IMPROVEMENT OF DEVISE TO ESTIMATE DERMAL EXPOSURE RATE OF PHOSPHORUS FLAME RETARDANTS IN INDOOR PRODUCTS

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Introduction:
Organophosphorus flame retardants (PFRs) are contained in various indoor products (e.g., car seats, curtains, and carpets) at high concentration. Because PFRs are not chemically bonded to the original material, they release into the environment easily by abrasion and/or volatilization. Exposure to PFRs results in health adverse effects such as endocrine disruption, possible carcinogenicity, and neurodevelopment disorders[1].

A car cabin is the indoor environment where people spent the third largest proportion of their day, after homes and offices[2]. In a previous study, the occurrence of PFRs in cars, theaters, furniture stores, offices, and electronics stores was measured. The highest PFR concentration was obtained in a nine-year car (tris (2-chloroisopropyl) phosphate: TCPP)[3]. Although the concentrations of PFRs in car indoor environment are likely to be high compared with those in home and office, the information on the occurrence of PFRs in car indoor environments has been limited. Therefore, exposure to PFRs in car cabin should be investigated.

Conventionally, inhalation of indoor air including vaporized PFRs and unintentional ingestion of indoor dust on which PFRs are adsorbed are recognized as major exposure routes of PFRs. Recent studies reported that the dermal exposure could be comparable to inhalation and dust ingestion[4]. To estimate the dermal exposure rate of PFRs, the EPISKIN epidermal model and human skin were used to evaluate permeabilities of PFRs through the skin. However, these conventional devises have disadvantages such as to require highly skilled professional techniques and expensive.

To overcome disadvantages, we developed a device which could estimate the dermal exposure rate based on the migration rate of PFRs from a product, which includes PFRs, to the devise. The devise consists of silicone, which is used to quantify personal exposure rate of semi-volatile organic compounds (SVOCs) such as polycyclic aromatic hydrocarbons (PAHs) and flame retardants in previous studies[5]. The silicone could be also suitable in terms of price and handling. Our previous study reported that the devise could successfully estimate the dermal exposure rate[6]. However, the effects of characteristics of the devise (e.g., type of silicone and thickness) on the analytical qualities have not been investigated.

In this study, to optimize the devise to measure the dermal exposure rates of PFRs via direct contact with products, the effects of type of silicone were quantitatively investigated using a kinetic model.

Materials and methods:
Sample
A car seat contains cresyl diphenyl phosphate (CsDPhP), triphenyl phosphate (TPhP), tris (2-chloroethyl) phosphate (TCEP), tricresyl phosphate (TCsP), and tris (2-chloroisopropyl) phosphate (TCPP), whose concentrations were 0.89 (CsDPhP), 0.15 (TPhP), 0.12 (TCEP), 0.07 (TCsP), and 0.03 (TCPP) wt%, respectively.

Pretreatment
Silicone sheets (2.5 cm × 2.5 cm) obtained from Company A (silicone devise A) and Company B (silicone devise B) were ultrasonicated with ethyl acetate/methanol (1:1, v/v) for 15 min twice, and then dried.

Migration experiment
The migration experiments, in which the silicone sheet was placed on the car seat, were performed in a incubator (25°C). At the predetermined time, the siliconce sheet was sampled. To simulate the body wight, a weight of 30 g cm^{-2} was placed on the silicon sheet[7].

Extraction procedure
The sampled silicone sheet was cut into two pieces, which were extracted by the Soxhlet extraction method for 16 hours with 200 mL acetone/hexane (1:1, v/v). The extract is concentrated to 1 mL with an evaporator and concentrated to 100 µL by nitrogen purge. The solvent is replaced with acetonitrile, and spiked with tributyl

phosphate (TBP)-d_{27} (20 µL) and $^{13}C_6$ -hexabromobenzene (HBBz) (50 µL) as internal standards, and diluted with acetonitrile (830 µL) to the final volume of 1 mL.

Anatytical method

The analysis of PFRs in the sampled silicone sheet was carried out by a liquid chromatography coupled with tandem mass spectrometry (LC-MS/MS) (Thermo Fisher Scientific Inc.) in atmospheric pressure chemical ionization (APCI) mode. A 2 µL aliquot of the extract was injected onto Accucore Vanquish C18 column (internal diameter: 2.1 mm, length: 100 mm, particle size: 1.5 µm) with water (Solvent A) and acetonitrile/methanol (1:4) (Solvent B) as the mobile phases at a flow rate of 0.3 mL min^{-1}. The column temperature was maintained at 50°C. The gradient program was as follows: isocratic at 5% solvent B for 0.5 min, isocratic at 100% solvent B for 6.5 min, isocratic at 100% solvent B for 8.0 min, isocratic at 5% solvent B for 0.1 min, and then isocratic at 5% solvent B for 1.9 min. The MS/MS were operated under selected reaction monitoring (SRM) mode. In this study, trimethyl phosphate (TMP), triethyl phosphate (TEP), tributyl phosphate (TBP), tris(2-ethylhexyl) phosphate (TEHP), tris(butoxyethyl) phosphate (TBOEP), triphenyl phosphate (TPhP), cresyl diphenyl phosphate (CsDPhP), 2-ethylhexyl diphenyl phosphate (EHDPhP), tricresyl phosphate (TCsP), tris(2-chloroethyl) phosphate (TCEP), tris(1,3-dichloro-2-propyl) phosphate (TDCPP), tripropyl phosphate (TPP), tris(2-chloroisopropyl) phosphate (TCPP), and triphenylphosphine oxide (TPhPO) were targeted.

Model for migration

In our previous study[8], we developed the model to simulate migration of PFRs from a product, which includes PFRs, to indoor dust attached on the product. In this study, we applied the model to simulate the migration of PFRs from the car seat to the silicone sheet. The migration rate could be calculated by the following equation.

$$\frac{dC_s}{dt} = k_s(C_s^* - C_s) \quad (1)$$

where C_s is the concentration of an individual PFRs in the silicone sheet (ng cm^{-3}), k_s is the migration rate constant (h^{-1}), and C_s^* is the equilibrium concentration of PFRs in the silicone sheet (ng cm^{-3}). C_s^* is given by the following equation.

$$C_s^* = K_s\, C_{car\ seat} \quad (2)$$

where K_s is the equilibrium constant (−).

$$C_s = C_s^*\,(1-e^{-kdt}) \quad (3)$$

By parameter fitting (the least squares method) using the data for the temporal dependence of the concentration of PFRs from the car seat to the silicone sheet, we determined k_s and C_s^*.

Results and discussion:

Recovery test

The recovery rates of PFRs added onto the silicon sheet A and B were measured. The results are shown in Figure 1. As for the silicone sheet A, the recovery rates ranged 45% (trimethyl phosphate: TMP)–133% (tris(1,3-dichloro-2-propyl) phosphate: TDCPP). The recovery rates of 10 PFRs targeted in this study (10 out of 14) were within the sufficient range (80%–120%). On the other hand, those for the silicone sheet B ranged 44% (TMP)–170% (tris(2-butoxyethyl) phosphate: TBOEP), and those of 10 PFRs were in the sufficient range.

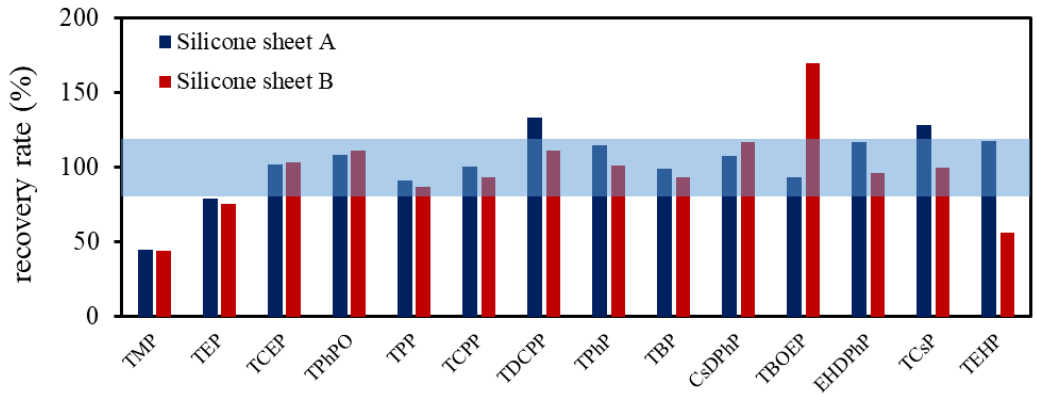

Figure 1: Recovery Rates of Organophosphorus Compounds

Migration experiment

The results of migration experiments are shown in Figure 2. The concentrations of PFRs in the silicone sheet A were gradually increased with the contact time with the car seat, and achieved at 48 (TCEP), 33 (CsDPhP), 17 (TCPP), 9 (TPhP), and 1 (TCsP) ng cm^{-3} in 4 hours. On the other hand, those of PFRs in the silicone sheet B were rapidly increased with the contact time, achieved at 371 (TCEP), 625 (CsDPhP), 144 (TCPP), 140 (TPhP), and 39 (TCsP) ng cm^{-3} in 4 hours, and then got the equilibrium.

The values of C_s^* and k_s in Eq. 1 were determined by the parameter fitting, which are listed in Table 1. The equilibrium concentrations (C_s^*) of PFRs in the silicone sheet A and B were 460 (TCEP), 210 (CsDPhP), 160 (TCPP), 80 (TPhP), and 18 (TCsP) ng cm^{-3}, 600 (TCEP), 590 (CsDPhP), 310 (TCPP), 150 (TPhP), and 44 (TCsP) ng cm^{-3}, respectively. The values of C_s^* for the silicone sheet B were 1.3–2.8 times higher than those of the silicone sheet A. On the other hand, the migration rates (k_s) of PFRs from the car seat to the silicone sheet A and B were 0.035 (TCPP), 0.030 (CsDPhP), 0.027 (TCEP), 0.025 (TPhP), and 0.017 (TCsP) h^{-1}, 0.85 (CsDPhP), 0.50 (TPhP), 0.33 (TCsP), 0.29 (TCEP), and 0.16 (TCPP) h^{-1}, respectively. The values of k_s for the silicone sheet B were 4.6–28 times higher than those of the silicone sheet A. From these results, the migration rates of PFRs from the car seat to the silicone sheets were depended on the type of silicone sheets, and the silicone sheet B has a higher affinity to PFRs.

The relationships between the octanol/water partition coefficient (log K_{OW}) of PFRs and parameters (K_s and k_s) are shown in Figure 3. The log K_{OW} and K_s showed the negative statistical correlation in silicone sheet A (r^2 = 0.789, $p < 0.05$). On the other hand, there were no statistical correlation in silicone sheet B (r^2 = 0.572, $p > 0.05$). No statistical correlations between the log K_{OW} and k_s in silicone sheets A (r^2 = 0.197, $p > 0.05$) and B (r^2 = 0.435, $p > 0.05$).

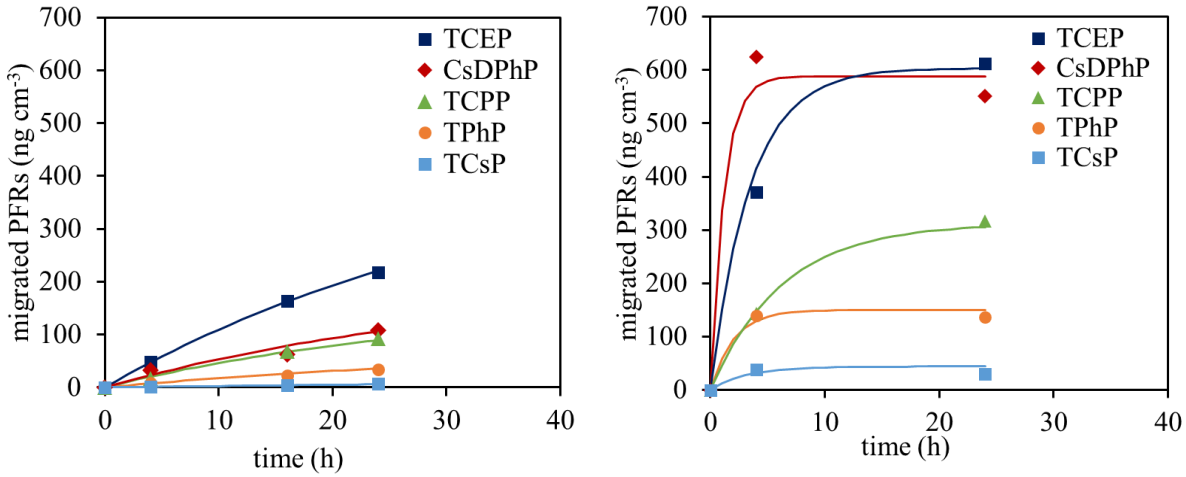

Figure 2: Migration Rates of PFRs from Car Seat to Silicone Sheets (Left: Silicone Sheet A, Right: Silicone Sheet B) (Lines in the figures show the estimated value by kinetic model)

Table 1: Kinetic Parameters for Model to Estimate Migration of PFRs from Car Seat to Silicone Sheet

Silicone sheet	Parameters	PFRs				
		TCEP	CsDPhP	TCPP	TPhP	TCsP
A	C_s^* (ng cm^{-3})	460	210	160	80	18
	k_s (h^{-1})	0.027	0.030	0.035	0.025	0.017
B	C_s^* (ng cm^{-3})	600	590	310	150	44
	k_s (h^{-1})	0.29	0.85	0.16	0.50	0.33

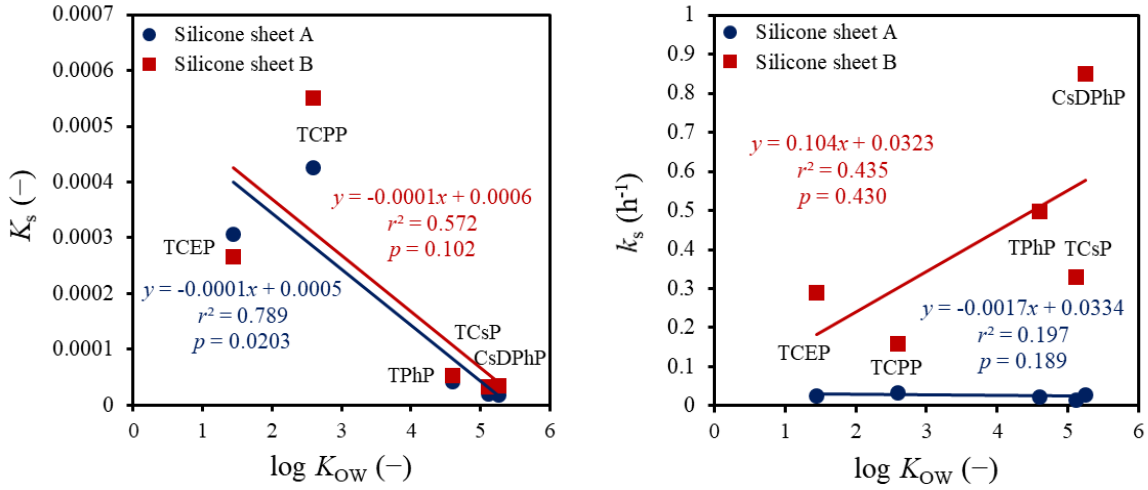

Figure 3: Relationship between Octanol/Water Partition Coefficient, log K_{OW}, and Equilibrium Constant, K_s, (Left) and Migration Rates, k_s, (Right)

Conclusions:

In this study, we compared the migration rates of PFRs from the car seat to the silicone sheets A and B. Experimental results revealed that the migration rates of PFRs was largely affected by the type of silicone sheet, those using the silicone sheet B was higher than those using the silicone sheet A. Consequently, the silicone sheet B is likely to be suitable to estimate the dermal exposure rates of PFRs via the direct contact with the product which includes PFRs.

The kinetic model developed could successfully describe the migration rates of PFRs using two kinetic parameters (the equilibrium concentration and the migration rate constant), which facilitates the estimation of the dermal exposure rates of PFRs via direct contact with the products and the health risks posed by PFRs in indoor products.

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