	622-96-8	O	O		$CH_3C_6H_4C_2H_5$	120.19	160-163
64	1,3,5-Trimethylbenzene	108-67-8	O	O	O	C_9H_{12}	120.21	165
65	2-Ethyltoluene	611-14-3	O			C_9H_{12}	120.19	164-165
66	β-Pinene	18172-67-3	O			$C_{10}H_{16}$	136.24	165-167
67	Decane	124-18-5	O			$C_{10}H_{22}$	142.28	174.1
68	1,2,4-Trimethylbenzene	95-63-6	O	O	O	$(CH_3)_3C_6H_3$	120.19	169
69	*tert*-Butylbenzene	98-06-6			O	$C_{10}H_{14}$	134.22	169
70	Benzyl chlororide	100-44-7		O		$C_6H_5CH_2Cl$	126.59	179
71	1,3-Dichlorobenzene	541-73-1		O	O	$C_6H_4Cl_2$	147.00	173
72	1,4-Dichlorobenzene	106-46-7	O	O	O	$C_6H_4Cl_2$	147.00	174
73	sec-Butylbenzene	135-98-8			O	$C_{10}H_{14}$	134.22	173
74	*p*-Isopropyltoluene	99-87-6			O	$C_{10}H_{14}$	134.22	176-178
75	1,2,3-Trimethylbenzene	526-73-8	O			C_9H_{12}	120.19	175
76	Limonene	5989-27-5	O			$C_{10}H_{16}$	136.24	175.5
77	1,2-Dichlorobenzene	95-50-1		O	O	$C_6H_4Cl_2$	147.00	181
78	*n*-Butylbenzene	104-51-8			O	$C_{10}H_{14}$	134.22	183
79	Nonanal	124-19-6	O			$C_9H_{18}O$	142.24	93
80	Undecane	1120-21-4	O			$C_{11}H_{24}$	156.31	195.9
81	1,2,4,5-Tetramethylbenzene	95-93-2	O			$C_{10}H_{14}$	134.22	196.8
82	Decanal	112-31-2	O			$C_{10}H_{20}O$	156.27	207-209
83	Dodecane	112-40-3	O			$C_{12}H_{26}$	170.34	216.3
84	1,2,4-Trichlorobenzene	120-82-1		O	O	$C_6H_3Cl_3$	181.44	214
85	Naphthalene	91-20-3			O	$C_{10}H_8$	128.17	218
86	1,2,3-Trichlorobenzene	87-61-6			O	$C_6H_3Cl_3$	181.45	219
87	Hexachloro-1,3-butadiene	87-68-3		O		$Cl_2CCClCClCCl_2$	260.74	210-220
88	Tridecane	629-50-5	O			$C_{13}H_{28}$	184.36	235.4
89	Tetradecane	629-59-4	O			$C_{14}H_{30}$	198.39	253.7
90	Pentadecane	629-62-9	O			$C_{15}H_{32}$	212.42	270.63
91	Hexadecane	544-76-3	O			$C_{16}H_{34}$	226.44	287

[1)]STD① : 52mix component indoor air standard
[2)]STD② : 62mix EPA TO-15 calibration mix
[3)]STD③ : EPA VOC mix 1 (12mix)+EPA VOC mix 2 (13mix)

Table 2. Individual VOCs levels (μg/m^3) in summer.

	Detection frequency (%)	Mean	SD	25th percentile	50th percentile	75th percentile	90th percentile	Min	Max	GM
Toluene	100	316.8	955.2	41.3	74.2	151.2	151.2	2.1	5774.5	81.2
Acetone	100	44.1	58.7	13.8	25.1	51.5	51.5	4.9	382.8	27.2
m,p-Xylenes	100	19.2	32.8	5.9	11.4	16.6	16.6	0.5	184.1	10.6
Ethylbenzene	100	13.6	30.2	4.2	6.8	11.5	11.5	0.2	160.9	6.6
Methyl ethyl ketone	100	10.2	7.2	4.7	8.1	14.9	14.9	0.4	33.7	7.8
1-Butanol	100	8.3	6.3	4.2	6.7	9.8	9.8	0.7	31.4	6.3
Benzene	100	6.5	8.9	3.2	4.1	5.6	5.6	1.8	49.2	4.6
Styrene	100	2.1	1.6	1.0	1.5	2.8	2.8	0.5	8.1	1.7
Naphthalene	98	7.6	15.5	1.5	2.3	7.2	7.2	0.3	102.4	3.1
o-Xylene	98	7.1	12.7	1.9	4.5	6.1	6.1	0.2	75.3	3.9
1,2,4-Trimethylbenzene	98	4.2	8.2	1.2	1.8	3.2	3.2	0.2	46.8	2.1
3-Ethyltoluene	98	3.7	6.8	0.7	1.4	2.9	2.9	0.2	31.6	1.6
1,3,5-Trimethylbenzene	98	2.3	4.4	0.5	0.8	1.8	1.8	0.3	23.0	1.0
4-Ethyltoluene	98	2.1	3.7	0.5	0.8	1.6	1.6	0.2	16.5	0.9
Trichlorofluoromethane	96	5.5	16.8	0.5	0.9	2.2	2.2	0.3	115.0	1.4
Cyclohexane	96	3.8	4.1	1.0	1.9	5.8	5.8	0.2	17.5	2.2
Chloroform	96	3.8	8.0	0.7	1.2	2.7	2.7	0.2	49.4	1.5
Isopropyl alcohol	94	36.6	188.5	1.7	3.6	10.4	10.4	0.1	1335.5	4.0
Butyl acetate	94	4.9	6.8	1.3	2.9	5.3	5.3	0.2	36.2	2.7
Ethyl acetate	92	14.5	25.8	4.0	7.0	13.4	13.4	0.2	153.7	6.2
Decane	92	2.9	2.3	1.5	2.4	3.5	3.5	0.3	10.8	2.1
2-Ethyltoluene	92	1.7	3.1	0.3	0.7	1.3	1.3	0.2	15.5	0.8
Carbon tetrachloride	92	0.8	1.5	0.5	0.6	0.7	0.7	0.3	11.4	0.6
Hexane	90	41.5	114.2	3.3	5.9	27.3	27.3	0.2	768.3	8.3
Nonanal	90	10.2	11.0	4.2	7.5	11.1	11.1	0.3	53.2	6.0
Tetradecane	90	6.5	11.7	2.0	4.3	6.2	6.2	0.4	79.3	3.5
Tridecane	90	5.9	12.0	1.5	2.5	5.7	5.7	0.4	83.8	2.9
Limonene	90	4.4	3.7	1.3	3.8	6.8	6.8	0.3	13.1	2.6
Heptane	90	4.3	6.8	1.6	2.3	4.4	4.4	0.2	42.8	2.3
Methyl isobutyl ketone	90	2.5	2.1	0.9	1.9	3.3	3.3	0.2	9.8	1.6
Dodecane	88	3.3	4.1	1.1	2.6	3.9	3.9	0.4	27.0	2.1
Methylene chloride	86	4.0	4.5	0.6	2.4	5.6	5.6	0.2	20.2	1.9
Trichloroethylene	86	3.0	3.1	0.7	1.9	4.4	4.4	0.3	13.1	1.7
Nonane	86	2.4	2.1	1.1	1.9	3.3	3.3	0.3	10.6	1.6
Octane	84	2.7	3.2	1.1	1.8	3.1	3.1	0.2	15.0	1.6
Pentadecane	82	2.6	4.0	0.8	1.7	2.5	2.5	0.4	18.9	1.5
Methyl tert-butyl ether	82	2.1	5.1	0.5	0.7	1.4	1.4	0.2	33.7	0.8
1,2,3-Trimethylbenzene	82	1.1	1.9	0.3	0.5	0.9	0.9	0.2	11.0	0.6
Hexadecane	80	5.8	10.7	1.1	1.9	4.0	4.0	0.5	58.6	2.4
Vinyl acetate	80	2.6	2.8	1.2	2.2	2.9	2.9	0.2	18.4	1.5
n-Propylbenzene +4-Chlorotoluene	80	0.8	1.0	0.3	0.4	0.8	0.8	0.2	6.7	0.5
α-Pinene	74	2.0	4.4	0.3	1.0	1.5	1.5	0.3	30.7	1.0
Undecane	74	1.9	1.8	0.4	1.4	2.4	2.4	0.3	8.5	1.2
1,2-Dichloroethane	74	0.7	0.7	0.2	0.5	0.8	0.8	0.2	3.6	0.5
1,1,1-Trichloroethane	74	0.4	0.1	0.3	0.3	0.5	0.5	0.3	0.8	0.4
tert-Butylbenzene	70	0.6	0.9	0.3	0.3	0.5	0.5	0.3	5.4	0.4
Isopropylbenzene	68	0.4	0.5	0.2	0.2	0.3	0.3	0.2	2.7	0.3
Carbon disulfide	64	0.9	1.5	0.2	0.2	0.7	0.7	0.2	6.0	0.4
2,2,4-Trimethylpentane	62	1.0	1.6	0.2	0.4	0.9	0.9	0.2	9.1	0.5
Decanal	60	3.0	4.5	0.3	1.8	3.7	3.7	0.3	27.4	1.4
β-Pinene	60	0.9	0.9	0.3	0.5	1.1	1.1	0.3	5.2	0.6
2-Chlorotoluene	54	0.6	1.0	0.3	0.3	0.4	0.4	0.3	5.7	0.4
Tetrachloroethylene	50	3.9	21.1	0.3	0.4	1.3	1.3	0.3	149.7	0.7
p-Isopropyltoluene	50	0.4	0.2	0.3	0.3	0.4	0.4	0.3	1.1	0.3
Chlorobenzene	44	0.3	0.1	0.2	0.2	0.2	0.2	0.2	0.6	0.3
1,4-Dichlorobenzene	38	1.0	2.5	0.3	0.3	0.3	0.3	0.3	15.0	0.5
Tetrahydrofuran	34	0.5	0.7	0.1	0.1	0.7	0.7	0.1	4.3	0.3
1,4-Dioxane	28	0.4	0.5	0.2	0.2	0.4	0.4	0.2	3.0	0.3

Table 2. Continued.

	Detection frequency (%)	Mean	SD	25th percentile	50th percentile	75th percentile	90th percentile	Min	Max	GM
2,4-Dimethylpentane	22	0.8	1.4	0.2	0.2	0.2	0.2	0.2	7.7	0.4
1,2,4,5-Tetra-methylbenzene	20	0.4	0.3	0.3	0.3	0.3	0.3	0.3	1.6	0.3
1,1,2-Trichloro-trifluoroethane	18	0.4	0.1	0.4	0.4	0.4	0.4	0.4	0.9	0.4
2-Hexanone	12	0.4	0.6	0.2	0.2	0.2	0.2	0.2	3.9	0.3
Bromodichloromethane	8	0.4	0.1	0.3	0.3	0.3	0.3	0.3	1.2	0.4
1,2-Dichlorobenzene	6	0.5	1.3	0.3	0.3	0.3	0.3	0.3	8.6	0.3
1,1-Dichloroethane	4	0.5	1.3	0.2	0.2	0.2	0.2	0.2	8.0	0.2
n-Butylbenzene	4	0.3	0.1	0.3	0.3	0.3	0.3	0.3	0.8	0.3
1-Propanol	4	0.3	0.8	0.1	0.1	0.1	0.1	0.1	4.8	0.1
1,2-Dichloropropane	4	0.3	0.1	0.2	0.2	0.2	0.2	0.2	1.2	0.2
sec-Butylbenzene	2	0.3	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3
1,3-Butadiene	2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.6	0.1

Conditioned tubes were blocked by 6.35 mm Swagelok-type lids with PTFE ferrules and were stored in 50-mL glass vials with a septum.

2.3 Analysis

The samples were analyzed using a GC/MS (HP 6890/5973) with thermal desorption system (UNITY/ULTRA, Markes Inc.). The GC column was an Rtx-1 (0.32 mm × 105 m × 1.50 μm). In this study, 91 VOCs were identified using four different standards. The standards were 52 Component Indoor Air Standards (Supelco, Bellefonte, PA, USA), EPA VOC Mix 1 containing 12 chemicals (Supelco), EPA VOC Mix 2 containing 13 chemicals (Supelco), and EPA TO-15 Calibration Mix containing 62 chemicals (Supelco). The 91 chemicals are shown in Table 1. All standards were liquid-based, except the EPA TO-15, which was gas-based. Concentrations of individual compounds were determined according to calibration curves. The samples below LOD was estimated as a half of the LOD for the chemicals.

2.4 Statistical Analysis

Correlation analyses were used to evaluate the sources of compounds measured in the public spaces (SAS version 9.1, SAS Institute, Cary, NC, USA). For correlation analyses, compounds with frequencies of detection greater than 50% were included. Since the concentration data were consistent with lognormal distribution, a Spearman correlation matrix was calculated.

3. RESULTS

The mean TVOC concentrations in public spaces were 782 ± 1084 μg/m^3 in summer and 540 ± 380 μg/m^3 in winter. The mean TVOC concentrations were slightly higher in summer than in winter, although they were not significantly different (Paired t-test, $p = 0.14$). Cumulative distributions of TVOC in summer and winter are shown in Fig. 1. In summer, the highest concentrations were observed in the preschool (1718 μg/m^3), health care facility (1709 μg/m^3), art gallery (1667 μg/m^3), and elderly welfare facility (1046 μg/m^3). In winter, the highest concentrations were observed in the airport (2096 μg/m^3), underground market (854 μg/m^3), and health care facility (839 μg/m^3).

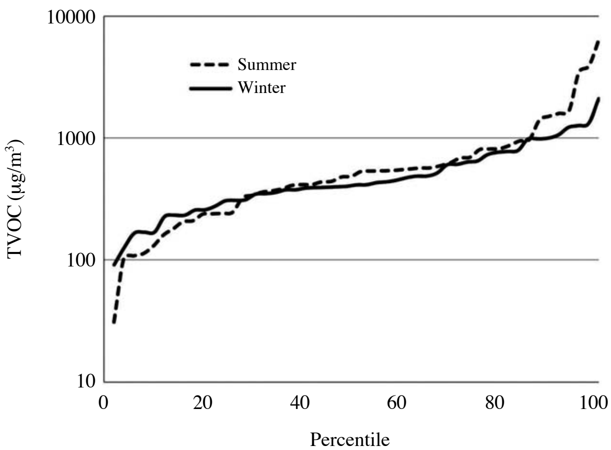

Fig. 1. Cumulative distribution of TVOC in public places in summer and winter.

In summer, acetone, methylethylketone, benzene, toluene, ethylbenzene, *m,p*-xylenes, styrene, and naphthalene were detected in all samples from the 50 locations. Another 33 chemicals were detected in more than 80% of samples, 11 chemicals were detected in less than 20% of the samples, and 21 chemicals were

Table 3. Individual VOCs levels (μg/m^3) in winter.

	Detection frequency (%)	Mean	SD	25th percentile	50th percentile	75th percentile	90th percentile	Min	Max	GM
Acetone	100	31	65.7	10.3	14.7	19.3	52.6	4.3	442.2	17.0
Benzene	100	8	5.0	5.1	6.7	9.0	12.3	2.4	23.3	6.9
Toluene	100	110	145.0	33.5	59.6	118.1	187.1	7.7	621.9	67.4
Ethylbenzene	100	16	29.7	4.2	6.4	12.1	21.7	1.3	141.5	7.7
m,p-Xylenes	100	19	23.9	7.0	10.7	19.4	38.4	2.0	138.6	11.9
Styrene	100	3	4.5	1.2	1.9	2.6	4.5	0.8	32.3	2.0
Isopropyl alcohol	98	37	194.9	3.0	4.5	8.8	18.0	0.1	1370.4	5.6
3-Ethyltoluene	96	3	4.2	1.0	1.6	2.7	9.3	0.2	17.1	1.9
1,3,5-Trimethylbenzene	96	2	2.0	0.6	0.9	1.4	4.6	0.3	9.1	1.0
2-Ethyltoluene	96	1	1.6	0.6	0.8	1.2	4.1	0.2	6.3	0.9
Trichlorofluoromethane	94	1	2.0	0.6	0.7	1.0	1.7	0.3	13.7	0.8
Methyl ethyl ketone	92	11	12.0	4.9	7.1	12.1	25.8	0.1	52.4	6.3
4-Ethyltoluene	92	2	2.0	0.5	0.9	1.3	4.8	0.2	8.5	1.0
Carbon tetrachloride	90	1	0.4	0.6	0.7	0.8	1.0	0.3	2.7	0.7
o-Xylene	90	6	7.5	2.2	4.1	7.5	16.0	0.2	42.5	3.6
Chloroform	88	1	1.2	0.4	0.8	1.3	2.9	0.2	4.7	0.8
Cyclohexane	88	4	6.5	1.4	2.6	4.8	7.8	0.2	40.0	2.3
1,2,4-Trimethylbenzene	88	6	7.8	1.4	2.8	4.4	16.5	0.2	36.9	2.6
Hexane	86	11	13.2	0.2	7.7	14.3	30.8	0.2	56.5	2.6
Decane	86	8	22.3	1.9	3.9	6.9	12.0	0.3	155.7	3.4
Naphthalene	86	2	3.2	0.9	1.3	2.6	4.4	0.3	20.1	1.4
Methylene chloride	82	4	7.0	1.1	2.0	3.3	5.9	0.2	44.4	1.7
Ethyl acetate	80	9	10.8	1.9	5.6	9.5	17.3	0.2	52.6	3.5
Butyl acetate	80	3	4.4	0.8	2.0	3.9	7.1	0.2	24.7	1.6
Trichloroethylene	78	3	5.6	0.7	2.0	3.3	6.0	0.3	28.1	1.6
Nonane	76	4	5.5	1.2	2.4	5.2	7.8	0.3	32.3	2.0
Limonene	73	16	43.8	0.3	5.9	11.5	32.1	0.3	301.5	3.8
Tetradecane	71	3	3.7	0.4	2.0	4.4	6.8	0.4	21.7	1.7
Tridecane	69	4	5.9	0.4	1.6	3.1	9.6	0.4	32.4	1.6
Undecane	65	3	3.9	0.3	1.3	2.8	6.7	0.3	23.8	1.2
Pentadecane	65	1	1.2	0.4	0.8	1.5	3.0	0.4	6.6	0.9
Heptane	61	5	7.2	0.2	1.9	4.8	15.0	0.2	31.4	1.4
Octane	61	3	3.7	0.2	1.3	3.2	5.1	0.2	19.6	1.1
Nonanal	61	4	4.1	0.3	2.9	7.2	9.9	0.3	15.2	1.8
1,2-Dichloroethane	59	1	0.8	0.2	0.4	0.6	0.8	0.2	5.8	0.4
Methyl isobutyl ketone	59	2	8.5	0.2	0.7	1.1	2.1	0.2	59.9	0.6
n-Propylbenzene +4-Chlorotoluene	57	1	1.5	0.2	0.5	0.9	2.8	0.2	6.8	0.6
1,2,3-Trimethylbenzene	57	1	1.7	0.2	0.5	1.3	3.8	0.2	8.3	0.6
Isopropylbenzene	55	1	0.7	0.2	0.2	0.5	1.6	0.2	4.1	0.4
α-Pinene	55	1	2.1	0.3	0.5	1.4	2.8	0.3	9.9	0.7
Carbon disulfide	54	7	17.9	0.2	0.8	2.9	16.1	0.2	83.6	0.9
1-Butanol	49	3	8.4	0.2	0.2	2.6	5.3	0.2	58.1	0.7
Methyl tert-butyl ether	47	4	8.3	0.2	0.2	2.5	6.9	0.2	36.2	0.7
1,1,1-Trichloroethane	47	1	1.3	0.3	0.3	0.5	0.7	0.3	9.2	0.4
2,2,4-Trimethylpentane	47	3	6.7	0.2	0.2	2.0	7.0	0.2	41.8	0.8
tert-Butylbenzene	47	1	0.8	0.3	0.3	0.5	1.9	0.3	4.2	0.4
Dodecane	47	3	6.2	0.4	0.4	3.6	9.3	0.4	35.4	1.2
p-Isopropyltoluene	41	1	0.5	0.3	0.3	0.6	1.3	0.3	2.6	0.4
Hexadecane	41	1	1.4	0.5	0.5	1.5	3.2	0.5	7.4	0.8
Tetrachloroethylene	22	18	88.6	0.3	0.3	0.3	1.4	0.3	570.5	0.6
1,1,2-Trichloro-trifluoroethane	18	1	1.4	0.4	0.4	0.4	1.6	0.4	7.9	0.5
β-Pinene	18	0	0.4	0.3	0.3	0.3	1.1	0.3	2.2	0.4
Tetrahydrofuran	14	1	6.5	0.1	0.1	0.1	1.0	0.1	45.4	0.2
Vinyl acetate	12	0	0.8	0.2	0.2	0.2	1.5	0.2	3.6	0.2
Chlorobenzene	10	0	0.1	0.2	0.2	0.2	0.2	0.2	0.7	0.3
2,4-Dimethylpentane	8	1	1.5	0.2	0.2	0.2	0.2	0.2	7.0	0.3
Bromodichloromethane	8	0	0.7	0.3	0.3	0.3	0.3	0.3	4.7	0.4

Table 3. Continued.

	Detection frequency (%)	Mean	SD	25th percentile	50th percentile	75th percentile	90th percentile	Min	Max	GM
Dibromochloromethane	8	1	0.4	0.4	0.4	0.4	0.4	0.4	3.1	0.5
1,4-Dichlorobenzene	6	1	1.0	0.3	0.3	0.3	0.3	0.3	5.5	0.4
sec-Butylbenzene	4	0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3
n-Butylbenzene	4	0	0.0	0.3	0.3	0.3	0.3	0.3	0.4	0.3
1,3-Dichlorobenzene	2	0	1.2	0.3	0.3	0.3	0.3	0.3	8.8	0.3
1,2-Dichlorobenzene	2	0	0.6	0.3	0.3	0.3	0.3	0.3	4.6	0.3
1,2,4,5-Tetramethylbenzene	2	0	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.3

not detected in any samples. The individual VOC concentrations of 10 μg/m^3 or more were toluene (316.7 μg/m^3), acetone (44.1 μg/m^3), hexane (41.5 μg/m^3), isopropyl alcohol (36.6 μg/m^3), *m,p*-xylenes (19.2 μg/m^3), ethyl acetate (14.5 μg/m^3), ethylbenzene (13.6 μg/m^3), methyl ethyl ketone (13.6 μg/m^3), and nonanal (10.1 μg/m^3). These nine compounds comprised 64.8% of TVOCs. The individual VOC levels in summer are shown in Table 2.

In winter, toluene, acetone, *m,p*-xylenes, ethylbenzene, benzene, and styrene were detected in all samples from the 49 locations. Another 18 chemicals were observed in more than 80% of the samples, 14 chemicals were found less than 20% of the samples, and 27 chemicals were not detected in any samples. Compounds with individual VOC concentrations of 10 μg/m^3 or more were toluene (109.9 μg/m^3), isopropyl alcohol (36.6 μg/m^3), acetone (31.0 μg/m^3), *m,p*-xylenes (18.8 μg/m^3), tetrachloroethylene (17.6 μg/m^3), limonene (16 μg/m^3), ethylbenzene (15.9 μg/m^3), hexane (11.0 μg/m^3), and methyl ethyl ketone (11.2 μg/m^3). These nine compounds comprised 49.6% of TVOCs. The individual VOC levels in winter are shown in Table 3.

Some compounds had occasional high values. This was apparent for isopropyl alcohol in which the mean was about 8 and 10 times larger than the median. Three compounds with medians greater than 10 μg/m^3 were toluene, acetone, and *m,p*-xylenes. Another six compounds had medians greater than 5 μg/m^3 in summer: methyl ethyl ketone (8.1 μg/m^3), nonanal (7.5 μg/m^3), ethyl acetate (7.0 μg/m^3), ethyl benzene (6.8 μg/m^3), 1-butanol (6.7 μg/m^3), and hexane (5.9 μg/m^3). Four compounds had medians greater than 5 μg/m^3 in winter: benzene (6.7 μg/m^3), ethylbenzene (6.4 μg/m^3), limonene (5.9 μg/m^3), and ethyl acetate (5.6 μg/m^3).

Several compounds were closely correlated with other compounds. The criteria for determining correlations between individual VOCs were an $R > 0.9$ and a P-value (or significance probability value) < 0.001. Based on these criteria, the correlations of different individual VOCs in summer and winter are summarized in Tables 4 and 5, respectively. Among the 91 targeted VOCs in this study, 18 VOCs showed strong cor-

Table 4. Correlation of VOCs in summer.

Compounds	Correlated compounds	Pearson correlation (R)
Ethylbenzene	2-Chlorotoluene	0.980
	Isopropylbenzene	0.981
	tert-Butylbenzene	0.932
	m,p-Xylenes	0.976
	o-Xylene	0.973
	1,2,3-Trimethylbenzene	0.949
	1,2,4-Trimethylbenzene	0.955
m,p-Xylenes	2-Chlorotoluene	0.950
	Isopropylbenzene	0.970
	tert-Butylbenzene	0.953
	o-Xylene	0.995
	1,2,3-Trimethylbenzene	0.960
	1,2,4-Trimethylbenzene	0.962
o-Xylene	2-Chlorotoluene	0.954
	Isopropylbenzene	0.966
	tert-Butylbenzene	0.961
	1,2,3-Trimethylbenzene	0.972
	1,2,4-Trimethylbenzene	0.970
	Heptane	0.905
Toluene	Ethyl acetate	0.943
1,2,3-Trimethylbenzene	2-Chlorotoluene	0.943
	Isopropylbenzene	0.965
	tert-Butylbenzene	0.986
	1,2,4-Trimethylbenzene	0.994
	Heptane	0.922
1,2,4-Trimethylbenzene	2-Chlorotoluene	0.943
	Isopropylbenzene	0.973
	tert-Butylbenzene	0.991
	Heptane	0.918
1,3,5-Trimethylbenzene	2-Ethyltoluene	0.993
	3-Ethyltoluene	0.988
	4-Ethyltoluene	0.985
2-Ethyltoluene	3-Ethyltoluene	0.986
	4-Ethyltoluene	0.983
3-Ethyltoluene	4-Ethyltoluene	0.999
2-Chlorotoluene	Isopropylbenzene	0.964
	tert-Butylbenzene	0.915
Isopropylbenzene	*tert*-Butylbenzene	0.963
Tridecane	Dodecane	0.946
	Tridecane	0.932
	Naphthalene	0.904

Table 5. Correlation of VOCs in winter.

Compounds	Correlated compounds	Pearson correlation (R)
m,p-Xylenes	*o*-Xylene	0.979
1,2,3-Tri-methylbenzene	Isopropylbenzene	0.935
	1,2,4-Trimethylbenzene	0.984
	1,3,5-Trimethylbenzene	0.975
	2-Ethyltoluene	0.957
	3-Ethyltoluene	0.962
	4-Ethyltoluene	0.965
1,2,4-Tri-methylbenzene	Isopropylbenzene	0.931
	1,3,5-Trimethylbenzene	0.987
	2-Ethyltoluene	0.969
	3-Ethyltoluene	0.978
	4-Ethyltoluene	0.980
	n-Propylbenzene + 4-Chlorotoluene	0.922
1,3,5-Tri-methylbenzene	2-Ethyltoluene	0.995
	3-Ethyltoluene	0.992
	4-Ethyltoluene	0.990
	n-Propylbenzene + 4-Chlorotoluene	0.939
2-Ethyltoluene	3-Ethyltoluene	0.991
	4-Ethyltoluene	0.989
	n-Propylbenzene + 4-Chlorotoluene	0.961
3-Ethyltoluene	4-Ethyltoluene	0.992
	n-Propylbenzene + 4-Chlorotoluene	0.966
4-Ethyltoluene	*n*-Propylbenzene + 4-Chlorotoluene	0.945
	Isopropylbenzene	0.911
Decane	Limonene	0.940

relations with other VOCs in summer, including ethylbenzene, *m,p*-xylenes, *o*-xylene, isopropylbenzene, *tert*-butylbenzene, 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, heptane, toluene, 2-ethyltoluene, 3-ethyltoluene, 4-ethyltoluene, ethyl acetate, dodecane, tridecane, naphthalene, and 2-chlorotoluene. In winter, 13 VOCs showed strong correlation with other VOCs, including *m,p*-xylenes, *o*-xylene, isopropylbenzene, 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, 2-ethyltoluene, 3-ethyltoluene, 4-ethyltoluene, *n*-propylbenzene + 4-chlorotoluene, decane, and limonene.

4. DISCUSSION

In Korea, the indoor air quality of public places is regulated by the Indoor Air Quality Control in Public Use Facilities Act. The recommended TVOC level is 500 $\mu g/m^3$. VOC levels should be measured once every 2 years and maintained below the guideline. When the VOCs were measured at 50 locations during the summer, 25 locations exceeded the guideline. When the VOCs were measured at 49 locations during the winter, 17 locations exceeded the guideline. Thus, a significant proportion of indoor public places were noncompliant with regulations.

In this study, 72 individual VOCs were identified from indoor air samples. The number of individual VOCs in one indoor air sample can be as many as 250 (Nathanson, 1993). However, 20-30 compounds account for 50-75% of the TVOC in indoor air samples (Molhave *et al.*, 1997). In this study, nine VOCs with more than 10 $\mu g/m^3$ accounted for 64.8% of the TVOC in summer and 49.6% in winter. Seven VOCs (toluene, acetone, hexane, isopropyl alcohol, *m,p*-xylenes, ethylbenzene, methyl ethyl ketone) were detected at levels of more than 10 $\mu g/m^3$ in both seasons. Ethyl acetate and nonanal were included in summer and tetrachloroethylene and limonene were included in winter. In particular, the source of the limonene may have been the high consumption of tangerines in Korea.

Six VOCs (toluene, acetone, *m,p*-xylenes, ethylbenzene, benzene, styrene) were detected in 100% of the samples in summer and winter. In summer, methylethylketone and 1-butanol were also detected in all samples. Although many VOCs are present in indoor air, the dominant VOCs in indoor air are toluene, *m,p*-xylenes, ethylbenzene, and benzene, and the dominant VOC profile recorded in this study agreed with those reported for nonresidential spaces (Salonen *et al.*, 2009; Tang *et al.*, 2005; Chao and Chan, 2001; Baek *et al.*, 1997). Based on the location and type of building, some other VOCs may be present. In mechanically ventilated buildings in Hong Kong, chloroform and trichloroethylene were also found in 100% of the samples (Chao and Chan, 2001). When VOCs were measured in problematic buildings, the most abundant VOCs were 2-(2-ethoxyethoxy)ethanol, acetic acid, 1,2-propanediol, and toluene (Salonen *et al.*, 2009).

Several studies have reported on individual VOCs in public spaces. We summarized the indoor concentrations of selected VOC species and compared them with those in other regions, as shown in Table 6 (Eklund *et al.*, 2008; Tang *et al.*, 2005; Chao and Chan, 2001; Kim *et al.*, 2001; Baek *et al.*, 1997). The VOC concentrations showed similar trends. In our study, the toluene concentration during summer was the highest. A shopping mall in Ghangzou reported high concentrations for almost all species (Tang *et al.*, 2005). In Korea, new apartment buildings have guideline levels for benzene (30 $\mu g/m^3$), toluene (1000 $\mu g/m^3$), ethylbenzene (360 $\mu g/m^3$), xylenes (700 $\mu g/m^3$),

Table 6. Comparison of indoor VOCs level in several public places (μg/m^3).

Compounds	Public spaces, Korea (Current study)		Korea Office[1)]	Birmingham, AL Department store[2)]	Hong Kong Public spaces[3)]	Ghuangzou, China Shopping mall[4)]	NJ Shopping center[5)]
	Summer	Winter					
Benzene	6.5	7.9	12.6	10.5	8.1	78	1.2
Toluene	316.8	109.9	80.4	56.7	52.8	142	144
Ethylbenzene	13.6	15.9	7.6	3.4	7.3	19	0.6
m,p-Xylenes	19.2	18.9	23.4	12	18.9	41.9	3.5
o-Xylene	7.1	6.5	14.5	3.5	5.5	8.9	
Styrene	2.1	2.8	5	1.1	5.1	13	0.2
1,2,4-Trimethyl-benzene	4.2	5.5	14.6	3.4	2.2	9.9	1.1
1,3,5-Trimethyl-benzene	2.3	1.7	6.4	0.8	8.8	3.4	0.2

[1)]Baek et al., 1997
[2)]Kim et al., 2004
[3)]Chao *et al.*, 2001
[4)]Tang, 2005
[5)]Eklund, 2008

and styrene (300 μg/m^3) before occupation. Currently, no specific guidelines have been established for individual VOCs in public spaces in Korea. As BTEX was dominant in both detection frequency and concentration levels, considering the implementation of air quality guidelines may be necessary.

When we determined correlations between individual compounds, 19 and 14 VOCs showed strong correlations with other VOCs in summer and winter, respectively. Many compounds were included in both seasons: *m,p*-xylenes, *o*-xylene, isopropylbenzene, 1,2,3-trimethylbenzene, 1,2,4-trimethylbenzene, 1,3,5-trimethylbenzene, 2-ethyltoluene, 3-ethyltoluene, and 4-ethyltoluene. Alkylbenzenes are well known as anthropogenic chemicals coming from the vehicular emissions of gasoline burning in spark-ignition engines (Chao and Chan, 2001). The main components of these gasoline emissions are benzene, toluene, ethylbenzene, *m,p*-xylenes, *o*-xylene, *p*-ethyltoluene, and 1,2,4-trimethylbenzene (Oelert *et al.*, 1974). Therefore, we suggest that indoor spaces in Korea are being affected by the infiltration of polluted outdoor air.

The sampling of VOCs can be affected by various conditions. One of the critical factors is the adsorbent tube used. When two types of adsorbent tube [a single adsorbent of 300 mg Tenax-TA and a double adsorbent of Tenax-TA in front (100 mg) and Carbotrap (200 mg)] were compared, the recorded TVOC levels were comparable, but the single tube showed slightly higher levels. Relative percent differences between the two methods indicated that the single tube may collect larger amounts of VOCs. A tube with Tenax-TA and Carbotrap was validated in experiments and field study (Kuntasal *et al.*, 2005). The tube showed high recoveries, in the range of 80-100% and MDL from 0.01 to 0.14 ppb. The sampling method also showed good linearity ($R^2 > 0.99$) and precision ($< 8\%$) values (Kuntasal *et al.*, 2005). Two adsorbent tubes showed precisions of 20-30% for most aromatic VOCs (Baek and Moon, 2004).

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