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FORMATION OF POLYCHLORINATED DIBENZO-*p*-DIOXIN FROM 2,4,4'-TRICHLORO-2'-HYDROXYDIPHENYL ETHER (IRGASAN® DP300) AND ITS CHLORINATED DERIVATIVES BY EXPOSURE TO SUNLIGHT

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SUMMARY

Exposure to sunlight in the solid state of 2,4,4'-trichloro-2'-hydroxydiphenyl ether (Irgasan® DP300) (I) produced dichlorodibenzo-*p*-dioxin(s) (di-CDD) and a trace amount of trichlorodibenzo-*p*-dioxin (tri-CDD) together with three chlorinated derivatives of Irgasan DP300, 2',3,4,4'-tetrachloro-2-hydroxydiphenyl ether (II), 2',4,4',5-tetrachloro-2-hydroxydiphenyl ether (III) and 2',3,4,4',5-pentachloro-2-hydroxydiphenyl ether (IV). These chlorinated derivatives gave various polychlorinated dibenzo-*p*-dioxins (PCDDs) upon exposure to sunlight; *i.e.*, II gave 1,2,8-tri-CDD and a tetrachlorodibenzo-*p*-dioxin (tetra-CDD); III gave di-CDD(s), 2,3,7-tri-CDD and a tetra-CDD and IV gave three pentachlorodibenzo-*p*-dioxins (penta-CDDs) with two tri-CDDs and four tetra-CDDs. Upon exposure to sunlight of commercial textile products containing Irgasan DP300, 0.02–0.03% of the agent was converted into di-CDD(s). These results suggest that Irgasan DP300 is one of the precursors of various PCDDs in the environment.

INTRODUCTION

The environmental pollution by polychlorinated dibenzo-*p*-dioxins (PCDDs) has recently become a serious problem[1–4]. The PCDDs are considered to originate from not only the contamination in chemicals[5] and accidents in chemical plants[6,7] but also the thermal and photochemical reactions of their precursors such as chlorinated phenols[8–10]. For example, PCDDs are formed upon the incineration of municipal refuse[11–15]. Therefore, it is of environmental and toxicological importance to study their formation mechanism and precursors[16–18].

2,4,4'-Trichloro-2'-hydroxydiphenyl ether (Irgasan® DP300) (I) is a chlorinated phenol that is widely used as an antimicrobial agent for textile products and as a bacteriostat for shampoo, toilet soap and cosmetics[19–25]. We reported previously[26] that Irgasan DP300 was chlorinated with sodium hypochlorite, a domestic bleaching

agent, to afford 2′,3,4,4′-tetrachloro-2-hydroxydiphenyl ether (II), 2′,4,4′,5-tetra-chloro-2-hydroxydiphenyl ether (III) and 2′,3,4,4′,5-pentachloro-2-hydroxydiphenyl ether (IV). Furthermore, Irgasan DP300 and the three chlorinated derivatives (II, III and IV) were shown to be converted to various PCDDs by heating or UV irradiation[26]. The combustion of fabrics containing them also gave PCDDs[27].

Recently, Miyazaki et al.[28] detected methylated Irgasan DP300 in fish and shellfish from the Tama River and the Tokyo Bay in Japan. Moreover, Onodera et al.[29] reported that the three chlorinated derivatives were formed upon disinfection and deodorization with sodium hypochlorite of water containing Irgasan DP300. In order to prevent pollution by PCDDs, it is important to study whether or not these compounds give PCDDs under environmental conditions.

In this paper, we examined, by means of capillary gas chromatography–mass spectrometry (capillary GC–MS), the possibility that exposure of Irgasan DP300 and its chlorinated derivatives to sunlight gives PCDDs.

EXPERIMENTAL

Reagents
        2,4,4′-Trichloro-2′-hydroxydiphenyl ether (Irgasan DP300) (I) was obtained from Ciba-Geigy (Basle, Switzerland), 1,2,4-trichlorodibenzo-p-dioxin (1,2,4-tri-CDD) and 2,3,7,8-tetrachlorodibenzo-p-dioxin (2,3,7,8-tetra-CDD) from Gasukuro Kogyo (Tokyo, Japan). The three chlorinated derivatives (II, III and IV) of Irgasan DP300 and dichlorodibenzo-p-dioxin (di-CDD, a mixture of 2,7- and 2,8-di-CDD) were synthesized as reported previously[26]. All organic solvents were of residual pesticide analysis quality (Wako Pure Chemical, Tokyo, Japan). Other reagents were of analytical reagent grade.

Fabrics
        Of the commercial textile products treated with antimicrobial agents, fabrics in which Irgasan DP300 was detected[22] were used as samples.

Conditions for capillary GC–MS
        A Shimadzu DF2000 GC–MS system equipped with a GC-MSPAC 1100 data-processing system was used with an Shimadzu CBP5-50-05 capillary column (50 m × 0.35 mm I.D.). The column temperature was programmed from 140 to 260°C at 4°C/min. The injection temperature and the separator temperature were set at 260 and 280°C, respectively. Helium was used as the carrier gas at 1.3 kg/cm^2.

Exposure of Irgasan DP300 and its chlorinated derivatives to sunlight
        A 5-mg amount of Irgasan DP300 or each chlorinated derivative was dissolved in 1 ml of acetone and placed in a glass plate (diameter 120 mm). The solvent was evaporated at room temperature and the resulting thin layer was exposed to sunlight, $(8-10) \cdot 10^4$ lux), for 18 h. The photolysate was dissolved in an adequate volume of acetone and the aliquot was analysed by high-performance liquid chromatography (HPLC) was previously reported[26] to quantify the residual amount of Irgasan DP300. After elution of Irgasan DP300 from the column, the eluate containing the chlorinated derivatives was pooled and evaporated to dryness. The residue was methylated with

ethereal diazomethane and analyzed by capillary GC–MS for identification and quantitation of compounds II–IV.

For the determination of PCDD(s) formed, the residual acetone solution of the photolysate was concentrated to *ca.* 0.1 ml. The concentrate was diluted in 10 ml of *n*-hexane and placed on a silica gel column (160 mm × 12 mm I.D.) packed with 10 g of Kieselgel 60 (Merck). The PCDD(s) was eluted from the column with 200 ml of *n*-hexane. The dioxin fraction was concentrated to 0.1 ml and analysed by capillary GC–MS. To quantify the amount of PCDD(s) originally present in the parent compound, a 5-mg amount of each compound was dissolved in 1 ml of *n*-hexane, chromatographed on a silica gel column and analysed by capillary GC–MS in the manner described above. Without photolysis, no PCDD (< 0.0004%) was detected in each compound.

Exposure of commercial textile products containing Irgasan DP300 to sunlight

Samples used as textile products were two commercial men's socks with differing loadings of Irgasan DP300. Each sample was cut into two equal pieces, one of which was weighed and exposed to sunlight, $(8–10) \cdot 10^4$ lux, for 18 h. The fabric was refluxed with 250 ml of methanol–acetic acid (9:1) for 30 min and filtered through a glass filter (3G2). Then, the fabric was refluxed again with 250 ml of ethyl acetate for 30 min and filtered. The filtrates were pooled and the solvent was evaporated. The residue was dissolved in a small volume of ethyl acetate and chromatographed on silica gel as described above. The dioxin fraction eluted from the column with *n*-hexane was evaporated and the residue was dissolved in an adequate volume of *n*-hexane for repeated clean up by silica gel column chromatography using *n*-hexane as an eluent. The eluate was concentrated and placed on an alumina column[30] (55 mm × 15 mm I.D.) packed with 10 g of basic aluminium oxide (Alumina Woelm B, Akt. 1; Woelm Pharma). The interfering substances were removed by eluting successively with 50 ml of *n*-hexane and 100 ml of 2% dichloromethane in *n*-hexane. PCDD(s) was then eluted from the column with 200 ml of 20% dichloromethane in *n*-hexane. The dioxin fraction was concentrated to 0.1 ml and analyzed by capillary GC–MS. For correction of the background amount(s) of PCDD(s), another piece of the sock was treated in the same manner except that exposure to sunlight was omitted. Prior to photolysis no PCDD (< 0.002 μg/g) was detected in the fabrics.

Quantitation of PCDDs

Di-CDD was quantified by the intensity of the molecular ion (M^+) peak at m/z 252 (base peak) in the mass spectrum using a mixture of 2,7- and 2,8-di-CDD as a standard. Similarly, the amounts of tri-CDD and tetra-CDD were determined from the intensities of the M^+ peaks at m/z 286 and 320 in the mass spectra using 1,2,4-tri-CDD and 2,3,7,8-tetra-CDD as standards, respectively. Pentachlorodibenzo-*p*-dioxin (penta-CDD) was quantified by the intensity of the M^+ peak at m/z 354 which was assumed to be the same as that at m/z 320 of tetra-CDD because of the lack of an authentic standard.

RESULTS AND DISCUSSION

Exposure of Irgasan DP300 and its chlorinated derivatives (II–IV) to sunlight

Irgasan DP300 and its chlorinated derivatives were exposed to sunlight and the amounts of chlorinated 2-hydroxydiphenyl ethers or PCDDs in the photolysates were determined as follows.

Intermolecular migration of a chlorine atom(s). Exposure of Irgasan DP300, II, III and IV to sunlight gave chlorinated and dechlorinated products by intermolecular chlorine atom migration. Table I shows the amounts of II, III and IV formed from Irgasan DP300. The commercially available Irgasan DP300 originally contained 0.003% of III as a contaminant. Upon exposure of Irgasan DP300 to sunlight, the amount of compound III was markedly increased with the appearance of an equal amount of II and a trace amount of IV. These results indicate that Irgasan DP300 can yield the three chlorinated derivatives not only by treatment with sodium hypochlorite[26,29] but also by exposure to sunlight.

Table II shows the intermolecular chlorine atom migration of compounds II–IV upon exposure to sunlight. Both II and III were chlorinated to IV and dechlorinated to Irgasan DP300, whereas IV gave Irgasan DP300, II and III by loss of chlorine atoms.

Formation of PCDDs. Fig. 1 shows the total ion monitoring (TIM) and mass chromatograms of the dioxin fraction separated from the photolysate of Irgasan DP300 (capillary GC–MS). Di-CDD(s) (M^+ peak at m/z 252) and a trace amount of tri-CDD (M^+ peak at m/z 286) were detected at 20.6 and 24.7 min, respectively. Other peaks were almost entirely due to phthalic acid esters as contaminants.

Though the di-CDD(s) showed the same retention time as that of 2,8-di-CDD, which is formed by intramolecular dehydrochlorination between the 2-chlorine atom and 2'-hydroxyl group of Irgasan DP300, its structure remains uncertain because 2,8-di-CDD was not separated from 2,7-di-CDD under the conditions employed in this study. On the other hand, the tri-CDD was neither 1,2,8- nor 2,3,7-tri-CDD. Therefore, it was not produced by the intramolecular dehydrochlorination of compound II and III once formed.

TABLE I

INTERMOLECULAR CHLORINE ATOM MIGRATION UPON EXPOSURE OF 2,4,4'-TRICHLORO-2'-HYDROXYDIPHENYL ETHER (IRGASAN DP300) (I) TO SUNLIGHT

Each compound was quantified by HPLC.

Sample	Amounts of Irgasan DP300 and its chlorinated derivatives detected (%)			
	I	*II*	*III*	*IV*
Untreated*	99.4 ± 0.04	N.D.	0.003 ± 0.0001	N.D.
Photolysate**	53	0.14	0.13	0.02
	(45–61)	(0.07–0.21)	(0.09–0.16)	(Trace–0.04)

 * Values are the averages ± S.D. of four experiments and calculated on the basis of the initial amount. N.D. is below 0.0003%.

 ** Values are the averages of two experiments with the ranges of the data in parentheses and calculated on the basis of the initial amount.

TABLE II

INTERMOLECULAR CHLORINE ATOM MIGRATION UPON EXPOSURE OF THE CHLOR-INATED DERIVATIVES (II–IV) OF IRGASAN DP300 (I) TO SUNLIGHT

Each compound was quantified by HPLC. Values are calculated on the basis of the initial amount (5 mg) and are the averages of two experiments with the ranges of the data in parentheses.

Starting material of photolysate	Amounts of Irgasan DP300 and its chlorinated derivatives (%)			
	I	II	III	IV
II	0.85	69	0.29*	0.3*
	(0.58–1.12)	(63–75)	(0.24–0.34)	(0.14–0.31)
III	0.87	0.12*	51	0.62*
	(0.54–1.19)	(Trace–0.24)	(39–62)	(0.34–0.89)
IV	0.11	Trace*	2.74*	35
	(0.10–0.12)	(Trace–0.02)	(1.84–3.63)	(33–36)

* Values are corrected by the background amount and the recovery of each compound. Trace is between 0.01 and 0.02%.
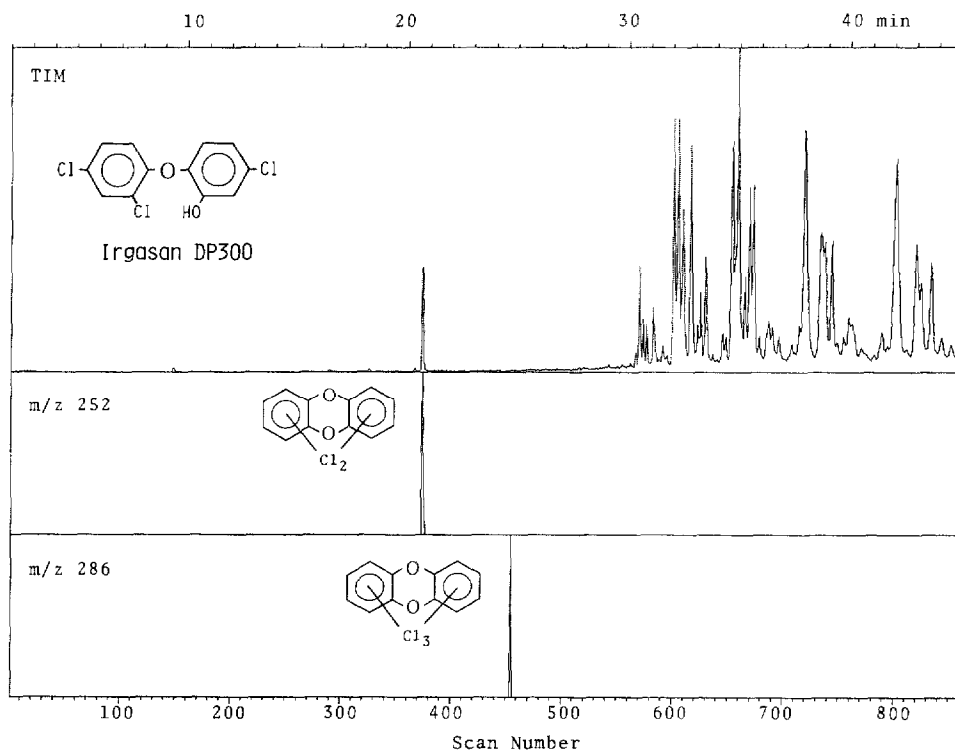

Fig. 1. TIM and mass chromatograms of the dioxin fraction from the photolysate of Irgasan DP300 with sunlight.

Fig. 2 shows the TIM and mass chromatograms of the dioxin fraction from the photolysate of compound II. A major peak at 26.0 min was assigned due to 1,2,8-tri-CDD according to its retention time[27], which was presumably formed by the intramolecular dehydrochlorination of II. In addition, small amounts of tetra-CDD (M^+ peak at m/z 320) and tetrachlorodiphenyl ether (M^+ peak at m/z 306) were detected at 29.6 and 24.8 min, respectively.

The TIM and mass chromatograms of the dioxin fraction from the photolysate of compound III are shown in Fig. 3. 2,3,7-Tri-CDD[27] was detected at 25.6 min with di-CDD(s) at 20.6 min and tetra-CDD at 29.3 min. The 2,3,7-tri-CDD was a major product formed by the intramolecular dehydrochlorination of III. Tetrachloro-diphenyl ether and two isomers of pentachlorodiphenyl ether (M^+ peak at m/z 340) were also found at 24.8, 27.6 and 28.5 min, respectively. Since the tetra-CDDs formed from compounds II and III were not 1,2,3,8-tetra-CDD as judged by their retention times, they were not produced by the intramolecular dehydrochlorination of IV once formed from II or III.

As shown previously[26], the di-CDD, 1,2,8-tri-CDD and 2,3,7-tri-CDD were formed upon UV irradiation of Irgasan DP300, II and III, respectively, though their amounts were small as those obtained in this study. However, no evidence was obtained for the formation of PCDD(s) from compound IV by UV irradiation. On the
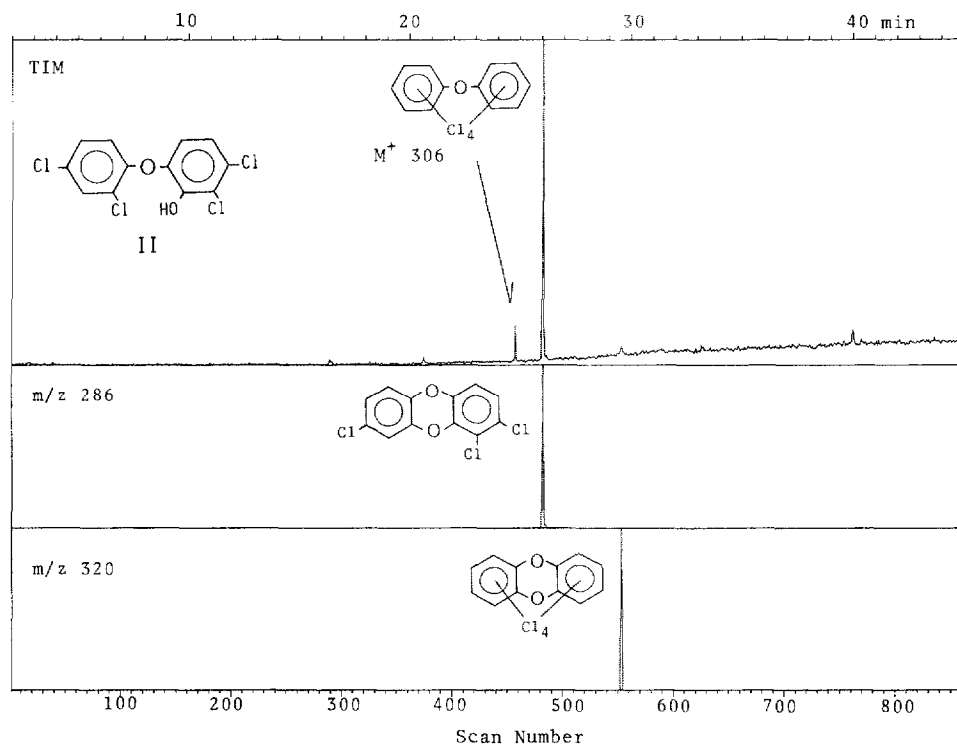

Fig. 2. TIM and mass chromatograms of the dioxin fraction from the photolysate of compound II with sunlight.
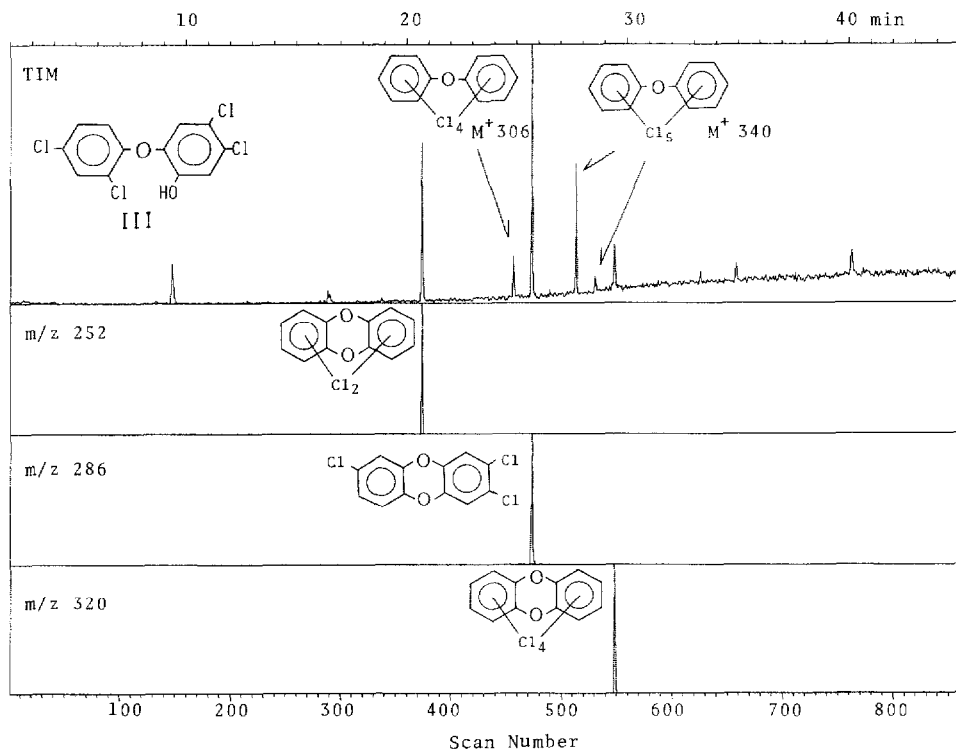
Fig. 3. TIM and mass chromatograms of the dioxin fraction from the photolysate of compound III with sunlight.

contrary, exposure of IV to sunlignht gave various PCDDs as shown in Fig. 4, though their amounts were very small; two tri-CDDs were detected at 24.7 and 25.6 min. The latter was identified as 2,3,7-tri-CDD[27]. Four tetra-CDDs were detected at 28.2, 29.3, 29.6 and 30.2 min. The last one is identified by its retention time as 1,2,3,8-tetra-CDD[27] formed by the intramolecular dehydrochlorination of IV. The amounts of the tetra-CDDs at 28.2 and 29.6 min were very small. The former was detected in only one of two experiments. Furthermore, three penta-CDDs were detected at 34.2, 34.6 and 35.8 min, though the amount of the second was very small and detected in one of two experiments.

These results are summarized in Table III. Irgasan DP 300, II and III gave two, two and three PCDDs, respectively, whereas IV gave nine PCDDs. The extent of conversion of each compound into PCDDs reached 0.09–0.18%.

Though the tri-CDDs, major products from compounds II and III, were presumably formed by intramolecular dehydrochlorination of II and III, the occurrence of some of the other PCDDs cannot be explained by the mechanism that Irgasan DP300 and its chlorinated derivatives were further chlorinated by inter-molecular chlorine atom migration followed by intramoleclar dehydrochlorination. Buser[31] reported that octachlorodibenzo-*p*-dioxin, a major contaminant at levels up to hundreds of ppm in commercial chlorinated phenols[32], was dechlorinated by UV
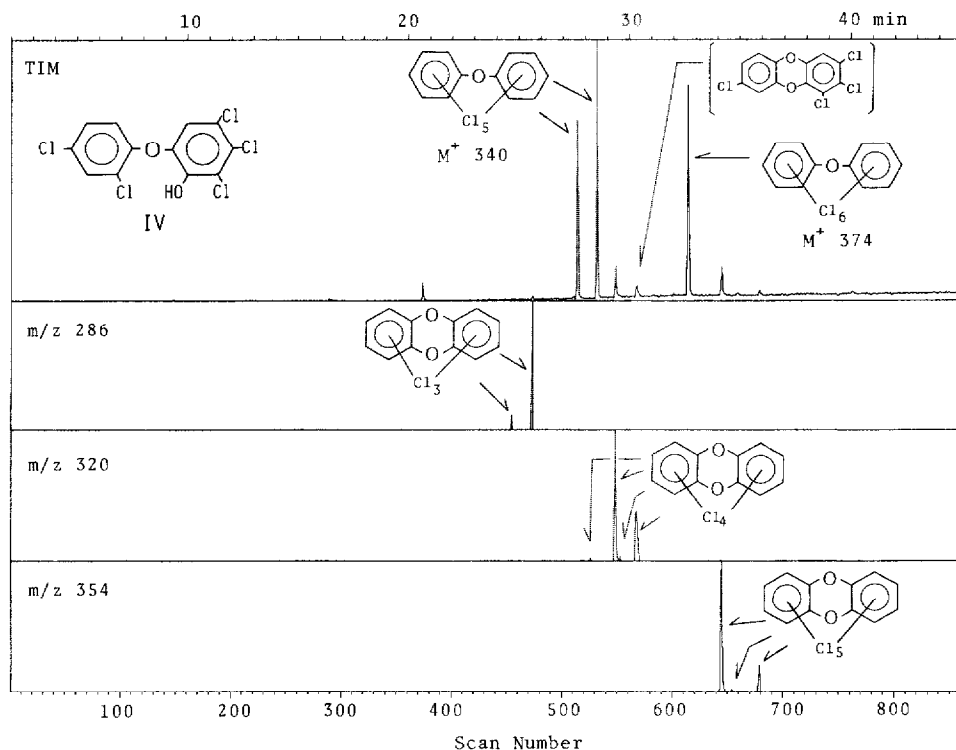
Fig. 4. TIM and mass chromatograms of the dioxin fraction from the photolysate of compound IV with sunlight.

irradiation to give trace amounts of tetra-CDDs, penta-CDDs, hexachlorodibenzo-*p*-dioxins and heptachlorodibenzo-*p*-dioxins. The present study shows that sunlight exposure of Irgasan DP300 and chlorinated derivatives gave further chlorinated PCDDs as well as dechlorinated PCDDs. These results indicate that intermolecular chlorine atom migration occurs not only in Irgasan DP300 and its chlorinated derivatives but also in PCDDs once formed. Therefore, more complicated mechanisms may operate for the formation of various PCDDs upon photolysis with sunlight, *i.e.*, ring closure of compounds II–IV without elimination of a chlorine atom and intermolecular chlorine atom migration of PCDDs to give the higher chlorinated PCDDs, as observed in the pyrolysis of II–IV[26].

These results suggest that Irgasan DP300 is converted into various PCDDs *via* its chlorinated derivatives in the environment.

Formation of PCDDs from Irgasan DP300 contained in commercial textile products by exposure to sunlight

Fig. 5 shows the TIM and mass chromatograms of the dioxin fraction of the extract from the men's sock containing Irgasan DP300 exposed to sunlight. A small amount of di-CDD(s) was detected at 20.6 min in the chromatograms, determined to be 0.04 and 0.27 μg/g from the fabrics containing 158 and 789 μg/g Irgasan DP300

TABLE III

AMOUNTS OF PCDDs FORMED UPON EXPOSURE OF IRGASAN DP300 (I) AND ITS CHLORINATED DERIVATIVES (II–IV) TO SUNLIGHT

Values are the averages of two experiments with the ranges of the data in parentheses. The retention time of each PCDD is as follows: di-CDD, 20.6; tri-CDD; (a) 24.7, (b) 26.0, (c) 25.6; tetra-CDD; (d) 29.6, (e) 29.3, (f) 28.2, (g) 30.2; penta-CDD; (h) 34.2, (i) 34.6, (j) 35.8 min.

Compound	Amounts of PCDDs formed (%)[*]				
	Di-CDD	Tri-CDD	Tetra-CDD	Penta-CDD	Total
I	0.095	0.002[a]	N.D.	N.D.	0.097
	(0.080–0.110)	(0.002 × 2)			
II	N.D.	0.18[b]	0.004[d]	N.D.	0.184
		(0.14–0.22)	(0.004 × 2)		
III	0.014	0.093[c]	0.016[e]	N.D.	0.123
	(0.012–0.015)	(0.061–0.124)	(0.014–0.017)		
IV	N.D.	0.001[a]	0.001[d]	0.023[h]	
		(0.001 × 2)	(Trace–0.001)	(0.019–0.026)	
		0.009[e]	0.038[e]	Trace[i]	0.092
		(0.006–0.012)	(0.033–0.042)	(N.D.-Trace)	
			Trace[f]	0.004[j]	
			(N.D.–Trace)	(0.003–0.004)	
			0.016[g]		
			(0.016 × 2)		

* Values are calculated on the basis of the initial amount (5 mg). N.D. is below 0.0004%. Trace is about 0.0004%.
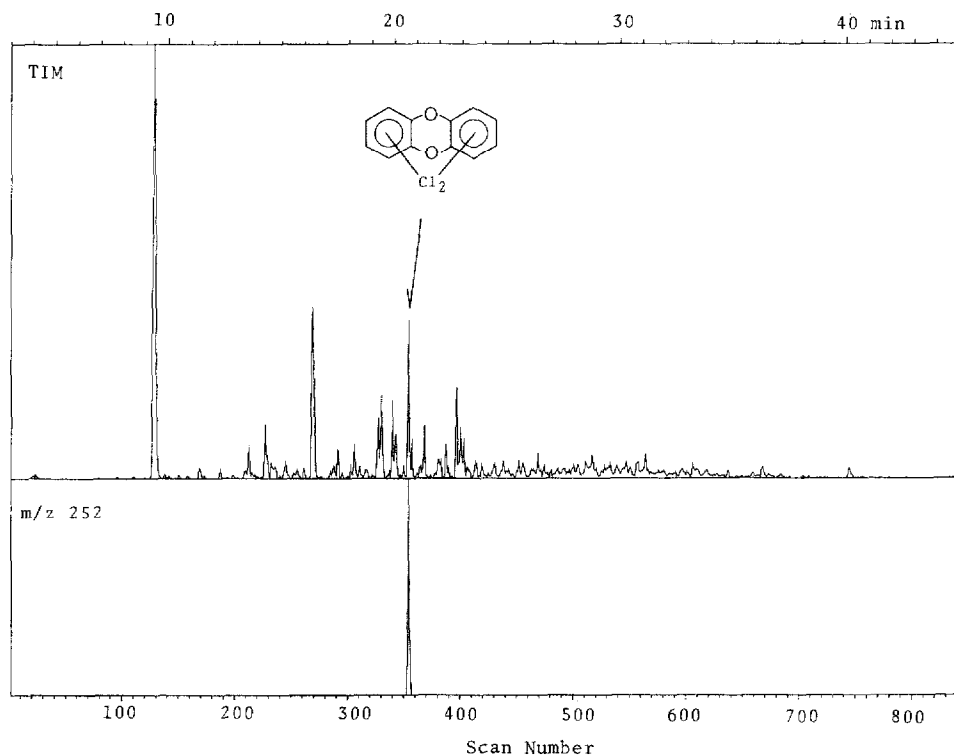

Fig. 5. TIM and mass chromatograms of the dioxin fraction from commercial men's socks containing Irgasan DP300 after exposure to sunlight.

respectively. Thus, the photolytic conversions of Irgasan DP300 into di-CDD(s) in the two fabrics were estimated to be 0.02 and 0.03%, respectively. Although 2,7- and 2,8-di-CDD derived from Irgasan DP300 are less toxic than other higher chlorinated PCDDs[33,34], the formation of di-CDD(s) in fabrics is undesirable for users.

In this study, we have demonstrated that the three chlorinated derivatives II–IV, the precursors[8,26,27] of more toxic PCDD[33,34], were formed from Irgasan DP300 upon exposure to sunlight, though their amounts were less than those formed by bleaching with sodium hypochlorite[26]. As with UV irradiation, the extents of conversion of Irgasan DP300 and its chlorinated derivatives into PCDDs upon exposure to sunlight were less than those obtained by the thermal conversion[26,27]. However, such photolytic conversion into PCDDs with sunlight may easily occur under the conditions of our daily life and environment. Thus, the use of Irgasan DP300 and its abandonment in the environment may be causative of the pollution by various PCDDs.

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