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In-Use Testing and Interpretation of Chemical-Resistant Glove Performance

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Issuing gloves to workers is the most common approach to protecting against skin contact with hazardous chemicals. Typically, glove materials are selected and duration of wear is estimated based on comparisons of laboratory test data. Those who select the glove materials often fail to verify their selections by testing the glove during actual use. This failure poses a common but potentially serious hazard to workers. Although methods are available for assessing permeation rates during actual use, such testing is unlikely without acceptable exposure guidance criteria for decision making. This document reviews methods for testing glove performance during actual use and suggests an approach for estimating acceptable exposure guidance criteria for evaluation of chemicals that are systemically absorbed. It is the authors' opinion that as of now an approach to estimating exposure criteria for chemical irritants and sensitizers may not be feasible. With available data resources, acceptable glove exposure criteria could be generated for use in assessing the risk of using specific gloves for handling many compounds in occupational settings.

Keywords Occupational, Glove Performance, Evaluation, Documentation, Permeation Resistance, Duration of Use, Chemical-Resistant

Chemical protective clothing (CPC)—particularly glove protection—is generally recognized as a final line of defense for protecting workers' skin from hazardous chemicals. CPC should only be depended on when engineering, administrative, and task-modification controls are not sufficient to ensure adequate protection. Skin contact with chemicals may lead to systemic absorption with subsequent illness—the cost of which is difficult to quantify, or to dermatitis, which has an associated cost of at least \$1 billion per year.⁽¹⁾ CPC use is common in many workplaces, amounting to at least \$800 million in annual

sales in the U.S. market. Therefore, selecting CPC properly is important.

In a companion article, we discussed the complexities of adequately selecting appropriate glove materials.⁽²⁾ Because of the uncertainty introduced by the influence of the workplace environment on glove performance, we proposed that in-use testing be conducted to confirm the glove selection decisions that were initially based on laboratory data. The present article describes available methods for in-use testing of gloves and an approach for estimating acceptable duration of glove use that is based on an appropriate health effect endpoint.

In a recent editorial, Fenske and van Hemmen addressed the need for the occupational health community to establish skin exposure limits.⁽³⁾ They asserted that dermal exposure limits are necessary for two reasons: (1) the “formalization of airborne concentration guidelines into legal standards” has resulted in a focus by occupational hygienists on compliance with airborne standards; and (2) this cultural attitude of compliance with established limits has created a reluctance to document exposures that cannot be related to a safe exposure limit.

Determining the amount of skin absorption by measuring the compound in the body, as with biological monitoring, can indirectly determine whether skin exposure is occurring. However, biological monitoring and skin exposure monitoring suffer similarly in the need for guidance criteria. Whenever a biological media sample is taken or skin exposure is measured, the question is asked, “What does the result mean?” Both the worker and the company want to know, “Is this a safe exposure?” The absence of exposure criteria for skin during almost 30 years of regulatory compliance requirements in the United States and the lack of progress in controlling skin exposures strongly suggest that skin exposures will not be seriously addressed until exposure criteria are available.

The recently updated Occupational Safety and Health Administration (OSHA) Personal Protective Equipment (PPE) Standard,⁽⁴⁾ and the European Community Workplace Directive for the Use by Workers of Personal Protective Equipment,⁽⁵⁾ as well as Directive 67/548/EEC that prohibits exposure to irritants and corrosive chemicals,⁽⁶⁾ present opportunities to take the first step in establishing allowable quantitative skin exposure

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guidelines. Although the OSHA PPE standard lacks detailed guidelines on how to evaluate CPC, the requirement to “base the selection . . . on an evaluation of the performance of the hand protection relative to the task(s) to be performed, conditions present, duration of use, and the hazards or potential hazards identified”⁽⁴⁾ leaves open the possibility of the need to perform in-use verification of the selected CPC. Rather than basing the selection of CPC only on laboratory data and assuming adequate skin exposure protection during use, policies should encourage in-use validation of CPC performance.

During the review period of the OSHA PPE standard, participants suggested that OSHA provide acceptable performance criteria and test methods for evaluating the performance of gloves and provide better guidance on the process of selecting appropriate gloves. Unfortunately, the final standard did not provide such information. Utilizing passive skin exposure methods to measure breakthrough while the CPC is in use, and comparison of these results to estimates of acceptable exposure for the skin, would result in a higher degree of assurance that the selected CPC is providing the necessary level of protection.

Acceptable skin exposure for dermal absorption of systemic toxics can be defined as the skin exposure, combined with the worker’s airborne exposure over the 8-hour work shift, that results in a total exposure to the worker of less than the airborne occupational exposure limit (OEL), as exemplified by established PEL, REL, or TLV criteria.

THE ROLE OF PERMEATION RATE IN GLOVE SELECTION

In our companion article, we stressed that practical glove selection goes beyond looking at the barrier characteristics alone, and should be a balance providing adequate protection to prevent toxicity, achieve user acceptance, and allow the wearers the ability to perform the task. With highly hazardous chemicals (e.g., hydrofluoric acid, dimethylmercury), the glove must not allow any exposure in order to be acceptable. For all chemical exposures, ideally the goal of zero tolerance should be sought. However, in many situations when using less toxic chemicals with recognized threshold values for toxic effects, it is reasonable that a glove with less than maximum barrier ability may sometimes be selected so that a worker can adequately perform a given task. The final glove chosen should reduce the risk from chemical exposure when used for a particular application to comply with the guideline that skin exposure combined with the worker’s airborne exposure results in a total exposure to the worker that is less than the exposure dose received at the 8-hr time-weighted average (TWA) airborne exposure limit.

Permeation can be affected by several variables, as reported in our companion article. Two kinetic measures of glove performance are commonly reported in laboratory glove permeation studies: detectable breakthrough time (BTT), and steady-state permeation rate (SSPR, or simply PR). There is usually a non-linear increase in the rate of permeation before reaching the SSPR, which is referred to as the lag time, and is depicted in

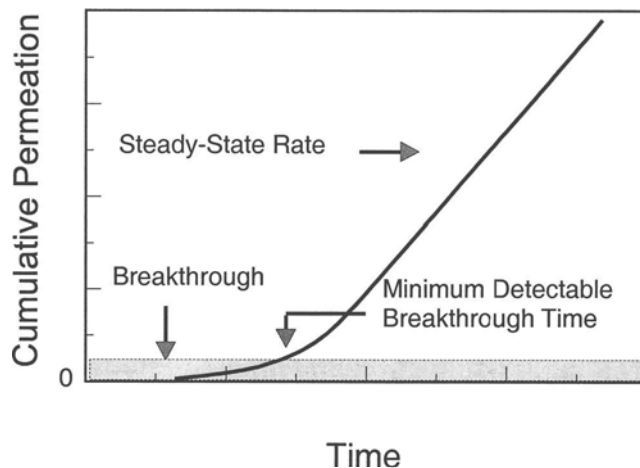


FIGURE 1

Hypothetical depiction of kinetics of diffusive permeation through a polymeric membrane in a closed-loop test system. Cumulative permeating mass of chemical is plotted against time.

Figure 1. The ideal glove would have both a long BTT and low SSPR. A chemical/glove combination might be described by one of four classifications (Table I).

When systemic toxicity is the most important consideration, the permeation rate of the chemical/glove combination may be the most critical factor. During actual use, some exposure to systemically active chemicals may be acceptable if the exposure is below the threshold exposure that results in adverse health effects. Existence of airborne maximum exposure criteria established by many countries are a clear confirmation of adopting this practice. Only when the wearer is allergic to a chemical or it is highly toxic (e.g., acutely lethal, human carcinogens) should breakthrough detection time be the main consideration in the glove selection process. Again, in these cases a zero tolerance glove should be sought.

TECHNIQUES FOR EVALUATING IN-USE GLOVE PERFORMANCE

Interpreting chemical exposure measurements underneath CPC may be a bit easier than interpreting results from sampling unprotected skin, as it approximates a closed system. Chemicals

TABLE I

Possible combinations of glove performance parameters	
Short BTT and:	Long BTT and:
Low SSPR (ex. PTFE + dichloromethane)	Low SSPR (ex. Viton + vinyl chloride)
High SSPR (ex. Nitrile + chloroform)	High SSPR (ex. Unknown to occur unless delayed degradation occurs)

that permeate gloves, for instance, are less likely to be lost through volatilization. Second, the chemicals are in direct contact with the skin, and the possible confounding influence of skin soiling should theoretically not exist. Finally, chemicals permeating the CPC reach the skin under occlusion, an exposure condition similar to the way much of the topical dosing and skin permeation research is experimentally conducted. Under occlusion, the permeation of chemicals and the response of irritants and allergens in the skin can be heightened several-fold.^(7,8)

Under-glove sampling can be performed using a variety of sorbent materials to collect chemicals permeating through a glove. The most common approach to date has been a thin cotton (or cotton/polyester) glove worn underneath the protective glove.^(9,10) In this simple configuration, three assumptions are made: (1) the cotton liner traps most of the permeant without it passing through to the skin; (2) the permeant is stable and recoverable from the cotton collection media; and (3) any chemical contaminant found in the cotton glove is due to passage through the protective glove. These assumptions have not been adequately addressed in the current literature.

Simple precautions might improve field performance of this approach to under-glove dosimetry. To minimize the possibility of permeation (i.e., loss) to the skin (assumption 1), a third thin glove resistant to the target chemical might be worn underneath the cotton glove. This precaution will also alleviate some of the analytical complications due to potential interferences from skin oils, skin care products, and sweat constituents. Assumption 2 can be addressed in the laboratory by spiking cotton gloves with the analyte and storing for durations and temperatures that simulate field sampling conditions and subsequent storage. Assumption 3 must be controlled in the field setting, as otherwise the collection media may simply be picking up skin contamination from previous unprotected contact. Therefore, care must be taken to adequately decontaminate the skin before the sampling glove and outer glove are donned.

Once these sampling issues are satisfied, field testing can be performed. The following illustrates how in-use testing during various durations of wear and during different levels of activity can be used to evaluate glove performance.

During one investigation of 4,4'-methylenedianiline (4,4'-MDA) exposure, workers' gloves were collected after various durations of use and turned inside-out, 20 ml of alkaline methanol was poured into the glove, and the solvent was vigorously shaken within the glove for 30 seconds. The rinsate was later quantified in the laboratory to determine the outer glove amount. Cotton glove liners that were worn underneath the gloves were also analyzed after solvent extraction. The quantity of MDA found in the cotton glove after multiplying by the time the outer glove was worn was predicted in linear regression analysis by the quantity of MDA found outside the glove in the rinsate, producing an r^2 equal to 0.94 after log transformation of both variables, thus explaining most of the variation in the inside glove concentration.⁽¹¹⁾

Other sorbent collection media have been used to collect permeants under gloves, including activated carbon cloth, silastic rubber sheet, C₁₈ sorbent filters, and others. Silicone rubber sheet (Silastic, Dow-Corning, Midland, MI) is, to the best of our knowledge, the earliest reported sorbent used for collection in laboratory tests to evaluate barrier permeation of nonvolatile compounds.⁽¹²⁾ This material had a much greater capacity to retain pesticides than filter paper, polyester/ rayon gauze, or cotton gauze, but its absolute capacity to collect analytes had not been reported.⁽¹³⁾ In fact, Pinette et al. questioned the absorptive capacity of silicone rubber sheet and produced inconclusive but suggestive data to indicate that collection was not complete.⁽¹⁴⁾

Cohen and Poppendorf reported using an activated carbon cloth for collecting 10 solvents with a mean retention between 36 percent and 87 percent, and suggested its use for sampling under CPC.⁽¹⁵⁾ Hirayama and Ikeda reported different performances among several types of carbon cloth and found that some tolerated high humidity well, making them applicable for use under gloves.⁽¹⁶⁾ Perkins and Vescial created a whole-hand carbon felt glove to determine solvent permeation during flexing.⁽¹⁷⁾ A small, self-adhesive sampler consisting of a carbon cloth pad and a colorimetric indicator is now commercially available. This sampler can be affixed to the skin underneath a glove to detect the permeation of a variety of chemicals.⁽¹⁸⁾

One report of laboratory testing of charcoal cloth pads found that the analyte recovery of different solvents varied, being least for high boiling point compounds. Recovery of analytes from the pads was performed by thermal desorption. When these small charcoal pads were worn under the protective gloves of some industrial workers, milligram quantities of xylene were absorbed when little was expected based on manufacturer's laboratory test data.⁽¹⁹⁾

Vo et al. evaluated recovery of methanol, acetone, ethyl methyl ketone, trichloroethylene, tetrachloroethylene, toluene, *m*-xylene, and *d*-limonene from these charcoal pads using microwave-solvent extraction and gas chromatography. Recovery of solvents with boiling points below 110°C was better than 90 percent, and for solvents with boiling points above 110°C, recovery was between 80 to 90 percent.⁽²⁰⁾

In addition to the sorbents mentioned, new membrane sorbents designed for collecting organics in aqueous solutions are becoming increasingly available and may very well fit the need for under-glove dosimetry (e.g., 3M Co., St. Paul, MN; Baker Chemical, Phillipsburg, NJ). These sorbents are about 1 mm thick and highly flexible, making them adaptable to under-glove dosimetry. Laboratory evaluation of a C₁₈ resin sorbent filter for acetone, methanol, trichloroethylene, and toluene found the sorbent to be more sensitive to glove permeation than the ASTM F739 method. Recovery for all solvents was between 72 percent to 94 percent over a spiking range of 0.2–1.8 μ l. Precision was excellent, with relative standard deviations \leq 4 percent.⁽²¹⁾

Historically, permeation testing has been limited to solvents and gaseous chemicals. It is important to appreciate that this focus has been due to the requirement for a gas in the receptor side

of the standard two-sided permeation test system. Chemicals permeating through the test membrane volatilize into the receptor gas and the receptor gas is subsequently sampled. Presently there is not a generally accepted method for testing the permeation of nonvolatile chemicals. About 80 percent of the threshold limit value (TLV[®]) compounds with a skin notation have a vapor pressure less than 5 mm Hg and therefore these compounds would not be good candidates for testing with the ASTM method. Thus, for these compounds no glove material recommendation would likely be available. Fricker and Hardy provide evidence that even solid chemicals can solubilize into the protective membrane of CPC and permeate through to the skin.⁽²²⁾ Although some approaches have been suggested to perform testing of low volatile compounds such as periodically wiping the inside of the membrane material or using aqueous collection and sequential HPLC analysis to sample for the permeant, the above solid sorbents might offer an alternative convenient approach to this testing dilemma.⁽¹⁴⁾

In addition to the sorbents described above that may be used for quantitative evaluation of chemicals under gloves, a variety of colorimetric indicators are available that can qualitatively detect polar solvents, aromatic amines, aromatic isocyanates, acids and alkalis, hydrazines, and other classes of chemicals (CLI Inc., Des Plaines, IL). Colorimetric indicators rely on reagents that turn color when the reagent encounters certain types of chemicals. The reagents are encapsulated so that the offending chemical must first breach this barrier before color develops. Through further research and development, additional reagents and varying encapsulate characteristics could expand the use of these devices to include more compounds and offer semi-quantitative detection. This approach presents a low-cost option for screening glove performance.

In retrospect, the current state of passive dermal monitoring is analogous to the introduction of the charcoal tube for air monitoring several decades ago.⁽²³⁾ With respect to passive dermal monitoring, even more rapid progress in method development could occur, given the greater availability of advanced sorbent technology and present knowledge.

STRATEGIES FOR FIELD TESTING GLOVE PERFORMANCE

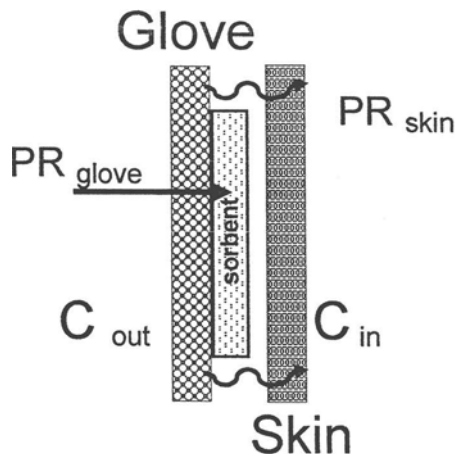
In-use testing may be approached using a variety of techniques. We have discussed the use of under the glove sampling media, and the use of cotton gloves between the test glove and a thin barrier glove. An additional sampling design for an appropriate collection media consists of affixing the sorbent to the inside surface of the glove and covering it with a permeable-resistant film. The film serves to isolate the collection media to a defined area on the inside surface of a glove. This way, the result obtained from analyzing the collection media can be reported as mass per surface area ($\mu\text{g}/\text{cm}^2$), that is, surface concentration. If the duration of measurement is known, the result can be expressed as mass/cm²/hr, which is equivalent to mass permeation rate or flux.

Does $PR_{\text{glove}} = PR_{\text{skin}}$?

$$PR(\mu\text{g}/\text{cm}^2/\text{hr}) = Kp(\text{cm}/\text{hr}) \times C(\mu\text{g}/\text{cm}^3)$$

Obtain PR_{glove} from sorbent

Calculate maximum $PR_{\text{skin}} = Kp \times C_{\text{sat}}$



If $PR_{\text{glove}} > PR_{\text{skin}}$, assume PR_{skin} for C_{sat}

If $PR_{\text{glove}} < PR_{\text{skin}}$, $PR_{\text{skin}} = PR_{\text{glove}}$, i.e., complete skin absorption of PR_{glove} .

FIGURE 2

An empirical approach for obtaining permeation rate through gloves during in-use testing and the selection of an assumed skin permeation rate to use in risk analysis. The problem depicted concerns whether to choose the glove permeation rate or the skin permeation rate as the limiting flux that is used for estimating risk of transfer into the body. The rationale shown might be used to select a permeation rate for this calculation.

An alternative design is to affix the collection media to the underside of the glove and eliminate the permeable-resistant film. This approach allows lateral diffusion paths between the hand and glove (see Figure 2, diagram). Although this approach might be more difficult to interpret quantitatively, because a defined surface area is not known, it allows the detection of both permeation from broader areas and penetration through pinhole leaks from distant sites that allow significant amounts of solvent to enter between the hand and glove.

Since lateral diffusion of a chemical (underneath the glove) might occur, isolation of the glove from the outside might be prudent during sampling. Diffusion of volatilized chemicals from outside the glove might occur around the cuff. Sealing the cuff at the wrist with tape during sampling might help simplify comparisons between gloves if diffusion of volatilized chemicals could occur from outside the glove. Conversely, the loss of permeating compounds from inside the glove could vary depending on

the tightness of the glove fit and confound the results. These considerations apply to testing any other CPC, especially when significant outside vapor concentrations are present.

One common criticism of skin sampling is the difficulty in determining the appropriate placement of small-area dosimeters. With ongoing measurement of skin exposures, chemical distribution could be determined and the future placement of collection media more efficiently allocated. Typically, the areas of greatest exposure under gloves are likely to correspond to pressure points. Exposure to other skin areas could be estimated from fewer samples once the distribution of contamination is generally known. For example, in an industrial operation involving work with polyimide and epoxy resins containing the aromatic amine 4,4'-methylenedianiline (Figure 3), the highest concentrations underneath gloves were on the thumb and forefinger.⁽¹¹⁾ This might be expected because these digits are used most often.

Another strategy for evaluating glove performance in the workplace is to start with the manufacturer's published BTT and sample for this period using a small group of workers performing tasks with a chemical. If exposure is detected, halve the sampling time and retest. If permeation occurs too rapidly through the test glove to be of practical use and alternative glove materials are available, evaluate other glove materials using the same strategy until a satisfactory glove is found. This scenario assumes that one has the good fortune of easily finding a usable glove that performs without detectable breakthrough for the duration of needed use and that it can be discarded without significant economic cost. If this is not the case, and breakthrough is detected, the potential health effects of the resulting dermal exposure must be reevaluated.

Another alternative or supplementary strategy for testing the effectiveness of gloves is to assess human uptake or response to the chemical(s) that the glove is intended to prevent. Biological

testing methods to determine the effectiveness of glove barriers to prevent both systemic absorption and skin response to allergens have been described.^(24,25) In the first instance, venous blood concentrations were measured, and the worker served as the sampler; in the second instance, allergic response was graded for persons previously sensitized to the test allergens. Although these examples were obtained in a laboratory setting, they are analogous to biological monitoring and medical surveillance in the workplace, respectively. Biological monitoring techniques currently exist for only a limited number of substances. Either approach could be used initially to validate exposure prevention efforts.

Although we have been addressing the use of testing methods and strategies for assessing glove performance, in-use testing with under glove passive dosimeters can also be used to assess work practices and glove use. Contamination of skin prior to donning CPC, especially gloves, is probably common. Once the performance of gloves after in-use testing is known, glove use deficiencies in work practices can be assessed by a variety of glove rinse or passive sorbent sampling methods as described in this paper.

PROPOSED BASIS FOR DERIVING UNDER-GLOVE SKIN EXPOSURE LIMITS

As mentioned in the section on techniques for testing, the gloved hand presents a unique, and somewhat simplified, skin exposure situation. First, the gloved skin is occluded. This makes under-glove exposure comparable to experimental protocols that expose the skin to chemicals under patches or chambers. Second, by designing the sampler appropriately, measured exposure can be limited to those compounds penetrating the glove. The combination of these features should facilitate both the analysis and toxicological interpretation of under-glove concentration measurements.

When considering dermal exposure limits, two concerns must be addressed. Penetration of the chemical into the body can affect an internal target organ or tissue (causing systemic toxicity), or the chemical may directly affect the skin, causing irritation or allergic sensitization. Reference sources, such as the American Conference of Governmental Industrial Hygienists (ACGIH[®]) Documentation for TLVs,⁽²⁶⁾ American Industrial Hygiene Association (AIHA) Workplace Environmental Exposure Level (WEEL) guides,⁽²⁷⁾ HSE Criteria Documents for an Occupational Exposure Limit (OEL),⁽²⁸⁾ German MAKs,⁽²⁹⁾ Swedish Consensus Reports,⁽³⁰⁾ or Hazardous Substances Database online (<http://toxnet.nlm.nih.gov>) usually provide useful information about a chemical's potential health effects. The nature of the health effect and the potential of the chemical to cause the health effect are two determinants of an acceptable dermal exposure.

An important determinant of systemic toxicity is the dose rate, that is, the amount of chemical delivered to the target site absorbed per unit time. For skin exposure, a systemically absorbed dose depends on surface concentration, skin permeation

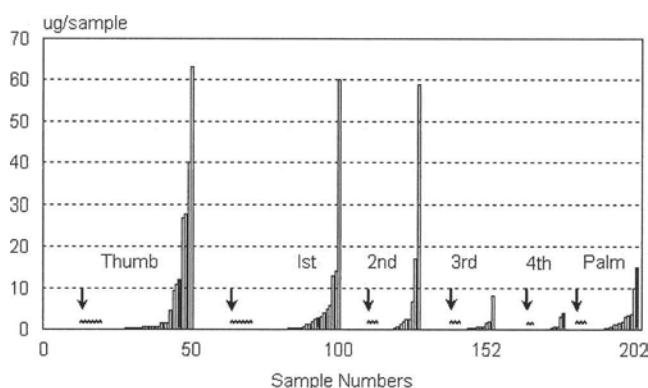


FIGURE 3

Distribution of methylenedianiline (4,4'-MDA) found under protective gloves using cotton liner dosimetry. Concentrations are shown for each digit (finger) and palm as detected in each sample, indicating which parts of the hand are most likely to be exposed. Arrows point to the sample where the analyte was found at the lowest analytical limit of detection.

rate, area of exposed skin, and duration of exposure. Similarly, a worker's airborne exposure depends on the airborne concentration, the absorption rate from the lungs, the workers breathing rate, and the duration of the exposure. Established 8-hour occupational exposure limits (OEL) for air contaminants reflect the capacity of a typical person to detoxify or eliminate the dose, and have a number of safety factors reflecting uncertainties in the data, variations in individual responses, and the severity of the toxic effect. Chemicals absorbed from the respiratory tract and chemicals absorbed through the skin both enter the body through pathways bypassing the portal circulation to the liver.⁽³¹⁾ If differences in the extent of absorption are considered, the existing inhalation OEL might therefore provide an exposure guideline for setting allowable dermal exposure limits for systemic toxics.

Airborne OELs intended to protect against respiratory and eye irritation are probably of little relevance to protecting the skin from irritation and allergic sensitization, and, conversely, dermal absorption is not likely to be relevant to respiratory and eye irritation. The intact skin is far less permeable than the respiratory system or eye and more resistant to adverse effects.

Unlike cutaneously absorbed systemic toxins whose effects depend on the total amount of exposed skin surface area, irritant and allergenic skin responses to chemicals are primarily related only to the concentration on the skin surface and the duration of exposure. Very small skin areas may be exposed, resulting in a localized irritant response or generalized skin sensitization.⁽³²⁾ Thus, the toxicological data and the approach for assessing the risks of skin exposure to irritants and sensitizers are quite different from that used to assess risks from compounds potentially contributing to systemic toxicity.

Presently, no national or consensus standards body has established skin exposure limits that are quantitative. Instead, qualitative criteria in the form of a skin notation have been widely adopted to augment air OELs. The skin notation as defined is based only on the ability of a chemical to increase systemic dose (e.g., ACGIH TLV booklet), but in practice may be inconsistently applied and include some compounds having effects on the skin as a target organ.^(26,33–35)

To improve the consistency with which skin notations are applied to chemicals with OELs, simple approaches have previously been proposed. One proposed criterion for chemicals that can contribute to systemic toxicity is assigning a "skin notation" when skin absorption can contribute greater than 30 percent of the allowable 8-hour TWA inhalation dose when the skin contact area is equal to 2 percent of the body surface, for example, palms and fingers, or 360 cm².⁽³³⁾ Alternatively, the Dutch Expert Committee for Occupational Standards has proposed that the skin notation be applied when the amount absorbed by both hands and forearms in one hour could amount to more than 10 percent of the amount absorbed via the lungs during exposure to the OEL for 8 hours.^(36,37)

We suggest that health-based maximum skin exposure concentrations can be estimated and used for in-use glove performance testing. These quantitative acceptable exposure concen-

trations, combined with under-glove passive dermal monitoring techniques that were described earlier, could determine the exposure resulting while wearing a particular glove type during actual use. The suggested approach described below might be used in risk assessments for systemically absorbed chemicals. We believe that under-glove maximum exposure concentrations are less readily derived for chemicals having direct effects on the skin, for example, allergens and irritants, due to the limitations of existing toxicological data. Current research efforts to measure the potency of such chemicals may lead to the development of acceptable skin exposure concentrations in the future.

CALCULATION OF ACCEPTABLE GLOVE USE AND RATIONALE FOR SYSTEMICALLY ABSORBED CHEMICALS

Two questions might be asked regarding in-use evaluation of the protection afforded by gloves. One question is whether the measured permeation exceeds an acceptable quantity during the period the glove was used. Here we could simply compare the measured amount found under the glove over the course of the workday to an established health-based exposure limit. Another more specific and potentially useful question might be how long a glove can be used before unacceptable exposure occurs.

Example of Using In-Use Glove Measurement Data to Evaluate Acceptability

The following example demonstrates a general approach for estimating the acceptability of a chemically protective glove when the permeation beneath the glove has been measured. This example is for compounds where dermal absorption contributes to the systemic toxicity and compares the estimated contribution of exposures by way of the gloved hands to the calculated exposure by inhalation using established air concentration criteria.

Worker exposure by the inhalation route is calculated by assuming an 8-hr. respiration volume of 10 m³ and control of workers' airborne exposure to 50 percent of the OEL (action level) or less (lung retention and absorption coefficients are assumed to be included in the OEL):

$$\text{TWA skin dose} = \text{number of gloves used} \times \text{Conc} \times \text{SA} \times \text{SAF} \quad [1]$$

The dose absorbed by the gloved hands can be calculated from the measured exposure through the glove, in mg/cm², after a glove use. If the skin permeation rate is not known, a skin absorption factor of 50 percent can be used to calculate absorbed dose. This default assumption is biologically plausible, as well as midway between zero and 100 percent. If only the palm and contact points of the fingers are involved in an activity, assume an exposed skin area of 410 cm².⁽³⁷⁾ If the whole hand is immersed, the hand surface area should be assumed to be 840 cm². The total area of an average glove including cuffs is 1300 cm². To calculate the skin absorbed dose, one must know or assume the following:

Conc = measured concentration per glove use (mg/cm²)

SA = surface area (nominally 410 cm²)

SAF = skin absorption factor, assumed to be 50 percent unless otherwise empirically known

Thus,

$$\text{inhalation OEL dose} = 10 \text{ m}^3 \times 0.5 \text{ OEL (mg/m}^3\text{)} \quad [2]$$

The relative skin absorbed dose, RSAD, is the ratio of the skin dose to the inhalation dose expressed as a percent.

$$\text{RSAD} = \frac{\text{skin dose}}{0.5 \times \text{inhalation OEL dose}} \times 100 \quad [3]$$

If RSAD is equal to 50 percent of the inhalation dose at half the OEL (action level), that is, skin dose equals 25 percent of the OEL, the combined total systemic dose (50% inhalation + 25% skin) would equal 75 percent of the OEL. Therefore, a prudent action could be to modify CPC if RSAD exceeds 50 percent as calculated by Eq. 3. If the inhalation exposure is at greater than half the PEL, the skin dose should be lowered proportionally so that the combined inhalation exposure and skin dose do not exceed the OEL.

Breakthrough times are not an issue in the above calculations because only concentrations are measured. The concentration could be calculated from manufacturer's data using the permeation rate, the breakthrough time, and the time for glove wearing. The potential errors in the calculation due to varying conditions of glove use suggest that a calculated concentration value should be used only for initial glove selection or else safety factors of perhaps as high as an order of magnitude should be applied.

For risk estimation based on the amount of chemical permeating the inside of the glove, an appreciable lag time may exist before measurable breakthrough of chemical occurs. The grey band in Figure 1 represents the unmeasurable exposure that occurs before detection of breakthrough. This delay represents a period during which very little exposure is expected to occur. In practice, measurable breakthrough may not occur for minutes to hours after initial contact. Once measurable breakthrough occurs, the permeation can exponentially increase until steady-state rate is achieved. Actual time to measurable breakthrough can be determined as part of in-use testing, but is not needed in the above approach to compare glove performance with the acceptable skin exposure since Eq. 2 is simply a summation of the mass of analyte penetrating a glove or several gloves worn during the day. The second example provided below describes how permeation rate and measurable breakthrough lag time data can be used to estimate how long selected CPC can be safely worn.

Example of Estimating Acceptable Use Duration

Some glove manufacturers have included glove permeation ratings in their glove selection charts to simplify the selection process. A glove/solvent combination is rated very good if the measured permeation rate is less than 9 $\mu\text{g/cm}^2/\text{min}$

(0.54 mg/cm²/hr).⁽³⁸⁾ However, if the potential toxicity of exposure is not considered, the permeation rate alone may be insufficient for assuring worker safety.

The following examples illustrate how health-based criteria (inhalation OELs) might be used and how a glove usage time might be calculated. This approach parallels the recent proposal of Walker et al. for calculating the maximum skin exposure time for chemicals that can be absorbed through the skin.⁽³⁹⁾ In this example, a glove rated as very good based on the manufacturer's permeation rate was selected for two chemicals with quite different systemic toxicities. For simplicity, a BTT of zero was assumed in this example. In-use testing is advised to determine actual measured BTT. After BTT is established, PR represents the permeating mass over time after breakthrough. PR empirically determined by field testing will include the non-steady-state permeation immediately after BTT. How significant this is to the skin exposure dose is difficult to assess as it is seldom reported in the published literature on permeation testing. Nevertheless, BTT and PR should be empirically field tested to confirm initial estimates obtained from laboratory testing. In practice, BTT might be added to the estimated time until reaching an unacceptable dose as calculated from PR.

To estimate the time chemical dose received through a glove exceeds an acceptable amount, the permeation rate and area of exposed surface must be available. From these two variables glove dose rate can be estimated by

$$\text{Glove dose rate} = \text{PR}_{(\text{mg/cm}^2/\text{hr.})} \times \text{SA}_{(\text{cm}^2)} = \text{mg/hr.} \quad [4]$$

Examples for estimating duration of acceptable use:

compound 1

Methyl alcohol, OEL = 200 ppm = 260 mg/m³

Inhalation dose = 10 m³ × 260 mg/m³ × 0.5 OEL = 1300 mg

Allowable glove dose = 0.5 OEL (action level) = 650 mg

Glove permeation rate = 0.54 mg/cm²/hr × 410 cm² = 221 mg/hr

The calculated permeation rate of methyl alcohol through human skin is 1.3 mg/cm²/hr.⁽⁴⁰⁾ Since the permeation rate through the skin is much greater than the permeation through the glove, we assumed that all of the chemical permeating the glove would be absorbed into the skin.

Allowable time for skin exposure = 650 mg/221 mg/hr = 2.9 hours

compound 2

Methyl hydrazine, OEL 0.2 ppm = 0.35 mg/m³

Inhalation dose = 10 m³ × 0.35 mg/m³ × 0.5 OEL = 1.75 mg

Allowable glove dose = 0.5 OEL (action level) = 0.84 mg

Glove permeation rate = 0.54 mg/cm²/hr × 410 cm² = 221 mg/hr

$$\begin{aligned} \text{Skin absorbed dose} &= \text{SAF}(0.5) \times 221 \text{ mg/hr.} = 110 \text{ mg/hr} \\ \text{Allowable time for skin exposure} &= 0.84 \text{ mg}/110 \text{ mg/hr} = \\ &0.0076 \text{ hr, or 27 seconds} \end{aligned}$$

(Note: These chemicals are systemically toxic and currently have a skin notation. They permeate rapidly through the skin. Therefore, it might be assumed that 100 percent of the chemical permeating the glove was absorbed by the skin under occlusion, or the default assumption of 50 percent absorption could be used.)⁽²⁶⁾

This example clearly illustrates that by taking into account relative toxicity using air OELs, a “very good” glove may allow very dangerous exposures in the case of methyl hydrazine after a short period of wear. Current efforts to aid the glove selection process via inclusion of only glove permeation data without considering the toxicity of the permeant may result in a false sense of security. Those responsible for making glove selections must be cognizant of this fact.

DISCUSSION

Several technical aspects related to the assumptions used in the proposed approaches merit additional discussion. One question is how permeation data obtained from laboratory barrier testing relate to permeation through gloves in use. A related question is how readily chemicals that have permeated a glove in use will be absorbed through the skin. In Eq. 4, a laboratory-generated glove permeation rate was used to estimate the skin permeation rate, as 100 percent of the glove permeation mass was assumed to be absorbed. This assumption seems plausible, is easy to use, and if incorrect would err on conservatively overestimating dose. However, laboratory permeation rates may overestimate permeation in use, as described below.

With the gloved hand, chemicals must first permeate the glove membrane, then an aqueous (sweat) layer, and finally the stratum corneum. The glove and skin probably represent the two main barriers to permeation, although highly lipid-soluble compounds have limited ability to partition into sweat because of their low aqueous solubility. The greater barrier of the above layers to permeation should probably be used in Eq. 4 to estimate skin permeation rate. Experimentally determined SSPR for glove materials may represent worst case conditions in which the receptor chamber is kept near zero concentration and therefore the concentration gradient is maximized.

In use, a glove worn on a human hand is in contact with sweat and skin that has a limited capacity to absorb chemicals. Thus, if the concentration gradient across the glove matrix is not maintained as at time zero, the permeation rate is expected to decrease once chemical accumulation underneath the glove occurs. A conservative estimate is that for most low molecular weight compounds (< 150 daltons), establishment of the steady-state concentration gradient across the skin takes only 10 minutes.⁽⁴¹⁾ Thus, for rapidly absorbing solvents, equilibration to the steady-state permeation from the glove to the skin also probably occurs quickly.

Fick's Law predicts permeation of compounds through the skin quite well when the compound is in dilute solution. The law states that the permeation of the compound (F_s) equals $C_s \times K_p$, where C_s is the concentration of the compound ($\mu\text{g}/\text{cm}^3$) and K_p is the permeation coefficient (cm/hr). Several approaches have been proposed for estimating skin permeation coefficients for chemicals from aqueous solution when they have not been experimentally determined. Permeation coefficients are concentration independent when solubility in the permeating matrix is infinite. They are used to calculate amounts of chemicals absorbed through the skin given any exposed area, concentration, and duration of exposure. The revised Robinson model equation has been compared with other models and provides a good estimate of the permeation coefficients for compounds in saturated aqueous solutions.⁽⁴²⁾ This model may be applicable to organic compounds in sweat-covered skin, where the maximum concentration of the compound contacting the skin may approximately equal the aqueous saturation concentration.

Since permeation is the product of the permeation coefficient and the concentration in aqueous solution, the maximum permeation (Max P) of a compound in an aqueous solution can be estimated by

$$\text{Max P} = K_p \times \text{WS} \text{ (mg/cm}^2\text{/hr)} \quad [5]$$

where WS = maximum solubility of the compound in water (in mg/cm^3 or in moles/cm^3)

For highly water-soluble chemicals in sweat, the Max P should approach the permeation for these chemicals when pure. On the other hand, the Max P as predicted by Fick's Law should decrease for compounds with increasing octanol-water partition coefficient, even though the permeation coefficient increases. When lipophilic compounds are in aqueous solution, permeation rate and permeation coefficient are inversely related because the maximum water saturation concentration (i.e., WS) of lipophilic compounds decreases with increasing lipophilicity. Since permeation is concentration-dependent, the mass of lipophilic compound entering the skin should therefore decrease as water solubility decreases. However, in practice this physical law has limitations because of the effect of partitioning between matrix phases. Lipophilic compounds will preferentially accumulate in similar lipophilic matrixes and partition out of aqueous solution. Empirical data indicate that the skin permeation of lipophilic compounds from saturated aqueous solutions is often greater than, or at least equal to, the permeation rate of neat chemicals. For example, pure aniline has a reported skin permeation rate of 0.2–0.7 $\text{mg}/\text{cm}^2\text{/hr}$, while in saturated aqueous solution the permeation rate is 1.4 $\text{mg}/\text{cm}^2\text{/hr}$.^(43,44) With benzene, the permeation rate for neat and saturated aqueous benzene are 0.22 and 0.20, respectively.^(45,46)

Experimental animal data indicate what happens to the glove permeation rate when a glove membrane is put onto skin.⁽²⁴⁾ Even for highly permeable glove membranes for which the reported permeation rate exceeded the skin absorption rate, a 25 percent reduction of absorbed dose through the skin was

found compared with unprotected exposure to toluene. Laboratory testing indicated a PR for toluene through the test glove membrane of $\sim 300 \mu\text{g}/\text{cm}^2/\text{min}$; the empirical PR through miniature pig skin is only $5.3 \mu\text{g}/\text{cm}^2/\text{min}$. Even though PR_{glove} is potentially much greater than PR_{skin} , the glove barrier still offered some protection. This may be due to a decline in the concentration gradient across the glove from saturation of the aqueous layer under the glove and/or the saturation of the stratum corneum, resulting in a reduction in the diffusion rate that we postulated earlier. The permeation through the skin is the rate-limiting barrier in this example, and the laboratory determination of PR_{glove} appears to overestimate the skin absorbed dose. A better approximation of PR_{glove} of this relatively nonpolar organic solvent would be obtained from PR_{skin} using either the neat chemical or saturated aqueous solution.

In a second experiment on the effect of barrier protection on uptake from skin, n-butanol was tested as before, but the skin had been stripped of its stratum corneum with cellophane tape.⁽²⁴⁾ Stripped skin had much greater permeability to n-butanol than intact skin, so PR_{skin} was probably much greater than PR_{glove} . When the glove membrane was used, about a 24-fold reduction in skin uptake was measured. In this case, clearly the glove membrane is the rate-limiting barrier against dermal uptake.

The findings from the above study suggest that if PR_{glove} is much greater than PR_{skin} , the permeation for the skin should be used to estimate delivery rate through the glove and skin absorbed dose. Again, skin Kps can be obtained using the appropriate mathematical model or experimentally measured. From the Kp and the water saturation concentration of the compound, a practical estimate of the permeation through the glove might then be calculated. Complete absorption of the predicted amount might be assumed over the exposed area since it is the skin permeation estimate that is used in this case to estimate the practical glove permeation rate. In-use testing could be performed to verify the actual measurable breakthrough time. On the other hand, if PR_{glove} is less than or equal to PR_{skin} , PR_{glove} should be used for estimating the dose rate to the skin as the glove will be the main rate-limiting barrier. Figure 2 summarizes this scheme.

A final consideration regarding skin absorption rates is the high likelihood that the permeation rate through skin that has been chronically covered by a glove is greater than for uncovered skin.⁽⁴⁷⁾ The suggested mathematical model for calculating Kp is in regard to healthy skin. Workers' skin may be further damaged by abrasion, cuts, and dermatitis. Given these considerations, and present uncertainties, selecting an approach that would conservatively overestimate absorbed skin dose might be best. For these reasons, assuming that the stratum corneum will absorb chemicals at a rate that is greater than just described for toluene might be more prudent. Further research is needed.

BTT is an important variable in this model, since most glove selections are made with gloves that provide relatively long BTT in laboratory testing. Actual BTT can be determined by in-use testing. In a review of the few in-use assessments performed to date, BTT was appreciably shorter than indicated by laboratory

tests.⁽²⁾ Therefore, assuming laboratory data to be accurate for the conditions in which the glove is used might be erroneous. To overcome this possible problem, the BTT found during field testing might be added to the calculated acceptable usage duration relative to an absorbed dose.

Also regarding the gloved hand, the skin of the palm (although much thicker than at other sites) is about as permeable to lipophilic chemicals as other skin sites such as the forearm. This is supported by empirical data for benzene, hydrocortisone, parathion, and malathion.^(48,49) Therefore, empirical permeation determined on human skin, or calculated for human skin, should be relevant to the entire hand.

CONCLUSION

The advantages of basing glove selection on an in-use measurement represents a significant improvement over laboratory estimates of glove protection based on breakthrough detection times and permeation rates. In-use testing could provide useful information for the following:

1. optimizing glove use for durations based on actual workplace conditions. Gloves tested for continuous chemical immersion may provide longer protection if exposed infrequently. Vehicle effects that accelerate early breakthrough can be evaluated and changes implemented in glove polymer or solvent substitution to better control exposures.
2. choosing gloves based on price, tear resistance, or ease of use can be evaluated, and the impact on worker exposure documented.
3. producing objective in-use performance evaluation data, rather than assuming or ignoring the effect of ambient workplace conditions such as temperature, stretching, cosolvents, etc.
4. documenting exposure control provided by proper glove use, which would reinforce the importance of worker compliance with a CPC program.
5. relating the glove exposure measurement to a health-based exposure limit or other health criteria will allow consideration of the biological effect of the chemical to be included in the glove selection process.

The concept proposed here is to base glove selection criteria on the potential health effect, the relative toxicity of the agent, and objective in-use performance measurements, instead of only laboratory generated kinetic data and subjective judgement. The ideas presented in this article are suggested approaches for dealing with an albeit complex problem that presently is incompletely understood and commonly overlooked. The suggested approaches have not been evaluated for adoption by any guideline- or standard-setting bodies in the United States or elsewhere and are proposed solely at this time by the authors. We hope that these ideas will be discussed further among glove users and organizations setting guidelines.

Refinement of the assumptions made here should certainly be possible with additional studies. Generation of needed data will likely commence rapidly with the availability of initial glove performance criteria, considering by comparison the amount of information now available for measuring compliance with air OELs. Undoubtedly, as data are collected and more research is conducted, the approach to collecting and interpreting skin concentration results will be improved. As in the case of the air OELs of 50 years ago, only crude sampling methods and crude estimates of safe levels of exposure were available. The long-term result of these initial, yet imperfect efforts was a significant improvement in the control of inhalation exposures for workers worldwide. The same effort must now be applied to controlling skin exposure to chemicals in the workplace.

The proper selection of chemical protective gloves is an important step in minimizing dermal exposures to toxic chemicals. This decision process is too critical to be based only on assumptions. Having acceptable dermal exposure guidelines for comparison with in-use testing results would improve the objectivity of the selection process and increase the certainty of providing a safe workplace.

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