Estimating Dermal Exposure to Jet Fuel (Naphthalene) Using Adhesive Tape Strip Samples

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A simple, non-invasive dermal sampling technique was developed and tested on 22 human volunteers under laboratory conditions to estimate acute dermal exposure to jet fuel (JP-8). Two sites on the ventral surface of each forearm were exposed to 25 µl of JP-8 and the non-viable epidermis (stratum corneum) was sequentially tape-stripped using an adhesive tape. Samples were extracted with acetone and analyzed by gas chromatography/mass spectrometry. Analysis of the first tape strips indicated that JP-8 was rapidly removed from the stratum corneum over the 20 min study period. On average, after 5 min of exposure the first two tape strips removed 69.8% of the applied dose. The amount recovered with two tape strips decreased over time to a recovery of 0.9% 20 min after exposure. By fitting a mixed-effects linear regression model to the tape strip data, we were able to estimate accurately the amount of JP-8 initially applied. This study indicates that naphthalene has a short retention time in the human stratum corneum and that the tape stripping method, if used within 20 min of the initial exposure, can be used to measure reliably the amount of naphthalene initially in the stratum corneum due to a single exposure to jet fuel. We are currently investigating the applicability of the developed mixed-effects linear regression model to estimate acute JP-8 exposure levels based upon naphthalene measurements from tape strips collected from occupationally exposed workers.

Keywords: dermal exposure; jet fuel; monitoring method; naphthalene; tape stripping

INTRODUCTION

There is a significant need for techniques that can help to determine the amount of a chemical absorbed into the skin following occupational or environmental exposure. Studies of skin toxicity have mainly focused on methods for evaluating skin irritation and allergic reactions, or for investigating the physico-chemical factors that influence skin penetration. Methods to assess the significance of dermal exposure are limited in both number and scope and fail to measure concentration in the skin per se (reviewed in Nylander-French, 2003). The recently developed tape stripping techniques (Cullander et al., 2000; Kristiansen et al., 2000; Nylander-French, 2000; Nylander-French et al., 2001) show promise in being able to measure the concentration of a contaminant in the skin. Thus, we further developed one of these techniques to assess acute dermal exposure to JP-8 jet fuel.

Jet fuels are composed of complex mixtures of petroleum hydrocarbons (aromatic and aliphatic), ranging from C4 to C18 compounds, which include gasoline and kerosene (National Research Council,
1996). Previously, jet propellant 4 (JP-4), which contains approximately 65% gasoline and 35% kerosene, was the primary jet fuel (Potter and Simmons, 1998). Because of its volatility and flammability (due to the large fraction of low molecular weight compounds), JP-4 was replaced by JP-8, a kerosene-based fuel. JP-8 is similar to the commercial jet fuel, Jet A-1, with the inclusion of additives such as icing inhibitors, metal deactivators, antioxidants, corrosion inhibitors and other compounds to improve lubricity and conductivity (White, 1999). The specific chemical composition of JP-8 (and other jet fuels) depends on crude and shale oils used for its production and is further defined based on performance characteristics like aromatic hydrocarbon content. Because JP-8 does not contain the lower molecular weight hydrocarbons (i.e. gasoline), it is less volatile than JP-4 (National Research Council, 1996). As a result, exposure by inhalation may potentially be lower, but dermal exposure may play a more significant role.

Numerous military personnel are exposed to jet fuel, including pilots, flight crews, maintenance workers and non-aircraft-related airport workers (Zeiger and Smith, 1998). Exposures occur during low ambient temperature engine starts, refueling and fuel handling (splashes), repair of leaks, engine repair and fuel cell maintenance (Smith et al., 1997; McDougal et al., 2000; Pleil et al., 2000). Fuel cell maintenance personnel are likely to encounter high exposures because repair work often requires the workers to enter the fuel cell, which always contains residual fuel. Typically, workers enter a fuel cell wearing only cotton clothing to protect against collection of static charge. Cotton offers little protection against dermal exposure; in fact, cotton clothing may increase exposures since it acts like a reservoir, keeping a continuous supply of fuel on the skin. In the military, foam is used in fuel cells as a fire suppressant matrix and physical removal of foam saturated by jet fuel can significantly increase dermal exposure to jet fuel.

Most information available on human health effects is from exposures to jet fuels JP-4, JP-5, JP-7 and Jet-A. Most commonly reported symptoms include headaches, dizziness, nausea, conjunctivitis, mild hypertension, difficulty breathing, eye and skin irritation and skin inflammation (Knave et al., 1976, 1978, 1979; Struwe et al., 1983; Porter, 1990). Neurological effects, such as fatigue, impairment of hand–eye coordination, memory defects, euphoria, depression, sleep disturbances, memory impairment and postural imbalance, have also been observed (Knave et al., 1976, 1978, 1979; Struwe et al., 1983; Porter, 1990; Smith et al., 1997). Studies on human health effects from JP-8 exposures are limited. Fuel cell maintenance workers had increased exhaled breath concentrations of the less volatile compounds (undecane and dodecane) and had relatively lower concentrations of the higher vapor pressure compounds compared with other workers, which may have been attributed to dermal absorption (Pleil et al., 2000).

Since JP-8 is a performance specification fuel and the composition can vary, the USAF uses a ‘generic’ JP-8 for all toxicological studies. Jet fuels are composed of hundreds of aliphatic and aromatic hydrocarbons. Therefore, assessing exposure to jet fuel as a whole is impossible. Thus, for exposure assessment purposes, a marker compound (component of the mixture) is often identified and used to represent the mixture. Naphthalene (C_{10}H_{8}, CAS no. 91-20-3) was chosen as a marker of exposure to JP-8 for the following reasons: (i) it is one of the 13 components that comprise 29% of the base fuel and is present at >1% v/v concentration (Potter and Simmons, 1998; Riviere et al., 1999); (ii) it is easily identified by gas chromatography/mass spectrometry (GC/MS) at low concentrations; (iii) it was not present in the tape adhesive; (iv) it was not found in control (blank) skin tape strip samples; (v) naphthalene (or its metabolites) is commonly used as a marker for exposure in other sampling media, e.g. ambient air, exhaled breath, urine and blood by other investigators (Riviere et al., 1999; McDougal et al., 2000; Baynes et al., 2001; Kanikkannan et al., 2001).

The goal of this study was to develop a non-invasive tape stripping technique to assess acute dermal exposure to JP-8 and to determine the quantity of naphthalene deposited directly onto the skin. Preliminary data were obtained from 22 volunteers exposed to four 25 µl applications of JP-8 using naphthalene as a marker of JP-8 exposure. The experimental tape strip data were used to develop a mixed-effects linear regression model that will allow estimation of acute JP-8 exposure levels based upon naphthalene measurements from tape strips collected from occupationally exposed workers.

MATERIALS AND METHODS

Chemicals

JP-8 was provided by the USAF Research Laboratory (Wright-Patterson Air Force Base, OH). Solid scintillation grade naphthalene (>99% pure) and solid deuterated naphthalene (naphthalene-d_8, 98%) (Aldrich, Milwaukee, WI) were utilized as a standard and as an internal standard, respectively. Acetone (nanograde) (Malinckrodt Baker, Paris, KY) was used as an extraction solvent to remove jet fuel components from the tape strip samples and as a solvent for solid naphthalene and naphthalene-d_8.

Study population and tape stripping method

Cover-Roll® adhesive tape (Beiersdorf AG, Germany), a self-adhesive gauze with a woven polyester backing and polyacrylate adhesive, was tested on 22 human volunteers (11 males and 11 females)
for its capacity to remove JP-8 applied to the skin. The average age of the study population was 33 ± 9 yr, ranging from 22 to 56 yr, and consisted of 11 Caucasians, five Asians, four Hispanics and two African-Americans. Six of the volunteers had light/fair skin, 11 had medium/brown skin and five had dark/black skin.

Two sites on the ventral surface of each arm (four sites total) were each exposed to 25 µl of JP-8. The four sites corresponded to 5, 10, 15 and 20 min JP-8 exposure. For all subjects, the 5 and 10 min sites were on the right arm and the 15 and 20 min sites were on the left arm. Also, a control tape strip sample was collected from an unexposed site on each arm near the wrist. Fuel was applied neat to the non-occluded skin using a micropipette and a two-well aluminum application chamber to define the exposure sites. Both wells in the aluminum chamber measured 2.5 cm (width) × 4.0 cm (length) × 1.3 cm (height), with a total area of 10 cm² per well, and were 4 cm apart. An aluminum tab (2.2 cm long and 0.2 cm thick) was placed in the center of each well and secured to extend 0.08 cm below the chamber-skin surface. The tab was designed to keep the skin flat and prevent it from ‘doming’ inside the chamber and cause the fuel to pool around the interior walls when pressure was applied to seal the chamber. During exposure, the chamber was held in place for 5 min on all sites. After the desired exposure time elapsed, adhesive tape, precut to 2.5 cm × 4.0 cm, was applied to the exposed site. Prior to application, the adhesive tape was inspected for defects and the exposure site was observed to determine whether the applied material had spread outside the desired area. After the 2 min adhesion time (Surakka et al., 1999; Nylander-French, 2000), the adhesive tape was removed slowly with constant force at a 45° angle using clean forceps (rinsed in acetone between each tape stripping) and placed in a 20 ml scintillation vial containing 5 ml of acetone and 20 µl of 25 µg/ml naphthalene-d₈. The second and third tapes were carefully applied to the same site immediately after the previous tape was removed and were also retained on the skin for 2 min. The vials were placed on a rotation shaker for 30 min at 250 r.p.m. and stored at 4°C until analysis by gas chromatography–mass spectrometry (GC–MS). Prior to GC–MS analysis, adhesive tape was removed from each vial using clean forceps and any remaining acetone in the tape was squeezed back into the vial. Gloves were changed and the forceps were rinsed between each sample to avoid cross-contamination.

This study was approved by the Institutional Review Board on Research Involving Human Subjects, School of Public Health, The University of North Carolina at Chapel Hill.

Chemical analysis

Acetone extracts were concentrated from 5 to 0.5 ml using compressed nitrogen and then transferred to 2 ml amber autoinjector vials for GC/MS analysis. Media blank samples (one for every 20 samples) were prepared using the same procedure.

A HP 5890A Series II gas chromatograph equipped with an HP 7673 auto injector, an HP 5972 electron ionization quadrupole mass spectrometry detector (Hewlett-Packard, Palo Alto, CA) and DB-5MS column (30 m, 0.25 mm inside diameter, 0.25 µm film thickness) (J&W Scientific, Folsom, CA) was used. Injector and detector temperatures were 250 and 280°C, respectively. The oven temperature was initially held at 45°C for 2 min and then increased at 2°C/min to 72°C and held for 20.5 min. After naphthalene and naphthalene-d₈ eluted (~34 min), the oven temperature was increased at 50°C/min to 260°C and held for 8 min to remove later eluting compounds present in the fuel. Injections were made in the split/splitless mode using helium as the carrier gas. The column head pressure was controlled via an electronic pressure control system and maintained at 7.5 pounds per square inch gauge.

The MS was operated in the selected ion monitoring (SIM) mode. Ions at m/z 128 and 102 were monitored for naphthalene and ions at m/z 136 and 108 for naphthalene-d₈. These ions were selected based on fragmentation patterns of the compounds observed while analyzing JP-8 samples with the GC/MS operated in the SCAN mode.

The estimated analytical limit of detection (ALOD) for naphthalene, determined as a signal-to-noise ratio of 3:1, was 8 pg/µl injected. This corresponds to a surface concentration of 0.4 ng/cm² skin.

Extraction efficiency of naphthalene from the tape and naphthalene content in ‘generic’ JP-8

Tape samples (in quadruplicate) were prepared by adding 25 µl of JP-8 to a piece of adhesive tape (2.5 cm × 4.0 cm) in a 20 ml scintillation vial. The vial was capped and, after 5 min, 5 ml of acetone and 20 µl of 25 µg/ml naphthalene-d₈ internal standard were added. Control samples (in quadruplicate) were prepared by adding 25 µl of JP-8 to a vial without tape. The concentration of naphthalene in ‘generic’ JP-8 was determined by GC/MS analysis of the four samples without adhesive tape, assuming a density of 0.81 g/cm³ for JP-8 (Potter and Simmons, 1998). On average, there was 1732 ± 330 ng of naphthalene/µl JP-8 (43300 ng in 25 µl of JP-8), 0.21 ± 0.04% by weight. No significant difference was observed between the amount of naphthalene recovered from samples with or without tape (P = 0.2898; SAS Proc ANOVA), thus indicating an extraction efficiency of 100%.

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**Determination of chamber loss**

After exposure, JP-8 residue on the chamber was determined by rinsing the chamber with 10–15 ml of acetone. An average of 12 213 ± 3130 ng naphthalene was found on the chamber [95% confidence interval (CI) 9146–15 280 ng, n = 4]. This equates to an average JP-8 volume of 7 µl (95% CI 5–9 µl). Therefore, the best estimate of the amount of naphthalene applied to the skin was 31 087 ng (95% CI 28 020–34 154 ng) or 18 µl JP-8 (95% CI 16–20 µl).

**Statistical analysis**

All descriptive statistics concerning the study population, adhesive tape stripping and naphthalene content of JP-8 were determined using untransformed observations and SAS Proc MEANS (SAS Institute, Cary, NC).

Mixed-model multiple linear regression analyses (Proc MIXED) were used to determine the relative influence of fixed effects representing time, gender, age, race and skin pigmentation and to estimate the amount of JP-8 applied to the skin. Histograms and the Shapiro–Wilks test for normality of the log-transformed observations indicated that the data were approximately log-normal. Thus, naphthalene concentrations were natural log transformed for statistical analyses. Each covariate was added to the model separately using a forward selection method and only those covariates with P values <0.10 were kept in the final model. Since no significant differences for the first or second tape strip data were observed between males and females and between age groups or among races or types of skin pigmentation, only time was retained in the final model. The final model was defined as:

\[
E(Y_{ij}) = E(\ln X_{ij}) = \beta_0 + \beta_1 T_j + \beta_2 T_j^2
\]

where \(i = 1, 2, \ldots, 22\) subjects and \(j = 1, 2, 3, 4\) measurements on the \(i\)th subject (\(T_1 = 5\) min, \(T_2 = 10\) min, \(T_3 = 15\) min and \(T_4 = 20\) min).

Here, \(X_{ij}\) is the measured exposure (amount of naphthalene on the tape strip) for the \(j\)th measurement for the \(i\)th subject, \(Y_{ij}\) is the natural logarithm of \(X_{ij}\). \(\beta_0\) is the intercept term, \(\beta_1\) and \(\beta_2\) are the regression coefficients representing the linear and quadratic effects of time on measured log transformed exposure level and \(T_j\) is a regressor variable representing the time adhesive tape strips were collected after JP-8 application.

Since exposure measurements collected on the same person and taken closely together in time tend to be correlated, the following three covariance structures were evaluated.

- **Compound symmetry (CS).** A common correlation is estimated and represents the correlation, \(\rho\), between any pair of measurements, namely \(\text{var}(Y_{ij}) = \sigma^2\), \(\text{corr}(Y_{ij}, Y_{j'}) = \rho\), \(j \neq j'\).

- **Autoregressive order one \([AR(1)]\).** A common correlation parameter \(\rho\) is estimated, but the correlation itself decreases as a function of the number of time intervals between measurements, namely \(\text{var}(Y_{ij}) = \sigma^2\), \(\text{corr}(Y_{ij}, Y_{j'}) = \rho^{\mid j - j'\mid}, j \neq j'\). For example, the correlation between the 5 and 10 min, 10 and 15 min and 15 and 20 min measurements is \(\rho^2\), since there are two time intervals between measurements. Similarly, the correlation between the 5 and 20 min measurements is \(\rho^3\), since there are three time intervals between measurements.

- **Unstructured (UN).** All possible variances and correlations are estimated with this general covariance structure, namely \(\text{var}(Y_{ij}) = \sigma^2\), \(\text{corr}(Y_{ij}, Y_{j'}) = \rho_{ij}, j \neq j'\).

Two model fit criteria produced by Proc MIXED (Akaike’s information criterion and Schwarz’ Bayesian criterion) were used to determine which one of these three covariance structures best represents the available data. These criteria involve log-likelihood values adjusted for the number of parameters estimated. The covariance structure with the largest criteria values is considered the most desirable.

**RESULTS**

The average amount of naphthalene collected on the first tape strip at the 5 min site was 21 551 ng (12.4 µl JP-8) and decreased to 242 ng (0.1 µl JP-8) at the 20 min site (Table 1). Likewise, the average amount of naphthalene collected on the second tape strip decreased from 147 (0.1 µl JP-8) to 22 ng (0.01 µl JP-8) from 5 to 20 min (Table 1). The total amount of naphthalene collected with two sequential tape strips ranged from 21 697 ng at the 5 min site to 265 ng at the 20 min site. Analysis of the third tape strip data revealed naphthalene concentrations at or below the ALOD and, thus, these results are not shown.

On average, the first tape strip after 5 min exposure removed 69.3% of the applied naphthalene. The amount recovered with the first tape strip decreased over time to a recovery of 0.8% after 20 min exposure. The coefficient of variation (CV) for the first tape strip data was 15.2% at the 5 min site, but increased to 29.8% at the 10 min site and to 100% at the 15 and 20 min sites. The opposite pattern was observed for the second tape strip data; the CV decreased over time from 116 to 38.0%. Investigation and subsequent removal of two outliers (>3 SD above mean at the 5 min site) decreased the CV from 116 to 42.4% for the second tape strip data at the 5 min site. Although the other sites were less affected, removal
of these observations produced more uniform coefficients of variation. No outliers were observed in the first tape strip data. No significant differences (5% level) in removal efficiency were observed between males and females and between age groups or among races or types of skin pigmentation.

**Mixed-effects linear model**

The log-transformed amounts of naphthalene removed by the first tape strips are illustrated in Fig. 1. Initially, the removal efficiency of naphthalene by the first tape alone and by the first and second tapes jointly from the surface of the stratum corneum was investigated using both first order and second order mixed-effects models. The analyses indicated that the second tape strip did not contribute significantly to model prediction. Thus, all mixed-model analysis results are for the first tape strip data only. The estimated linear and quadratic effects of time ($\hat{\beta}_1$ and $\hat{\beta}_2$, respectively) on log-transformed exposure, the estimated intercept ($\hat{\beta}_0$) and the model fit criteria using the three different covariance structures are provided in Table 2. In all three models, $\hat{\beta}_0$, $\hat{\beta}_1$ and $\hat{\beta}_2$ were significantly different from 0 (all $P$ values < 0.0001). The model with the unstructured covariance structure fitted the data best and so was chosen as the final model (see Fig. 1). This is not surprising because, with an unstructured covariance structure, all possible variances and correlations were estimated.

The estimated intercept of the best fitting mixed-effects linear model equation was used to estimate the average amount of naphthalene initially applied to the exposed sites. By inserting 0 for time in the final model, $\hat{\beta}_0$ estimates the amount of naphthalene initially applied to the skin. Since this value is on the natural logarithm scale, it must be converted by taking the anti-logarithm of the intercept $e^{\hat{\beta}_0}$. The following two expressions were used to determine...
the estimated amount of naphthalene applied to the skin and the corresponding 95% CI:

\[
\text{Estimated amount of naphthalene applied to skin} = e^{\hat{\beta}_0} = e^{(10.36)} = 31571 \text{ ng naphthalene}
\]

\[
95\% \text{ CI} = (e^{[\hat{\beta}_0 \pm (1.96) \text{SE} (\hat{\beta}_0)]} = e^{10.36 \pm 1.96(0.099)})
\]

\[
= (26003 - 38332 \text{ ng})
\]

The estimated average amount of naphthalene applied to the skin was 31571 ng (95% CI 26003–38332 ng), which corresponds to 18 μl of JP-8 (95% CI 15–22 μl). Since the best estimate of the amount of JP-8 applied was 18 μl (95% CI 16–20 μl) when taking into account chamber loss, the model predicts the amount of JP-8 initially applied well.

**DISCUSSION**

The tape stripping technique developed using Cover-Roll® adhesive tape to assess dermal exposure to JP-8 with naphthalene as a marker is simple, efficient and chemical-specific. Essentially 100% naphthalene (JP-8) spiked on blank tape strips was removed with 5 ml of acetone after 30 min extraction. The first tape strip data indicated that the amount of naphthalene on the stratum corneum surface rapidly decreased over the 20 min exposure period. CVs increased from 15.2 (5 min site) to 100% (15 and 20 min sites) for the first tape strip data. This increase in variability, especially for the 15 and 20 min measurements, was most likely due to the application procedures. At the 15 and 20 min sites, the application chamber was held in place for 5 min (the same as the 5 and 10 min sites) and then removed. This allowed JP-8 to spread outside the exposed area (up to 1.5 cm) and, thus, outside the area for tape stripping. In contrast, CVs for the second tape strip data decreased from 116 (5 min site) to 38.0% (20 min site). Removal of two outliers decreased the CV from 116 to 42.4% and 64.5 to 49.4%, respectively.

Although other sites were less affected, removal of these subjects produced more uniform CVs for the second tape strip data. No outliers were observed in the first tape strip data. The increased variability at the 5 and 10 min sites may be the result of small amounts of naphthalene/JP-8 inadvertently left on the skin after the first tape stripping and, thus, subsequently collected with the second tape strip. However, the tape strips were placed over exposed areas as carefully and accurately as possible.

Factors affecting variability in the tape strip data may include: (i) the amount of stratum corneum collected with each tape; (ii) physical attributes of the skin such as hair and hair follicles; (iii) the amount of fuel actually applied to the skin (residue on chamber); (iv) evaporation from the skin surface; (v) contamination from gloves or forceps (while collecting and processing tape strips). Dreher et al. (1998) found that the amount of stratum corneum collected with the first and second tape strips varied among individuals. Also, more stratum corneum was collected with the first tape strip than with the second. However, we have observed that the Cover-Roll® tape has good adhesion to human skin (including those with hair) and that it uniformly removes the stratum corneum (Nylander-French et al., 2001; Chao and Nylander-French, 2004). We have also observed that the mean mass of keratin protein removed with tape strips is not affected by exposure to jet fuel nor by sex, age, ethnicity or skin pigmentation (Chao and Nylander-French, 2004).

The fact that naphthalene was detected in the second tape strips and that the mean concentration on the second tape strips at the 10 min site was higher than at the 5 min site (after removal of two outliers) indicates that naphthalene penetrated into the stratum corneum. Riviere et al. (1999) found that aromatic hydrocarbons (naphthalene) penetrated pig skin (isolated perfused porcine skin flap) better than aliphatic hydrocarbons when JP-8 was topically applied (non-occluded). McDougald et al. (2000) found a similar penetration pattern when JP-8 was

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**Table 2. Estimated linear and quadratic effects (\(\hat{\beta}_1\) and \(\hat{\beta}_2\), respectively) and the estimated intercept (\(\hat{\beta}_0\) of the mixed-effects linear model (model-fit criteria computed by Proc Mixed))**

<table>
<thead>
<tr>
<th>Covariance structure</th>
<th>Mixed-effect model(^b)</th>
<th>Akaike’s criterion, Schwarz’ Bayesian criterion</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compound symmetry</td>
<td>(\hat{Y}_{ij} = 11.18 - 0.18T_j - 0.007T_j^2)</td>
<td>-114.25, -116.69</td>
</tr>
<tr>
<td>Autoregressive order one</td>
<td>(\hat{Y}_{ij} = 11.06 - 0.17T_j - 0.007T_j^2)</td>
<td>-113.94, -116.38</td>
</tr>
<tr>
<td>Unstructured(^c)</td>
<td>(\hat{Y}_{ij} = 10.36 - 0.03T_j - 0.01T_j^2)</td>
<td>-72.90, -85.11</td>
</tr>
</tbody>
</table>

\(^a\) \(\hat{Y}_{ij}\) is the estimated response for subject \(i\) at time \(j\).

\(^b\) Final model.

\(^c\) Estimated standard error of \(\hat{\beta}_0\) = 0.099.
applied to rat skin. The authors attributed the rapid penetration of aromatic hydrocarbons to the lipophilic nature of JP-8. Baynes et al. (2001) found that JP-8 performance additives acted synergistically and increased the penetration of naphthalene in pig skin. In general, naphthalene is believed to evaporate easily from the surface of the skin; however, our study on human volunteers indicates that only ~5% of the naphthalene applied in JP-8 evaporates from the skin during a 20 min exposure period (Chao and Nylander-French, 2004).

Another goal of this study was to investigate the applicability of mixed-effects linear regression models to estimate the amount of contaminant in the first cell layers of stratum corneum after an a priori determined exposure period. Mixed-effects linear regression models were fitted to the data to build a final model that included all covariates significantly associated with exposure. Exposure time was the only covariate significantly associated with exposure (age, gender, race and skin pigmentation were not). The best fitting mixed-effects model

\[ \hat{Y}_{ij} = 10.36 - 0.037T_i - 0.017T_j^2 \]

estimated that 18 \( \mu l \) (95% CI 15–22 \( \mu l \)) was applied to the skin. Thus, this model predicts the best estimate of the amount (18 \( \mu l \), 95% CI 16–20 \( \mu l \)) applied to the skin well.

The results of this study suggest that the developed tape stripping technique could be used to measure dermal exposure to jet fuel in a field setting and that the results obtained with this method may be used: (i) to determine the amount of naphthalene and JP-8 on the skin at the time of tape stripping; and (ii) to estimate the amount of naphthalene on the skin at some point in time before tape stripping using mixed-effects linear regression models.

In order to further develop and test the applicability and efficacy of the tape strip method and mixed-effects linear regression models to estimate dermal exposure to JP-8, we are currently investigating in more detail the effect of JP-8 and naphthalene evaporation from and penetration into the stratum corneum. This work is conducted both with data collected in laboratory studies on human volunteers and in occupationally exposed fuel cell maintenance workers, whose exposure was measured with personal breathing zone air sampling and biological monitoring (i.e. urine, blood and exhaled breath). Thus, we will gain valuable information about the function and capacity of tape stripping of the stratum corneum in assessing dermal exposures.

In summary, the tape stripping technique, in conjunction with statistical modeling of dermal exposure, offers a starting point for the development of dermal assessment methods for both volatile and non-volatile compounds. With the results from the field evaluations, we will be able to understand the utility of this technique to assess dermal exposures and, if warranted, we will be able to make the required modifications.

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