Assessment of Dermal Exposure During Airless Spray Painting using a Quantitative Visualisation Technique

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The range of dermal exposure to non-volatile compounds during spray painting was studied in a semi-experimental study involving three enterprises and 12 painters. A fluorescent tracer was added to the paint and deposition of the tracer on clothing and uncovered parts of the skin was assessed using video imaging and processing techniques. A container (volume 36 m3) was sprayed with a colourless lacquer (varnish) containing 66.7 mg/l fluorescent whitening agent. All painters sprayed the outside of the container. Nine painters repeated the painting a second time and five also sprayed the inside of the container. The painters wore white Tyvek™ coveralls, but no gloves. Duration of spraying the outside ranged from 4 to 21 min with a mean of 10 min and the amount of paint sprayed ranged from 3.0 to 12.8 l (mean 6.6 l). The mass of tracer deposited on the coverall ranged from 2.2 to 471 μg (90th percentile 256 μg), whereas, mass deposited on skin (i.e. the hands, wrists, and face) ranged from 0.01 to 52 μg tracer (90th percentile 20 μg). The quantity of tracer on the coverall was three times higher after spraying the inside of the container compared to spraying the outside, whereas the quantity on the skin was similar in both cases. On average 10% of the surface area of the coverall and skin was exposed during spraying the outside. Exposures, expressed in units of mass per area exposed were slightly higher for skin compared to coverall.

In this study, deposited mass of tracer was correlated with an alternative exposure metric, i.e. surface area exposed multiplied by the duration of exposure, which has been proposed as a surrogate for uptake. Using a quantitative fluorescent tracer technique, it could be demonstrated that body parts which showed the lowest mass of tracer had the highest exposure as mass per surface area. Compared to other techniques which only determine mass, the ability to identify and quantify the actual surface area exposed is a clear advantage of the quantitative fluorescent tracer technique.

Keywords: dermal exposure; spray painting; visualisation; quantification technique

INTRODUCTION

During airless spray painting, aerosols are generated as the pressurised liquid paint passes through the spray gun nozzle. Paint aerosols, which contain non-volatile resins, fillers, binders and pigments, and solvents, may either impact onto the surface being sprayed, or may remain in the air compartment until deposition on other surfaces or onto the workers clothing or skin compartment. Alternatively, the aerosols may stay airborne long enough to enable evaporation of the volatile parts, leading to inhalation exposure to both aerosol and vapour.

There has been considerable investigation of the inhalation exposure from spray painting (e.g. Carlton and Flynn, 1997a,b), although as far as we are aware there are no published data on the likely dermal exposure from such processes.
Measurement of (potential) dermal exposure, i.e. exposure on clothing and on skin, can be undertaken using a variety of methods (Fenske, 1993). However, sampling techniques that require chemical analysis, e.g. surrogate skin and removal techniques, are not easy to apply because of the complexity of the paint composition and its changes during the process of drying and curing. Limited quantitative methods for chemical analysis, and absorption by the sampling matrix or worker’s skin, may hamper adequate recovery of the paint components. In situ assessment of exposure by the introduction of a non-volatile fluorescent tracer into this process and evaluation using digital image acquisition and processing would avoid recovery and analysis of paint components. In addition, quantitative visualisation generates data on the surface area that is actually exposed. Area exposed is considered to be a key factor for uptake (Cherrie et al., 2000). Therefore, the quantitative visualisation technique was considered a promising approach to assess dermal exposure during spray painting.

The major objective of this investigation was to determine both mass of fluorescent tracer deposited on the skin and the clothing of painters spraying a container and the surface area of skin and clothing that was exposed. In addition, we explored the use a surrogate exposure metric related to the mass of contaminant that could pass through the stratum corneum. It was designed as a semi-experimental study, since colourless paint (varnish) had to be used to enable visualisation and quantification of the emitted fluorescence. A secondary aim was to compare the mass of tracer on the workers’ clothing determined by the fluorescence technique with that obtained from a chemical analysis, to indicate the relative performance of the fluorescent tracer technique.

MATERIALS AND METHODS

The study was conducted in three offshore metal construction workplaces. Twelve professional airless spray painters painted the same 36 m³ (6×2.5×2.4 m) container at least twice. The outside of the container (including the top) was painted 21 times, whereas the inside of the container was painted five times. A colourless paint (Silvatane) was used, diluted with refined petrol (boiling point 100–140°C), containing 1.4 g/l fluorescent whitening agent (Uvitex OB). At all three enterprises the container was located in a hall with general exhaust ventilation. The painters had to move around the object to paint the outside at an average (spray)gun-to-object distance of 1 m (range 0.5–1.5 m). The painters wore hooded white Tyvek™ coveralls, but no gloves. Prior to and immediately after spraying, each worker was exposed to long-wave u.v. light and images were taken from five locations of the skin, i.e. palms and back of the left and right hand and the head (front side). In addition, post-exposure images were taken of the sprayer’s coverall, divided in 34 parts for this assessment, i.e. front and back side of left and right lower leg, upper leg, forearm, upper arm, left and right of the hood, and eight front and eight back parts of the torso.

The images were recorded and analysed using the VITAE system which has been described by Bierman et al. (1998). Briefly, the VITAE system consists of an illumination setup, an image acquisition and processing system. Basically, the illumination set up consists of two armatures, each holding two TL D-light bulbs with a distance of 50 cm in between. This set up results in an homogeneous illumination in a 50×50 cm frame at a distance of 1 m. Body parts and parts of the coverall were positioned in the frame. Images were recorded using a video camera that was located in between and were digitzised with a frame grabber installed in a PC. Images digitised with this equipment consist of 512×512, 8 bits picture elements (pixels). This implies that at a distance of 1 m between object and camera, each pixel covers an object surface area of 0.775 mm². Each pixel may have a value from 0 to 256, usually referred to as grey value. For each pixel in an image of the skin, the grey values prior to exposure and post exposure were compared. For Tyvek™ parts only post exposure grey values were determined. Image analysis was performed using Scil Image analysis software implemented on a PC using Visual C++.

A linear relationship between the mean grey levels (up to grey level 60) and the amount of Uvitex OB on Tyvek™ and skin was observed for the 30–250 ng/cm² and the 50–1000 ng/cm² ranges, respectively. Calibration equations per entire image were

$$\text{Grey value} = 8.20 + 14.46 \times \text{Amount (ng Uvitex OB)}, R^2 = 0.86$$

for Uvitex OB on Tyvek™, and

$$\text{Grey value} = 6.15 + 8.62 \times \text{Amount} + 2.01 \text{ (Skin (pre-exposure grey level)}}$$

for Uvitex OB on skin.

The amount of tracer detected within one image is divided by the number of pixels, i.e. an object surface area of 0.775 mm², to derive the metrics amount of Uvitex OB per cm².

The surface area (A) covered with fluorescent agent was evaluated for six sections of the coverall (lower and upper legs, forearms, upper arms and hood) and two areas of the skin (head and hands). It was not possible to estimate the uptake of the tracer or any of the paint components. However, for a contaminant substance present at a single concentration, i.e. the concentration of the contaminant in the mass deposited on skin or clothing, Cherrie et al. (2000) suggest that uptake would be proportional to the product of the area exposed and the duration of exposure, i.e. A·t, and this is proposed as an alternative...
exposure metric. Duration of exposure should be read as time of residence of the contaminant on the skin. For the present spray scenario, where images were taken immediately following spraying, time of residence is equal to the actual time of spraying. We have used this measure as a surrogate for uptake through the stratum corneum and compare this with mass of tracer deposited.

In addition to VITAE-analysis, 44 coverall parts were chemically analysed using fluorescent detection (excitation: 371 nm; emission: 425 nm) with a limit of detection of 5 µg/l. Depending on the extraction volume the limit of quantification ranged from 1 µg for a forearm section to 4.5 µg for a torso section. In the laboratory the extraction efficiency or recovery of Uvitex OB in paint from Tyvek™ was tested after a drying period of approximately 2 and 4 h. Recovery after 2 h was approximately 100%, whereas after 4 h the recovery decreased to approximately 70%. After a time of residence of 24 h in the extraction liquid (refined petrol) the recovery increased to approximately 100%.

Samples of the paint were collected to determine the actual concentration of the Uvitex OB concentration in the spray liquid. Spray volumes were assessed by weighing the spray tank prior and after spraying. On each sampling day two blanks and two field spikes were collected, one at a low level of fortification of Tyvek™ coverall parts (range 8–34 µg Uvitex OB in paint), and one at a high level of fortification (103 µg Uvitex OB in paint).

Descriptive statistics were calculated for the total mass of tracer on the coverall and the skin. The Mann–Whitney test was used to study differences between workplaces. Since nine workers sprayed the outside of the container twice the Wilcoxon signed-ranks test was used to compare spray characteristics from both sessions. Relationships between exposure and duration, exposure and spray volume, and mass deposited and surface area exposed and duration were analysed by linear regression. Agreement between chemical and VITAE analysis were studied by calculations and plots of means and differences over the data range, according a method given by Bland and Altman (1986). Similar to clinical measurements no ‘gold standard’ is available for evaluation of dermal surrogate skin exposure in field practice, and both methods give estimates of the ‘true exposure’.

RESULTS

Spray parameters

The observed spray time ranged from 4 to 21 min and the spray volume ranged from 3.0 to 12.8 l. Mean duration of spraying the outside of the container were 11.5, 9.8 and 11.8 min for the three workplaces, respectively, whereas average spray volumes were 7.0, 6.1, and 6.5 l. No statistically significant differences (P>0.05) were observed between the work- places or between the first and the second painting sessions for these parameters. Different spray gun orifices were in use, with diameters ranging from 130 µm in the first workplace to 330 µm in third workplace. Spray rates ranged from 0.37 to 0.83 l/min.

The concentration Uvitex OB in 30 samples of paint ranged from 39 to 108.6 mg/l (mean: 64.8 mg/l), whereas the expected concentration was 66.6 mg/l. The actual concentration was used in the statistical analysis. Mean recoveries of the field spikes were 106% (range 100–110%) and 108% (92–125%) for high and low level of spikes, respectively.

Level of exposure

Exposure during the first spray application of the containers’ outside was significantly higher than exposure during the second time, P<0.03 for skin and P<0.04 for Tyvek™ coverall, respectively. The amount of Uvitex OB tracer detected on the Tyvek™ coveralls and skin did not follow either a normal or log-normal distribution. Statistical significant differences (P<0.003) were observed between the mass on the coverall while spraying the inside and the outside of the container. The arithmetic mean mass (and standard deviation) of Uvitex OB detected on coveralls were 558 µg (±294, N=5) and 144 µg (±127, N=21), during spraying the inside and the outside, respectively. No significant differences were observed for the mass of tracer on the skin; with arithmetic mean mass (and standard deviation) of 11 µg (±12) and 7.4 µg (±13) for spraying the inside and the outside, respectively. Similar results were observed for the exposure metrics mass per surface area exposed, with a significant difference for coveralls [AM’s 90 (±10) ng/cm² and 60 (±20) ng/cm²], spraying containers’ inside and outside respectively. There was no significant difference between skin exposure while spraying the inside [AM:120 (±50) ng/cm²] and the outside [AM: 90 (±80) ng/cm²].

On average 398 mg/kg Uvitex OB was deposited on body and skin during painting the containers’ outside (range 12–1896 mg/kg, N=21).

The summary statistics of the contamination of the body during spraying the outside of the container for all three workplaces are given in Table 1. No statistically significant differences were observed between the workplaces for the mass deposited on coverall or the area exposed multiplied by duration. A significantly lower amount of tracer was deposited on skin in workplace A compared to workplaces B and C, although no statistically significant differences were observed for the area exposed multiplied by duration. A good relationship between the amount of tracer versus the area exposed multiplied by duration is observed for both skin and coverall, with R² 0.82 (P<0.001) and 0.85 (P<0.001), respectively. In Fig. 1 the amount of tracer versus the area exposed multiplied by duration is plotted for skin.
Table 1. Distribution of the mass and exposure (Area exposed $\times$ duration of exposure) of fluorescent tracer detected on coverall and skin spraying the containers’ outside

<table>
<thead>
<tr>
<th>Workplace</th>
<th>AM (±SD)</th>
<th>GM (GSD)</th>
<th>Range</th>
<th>AM (±SD)</th>
<th>GM (GSD)</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coverall</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>154 (±156)</td>
<td>83 (3.8)</td>
<td>11–472</td>
<td>23 684 (±24 858)</td>
<td>12 461 (3.7)</td>
<td>2244–69 523</td>
</tr>
<tr>
<td>B</td>
<td>125 (±80)</td>
<td>107 (1.8)</td>
<td>47–290</td>
<td>18 322 (±11 555)</td>
<td>15 175 (2.0)</td>
<td>4572–38 152</td>
</tr>
<tr>
<td>C</td>
<td>179 (±168)</td>
<td>130 (3.9)</td>
<td>2.2–449</td>
<td>291 125 (±22 479)</td>
<td>15 632 (4.7)</td>
<td>1404–53 253</td>
</tr>
<tr>
<td><strong>Skin</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>0.3* (±0.4)</td>
<td>0.04 (13)</td>
<td>0.0–11</td>
<td>101 (±150)</td>
<td>18.4 (10.9)</td>
<td>0.5–400</td>
</tr>
<tr>
<td>B</td>
<td>10* (±11)</td>
<td>5.0 (4.2)</td>
<td>0.5–33</td>
<td>715 (±607)</td>
<td>467 (3.1)</td>
<td>55–1649</td>
</tr>
<tr>
<td>C</td>
<td>13* (±20)</td>
<td>1.6 (17)</td>
<td>0.06–52</td>
<td>671 (±827)</td>
<td>236 (6.7)</td>
<td>18.7–2118</td>
</tr>
</tbody>
</table>

*a Statistical significant difference ($P<0.01$).

Fig. 1. Plot of the surface area exposed multiplied by the duration of exposure versus mass of tracer deposited on skin.

Distribution of exposure and area exposed

The leg section of the coverall contributed the largest mass of tracer detected during spraying the outside of the container, as shown in Fig. 2. On average 54% (±30%) of the total mass was deposited on the lower legs and 18% (±19%) on the upper legs. Skin deposition, i.e. hands and forehead, contributed on average 3.6% and 2.3%, respectively to the total mass of tracer deposited. A similar pattern of contamination was observed for spraying the inside of the container.

The highest proportion of the area exposed of any body section was observed for the lower legs and the lowest for the head for both spraying scenarios (Table 2). The area exposed on the upper legs, torso parts, forearms, upper arms and hood, were all in the same range, i.e. 4–9% and 19–31% for spraying the inside and spraying the outside of the container, respectively. On average 9.3% of the surface area of the coverall was exposed during spraying the outer surface of the container, whereas the average area exposed of the coverall during spraying the inside of the container was 28%. Similar figures were seen for the hands, where the average area exposed during spraying the outside and the inside of the container were 10 and 17%, respectively.

Modifiers of exposure

The results from one worker who sprayed much more paint (12.8 l) during more time (21 min) than the others was excluded from the regression analysis.

Fig. 2. Distribution of mass Uvitex OB deposited on coverall and hands during spraying the outside of the container (N=21).
Table 2. Area identified as contaminated during spraying, expressed as percentage of the total surface area

<table>
<thead>
<tr>
<th>Body part</th>
<th>Outside (N=21)</th>
<th>Inside (N=5)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AM (%)</td>
<td>SD</td>
</tr>
<tr>
<td>Lower legs*</td>
<td>29</td>
<td>20</td>
</tr>
<tr>
<td>Upper legs*</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Torso*</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Forearms*</td>
<td>9</td>
<td>10</td>
</tr>
<tr>
<td>Upper arms*</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Hood*</td>
<td>8</td>
<td>11</td>
</tr>
<tr>
<td>Hands*</td>
<td>10</td>
<td>12</td>
</tr>
<tr>
<td>Head*</td>
<td>1</td>
<td>3</td>
</tr>
</tbody>
</table>

*Coverall.
*Skin.

There was a moderate, but significant association between amount of tracer detected on the coverall and duration of spray painting ($R^2=0.21$, $P=0.025$), and spray volume ($R^2=0.26$, $P=0.012$). Spray duration and spray volume were strongly correlated ($r_P=0.8$), and so multiple regression analysis was not performed.

**Comparison of fluorescent tracer assessment and chemical analysis**

In this study less than 2% of all images (N=884) were ‘overexposed’, i.e. exceeded the upper grey level of 60. However, at the lower end of the range of quantification, i.e. at the limit of quantification (LOQ) difficulties may arise in extrapolating the limit of detection at the level of image pixels, i.e. in identifying a distinct area exposed within an image. We have studied the LOQ in chemical analysis with that of the VITAE analysis. Thirty-four out of 44 coverall parts which were both analysed by VITAE and by chemical analysis showed a greater amount recovered by chemical analysis compared to VITAE detection. Mean difference between sections that were not identified as exposed by VITAE and the results of chemical analysis was 0.06 ng. Introduction of this surrogate LOQ for the VITAE analysis revealed a maximum increase of 33% in the levels at the lower end of the exposure range, indicating a relative lower VITAE response for low exposures.

This relative lower VITAE response for low exposures is also illustrated by plotting the mean masses against the differences of the amounts detected in the coverall parts by both methods [Fig. 3(A)]. This figure also shows that the differences between both methods observed for high exposure levels exceed the mean±SD, which indicates poor agreement of both methods for the higher ranges of exposure. Figure 3(B) shows that for low amounts of tracer deposited on the coverall parts, large differences could be observed (expressed as percentages of the mean), whereas the relative difference decreases with increase of the mean.

**DISCUSSION**

The mass of fluorescent tracer detected on the spray painters clothing and skin showed a relatively large variation for a group of workers using similar spraying technique to spray the same object. In this study the highest deposition of tracer mass was observed on the lower legs and this was the body section that showed the highest percentage of area exposed. It was shown that the skin compartment received the highest exposure in units of mass per surface area exposed during spraying the outside of the container [90 (±80) ng/cm²], compared to the coverall compartment [60 (±20) ng/cm²], although this was reversed when the deposited mass was considered, i.e. 7.4 μg (±13) on the skin and 144 μg (±127) on the coverall.

For the actual process of exposure, i.e. process of deposition of paint aerosols during actual spraying, both mass deposited and area exposed seem to be linearly related with time, so a good correlation is observed for mass and $A(t)$ (Fig. 1). Thus, for the present exposure scenario, where a relatively constant concentration is assumed of the tracer in the paint landed on the skin, determination of mass at the end of the actual spraying time might be a good indicator of uptake. However, when the time of residence exceeds the actual time of spraying, e.g. the contaminant will be removed from the hands after one hour, $A(t)_{t=t_{spraying}+60}$ will be increased but the mass will be more or less the same. For such an exposure scenario obviously the relationship mass and $A(t)$ will not be linear and the relevance of mass as surrogate for uptake can be discussed.

This present method to assess dermal exposure is a tracer method, therefore the results obtained by this method should be translated to real-life paint components. A key issue is the similar behaviour of the tracer and the paint components throughout the entire exposure process. Since mass is considered relevant for uptake for the present exposure scenario, the mass of tracer on skin and the initial concentration of the
Uvitex OB in the paint can be used to calculate the mass of non-volatile paint components. A wide range of the Uvitex OB concentration in paint was observed, which may be related that it is not easy to obtain homogeneous samples from suspensions. However, the deviation of the mean of the actual concentrations compared to the theoretical concentration in the paints is very low (<3%), and will not contribute substantially to the overall variances of exposure observed.

The accuracy of the VITAE-method, as well as that of the chemical method, is unknown but essential for evaluation of the results. Since all coverall parts were collected from the field study, no ‘true exposure’, i.e. known amounts of tracer, can be determined. Calculation of the correlation coefficient as a measure of strength of the relation between both methods does not indicate the agreement between them. Despite the high correlation ($r=0.79, P<0.001$) between the results obtained by VITAE and by chemical analysis...
(\(N=44\)) the plots given in Figs 3(A) and (B) indicate that the agreement over the range observed differs very much. Further research, e.g. method validation studies and ‘bench mark’ studies for performance comparison of methods to assess dermal exposure, is needed to clarify this observation.

If the chemical method would be accurate, results obtained by VITAE analysis may have limited accuracy, but, in addition to its ability to determine the surface areas exposed, its ability to collect a large data set is extremely important for reliable estimates of exposure for highly variable exposure scenarios and processes. Moreover, we consider that the VITAE-method has shown its advantages for risk assessment purposes, since it determines both the mass of tracer deposited on the body and the surface area exposed. This information can be used to estimate the uptake of contaminants through the stratum corneum.

**REFERENCES**


