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Potential dermal pesticide exposure affected by greenhouse spray application technique

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Abstract

BACKGROUND: Operator safety is still one of the main problems concerning greenhouse spray applications in South European horticulture. The main objective of this study was to compare potential dermal exposure (PDE) between traditional handheld spray application techniques (i.e. a standard spray gun walking forwards, a spray lance walking forwards and backwards) and novel spray application techniques with spray booms (i.e. a trolley, the Fumimatic and the Fumicar).

RESULTS: PDE varied from 19.7 mL h^{-1} for the Fumimatic to 460 mL h^{-1} for the spray lance walking forwards. Walking backwards reduced PDE by a factor 7. With the trolley, Fumimatic and Fumicar, PDE was respectively 20, 60 and 8 times lower than with the standard spray gun. With the spray lance, PDE was about 2.5 times higher than with the spray gun. Pesticide distribution over the operator's body was non-uniform and correlated strongly with the application technique. With the traditional techniques, exposure to the legs and feet represents 60–80% of the total exposure.

CONCLUSIONS: Novel spray application techniques using spray booms greatly decrease operator exposure because the operator is not walking directly into the spray cloud and the sprayed crop, and because of their higher capacity. Depending on the type of spray application, different parts of the body need to be protected most.
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Keywords: operator safety; horticulture; pesticide applications; spray boom; handheld application; vertical crops

1 INTRODUCTION

In Southern Europe, greenhouse spraying applications still cause problems regarding operator safety because of the high potential operator exposure and the lack of personal protective equipment and modern application techniques.

Estimates of exposure have been reported for several classes of pesticide[1] and for diverse types of application equipment.[2–5] These applicator studies vary in emphasis on assessing inhalation and dermal exposure, absorbed dose based on plasma or urine analysis and factors affecting extent of exposure, such as type of application equipment, type of protective clothing and crop type.[6,7] The majority of these studies indicate that dermal exposure is the main route of exposure for pesticide applicators, irrespective of the type of spray application.[8–13] Different authors have observed an important non-uniformity of dermal exposure from different kinds of spray application technique.[14–18] Most studies confirm that the region of the body most exposed is the hands.[15,19,20] That is why Fenske *et al*.[21] studied the efficiency of removal of pesticides from the operator's hands. This non-uniform pesticide deposition presents a major complication for the development of accurate dermal exposure sampling strategies.[22] As the exposure pattern is also strongly related to crop architecture,[7] this exacerbates the latter problem.

All the above-mentioned studies have raised concerns about the need for greater protection of operators and for improved spray application techniques. The use of chemical protective clothing as a method of exposure mitigation among pesticide applicators has been studied in detail by different researchers[23–33] for different types of spray application equipment such as aircraft[34] and helicopters,[35] field sprayers,[4,15] orchard sprayers,[32] vineyard sprayers[36–39] and different types of hand-operated sprayers.[20,35,40] Of these techniques, the use of handheld spraying equipment creates the highest exposure risk for the operator, especially compared with other techniques where the operator is well protected inside the tractor cab. With a handheld sprayer, the operator walks into the area that is being treated and can be covered with spray, particularly when treating large and dense crops such as cucumber and tomatoes.[5,11,20] Moreover, droplet size, which is closely related to the applied spray application technique and pressure,[41] was generally found to be one of the critical factors in determining operator contamination.[18,20]

Particularly for the application of pesticides in greenhouses, a wide range of spray application techniques are used[42] that all have their specific characteristics with regard to operator exposure.[20,43,44] At this moment, there is still a lack of data on operator exposure levels during different types of spray application in greenhouses.[20] Moreover, operator exposure data can be helpful in further development of exposure models and databases for risk assessment and pesticide registration,[3,11,45,46] such as the European Predictive Operator Exposure Model (EUROPOEM),[47]

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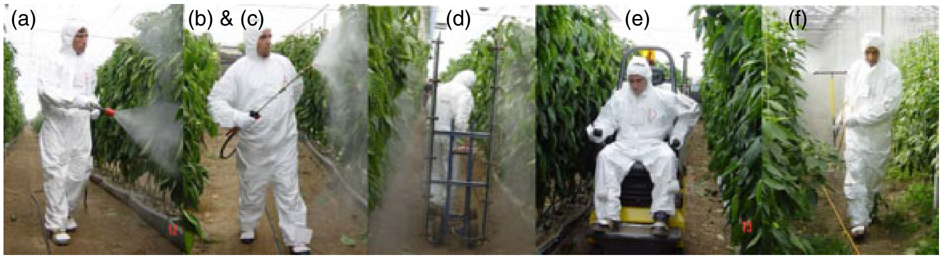

Figure 1. Different spray application techniques evaluated in this study: (a) standard spray gun; (b) spray lance, walking forwards; (c) spray lance, walking backwards; (d) manually pulled trolley; (e) Fumimatic; (f) Fumicar.

the Pesticide Handlers Exposure Database (PHED)[48] and the Agricultural Handlers Exposure Database (AHED).[49] All of these are important because pesticides are known to have carcinogenic, neurological, reproductive and other adverse health effects in humans.[50,51] That is why there is a need for site-specific occupational hygiene advice.[12] Although care is also needed before[4,52] and after spraying,[53] the main objective of this study was to compare the potential dermal exposure (PDE) of various parts of the body between novel and traditional greenhouse spray equipment under actual working conditions when spraying large plants. This potential dermal exposure provides vital information on the quantity of a plant protection product that contaminates uncovered body regions and clothing worn by the operator.[54] In this study, operator exposure measurements were performed under field conditions in Almeria (Spain) in 2004 and in Crete (Greece) in 2006 using a patch sampling technique.[55,56]

2 MATERIALS AND METHODS

2.1 Spray application techniques

In total, six different spray application techniques were evaluated: (a) a spray gun, (b) a spray lance walking forwards, (c) a spray lance walking backwards, (d) a manually pulled trolley, (e) the Fumimatic and (f) the Fumicar (Fig. 1). The manually pulled trolley and the self-propelled Fumimatic (IDM-Agrometal,[57] Almeria, Spain) were both equipped with vertical spray booms (12 standard flat-fan nozzles),[58] while the manually pulled Fumicar (NOVI-FAM,[59] Almeria, Spain) was equipped with two short horizontal spray booms carrying eight hollow cone (disc-core) nozzles that moved vertically. With the last three techniques (d, e and f), both sides of the row were sprayed simultaneously. With techniques a, b and c, the operator was always spraying the left side of the row, going to the end of the row and back in accordance with normal practice. Techniques a, b, c, d and e were tested in Almeria (Spain, 2004) by four different operators; techniques a and f were tested in Crete (Greece, 2006) by four other operators. In both cases, the standard spray gun (technique a), still common practice, was used as a reference for a comparative assessment of the different techniques.

2.2 Experimental set-up

Operator exposure experiments were performed in four single pepper greenhouses in Spain[60] and Greece with different experienced operators to gain an insight into the potential exposure under realistic field conditions. Peppers are very common and valuable crops in these countries. The standard spray gun (technique a) was tested by eight experienced operators, and the other techniques (b to f) by four experienced operators, totalling 28 sprayings. For each spraying, a distance of 100–130 m of crop was treated, corresponding to a surface of 0.025–0.030 ha. The rows in each greenhouse were equivalent to 4000–5000 m ha^{-1}. The plants were positioned in single rows with a crop height of about 2.2 m. In a preliminary experiment, the driving and walking speeds for the different techniques (spray gun forwards and backwards and spray lance: ∼0.5–0.6 m s^{-1}, trolley: ∼1 m s^{-1}; Fumimatic: ∼1.5–1.8 m s^{-1}; Fumicar: ∼0.5–0.7 m s^{-1}) were measured to determine the desired flowrate to attain a volume rate of about 1000 L ha^{-1} of greenhouse area by changing nozzle type and spray pressure. This resulted in an effective application time varying from about 7 min for the spray lance and gun to about 1 min for the Fumimatic. All exposure measurements were normalised to a volume rate of 1000 L ha^{-1}. This is a typical dose for many greenhouse spray applications, theoretically corresponding to about 50 mL spray liquid m^{-2} crop surface, which is below the level that would cause run-off.[60–62]

The timing and locations of the measurements were organised in such a way that the different sprayings did not interfere with each other. Because another chelate was used for each application technique, the operators could use the same collectors for the different techniques.

2.3 Potential dermal exposure measurements

The potential dermal exposure (PDE) was assessed at 15 different places (Table 1)[4,63] on a Tyvek® (DuPont™) coverall with patches and on gloves using different mineral chelates (Mn, Co, Mo, Zn and B, Chelal®; BMS Micro-Nutrients NV, Belgium) as tracer elements according to the OECD guidelines.[64] Tannahill *et al.*[65] concluded that the patch method is suited for estimating PDE.

Table 1. Overview of the different parts of the body and their corresponding surfaces[4,63]

Part of body	Surface (cm^2)	% of total body	Part of body	Surface (cm^2)	% of total body
Head	1300	6.2	Upper leg right	1910	9.05
Back	3810	18	Lower leg left	1160	5.65
Chest	3550	16.8	Lower leg right	1160	5.65
Upper arm left	1455	6.9	Left foot	655	3.1
Upper arm right	1455	6.9	Right foot	655	3.1
Fore arm left	605	2.85	Left hand (cotton glove)	410	1.95
Fore arm right	605	2.85	Right hand (cotton glove)	410	1.95
Upper leg left	1910	9.05	**Total**	21 050	100

Table 2. Operational spray application parameters of the different sprayings

Spray application technique	Nozzles	Pressure (bar)	Total flowrate (L min^{-1})	Speed (m s^{-1})		Spray volume (L ha^{-1})	
				Avg	SD	Avg	SD
Standard spray gun	One disc-core nozzle	21.0[a]	3.6	0.51	0.08	1091	276
Spray lance forwards	Three disc-core nozzles	19.0[a]	3.6	0.57	0.06	1060	118
Spray lance backwards	Three disc-core nozzles	19.0[a]	3.6	0.57	0.07	1074	144
Trolley	12 TeeJet XR 8002	4.8[b]	12.0	1.07	0.14	946	121
Fumimatic	12 TeeJet XR 8005	3.1[b]	24.0	1.64	0.14	1227	99
Fumicar	Eight disc-core nozzles	8.0[b]	6.2	0.61	0.10	720	140

[a] Pressure at the pump.
[b] Pressure at the nozzles.

A total of 13 patches (head, back, chest, upper arms, forearms, upper legs, lower legs and feet), each measuring 10 × 10 cm^2, were attached to each operator's coverall to collect spray deposits. Each patch was composed of different layers, i.e. one layer of strong paper, one layer of plastic foil, two layers of Schleicher & Schuell filter paper (type 751; Filter Service NV) and one thin layer of gauze.[66] The plastic foil prevented the penetration of spray liquid through the patches to the coverall. As suggested by Fenske,[16] the patches were big enough to be a representative sample of the part of the body to which they were attached and to minimise potential error.[56] Each operator was also wearing a pair of cotton gloves with an average surface of about 410 cm^2 (Table 1) above a pair of latex gloves which prevented penetration to the skin. The exposure of the different patches was determined by measuring the amount of chelates on a surface of 10 × 10 cm^2. For the gloves, the amount of chelates was derived from the total surface of the gloves. The average surface of one glove is about 410 cm^2 instead of 10 × 10 cm^2. The amount of chelates on the gloves was therefore corrected by multiplying by a correction factor of 0.244. Similar methodologies using patches and gloves have been used before in previous studies to estimate PDE.[3–5,9,11,15,32,35]

Based on these individual exposure measurements, the PDE, defined as the total amount of spray liquid landing on the body including clothing, was calculated using the measured exposure of the patches and the standard surfaces of the corresponding parts of the body (Table 1). PDE is expressed both as mL spray liquid h^{-1} application[5,7,67,68] and as mL spray liquid 1000 L^{-1} spray applied.[69] In practice, volumetric pesticide concentrations in peppers might vary from 0.2 to 20 mL L^{-1}, depending on the type of product.[70]

The chelates are normally used as horticultural leaf fertilisers, and hence their use does not damage the crop and is no risk to the operator. For each application method, another chelate in tap water was used. The concentration of each mineral in the tank mixture was about 1500 mg L^{-1}. Besides these minerals, no other active ingredients or additives were used. Before and after each spraying, a tank sample was taken to know the exact concentration and to adjust the exposure results. All experiments were performed with a spray unit equipped with a continuous hydraulic mixing system. Inductively coupled plasma (ICP) analysis (VISTA-PRO; Varian, Palo Alto, CA) was used throughout to determine the amount of metals on the collectors after extraction with 0.14 M nitric acid (Merck Chemicals). Earlier experiments proved that there is no interference between these minerals, which is important for the ICP analysis. The detection limits in nitric acid for Mn, Co, Mo, Zn and B are very low, respectively 10, 5, 19, 10 and 12 ppb. The minerals used are therefore detectable in very small quantities.

Table 3. Comparison of the potential dermal exposure (PDE) of the different techniques with the standard spray gun set as 100% (± standard deviation)

Spray application technique	PDE (mL spray liquid h^{-1} application)		PDE (mL spray liquid 1000 L^{-1} spray applied)	
	%	SD	%	SD
Standard spray gun	100.0	±42.0	100.0	±42.0
Spray lance forwards	251.6	±74.0	251.6	±74.0
Spray lance backwards	37.9	±6.5	37.9	±6.5
Trolley	16.0	±5.9	4.8	±1.8
Fumimatic	10.7	±6.1	1.6	±0.9
Fumicar	22.1	±20.2	12.6	±11.6

Furthermore, mineral chelates are stable, and for each of them a high recovery can be reached.[71] No detectable amount of Mn, Co, Mo, Zn and B was found in a blank sample.

3 RESULTS AND DISCUSSION

3.1 Operational spray application parameters

Measured operational spray application parameters for the different sprayings are presented in Table 2, based on flowrate and spray time measurements and greenhouse characteristics. Exposure measurements were normalised to a spray volume of 1000 L ha^{-1}, taking into account variations in tank concentration and actual spray volume (varying from 720 to 1227 L ha^{-1}).

3.2 Total potential dermal exposure

Average total potential dermal exposure (PDE), expressed both as mL spray liquid h^{-1} application and as mL spray liquid 1000 L^{-1} spray applied, for the different techniques is presented in Fig. 2, together with the corresponding 95% confidence intervals. A considerable variation in exposure values between the different experienced operators for the same spraying technique was observed, which is comparable with other studies[5] or even better.[72] This variation is typical for exposure studies and is caused by differences in the way of spraying, the size and behaviour of the operators and the crop and greenhouse characteristics. Within this context, Calumpang[3] reports that a fully outstretched arm, a minimal body twisting and smooth hand movements reduce operator exposure.

In Table 3, PDE values for the different spray application techniques are compared relative to the standard technique,

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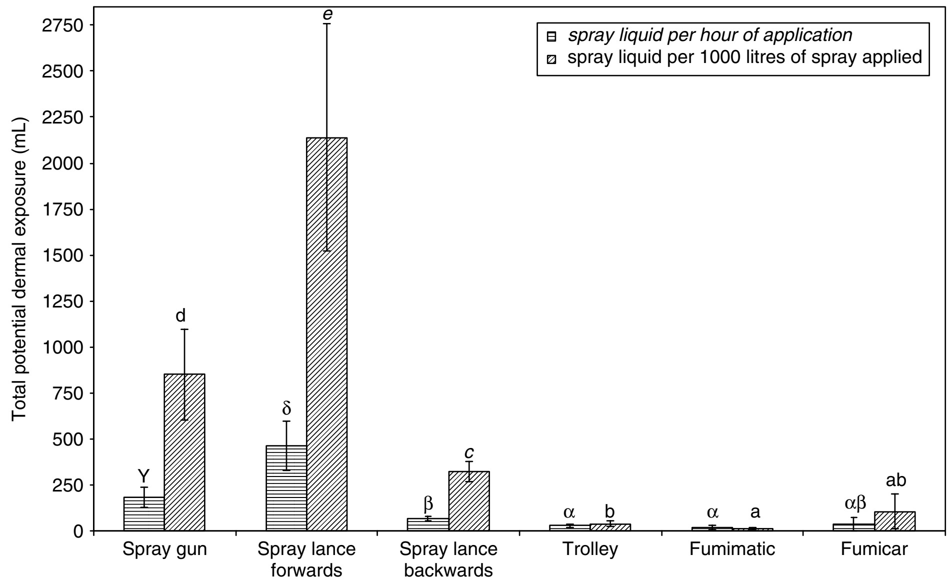

Figure 2. Average total potential dermal exposure expressed both as mL spray liquid h^{-1} application (values followed by the same Greek letter are not significantly different at the 0.05 level) and as mL spray liquid 1000 L^{-1} spray applied (values followed by the same Roman letter are not significantly different at the 0.05 level) for the different techniques, together with the corresponding 95% confidence intervals.

the spray gun, set as 100%. These results demonstrate that the difference in PDE between the different techniques was very high. PDE varies from 19.7 mL h^{-1} spray application (10.7%) for the Fumimatic to about 460 mL h^{-1} (251.6%) for the spray lance walking forwards. In similar studies, Hughes *et al.*[7,73] observed PDE values with a knapsack sprayer of 12, 78 and 140 mL h^{-1} spray time for Swiss chard, lettuce and broccoli respectively. In maize, researchers have reported values ranging from 25 to 258 mL h^{-1}.[6,7,74] PDE values between 116 and 173 mL h^{-1} were found for a handheld spray application of Barberton daisy,[68] and of 113 mL h^{-1} in green beans.[75] For handheld applications in tomatoes, PDE levels ranged from 22.4 to 62.5 mL h^{-1},[18,20,50] and in mandarins values between 550 and 1180 mL h^{-1} were measured.[5] The above-mentioned important differences in PDE values can mainly be attributed to differences in crop architecture (i.e. vertical versus horizontal crops)[7] and application technique.

Because of the higher capacity of spraying techniques using spray booms, differences among the spraying techniques are even more pronounced per 1000 L of spray applied, with PDE values ranging from 13.7 mL (1.6%) for the Fumimatic up to 2139.2 mL (251.6%) for the spray lance walking forwards, corresponding to 0.0014 and 0.21% of the spray liquid applied. For handheld spray applications in tomatoes, Machera *et al.*[20] measured PDE values ranging from 0.05 to 0.07% of the applied spray volume for a low spray pressure, and from 0.09 to 0.19% for a high spray pressure.

With the standard spray gun, a technique comparable with the spray lance, PDE was less than half that with the spray lance walking forwards (100% versus 251%) (Table 3), corresponding to 0.08% of the applied spray solution. The main reasons for this difference were the difference in length between the spray gun and the spray lance (40 cm), the ease with which the spray gun was handled compared with the spray lance and the fact that the spray lance had three nozzles, each spraying in a different direction and producing a finer, slower and bigger spray cloud.

While walking backwards with the spray lance, PDE was only 37.9% (SD = 6.5%) compared with the standard spray gun, corresponding to a PDE of 69.5 mL h^{-1} or 322.0 mL 1000 L^{-1} spray. This means that walking backwards reduces the exposure by a factor of about 7, mainly because the operator does not walk into the spray cloud. In addition, it is an easy technique that does not require any investment. Similar conclusions were reached by Thornhill *et al.*[76] and Bjugstad and Torgrimsen,[11] who measured a reduction in operator exposure by a factor varying from 4 to 20 for different application techniques (knapsack mistblower, knapsack sprayer, spray gun and CDA spinning disc sprayer) in cucumbers[11] and on grassland.[76] From these data it might be assumed that walking backwards using a spray gun would have been the best low-technology application method in terms of total potential dermal exposure.

PDE with the novel techniques using spray booms was very low compared with the spray gun, namely 4.8% (SD ± 1.8) for the trolley, 1.6% (SD ± 0.9) for the Fumimatic and 14.6% (SD ± 7.5) for the Fumicar per 1000 L of spray applied (Table 3). This means a reduction by a factor of about 20 for the trolley, by a factor of about 60 for the Fumimatic and by a factor of about 8 for the Fumicar compared with the standard spray gun. Because of the higher capacity of these techniques, reduction factors are lower per hour of spray application, namely about 6 for the trolley, 9 for the Fumimatic and 5 for the Fumicar. Compared with the 'worst' technique, i.e. the spray lance and walking forwards, all reduction factors are about 2.5 times higher. Earlier studies had already indicated that placing the nozzle behind the operator significantly reduced operator exposure because the operator was not walking directly into the spray cloud and the sprayed crop.[77]

The important differences in exposure, per 1000 L of spray applied, between the Fumimatic, the trolley and the Fumicar are, among other things, caused by the differences in operating speed (∼1.5–1.8 m s^{-1}, ∼1 m s^{-1} and ∼0.5–0.7 m s^{-1} respectively), which affect the exposure time. That is why exposure differences among these three techniques are less pronounced per hour of spray application. Additionally, the disc-core nozzles from the Fumicar produced a finer spray than the standard flat-fan nozzles from the Fumimatic and the trolley.[41] Besides their effect on operator exposure reduction, these techniques additionally

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Table 4. Amount of spray liquid (mean ± SD) for the different parts of the body on an area of 10 × 10 cm^2 per hour of spray application

	Spray gun		Spray lance forwards		Spray lance backwards		Trolley		Fumimatic		Fumicar	
Part of the body	Mean (mL)	SD	Mean (mL)	SD	Mean (mL)	SD	Mean (mL)	SD	Mean (mL)	SD	Mean (mL)	SD
Head	0.12	±0.10	1.84	±1.34	0.39	±0.55	0.08	±0.08	0.11	±0.08	0.42	±0.85
Back	0.04	±0.02	0.20	±0.15	0.07	±0.03	0.07	±0.07	0.05	±0.04	0.18	±0.37
Chest	0.07	±0.04	0.39	±0.47	0.10	±0.11	0.05	±0.02	0.03	±0.04	0.14	±0.21
Upper arm left	1.32	±1.70	1.50	±1.24	0.18	±0.21	0.16	±0.14	0.04	±0.05	0.07	±0.15
Upper arm right	0.30	±0.41	1.03	±1.38	0.13	±0.11	0.16	±0.15	0.04	±0.05	0.11	±0.13
Forearm left	0.72	±1.21	0.39	±0.32	0.29	±0.34	0.12	±0.08	0.05	±0.06	0.05	±0.09
Forearm right	0.43	±0.35	1.46	±1.18	0.23	±0.05	0.11	±0.07	0.01	±0.02	0.04	±0.08
Upper leg left	0.59	±0.52	0.72	±0.53	0.09	±0.01	0.09	±0.03	0.01	±0.03	0.08	±0.09
Upper leg right	0.50	±0.74	2.15	±2.30	0.33	±0.29	0.08	±0.02	0.01	±0.02	0.23	±0.33
Lower leg left	2.80	±2.37	8.58	±2.93	0.57	±0.29	0.18	±0.04	0.03	±0.05	0.04	±0.08
Lower leg right	1.23	±0.64	5.43	±1.95	0.83	±0.55	0.17	±0.06	0.01	±0.02	0.04	±0.08
Left foot	8.42	±4.89	13.86	±5.57	1.61	±0.74	0.47	±0.18	0.11	±0.17	0.21	±0.08
Right foot	3.43	±2.04	6.99	±1.91	0.92	±0.54	0.25	±0.03	0.07	±0.12	0.35	±0.18
Left hand	0.31	±0.16	1.42	±1.50	0.41	±0.19	0.82	±0.53	1.63	±1.30	1.02	±0.63
Right hand	0.32	±0.20	2.15	±1.59	1.95	±1.41	0.63	±0.17	1.19	±1.00	1.30	±0.45

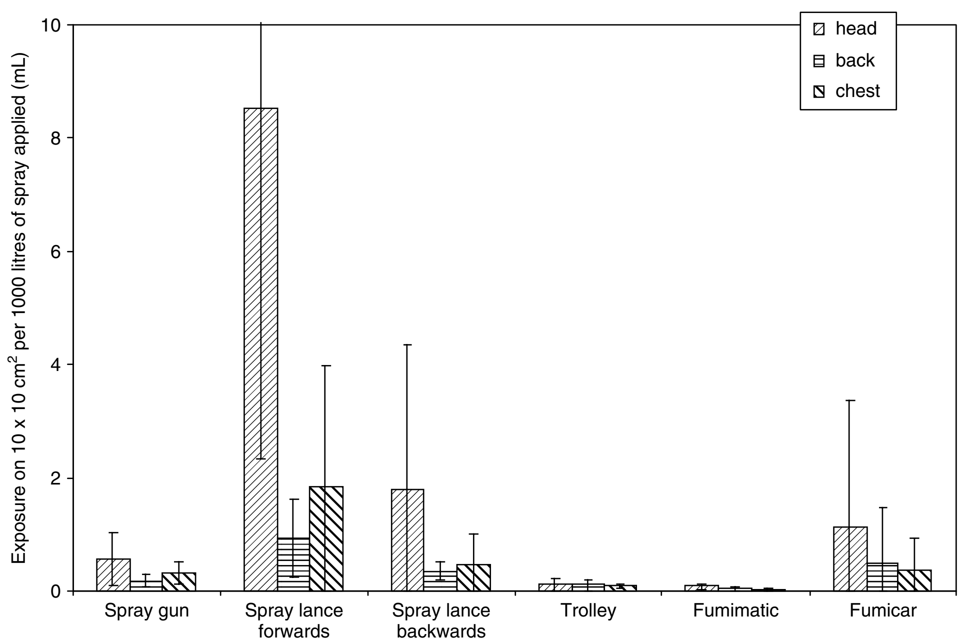

Figure 3. Exposure of the upper parts of the body on an area of 10 × 10 cm^2 per 1000 L of spray applied (± SD) for the different techniques.

increase productivity, reduce labour costs and give a better spray distribution.[60]

3.3 Exposure of the different parts of the body

Table 4 presents the exposure results expressed as the amount of spray liquid found on an area of 10 × 10 cm^2 per hour of spray application, and Figs 3, 4 and 5 per 1000 L of spray applied. Note that different scales have been used, indicating the important non-uniformity of dermal exposure, as suggested in previous studies.[14–16,18,78] Table 5 gives the relative contributions of each part of the body to the total PDE.

For the upper parts of the body – the chest, back and head (Fig. 3) – the exposure was low compared with the other parts of the body and varied from 0.02 mL (Fumimatic, chest, 4.9% of total PDE) to 8.53 mL (spray lance forwards, head, 5.2% of total) on 10 × 10 cm^2 per 1000 L of spray applied. For all techniques, exposure of the head was higher than that of the back and chest and ranged from 0.8% (spray gun) to 13.5% (Fumicar) of the total PDE (Table 5). Furthermore, the exposure with the traditional techniques (i.e. spray gun and lance) was higher on the chest than on the back, even when walking backwards. Both effects can be attributed to the heights of the plants, the small distance between head and spray cloud and the operator walking directly into the spray cloud.

Among the different techniques, for the trunk and head the exposure with the spray lance walking forwards was clearly the highest, and the exposure with the Fumimatic the lowest. It is remarkable that the exposure figures for these upper parts of the

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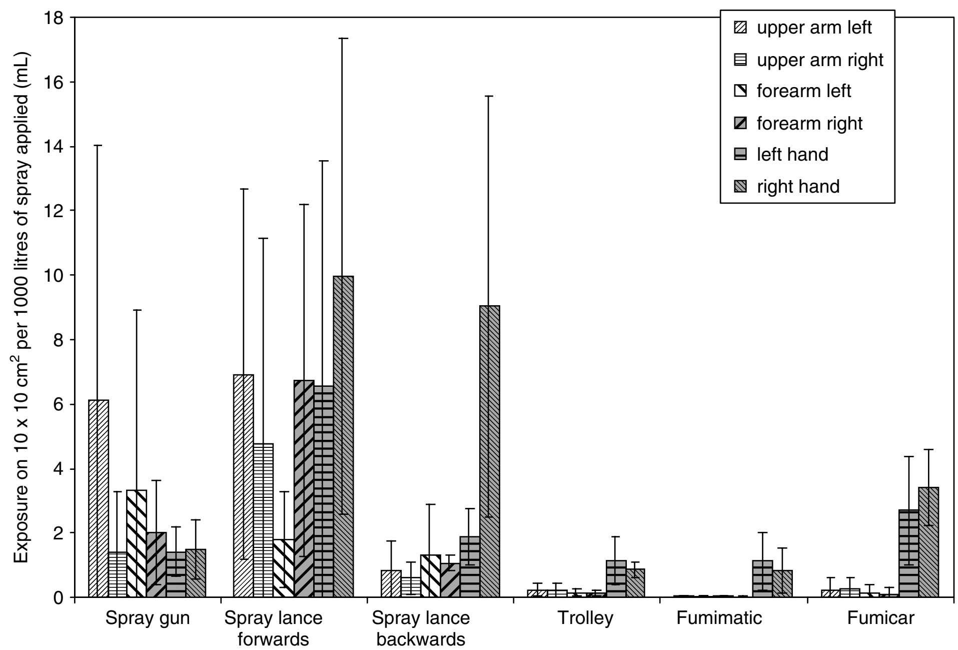

Figure 4. Exposure of the arms and hands on an area of 10 $\times$ 10 cm^2 per 1000 L of spray applied ($\pm$ SD) for the different techniques.

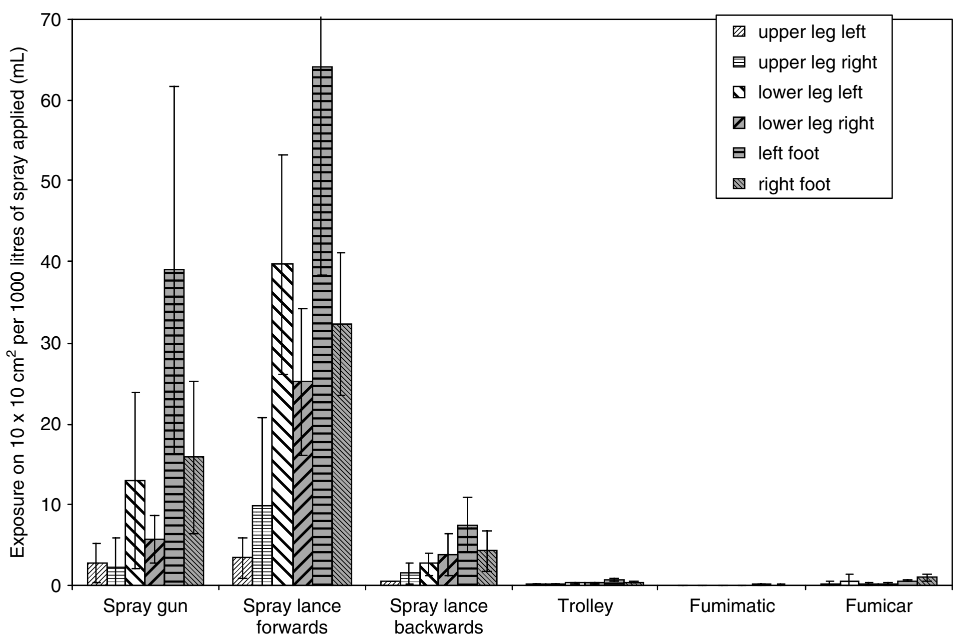

Figure 5. Exposure of the lower parts of the body on an area of 10 $\times$ 10 cm^2 per 1000 L of spray applied ($\pm$ SD) for the different techniques.

body are clearly lower for the spray gun and walking forwards than for the spray lance and walking backwards. Exposure differed by a factor of about 6 for back and chest, and by about 15 for the head. Reasons for this high exposure with the spray lance were mentioned above. The exposure of the upper parts of the body with the Fumicar is roughly one order of magnitude higher than the exposure with the trolley and Fumimatic. Again, this is probably caused by the finer spray, the higher exposure time and the smaller distance between body and spray cloud.

Looking at the exposure of the hands and arms (Fig. 4), the highest exposure of the hands was again highest with the spray lance walking forwards for the left as well as for the right hand, respectively 6.57 and 9.97 mL on 10 $\times$ 10 cm^2 per 1000 L of spray applied, although exposure of the hands only accounted for 3.2% of the total PDE (Table 5). The considerable difference between the left and the right hand using the spray lance was mainly caused by the formation of a large and fine spray cloud close to the right hand. Walking backwards with the spray lance, the exposure of the arms was strongly reduced except for the right hand.

With the spray gun, the exposure of the hands was relatively low compared with the rest of the arms and with the exposure with the spray lance. Exposure was comparable with that with the trolley or the Fumimatic, and even lower than the exposure of the hands with the Fumicar. With these innovative techniques using spray booms,

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Table 5. Relative contribution (%) of each part of the body in the total PDE for the different application techniques

	Spray gun	Spray lance forwards	Spray lance backwards	Trolley	Fumimatic	Fumicar
Head	0.8	5.2	7.3	3.5	7.2	13.5
Back	0.7	1.6	4.1	8.7	10.5	17.3
Chest	1.3	3.0	5.2	6.1	4.9	12.2
Upper arm left	10.5	4.7	3.7	8.1	3.0	2.7
Upper arm right	2.4	3.3	2.8	7.9	3.2	4.0
Forearm left	2.4	0.5	2.5	2.4	1.5	0.7
Forearm right	1.4	1.9	2.0	2.2	0.4	0.6
Upper leg left	6.1	3.0	2.5	5.6	1.2	3.6
Upper leg right	5.2	8.9	9.0	5.5	1.0	10.6
Lower leg left	17.7	21.5	9.5	6.9	1.6	1.1
Lower leg right	7.8	13.6	13.8	6.7	0.7	1.1
Left foot	30.0	19.6	15.2	10.6	3.8	3.4
Right foot	12.2	9.9	8.6	5.6	2.2	5.7
Left hand	0.7	1.3	2.4	11.4	33.9	10.3
Right hand	0.7	1.9	11.5	8.8	24.8	13.1
Total	100.0	100.0	100.0	100.0	100.0	100.0

the exposure of the hands was higher than that of the other parts of the arms and the body and represented 20.2% (trolley), 58.7% (Fumimatic) and 23.4% (Fumicar) of the total PDE (Table 5). The main reason for this was probably that most of the spray deposits on the hands did not come from the spray cloud or the drift but from touching the spraying equipment, as was also suggested by Landers.[79] Because the hands are involved in all essential aspects of spraying, the use of protective gloves is strongly recommended, irrespective of the type of spray application.[4,15,80,81]

With the spray gun there was also a substantial difference between the left and the right arm, which was not the case for the hands. For example, exposure of the left upper arm was about 4 times higher than exposure of the right upper arm and represented 10.5% of the total PDE. One reason for this difference was the fact that the operators sprayed the left side of the row, and consequently the spray cloud mainly touched the left side of the body. An additional factor is indirect contamination through contact with the sprayed plants.[5,7,18] Spraying the left side of the row while moving forwards is the normal practice in Southern European horticulture and was used by all the operators. Because of the short length of the spray gun, it is even possible that some liquid was sprayed directly on the left side of the operator. For the left arm, the exposure with the spray gun was in the same range as that with the spray lance, which was not the case for the other parts of the body. For the right arm, the exposure with the spray gun was about 3.4 times lower than with the spray lance walking forwards, again an indication of a small spray cloud and only a little drift.

With the Fumimatic, the exposure of the arms was almost nil because the spray cloud and the operator were separated by the tank, and the arms of the operator were situated in front of him while driving the Fumimatic. Using the trolley and the Fumicar greatly reduces the exposure of the arms, but some spray liquid (0.11–0.30 mL on $10 \times 10\ \text{cm}^2$ per 1000 L of spray applied) was still found because the arms of the operator were relatively close to the spray cloud and there was no real separation between the spray cloud and the operator.

Because the lower parts of the body come easily into contact with the falling droplets and spray cloud, the measured exposures on the lower legs and the feet were clearly the highest of the entire body, especially using the spray gun and spray lance (Fig. 5), which is confirmed, among others, by Bjugstad and Torgrimsen,[11] Camisa *et al.*[68] and Vidal *et al.*[44] Exposure of the legs and feet represented 80, 78 and 60% of the total PDE, respectively, for the spray gun, the spray lance forwards and the spray lance backwards (Table 5). In previous studies, very similar results were found for different types of handheld non-agricultural pesticide application,[82] for a greenhouse fogger[83] and for a knapsack sprayer equipped with controlled droplet applicators (CDA).[84] For the trolley, Fumimatic and Fumicar, exposure of the legs and feet was only 43, 11 and 26% respectively.

The highest exposure was found on the left foot using the spray lance forwards, i.e. 64.1 mL (SD $\pm$ 25.8) on $10 \times 10\ \text{cm}^2$ per 1000 L of spray applied, which is about 100 times higher than the theoretical plant deposit and represents 19.6% of the total PDE. Moreover, there was a general trend that, the lower the position on the legs, the higher was the exposure. That is why Machado-Neto *et al.*[74] suggested protecting the legs and feet of the users of knapsack sprayers applying paraquat. With the spray gun and lance, exposure of the left foot was generally higher than exposure of the right foot, again because the operator sprayed on the left side. Once again, the exposure with the spray gun was lower than with the spray lance walking forwards.

Walking backwards reduced exposure of the legs and feet by a factor of about 9. In this case, the difference between the left and the right side of the body was less clear because some operators sprayed the right side of the crop while walking backwards owing to their lack of experience with this specific technique. With the trolley and Fumicar, very small amounts of spray liquid were found on the legs and feet, varying from 0.10 to 0.90 mL on $10 \times 10\ \text{cm}^2$ per 1000 L of spray, and hence were within the same order of magnitude as the theoretical plant deposits. The exposure of the legs with the Fumimatic was almost nil. Exposure results of these individual parts of the body, combined with toxicological and physicochemical information on the pesticides used, can be helpful in advising growers what protective clothing they should wear.

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4 CONCLUSIONS

The operator exposure experiments demonstrated that the difference in total body exposure between the different spray application techniques in large plants (peppers) was very high. Potential dermal exposure (PDE) varied from 19.7 mL h^{-1} for the Fumimatic to 460 mL h^{-1} for the spray lance walking forwards. Walking backwards, an easy technique that does not require any investment, reduced PDE by a factor of 7. Walking forwards, PDE with the spray lance was about 2.5 times higher than with the spray gun.

With the trolley, Fumimatic and Fumicar, PDE for a constant spray volume was respectively 20, 60 and 8 times lower than with the standard spray gun, mainly because the operator was not walking directly into the spray cloud and the sprayed crop and because of the higher capacity of techniques using spray booms. In addition, these techniques might increase productivity, reduce labour costs and give a better spray distribution.

Besides a very large difference in total PDE among the different techniques, pesticide distribution over the operator's body was found to be non-uniform and strongly related to the application technique. Hence, depending on the type of spray application, different parts of the body need to be protected most. With the traditional handheld application techniques, exposure of the legs and feet represents 60–80% of the total PDE because these body parts easily come into contact with the falling droplets and spray cloud. The lower the position on the body, the higher is the exposure. In the worst case, estimated exposure was about 100 times higher than the theoretical plant deposit after spraying 1 ha. Besides the lower parts of the body, there was also a relatively high exposure of the hands, the forearms and the head. Depending on the side of the row that was sprayed with the lance or gun, there was a difference in exposure between the left and the right side of the body.

With the manually pulled trolley, the Fumicar and the Fumimatic, the exposure was the highest for the hands, representing, respectively, 20.2, 58.7 and 23.4% of the total body exposure. For these techniques, most of the spray deposits on the hands did not come from the spray cloud or the drift but from touching the spraying equipment. That is why the use of protective gloves is strongly recommended, irrespective of the type of spray application. The obtained exposure data can be helpful in developing exposure models and databases for risk assessment and pesticide registration.

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