JOURNAL OF AGRICULTURAL AND FOOD CHEMISTRY

Article

pubs.acs.org/JAFC

Assessment of the Exposure of Workers to the Insecticide Imidacloprid during Application on Various Field Crops by a Hand-Held Power Sprayer

Hoon Choi,[†,‡] Joon-Kwan Moon,[§] and Jeong-Han Kim*[,†]

[†]Department of Agricultural Biotechnology, Seoul National University, Seoul 151-742, Republic of Korea

[‡]Food Contaminants Division, Food Safety Evaluation Department, Ministry of Food and Drug Safety, Cheongwon-gun 363-951, Republic of Korea

[§]Department of Plant Life and Environmental Sciences, Hankyong National University, Ansung 456-749, Republic of Korea

ABSTRACT: Exposure assessment and risk assessment for imidacloprid were conducted for agricultural workers through mixing/loading and application with a power sprayer in four kinds of crop fields. The spray suspension was prepared with 10% wettable powder (250 g) for 5 min and applied on field crops for 1 h. A patch method and a personal air sampler with XAD-2 resin were used to monitor the dermal and inhalation exposure, respectively. In mixing/loading, the total dermal exposure on the whole body was 0.2 (cucumber) to 2.0 (apple) mg and the most exposed part of body was the hand (48−100% of total exposure). During the application of imidacloprid, whole dermal exposure was in the range of 2.9 (apple) to 9.5 (green pepper) mg. The primary sites exposed to pesticides were legs (51−79% of total exposure) in cucumber, green pepper, and paddy fields, whereas the primary sites were hands (35% of total exposure) in the apple field. The inhalation exposure was determined to be 0.2 (paddy) to 2.8 (cucumber) μg and 0.2 (paddy) to 3.0 (cucumber) μg during mixing/loading and application, respectively. The absorbable quantity of exposure and the margin of safety were determined for risk assessment. Workers were exposed through inhalation as 23−93 and 2−11% of the absorbable quantity of exposure during mixing and application, respectively. The margin of safety of all cases was much higher than 1, indicating the lowest possibility of risk.

KEYWORDS: *imidacloprid, exposure, apple, cucumber, green pepper, paddy*

INTRODUCTION

In agriculture, pesticides are indispensable for controlling many insect pests, diseases, and weeds during cultivation and storage, resulting in an important role in crop quality improvement as well as a reduction in work load and time. However, direct contact with pesticides by workers that handle and apply these agents can lead to harmful effects depending on the level of exposure and toxicity because pesticides are toxic compounds.[1] Therefore, it is positively necessary to quantify the occupational exposure to pesticides for safety evaluation of workers. The level of exposure is affected by the properties of the compound, but mainly by the type of work, the hygienic behavior of the workers, the time of contact with the chemical, and the equipment used for application of the pesticide.[2−4]

Passive dosimetry estimates the amount of pesticide adhering to the surface of skin or entering the body by inhalation with appropriate devices.[5] Whole body dosimeters (WBDs), patches, gloves, and socks were mainly used to measure dermal exposure. In the patch method, the potential contamination of the workers' skin and clothing is measured using a variable number of absorbent cloth or paper patches, attached to body regions inside or outside of clothing.[6] The glass tubes containing solid absorbents attached to battery-powered personal sampling pumps are generally used for monitoring of inhalation exposure, for the sake of convenience, the establishment of a standard respiratory rate, and the development of various solid adsorbents.[7,8] The pesticide exposure estimated or monitored is then compared to the relevant risk value, generally acceptable operator exposure level (AOEL), or no observable (adverse) effect level [NO(A)EL].

Many exposure studies have been conducted for agricultural workers such as mixer/loader and applicator in a greenhouse; in orchards, including apple, mandarin, and mango orchards; and in the paddy field.[2,9−16]

Imidacloprid is a neonicotinoid insecticide that has been used for the control of many insect pests. It has a broad spectrum of activity with long residual and systemic effect and low toxicity to nontarget organisms. It is poorly soluble in water (solubility of 61 mg/L) and is resistant to hydrolysis at pH 5−11. It acts as an antagonist to insects by binding to postsynaptic nicotinic receptors in the central nervous system after it is absorbed through contact and stomach action. Toxicity to mammalian is low as an LD_{50} (24 h, skin) of >5000 mg/kg, and the acceptable daily intake (ADI) value is 0.057 mg (kg of body weight)$^{-1}$ day^{-1}.[17]

To the best of our knowledge, there are no previously published studies comparing exposure patterns for workers among various crop plants, including the paddy field, during the application of imidacloprid. This study was conducted to compare the pesticide exposure pattern of mixers/loaders and applicators when imidacloprid was applied to fruit, upland, and

Received: July 18, 2013
Revised: October 7, 2013
Accepted: October 10, 2013
Published: October 10, 2013

paddy crops using a power sprayer. Major exposure characteristics in different crop fields were compared, and related risk assessments were conducted using the AOEL of imidacloprid.

■ MATERIALS AND METHODS

Chemicals. Imidacloprid wettable powder (Conidor, WP, 10%, Dongbu-hannong Chemical, Daejeon, Korea) was purchased from a local vendor. The analytical standard of imidacloprid (99.8% pure) was obtained from the manufacturing company and Rural Development Administration (RDA), Korea. All solvents were high-performance liquid chromatography (HPLC) grade and purchased from Fisher Scientific Korea Ltd. (Seoul, Korea).

Dermal Exposure Matrices. The patch for dermal exposure measurement was made by putting cellulose TLC (thin-layer chromatography) paper (17CHR, 1 mm thickness, Whatman International Ltd.) in the patch pocket (10 cm × 10 cm) with a circular exposure part (50 cm^2). The back of the TLC paper was covered with aluminum foil to prevent contamination.[1,2] The exposure of hands and feet was monitored with cotton gloves and socks.[18] The exposure of faces was evaluated using square cotton masks (200 cm^2).[1,3]

Personal Air Monitor. Inhalation exposure was measured using a personal air monitor equipped with an air pump (GilAir-3, Sensidyne, Clearwater, FL), a solid sorbent tube (ORBO 609 Amberlite XAD-2 400/200 mg, Supelco, Bellefonte, PA), and a glass fiber filter (type AE, SKC, Eighty Four, PA). The solid sorbent tube is dual-layered and contains one larger bed of absorbent (400 mg) followed by a smaller back-up bed (200 mg) to capture any sample breakthrough. The beds contain separators of glass wool to secure the beds in place. XAD-2 resin was used for trapping pesticides in air, whereas the glass fiber filter in 37 mm open-faced cassettes was used for collecting particles of the pesticide and filtering fine dust.

Fields and Application. The exposure studies were conducted in an apple field (Taegu Apple Research Institute, Gunwi-myeon, Gyeongbuk, Korea), a cucumber greenhouse (Pyongtaek, Gyeonggi, Korea), a green pepper field (National Horticultural Research Institute, Suwon, Korea), and a paddy field (College of Agricultural Life and Science, Seoul National University, Suwon, Korea). In each experiment, the temperature was monitored with a thermometer at the start and end of mixing/loading or spraying activity, which lasted for ∼2 h. The relative humidity was also noted using a hygrometer. The wind speed was obtained from the Korea Meteorological Administration by a mobile Internet system (Table 1). Workers for mixing/loading and application wore protective garments (SP protective, KleenGuard, Yuhan-Kimberly Korea Ltd., Seoul, Korea). The spray suspension was prepared for 5 min by mixing 10% Conidor WP (250 g, 1 pack) with 500 L of water in a mixing tank and stirring the mixture with a stick. The applicator sprayed the spray suspension using a power sprayer for 1 h by stepping backward and moving the lance up and down. Each trial was repeated twice.

Dermal and Inhalation Exposure Sampling. For dermal exposure sampling, dermal patches were placed on the outer protective garment over the body parts (forehead, front of neck, back of neck, chest/abdomen, back, upper arm, forearm, thigh, and shin) of workers,[8] who wore cotton gloves, cotton socks, and masks. After mixing/loading or spraying, exposure samples were removed for analysis of the pesticide concentration. In the case of inhalation exposure sampling, a glass fiber filter cassette and an XAD-2 resin tube were attached in the breathing zone with a clip, and an air pump was fastened on the belt. The air flow rate was 2 L/min. After mixing/loading or spraying, the XAD-2 resin and filter were removed and analyzed for pesticide content.

Extraction of Imidacloprid from Monitoring Matrices. Imidacloprid on patches, gloves, socks, and masks was extracted with 60, 300, 300, and 300 mL of acetone, respectively, when the materials were shaken at 200 rpm for 1 h. Pesticide trapped on the XAD-2 resin and filter was extracted with 10 mL of acetone. After the extract had been concentrated with a nitrogen evaporator (Reacti-Vap, Pierce, Rockford, IL) and dissolved in methanol, aliquots (10 μL) were analyzed via HPLC.

Table 1. Field Characteristics, Application, and Meteorological Conditions

	apple	cucumber	green pepper	paddy
field				
application area (m^2)	1600	630	742.5	2240
age of plants (years)	6	–	–	–
plant growth stage		fruiting stage		
planting density[a]	dense	dense	very dense	very dense
plant height (cm)	300	150	100–120	70
inner row distance[b] (cm)	70	25	40	10
row distance[c] (cm)	390	150	100	16
application				
application method		power sprayer		
lance length (m)	1.8	1.0	1.0	1.0
boom length (m)	7	1	1	8
climate				
temperature (°C)	26	24–27	26–27	28
relative humidity (%)	62–64	51–57	57	60
wind speed (m/s)	1.0–1.9	–	1.6–3.3	1.6

[a]The density at which plants are planted in a cultivated plot. [b]The distance between plants in a row. [c]The distance between rows in planting.

Analytical Conditions. Imidacloprid was analyzed using HPLC (Agilent 1100 series, Agilent Technologies Inc., Santa Clara, CA) with a Luna C18 column (5 μm particle size, 4.6 mm × 250 mm, Phenomenex, Torrance, CA). The mobile phase consisted of water and acetonitrile [55:45 (v/v)], and the flow rate was 1.0 mL/min. A variable-wavelength detector (Agilent Technologies Inc.) was used for detection at 270 nm.

Method Validation. Aliquots of standard solutions at concentrations from 0.001 to 1 mg/L were analyzed to determine their limits of detection (LODs) before their limits of quantitation (LOQs) were calculated. The method limit of quantitation (MLOQ) is a practical LOQ of the total analytical method and is usually calculated using the LOQ, injection volume, and extract solvent volume via an analytical method.[19] The coefficient of variation (CV) of the integrated peak area was calculated after two (0.1 and 1 mg/L) standard solutions had been analyzed five times by HPLC to check the repeatability of analysis. For the calibration curve linearity test, various standard solutions (LOD level of ∼10 mg/L) were analyzed and the linearity of the curve was investigated after preparation for 1 and 3 days. In a recovery test, three (MLOQ, 5 MLOQ, and 10 MLOQ level) standard solutions were spiked in control exposure samples to measure the recovery of pesticide from various matrices. For the field recovery test, a certain level (5 MLOQ) of pesticide was spiked on patches, gloves, socks, masks, and XAD-2 resin in field. Matrices were exposed to the outdoors for a period of time equivalent to the duration of the spray application to simulate field study conditions. A trapping efficiency test was conducted by spiking a 100 MLOQ level of a standard solution on the bottom of a U-shaped glass tube (Daejung Chemical, Daejeon, Korea) and passing air through the system at a rate of 2 L/min for 4 h. The U-shaped glass tube was heated to 70 °C to help volatilization of compounds. The residue in the U-shaped glass tube and the amount trapped in the XAD-2 resin were analyzed, and the mass balance was calculated. A breakthrough test was conducted by adding a 10 MLOQ level of a standard solution in the primary resin part of the solid sorbent tube and passing air through the tube at a rate of 2 L/min for 4 h. One primary and secondary part of the resin were analyzed separately. All analyses and tests were repeated three times.

Exposure Calculation. The dermal exposure intensity (micrograms per square centimeter) was calculated by dividing the amount (micrograms) of imidacloprid on the exposure matrix by the area (square centimeters) of the matrix. The dermal exposure amount (micrograms) per body part for Korean adult males was calculated by extrapolating the exposure intensity (micrograms per square centimeter) to the body surface area (square centimeter).[18] The inhalation exposure amount (nanograms) was determined by extrapolating the amount of pesticide trapped in the XAD-2 resin and filter (nanograms) to the total respiration volume during work activity using the working respiration rates (1270 L/min) for Korean adult males.[18]

Risk Assessment. Risk assessment was conducted with total exposure per day for agricultural workers. The potential dermal and inhalation exposure (PDE and PIE, respectively) per day were obtained by multiplying the corresponding exposure amount (micrograms) with five working activities because workers generally mix/load and apply the pesticide suspension five times per day using a powder sprayer. The actual dermal exposure (ADE) for the mixer/loader and applicator was calculated on the basis of rates of penetration through clothes of 1 and 10%, respectively,[18,20] and the assumption of 8% skin absorption.[21] The AQE (absorbable quantity of exposure, in milligrams per day) was obtained by adding ADE and PIE because inhalation exposure (PIE) is usually considered to be 100% absorbed.[2,22,23] The margin of safety (MOS)[24] for workers was calculated using following modified formula: MOS = AE/AQE. Acceptable exposure (AE) is obtained by multiplying the AOEL of imidacloprid (0.08 mg kg^{-1} day^{-1})[21] by body weight. The body weight for an average Korean adult male (70 kg) was obtained from KNHANES 2008–2010[25–27] with SAS (Statistical Analysis System version 9.1.3, SAS Institute Inc., Cary, NC).

RESULTS AND DISCUSSION

Selection of Crops and Pesticide. Apple, cucumber, green pepper, and rice were selected to represent orchard (apple), upland field (green pepper), paddy field (rice), or greenhouse (cucumber) and short crop (cucumber, green pepper, and rice) versus tall crop (apple). Imidacloprid was registered for all subject crops, and wettable powder (WP) was used because the powder usually drifts to contaminate workers during mixing/loading.

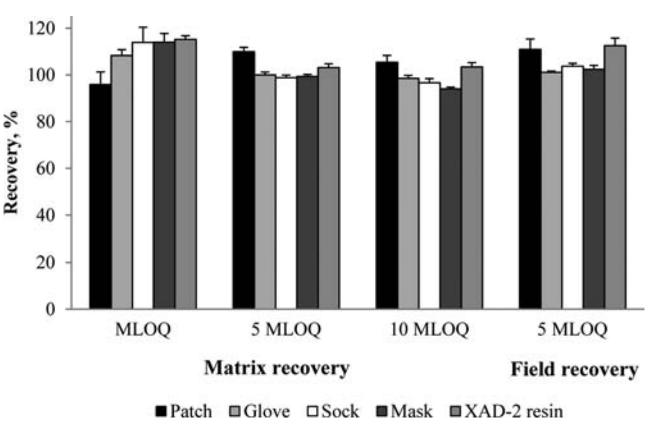

Figure 1. Recovery and field recovery of imidacloprid from matrices used in this study.

Table 2. Breakthrough Test and Trapping Efficiency Test for the XAD-2 Resin

test	treated level	recovery (%)[a]		
breakthrough	10 MLOQ (25 μg)	primary XAD	secondary XAD	total
		99.0 ± 1.2	1.0 ± 0.9	100.1 ± 2.0
trapping efficiency	100 MLOQ (250 μg)	residue	XAD	total
		95.8 ± 12.0	0.5 ± 0.4	96.3 ± 11.5

[a]The mean of three repeated tests was reported with the standard deviation.

Method Validation. The LOD was set at 0.5 ng for imidacloprid with a signal-to-noise ratio of >3. The LOQ was defined as 2.5 ng (=5 LOD). These were low enough to detect the trace level of imidacloprid. MLOQ levels for imidacloprid were determined to be 15, 75, 75, 75, and 2.5 μg for patches, gloves, socks, masks, and XAD-2 resin, respectively. The repeatability as the precision of analysis was good (CV < 3%). Calibration curves of imidacloprid were derived in the range of 0.05–10 mg/L. The linearity was consistent for 3 days (R^2 > 0.9999). The selectivity was excellent because no other interfering peaks were observed at the retention time of imidacloprid. The matrix extraction efficiency (Recovery) was in the range of 94–115%, and the RSD was <10% (Figure 1), indicating the reasonable extraction efficiencies. Field recovery values were 101–113% (CV = 0.5–4.0%), indicating any losses of pesticides due to transfer, storage, transit conditions, and exposure to light were not significant (Figure 1). A trapping efficiency test was conducted to measure the efficiency of the XAD-2 resin in trapping pesticides. The mass balance was 96.3 ± 11.5%, and <0.5% evaporated (Table 2). Therefore, the XAD-2 resin was shown to be useful for trapping those pesticides in air. A breakthrough test was used to evaluate the adsorption ability of the XAD-2 resin. Only 1% of imidacloprid was passed through to the secondary part of the resin (Table 2), indicating that the first resin part has a good holding capacity.

Dermal Exposure during Mixing/Loading. The dermal exposure to imidacloprid was 0.2 mg (cucumber) to 2.0 mg (apple) for mixing/loading (Table 3). The ratios of dermal exposure to total prepared active ingredient (a.i.) ranged from 0.001% (cucumber) to 0.008% (apple) and were within the range of 0.0007–0.59% as reported in previous studies.[2,13,15,28]

The highest level of exposure was observed on hands (48.3–100.0% of total dermal exposure), being similar to the report (19.0–99.9%) with fenvalerate and methomyl,[2,15] because hands for the mixer/loader were contaminated by the direct contact with the powder when the containers were torn open and the pesticide powder was poured into the reservoir to make a suspension. It is well-known that the level of exposure of hands is usually higher than that of other body parts, especially during the mixing/loading steps.[2,15,29–31] Therefore, recent studies had measured only exposure on hands as major exposure parts to evaluate the dermal exposure during mixing/loading,[28,32,33] as suggested by the national guideline of RDA.[34]

Dermal Exposure during Application. Machado-Neto[3] mentioned that ≥99% of total exposure occurred by the dermal route, and it was reported that the greatest level of potential exposure is through the dermal absorption during spraying operations.[35]

In this study, during imidacloprid application, dermal exposure was in the range of 2.9 mg (apple) to 9.5 mg

Table 3. Dermal Exposure during Mixing/Loading

field	body (mg)	hands (mg)	total (mg)	hand ratio[a] (%)	ratio to prepared a.i.[b] (%)
apple	0.7 ± 0.1	1.3 ± 1.6	2.0 ± 1.6	48.3 ± 39.3	0.008 ± 0.007
cucumber	0.02 ± 0.01	0.2 ± 0.1	0.2 ± 0.1	88.8 ± 8.8	0.001 ± 0.001
green pepper	0.7 ± 0.5	1.1 ± 0.8	1.7 ± 1.3	60.0 ± 3.0	0.007 ± 0.005
paddy	nd[c]	0.7 ± 1.0	0.7 ± 1.0	100.0 ± 0.0	0.003 ± 0.004

[a]Ratio of hand exposure to whole body exposure, including hands. [b]Ratio of total dermal exposure to prepared active ingredient. [c]Not detected.

Table 4. Dermal Exposure on Body Parts during Application

	apple		cucumber		green pepper		paddy	
body part	amount (mg)	intensity (μg/cm²)	amount (mg)	intensity (μg/cm²)	amount (mg)	intensity (μg/cm²)	amount (mg)	intensity (μg/cm²)
head	0.1 ± 0.0	0.2 ± 0.0	0.03 ± 0.04	0.06 ± 0.08	0.01 ± 0.00	0.03 ± 0.00	0.04 ± 0.01	0.1 ± 0.0
face	0.03 ± 0.01	0.06 ± 0.02	0.2 ± 0.3	0.5 ± 0.6	0.03 ± 0.01	0.06 ± 0.01	0.02 ± 0.00	0.04 ± 0.01
front of neck	0.02 ± 0.01	0.1 ± 0.0	0.01 ± 0.01	0.06 ± 0.05	0.006 ± 0.000	0.02 ± 0.00	0.01 ± 0.00	0.05 ± 0.01
back of neck	0.02 ± 0.01	0.1 ± 0.0	0.007 ± 0.001	0.04 ± 0.01	0.007 ± 0.002	0.04 ± 0.01	0.01 ± 0.00	0.04 ± 0.01
chest/abdomen	0.4 ± 0.1	0.1 ± 0.0	0.5 ± 0.6	0.2 ± 0.2	0.7 ± 0.2	0.2 ± 0.0	0.2 ± 0.1	0.06 ± 0.03
back	0.2 ± 0.1	0.06 ± 0.03	0.1 ± 0.0	0.04 ± 0.01	0.4 ± 0.3	0.1 ± 0.1	nd[a]	nd[a]
upper arms	0.2 ± 0.1	0.1 ± 0.1	0.3 ± 0.2	0.2 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	0.1 ± 0.0	0.04 ± 0.01
forearms	0.1 ± 0.0	0.07 ± 0.03	0.1 ± 0.0	0.1 ± 0.0	0.4 ± 0.0	0.4 ± 0.0	0.04 ± 0.01	0.03 ± 0.01
thighs	0.3 ± 0.1	0.1 ± 0.0	0.3 ± 0.0	0.1 ± 0.0	4.6 ± 1.1	1.7 ± 0.4	0.3 ± 0.2	0.1 ± 0.1
shins	0.5 ± 0.1	0.2 ± 0.1	1.3 ± 0.2	0.6 ± 0.1	2.9 ± 0.2	1.3 ± 0.1	0.6 ± 0.5	0.3 ± 0.2
hands	1.0 ± 0.8	1.1 ± 0.8	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1	0.3 ± 0.1
feet	0.1 ± 0.0	0.05 ± 0.01	0.1 ± 0.0	0.05 ± 0.02	0.02 ± 0.01	0.01 ± 0.01	0.03 ± 0.01	0.03 ± 0.01
total	2.9 ± 0.3	–	3.1 ± 0.7	–	9.5 ± 1.6	–	1.7 ± 0.9	–
ratio to applied a.i.[b] (%)	0.011 ± 0.001	–	0.013 ± 0.003	–	0.038 ± 0.006	–	0.007 ± 0.004	–

[a]Not detected. [b]Active ingredient (25 g of imidacloprid).

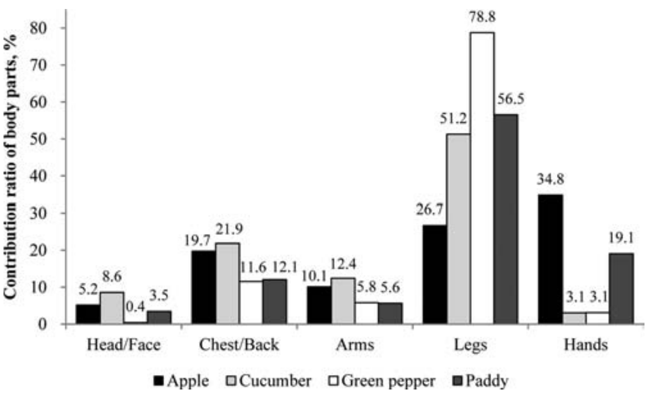

Figure 2. Distribution of dermal exposure on body parts during application.

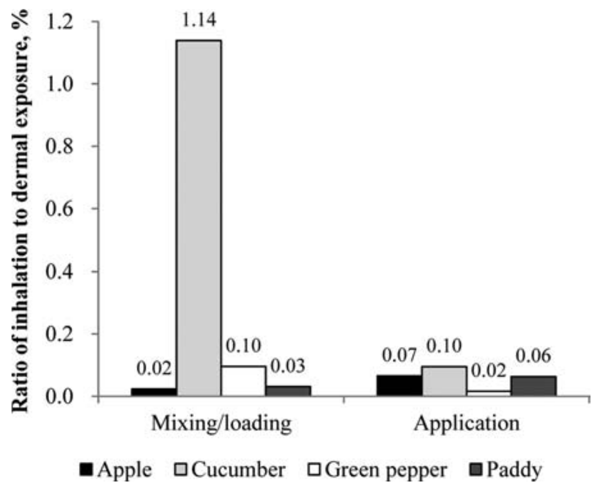

Figure 3. Ratio of inhalation exposure to dermal exposure during mixing/loading and application.

(green pepper), corresponding 0.007% (paddy) to 0.038% (green pepper), respectively, of the total applied a.i. (Table 4), being similar to the report (0.015−0.048%) with fenvalerate, methomyl, and acetamiprid.[2,15,28] In general, legs (thighs and shins) showed higher levels of exposure than upper body parts such as head, face, back, and arms.

The exposure patterns were similar among cucumber, green pepper, and paddy fields, which shows legs are the most exposed parts (51.2−78.8% of total exposure). In the green pepper field, exposure on legs was observed on both thighs and shins (48.2 and 30.6% of total exposure, respectively) while exposure was detected mainly on shins (36.9−41.8% of total exposure) in cucumber and paddy fields (Figure 2). Such exposure on the lower half of the body occurred because of the contamination through direct contact with the plants. In particular, the highest exposure in the green pepper field among various crop fields was due to the greatest contact frequency with the very dense foliage of green peppers.[14,36] In contrast to those three fields, most exposure was observed on hands (34.8% of total exposure) for the applicator in the apple field, the plants of which are taller than other crops (green pepper, cucumber, and rice) (Figure 2), because the applicator had to spray by lifting the spray lance over the head. In such cases, hands grabbing the spray lance must be contaminated with the spray suspension that streamed down the lance from nozzles. Only 26.7% of total dermal exposure was observed on legs in the apple field because of the wider row distance and lower foliar contact frequency.

Table 5. Determination of MOS Values for Mixer/Loaders and Applicators Spraying Imidacloprid on Various Crops[a]

worker	field	PDE[b] (mg/day)	ADE[c] (mg/day)	PIE[b] (mg/day)	AQE (mg/day)	MOS
mixer/loader	apple	10.1 ± 8.2	0.01 ± 0.01	0.002 ± 0.001	0.01 ± 0.01	640.6 ± 370.5
	cucumber	1.2 ± 0.6	0.001 ± 0.000	0.01 ± 0.00	0.02 ± 0.00	381.8 ± 96.4
	green pepper	8.7 ± 6.6	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.01	622.0 ± 563.5
	paddy	3.5 ± 4.8	0.003 ± 0.004	0.001 ± 0.000	0.004 ± 0.003	2294.3 ± 1989.4
applicator	apple	20.4 ± 2.4	0.2 ± 0.0	0.01 ± 0.00	0.2 ± 0.0	31.8 ± 2.6
	cucumber	26.1 ± 5.8	0.2 ± 0.0	0.02 ± 0.00	0.2 ± 0.0	24.5 ± 4.8
	green pepper	47.7 ± 7.8	0.4 ± 0.1	0.01 ± 0.00	0.4 ± 0.1	14.6 ± 2.3
	paddy	10.4 ± 5.8	0.1 ± 0.0	0.01 ± 0.00	0.1 ± 0.0	70.2 ± 33.7

[a]Abbreviations: PDE, potential dermal exposure; ADE, actual dermal exposure; PIE, potential inhalation exposure; AQE, absorbable quantity of exposure; MOS, margin of safety. [b]Calculated assuming a working number: mixing/loading and application are conducted five times a day with PS. [c]ADE = [PDE × 1% (mix/loader) or 10% (applicator) of penetration rate through clothes] × 8% of skin absorption.

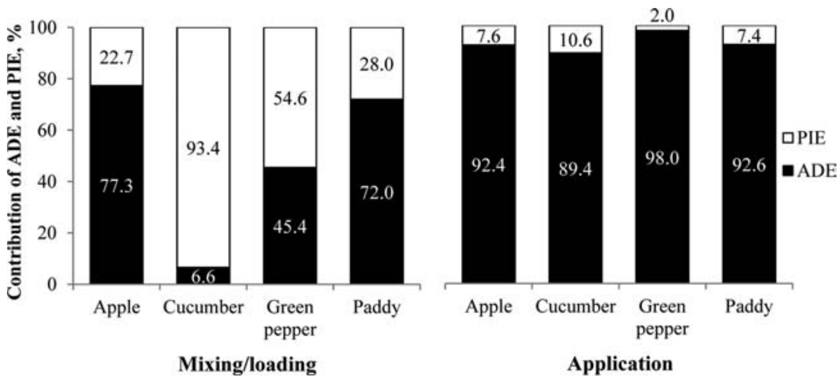

Figure 4. Contribution of ADE and PIE to AQE during mixing/loading and application. Abbreviations: ADE, actual dermal exposure; PIE, potential inhalation exposure; AQE, absorbable quantity of exposure.

In the case of the cucumber field, relatively higher exposure was observed on upper parts of the body such as head, face, chest, back and arms, similar to the data for the apple field, indicating a spray pattern higher than that in the green pepper field and rice paddy (Figure 2). Because the apple is usually more elevated than the cucumber, dermal exposure was higher on the head than on the face in the apple field whereas exposure was higher on the face than on the head in the cucumber field (Table 4). Face exposure and its intensity (0.5 ± 0.6 μg/cm^2) are the highest in the cucumber greenhouse, compared with other fields (Table 4), because the cucumber is taller than rice and green pepper, and indoor spray droplets can persist for significantly greater periods of time than under similar outdoor conditions[5] because of the lack of wind.

In conclusion, the primary factors for determining applicator exposure are the contact frequency with crops, foliar density, crop height, worker height, application habit of the worker,[37] and the location [outdoor or indoor field (greenhouse)].

Inhalation Exposure. Potential inhalation exposure occurs when airborne spray droplets or vapor is present in working areas resulting from mixing/loading or application of pesticides. The inhalation exposures during mixing/loading procedures were 0.5 ± 0.1, 2.8 ± 0.7, 1.7 ± 1.7, and 0.2 ± 0.1 μg in apple, cucumber, green pepper, and paddy fields, respectively, while those during application were determined to be 1.9 ± 0.6, 3.0 ± 0.1, 1.5 ± 0.1, and 1.1 ± 0.5 μg, respectively. Considering the working time (5 min for mixing/loading and 1 h for application) and respiration rate (1270 L/min), the exposure (nanograms) per unit respiration (cubic meters) was determined to be higher during mixing/loading [75.0 ± 16.5 ng/m^3 (apple), 445.8 ± 104.9 ng/m^3 (cucumber), 262.5 ± 268.7 ng/m^3 (green pepper), and 34.5 ± 14.1 ng/m^3 (rice paddy)] than during application [24.6 ± 7.9 ng/m^3 (apple), 39.1 ± 1.1 ng/m^3 (cucumber), 20.3 ± 1.2 ng/m^3 (green pepper), and 13.9 ± 6.1 ng/m^3 (rice paddy)]. These results indicated that higher levels of vapor or particles of the pesticide were found in working areas during mixing/loading procedures, but the total inhalation exposure was lower because of the shorter working time. The inhalation exposure was 2−13 times higher in the cucumber greenhouse than in other fields during mixing/loading and application. Therefore, it was demonstrated that the highest inhalation exposure occurred indoors (greenhouse) because of the closed system that lacked wind. However, inhalation exposure during application was <0.1% of dermal exposure (Figure 3), as reported in previous studies.[1−3]

Risk Assessment. Numerous default assumptions concerning the persistence of the chemical on the source, contact transfer, and the distribution of the dose on humans, clothing penetration, and day-to-day activity are required to transform experimental data into reliable estimates of the actual dose for exposure and risk assessment. It takes 20 min to prepare the spray suspension by filling a mixing tank with 500 L of water and mixing it with the pesticide product, while it takes 1 h for application of 500 L of a pesticide suspension with a power sprayer. Therefore, agricultural workers could conduct mixing/loading and application approximately five times a day because the feasible working duration is 6−7 h per day.

PDE and PIE were determined by extrapolating exposure amount to five working events per day. The actual dose (AQE) was calculated from ADE and PIE (Table 5). For the mixer/loader, AQE was in the range from 0.004 mg/day (paddy) to 0.02 mg/day (green pepper). The ratio of PIE to AQE during mixing/loading was 22.7% (apple) to 93.4% (cucumber)

(Figure 4), indicating inhalation is the major route for pesticide exposure in a closed environment like a greenhouse. Meanwhile, AQEs for the applicator ranged from 0.1 mg/day (paddy) to 0.4 mg/day (green pepper), and 2.0% (green pepper) to 10.6% (cucumber) of AQE occurred through inhalation (Figure 4). Because inhalation is the critical exposure route in a closed environment like a greenhouse, workers should wear protective equipment such as a mask to reduce the probability of inhalation exposure.

In risk assessment, AQE, the pesticide exposure estimated, was then compared to AE, the value obtained by multiplying the AOEL of imidacloprid[21] by body weight. AOEL is usually derived from NOAEL, from the most relevant toxicity study, divided by the appropriate safety or uncertainty factor.[38] In general, workers are considered at risk when they are exposed to a level higher than the AOEL. In this study, the MOS was determined to be much higher than 1, indicating all activities in all crop fields, including mixing/loading and application, are considered to be safe from imidacloprid exposure (Table 5). This was due to the low frequency of exposure, the low a.i. content of pesticide products (10%), the low toxicity (AOEL, 0.08 mg/kg), and the low skin absorption (8%) of imidacloprid.

■ AUTHOR INFORMATION

Corresponding Author

*Phone: +82-2-880-4644. Fax: +82-2-873-4415. E-mail: kjh2404@snu.ac.kr.

Author Contributions

H.C. and J.-K.M. contributed equally to this work.

Funding

This work was supported by the “Cooperative Research Program for Agriculture Science & Technology Development” (Project PJ905004) (Rural Development Administration, Republic of Korea) and in part by the Brain Korea 21 project.

Notes

The authors declare no competing financial interest.

■ REFERENCES

(1) Choi, H.; Moon, J. K.; Liu, K. H.; Park, H. W.; Ihm, Y. B.; Park, B. S.; Kim, J. H. Risk assessment of human exposure to cypermethrin during treatment of mandarin fields. *Arch. Environ. Contam. Toxicol.* **2006**, *50*, 437–442.

(2) Kim, E.; Moon, J. K.; Choi, H.; Hong, S. M.; Lee, D. H.; Lee, H. M.; Kim, J. H. Exposure and risk assessment of insecticide methomyl for applicator during treatment on apple orchard. *J. Korean Soc. Appl. Biol. Chem.* **2012**, *55*, 95–100.

(3) Machado-Neto, J. G. Determination of safe work time and exposure control need for pesticide applicators. *Bull. Environ. Contam. Toxicol.* **2001**, *67*, 20–26.

(4) Vercruysse, F.; Drieghe, S.; Steurtbaut, W.; Dejonckheere, W. Exposure assessment of professional pesticide users during treatment of potato fields. *Pestic. Sci.* **1999**, *55*, 467–473.

(5) U.S. Environmental Protection Agency. Occupational and residential exposure test guidelines (OPPTS 875. 1000, EPA 712-C-96-261); U.S. Environmental Protection Agency: Washington, DC, 1996; pp 3–24.

(6) Durham, W. F.; Wolfe, H. R. Measurement of the exposure of workers to pesticides. *Bull. W.H.O.* **1962**, *26*, 75–91.

(7) Chester, G. Worker exposure: Methods and techniques. In *Handbook of Pesticide Toxicology*; Krieger, R., Ed.; Academic Press: San Diego, 2001; pp 425–433.

(8) Kim, J. H.; Kim, K.; Lee, H. G. Measurement of human exposure to pesticide. *AgroBiotech* **1998**, *5*, 72–76.

(9) Baharuddin, M. R. B.; Sahid, I. B.; Noor, M. A. B. A.; Sulaiman, N.; Othman, F. Pesticide risk assessment: A study on inhalation and dermal exposure to 2,4-D and paraquat among Malaysian paddy farmers. *J. Environ. Sci. Health, Part B* **2011**, *46*, 600–607.

(10) Byoun, J. Y.; Choi, H.; Moon, J. K.; Park, H. W.; Liu, K. H.; Ihm, Y. B.; Park, B. S.; Kim, J. H. Risk assessment of human exposure to methidathion during harvest of cucumber in green house. *J. Toxicol. Public Health* **2005**, *21*, 297–301.

(11) Calumpang, S. M. F.; Medina, M. J. B. Applicator exposure to imidacloprid while spraying mangoes. *Bull. Environ. Contam. Toxicol.* **1996**, *57*, 697–704.

(12) Capri, E.; Alberici, R.; Glass, C. R.; Minuto, G.; Trevisan, M. Potential operator exposure to procymidone in greenhouses. *J. Agric. Food Chem.* **1999**, *47*, 4443–4449.

(13) Kim, E.; Moon, J. K.; Hong, S.; Park, K. H.; An, X.; Kim, J. H. Comparative exposure of operators to fenthion during treatment in paddy field. *J. Korean Soc. Appl. Biol. Chem.* **2012**, *55*, 827–830.

(14) Liu, K. H.; Kim, C. S.; Kim, J. H. Human exposure assessment to mancozeb during treatment of mandarin fields. *Bull. Environ. Contam. Toxicol.* **2003**, *70*, 336–342.

(15) Moon, J. K.; Park, S.; Kim, E.; Lee, H.; Kim, J. H. Risk assessment of the exposure of insecticide operators to fenvalerate during treatment in apple orchards. *J. Agric. Food Chem.* **2013**, *61*, 307–311.

(16) Ramos, L. M.; Querejeta, G. A.; Flores, A. P.; Hughes, E. A.; Zalts, A.; Montserrat, J. M. Potential dermal exposure in greenhouses for manual sprayers: Analysis of the mix/load, application and re-entry stages. *Sci. Total Environ.* **2010**, *408*, 4062–4068.

(17) Tomlin, C. D. S. *The pesticide manual*, 15th ed.; British Crop Protection Council: Hampshire, U.K., 2009; pp 645–647.

(18) Kim, E.; Lee, H.; Choi, H.; Moon, J. K.; Hong, S.; Jeong, M.; Park, K. H.; Lee, H. M.; Kim, J. H. Methodology for quantitative monitoring of agricultural worker exposure to pesticides. *Korean Journal of Pesticide Science* **2011**, *15*, 507–528.

(19) Lee, H.; Riu, M.; Kim, E.; Moon, J. K.; Choi, H.; Do, J. A.; Oh, J. H.; Kwon, K. S.; Lee, Y. D.; Kim, J. H. A single residue method for the determination of chlorpropham in representative crops using high performance liquid chromatography. *J. Korean Soc. Appl. Biol. Chem.* **2013**, *56*, 181–186.

(20) Predictive operator exposure model. *UK POEM: A user guide*; Pesticide Safety Directorate: York, U.K., 1992.

(21) European Food Safety Authority. Conclusion regarding the peer review of the pesticide risk assessment of active substance, imidacloprid. *EFSA Scientific Report* **2008**, *148*, 1–119.

(22) Fenske, R. A.; Day, E. W., Jr. Assessment of exposure for pesticide handlers in agricultural, residential and institutional environments. In *Occupational and residential exposure assessment for pesticides*; Franklin, C. A., Worgan, J. P., Eds.; John Wiley & Sons, Inc.: West Sussex, U.K., 2005; pp 11–43.

(23) Oliveira, M. L.; Machado-Neto, J. G. Use of manganese as tracer in the determination of respiratory exposure and relative importance of exposure routes in the safety of pesticide applicators in citrus orchards. *Bull. Environ. Contam. Toxicol.* **2003**, *70*, 415–421.

(24) Hughes, E. A.; Flores, A. P.; Ramos, L. M.; Zalts, A.; Glass, C. R.; Montserrat, J. M. Potential dermal exposure to deltamethrin and risk assessment for manual sprayers: Influence of crop type. *Sci. Total Environ.* **2008**, *391*, 34–40.

(25) Korea health statistics 2008: Korea national health & nutrition examination survey (KNHANES IV-2); Ministry of Health and Welfare: Seoul, 2009.

(26) Korea health statistics 2009: Korea national health & nutrition examination survey (KNHANES IV-3); Ministry of Health and Welfare: Seoul, 2010.

(27) Korea health statistics 2010: Korea national health & nutrition examination survey (KNHANES V-1); Ministry of Health and Welfare: Seoul, 2011.

(28) Kim, E.; Moon, J. K.; Lee, H.; Kim, S.; Hwang, Y. J.; Kim, B. J.; Lee, J.; Lee, D. H.; Kim, J. H. Exposure and risk assessment of operators to insecticide acetamiprid during treatment on apple

orchard. *Korean Journal of Horticultural Science and Technology* **2013**, *31*, 239−245.

(29) Franklin, C. A. Occupational exposure to pesticides and its role in risk assessment procedures used in Canada. In *Dermal exposure related to pesticide use*; Honeycutt, R. C., Zweig, G., Ragsdale, N. N., Eds.; ACS Symposium Series 273; American Chemical Society: Washington, DC, 1985; pp 429−444.

(30) Krieger, R. I. Pesticide exposure assessment. *Toxicol. Lett.* **1995**, *82*, 65−72.

(31) Ross, J. H.; Driver, J. H.; Cochran, R. C.; Thongsinthusak, T.; Krieger, R. I. Could pesticide toxicology studies be more relevant to occupational risk assessment? *Journal of Occupational Hygiene* **2001**, *45*, S5−S17.

(32) Kim, E.; Hwang, Y. J.; Kim, S.; Lee, H.; Hong, S.; Park, K. H.; Kim, J. H. Operator exposure to indoxacarb wettable powder and water dispersible granule during mixing/loading and risk assessment. *Korean Journal of Pesticide Science* **2012**, *16*, 343−349.

(33) Kim, E.; Lee, H.; Jeong, M.; Hong, S.; Kim, J. H. Hand exposure of operator to chlorpyrifos during mixing/loading and risk assessment. *Korean Journal of Pesticide Science* **2012**, *16*, 391−394.

(34) Standard for pesticide registration, administrative rule of pesticide management act (notification 2009-19, revised July 7, 2009, date of enforcement of July 7, 2009); Rural Development Administration: Suwon, Korea, 2009.

(35) Ambridge, E. M.; Haines, I. H. Some aspects of pesticides used and human safety in Southeast Asia. In *Proceeding of the 11^th^ International Congress of Plant Protection*; Mangallona, E. D., Ed.; Philippine Council for Agriculture, Forestry and Natural Resources Development: Manila, Philippines, 1987; pp 219−224.

(36) Machera, K.; Kapetanakis, E.; Charistou, A.; Goumenaki, E.; Glass, R. C. Evaluation of potential dermal exposure of pesticide spray operators in greenhouses by use of visible tracers. *J. Environ. Sci. Health, Part B* **2002**, *37*, 113−121.

(37) Vidal, J. L. M.; Gonzalez, F. J. E.; Frenich, A. G.; Galera, M. M.; Aguilera, P. A.; Carrique, E. L. Assessment of relevant factors and relationships concerning human dermal exposure to pesticides in greenhouse applications. *Pest Manage. Sci.* **2002**, *58*, 784−790.

(38) Hemmen, J. J.; van der Jagt, K. E. Generic operator exposure databases. In *Occupational and Residential Exposure Assessment for Pesticides*; Franklin, C. A., Worgan, J. P., Eds.; John Wiley & Sons, Ltd.: Chichester, U.K., 2005; p 198.