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RIEDAR K. OESTENSTAD , JIMMY L. PERKINS & VERNON E. ROSE

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Identification of Faceseal Leak Sites on a Half-Mask Respirator*

RIEDAR K. OESTENSTAD†, JIMMY L. PERKINS, AND VERNON E. ROSE

School of Public Health, University of Alabama at Birmingham, UAB Station, Birmingham, AL 35294

A method has been developed to identify the location and shape of respirator faceseal leak sites by the deposition of a fluorescent tracer. An aerosol generation, conditioning, and exposure system to provide a test environment with stable aerosol concentration and size distribution of 4-methyl-7-diethylaminocoumarin was designed and tested. Faceseal leak sites on a respirator mounted on a mannequin and worn by human subjects were identified by deposition of the tracer aerosol and subsequent observation under long-wave ultraviolet lighting. Test parameters were identified for the optimal definition of leaks. Photographic techniques were developed to document the identified leak sites.

This is the first of two papers which report the development and application of a technique to identify faceseal leak sites on half-mask, air-purifying respirators. This paper describes the aerosol and methods which were developed for this purpose and the tests conducted to identify faceseal leak sites on mannequins and human subjects. A subsequent paper discusses the distributions of leak sites and shapes and their association with facial dimensions for a panel of subjects wearing one brand of half-mask respirator.[1]

The past two decades have brought significant advances in respirator research. Most of those have been directed toward the quantification of respirator leakage through the use of quantitative fit testing. That technology has resulted in the development of the assigned protection factor concept and its incorporation into the American National Standards Institutes (ANSI) Z88.2, *American National Standard for Respiratory Protection,*[2] and the Occupational Safety and Health Administration's (OSHA) comprehensive health standards such as those for lead and asbestos.[3]

However, few studies have been reported in which the investigators attempted to identify leak sites on respirators. In an early qualitative fit test, coal powder was sprayed around the facepiece of a respirator, and leakage was identified by observing the coal deposited at leak site(s).[4]

Later, a quantitative fit test which could be modified to indicate leak sites was reported.[5] This method used Freon® gas as a test agent and a halide meter to measure leakage. To identify leaks, a small capillary tube attached directly to a Freon supply was moved around the facepiece. When the capillary was near a leak site, a strong deflection of the meter was noted.

Using this method, the authors found that the leakage of half-mask respirators varied substantially, even on multiple tests with the same individual wearing the same mask. They stated that the differences in fit were caused by variability of leaks around the nose. No indication as to the amount of this variance, the degree of penetration, or the prevalence of leakage around the nose was provided, and no other leak sites were indicated.

Leak sites could also be identified by a method which utilized photosensitive paper placed beneath the facepiece and light as a test agent.[6] In this method, the paper was cut into templates and placed inside the facepiece in a darkroom with photosafe lights. The subject then donned the respirator, and a high intensity light was moved around the facepiece. After the paper was developed, the location and degree of leakage was indicated by the presence of grey or black areas. Eight subjects wearing half-mask respirators and disposable respirators were tested with this method. It was noted that most leaks occurred around the nose and chin, and leaks occurred over a large area of the face. A limitation of this method was that since light travels in straight lines, it may not detect leaks that change direction.

Identification of respirator leak sites with a fluorescent tracer has also been reported.[7] In that method, a trace aerosol of optical brightener was applied to the immediate area of the respirator seal, and aerosol deposition at leak sites was documented by photographs taken under ultraviolet (UV) lights. Several types of half-mask respirators with imposed leaks were tested on a small number of subjects. Quantitative fit testing was conducted immediately prior to the fluorescent aerosol test. The method was able to identify imposed leaks with corresponding fit factors up to about 200. Aerodynamic streamlining within the respirator facepiece was also observed in mannequin tests using static (noncyclic) airflow but not on any of the human subjects.

The purpose of this work was to develop a method to identify faceseal leak location and shape on human subjects wearing well fitting, half-mask respirators by deposition of a test aerosol at the leak and subsequent visual detection and photographic doc-

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†Author to whom all correspondence should be addressed.

umentation. Feasibility of this approach was based on studies which had demonstrated particle deposition at respirator leak sites[8-10] and on others which demonstrated the ability to detect very small quantities of fluorescent tracers deposited on the skin.[11] Utilizing these findings, the authors selected a suitable test material, constructed an aerosol exposure system, and developed photographic techniques and a test protocol.

EXPERIMENTAL MATERIALS AND METHODS

The primary considerations for selection of a test agent were (1) that it be essentially nontoxic, (2) that very small quantities be visible on the skin, and (3) that it could be generated in concentrations and particle sizes used in current quantitative fit test methods which employ aerosols. After a review of the physical, toxicological, and optical properties of a number of fluorescent compounds, the fluorescent whitening agent 4-methyl-7-diethylaminocoumarin (MDC) was selected for use in the study.[11-15]

MDC is a member of a family of fluorescent whitening agents which absorb energy from long-wave UV light (320–400 nm) and convert it to visible light in the blue region (430–500 nm). It binds strongly to proteins on the outermost layers of the stratum corneum and is very highly visible under UV lights. Visible concentrations of MDC on the skin may be as low as 10 $\mu g/cm^2$.[11]

The aerosol generation, conditioning, and exposure system used in the study was patterned after that of Burgess et al.[16] A schematic diagram of this system is shown in Figure 1. This system nebulized an ethanol solution of MDC which was dried to produce a residual aerosol. The static charge on the aerosol and ethanol vapor in the carrier air were reduced before introduction into the exposure chamber.

The nebulizer was a modification of a design by Liu and Lee.[17] It allowed for the constant feed of fresh solution to be nebulized, thus avoiding an increase in solute concentration and a corresponding increase in the size of the residual aerosol.[18] The mass and size distribution output of the nebulizer was found to be very stable, but it required a relatively high liquid feed rate of about 2 mL/min.

Spatial and temporal measurements of chamber aerosol concentrations were made with a forward light-scattering photometer (Dynatech-Frontier Corp., Albuquerque, N.Mex.).

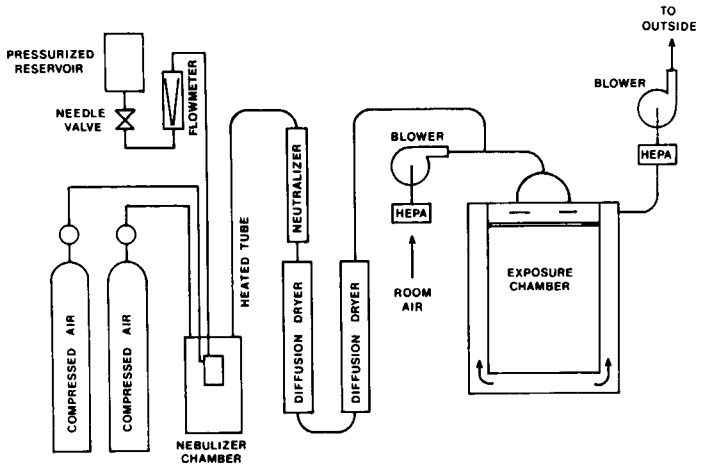

Figure 1—Aerosol generation, conditioning, and exposure system.

Photometer outputs measured across the chamber in perpendicular, eight-point traverses were within ± 4% of the mean value. Photometer outputs measured at 1-min intervals over a 2-hr test run were found to decrease slightly with time, but the value at the end of the test was within 10% of the value at the beginning of the test. Aerosol mass concentrations in the test chamber were measured by gravimetric methods. Concentrations were found to range from 18 to 50 mg/m^3 under various system operating conditions.

The aerodynamic size distributions of the aerosol produced under a variety of nebulizer operating conditions were measured with a Marple Personal Cascade Impactor (Andersen Samplers, Inc., Atlanta, Ga.). The sampling data from 17 tests were analyzed by a cascade impactor data reduction program which summarized Cunningham Correction Factor, aerodynamic cut size, cumulative frequency, and Reynolds Number values for each stage. It also tested for a log-normal distribution and calculated a least squares regression curve, an aerodynamic mass median diameter, and geometric standard deviation.[19]

The results of these analyses revealed that the test aerosol had an average aerodynamic mass median diameter of 0.55 μm and an average geometric standard deviation of 1.6. These values were within those recommended in Appendix A of ANSI Z88.2-1980 for quantitative fit testing[2] and would include particles shown by previous studies[8-10] to be deposited in respirator leaks.

The liquid aerosol was dried in a heated tube, and static charge on the particles was reduced by passing them through a neutralizer constructed to specifications of Carsey.[20] Static charge remaining on the particles was not measured. However, it was noted that there was no observable accumulation of particles on the chamber walls as would be expected if there were a high residual static charge.

The aerosol and carrier air then passed through two diffusion columns packed with 8-12 mesh activated carbon to reduce the concentration of ethanol vapor. The concentration of ethanol vapor in the test chamber remained at about 700 ppm, which required respirators worn by test subjects to be equipped with combination HEPA filters and organic vapor cartridges.

After leaving the diffusion driers, the conditioned aerosol was injected into the chamber dilution air. The dilution air, which was filtered through a tower packed with 8-12 mesh activated carbon and a HEPA filter, was blown into the exposure chamber at 0.2 to 0.25 m^3/min with a variable-speed, high-volume blower.

The chamber was constructed of clear Plexiglas® and clear, flexible vinyl. It consisted of a rigid top, 55 cm in diameter, on which two concentric Plexiglas rings were attached. The diameter of the inner ring, which formed the chamber wall, was 46 cm. Walls of the chamber and the exhaust plenum were formed by flexible vinyl which hung from the rings. A plastic shroud was added to outer wall to prevent aerosol from escaping into the laboratory environment in uncontrolled air currents around test subjects seated in the test chamber.

Dilution air and aerosol were introduced through the two inlet ports in the top of the chamber and were distributed into a shallow plenum by impaction plates. They then passed through a 2-cm layer of open cell polyurethane foam to ensure a homogeneous distribution within the test chamber. Air velocity through the test chamber was calculated to be between 2 and 3 cm/sec at the dilution airflow rates of 0.2 and 0.25 m^3/min. Since these velocities were below the range of available anemometers, they were not verified. However, smoke tube checks of airflow within the chamber indicated that flow was evenly distributed across

the chamber and was laminar. Air was exhausted to the outside through the annulus formed at the bottom of the chamber wall and the outside wall.

Mannequin Tests

The aerosol generating and exposure system was used with the MDC aerosol to conduct a series of quantitative fit tests on a mannequin to determine if the method of identifying leak sites was feasible. The tests consisted of a preexposure photograph under ultraviolet lights, fitting the mannequin head form with a half-mask respirator equipped with high efficiency cartridges, exposure of the mannequin to the MDC aerosol, and a post-exposure photograph under ultraviolet lights.

Airflow through the respirator was by both simulated respiration and continuous flow. Respiration was approximated with a pulmonary resuscitator connected to the mannequin head. A respiratory minute volume of about 9 L/min was produced using this system. This was below the average respiratory minute volume of about 14 L/min for an adult at a work rate of 0 kilogram-meter (0 Kg-M).[21] As a result, a series of tests was also conducted at continuous flow of 15 L/min through the mannequin.

The mannequin head was prepared by coating with an opaque latex film to eliminate fluorescent interference. The preexposure photograph was made to confirm the absence of any interfering materials. Lighting for the photographs was with two Spectroline Model XX-15N lights with UV transmitting filters (Spectronics Corp., Westbury, N.Y.). Maximum emission wavelength for these lights was 365 nm with a range of about 300 to 430 nm. The light provided about 1.8 μW of ultraviolet irradiation when placed at a distance of 35 cm from the mannequin's face.

The photographs were taken with a Nikon FE camera using an RMC Tokina 35–105-mm zoom lens and a Kodak 2E Gelatin Filter to remove ultraviolet light. Kodak Tri-X-Pan 400 ISO black and white film pushed to 1200 ISO was exposed at 5.6f for 1.0 sec for the preexposure photograph and 0.5 sec for the postexposure photograph. The exposed film was developed and printed with Kodak chemicals. Special attention was given to proper time, temperature, agitation, and chemical dilution to enhance film contrast.

A respirator was mounted on the mannequin with a wire placed between the facepiece and the headform to produce an artificial leak. The mannequin was placed in the test chamber, the generator was started and the aerosol concentration in the test chamber was allowed to equilibrate. Quantitative fit tests were conducted using a Dynatech-Frontier Model 264 Quantitative Fit Test System. At the conclusion of the test, the respirator was carefully removed and the mannequin head again was illuminated with ultraviolet light and photographed.

The postexposure photographs showed clear evidence of aerosol deposition at the location of the artificial leaks. An example of postexposure photographs of the mannequin is shown in Figure 2. It illustrates artificial leaks on both sides of the face with continuous airflow of 15 L/min through the facepiece. Note the aerosol deposition patterns indicating aerodynamic streamlining inside the facepiece.

Human Subject Tests

Before human subject tests were initiated, minor modifications were made to the generation and exposure system to provide higher and more consistent aerosol concentrations. Test duration

Figure 2—Aerosol deposition on mannequin after exposure with continuous airflow in the respirator.

to obtain visible deposition of aerosol was estimated from chamber aerosol concentration, measured penetration, and respiratory minute volume. Using these factors, human tests were conducted for about 40 min at an average MDC concentration of about 38 mg/m^3. UV lighting and photographic techniques were the same, except that a darkroom with mounted UV lights and a camera tripod were used to provide more consistent exposure conditions.

Test procedures for human subjects were developed from experience gained in conducting the mannequin tests. The protocol included (1) screening of potential subjects, (2) anthropometric measurements, (3) preexposure photographs, (4) respirator fitting, (5) quantitative fit testing, and (6) postexposure photographs. Criteria for selection of test subjects were (1) age between 21 and 50, (2) absence of any facial features which may have resulted in obvious respirator leakage (creases or folds in the skin, scars, sunken cheeks, or beards), and (3) absence of any medical conditions which would put subjects at risk as a result of wearing a respirator or being exposed to the test aerosol.

Facial anthropometric dimensions to be measured were developed from a review of previous research on respirator anthropometry[22-25] and consultation with the staff of Anthropology Research Projects, Inc., of Yellow Springs, Ohio. Those dimensions are listed in Table I.

Prior to the preexposure photographs, subject's faces were wiped with alcohol swabs to remove fluorescent materials, and their clothing was covered with a black shroud to eliminate interference from clothing. Their eyes were covered with opaque goggles while exposed to the UV lights.

TABLE I
Facial Dimensions

Biectoorbitale breadth
Bizygomatic breadth (face width)
Bigonial breadth
Menton-nasion length (face length)
Menton-subnasale length (lower face length)
Subnasale-nasion length (nose length)
Biocular breadth
Nasal root breadth
Nose width
Lip width
Bitragion-menton arc
Bitragion-subnasale arc

After the preexposure photograph, the subjects were fitted with a respirator, and a negative pressure fit check was performed. Care was taken not to disturb the facepiece until after completion of the fit test. The respirator used in the study was the U.S. Safety Series 200 Half-Mask which was available in small, medium, and large sizes (United States Safety Service Co., Kansas City, Mo.). The facepiece configuration was thought to be typical of most half-mask respirators. The size worn by each subject was determined by his or her face length. The respirators were probed with surface-mounted fittings for fit testing at a point on the vertical midline between the subject's nose and mouth.

The aerosol generating system was started and the chamber aerosol concentration allowed to equilibrate. The subjects performed a positive pressure check to ensure proper fit. After it was observed that the subjects could breath through the respirators without difficulty, they were seated on a chair with their heads and shoulders in the test chamber.

Real-time aerosol concentration in the test chamber and beneath the respirator were measured with a Dynatech-Frontier Model 264 Quantitative Fit Test Photometer. An initial check was made of the aerosol concentration inside the respirator to ensure that the leakage was less than 10%. The test was stopped if leakage of less than 10% could not be attained after adjustment of the facepiece. A standard quantitative fit test which included head movement exercises and talking was performed.[2]

Integrated photometer output for measurements in the test chamber and beneath the respirator were used to calculate fit factors. Under these sampling conditions, the measured concentration inside the respirator would be less than that expected from leakage alone caused by aerosol measurement during exhalation and lung retention of aerosol. As a result, the measured fit factor would be higher than the true fit factor. Fit factors were not corrected for this bias, which has been estimated to be about 5% to 12% by previous studies.[26,27]

At the conclusion of the test, the subjects were removed from the test chamber, and the respirator was carefully removed. Postexposure photographs to document visible aerosol deposition were immediately taken by the same procedure used for the pretest photograph.

DISCUSSION

Leak sites which could be detected visually and by photographic methods were classified as to their location (nose, cheek, or chin) and their one-dimensional shape (point or diffuse). Examples of postexposure photographs are shown in Figures 3 and 4. Note

Figure 3—Aerosol deposition on a subject with a diffuse chin leak (fit factor = 600).

Figure 4—Aerosol deposition on a subject with streamlining from a point nose leak (fit factor = 2300).

that the deposited aerosol on the subject in Figure 4 follows a streamlining pattern from the leak to the subject's nostril. Streamlining was hypothesized as being the cause of sampling bias in the determination of fit factors.[28] This observation confirms that this phenomenon occurs within the respirator facepiece worn by human subjects, and could account for the very high measured fit factor for this subject.

This study demonstrates the feasibility of identifying respirator faceseal leak sites with an aerosol of MDC using the described generation, conditioning, and exposure system. The system was found to be capable of providing a constant output of an aerosol with the desired size distribution characteristics. Sufficient deposition of the fluorescent tracer to allow visual detection of faceseal leak sites on a mannequin and human subjects was obtained. Photographic documentation of identified leak sites is presented.

This method could be used to determine the distributions of leak sites and shapes for groups of wearers, types of respirators, various breathing rates, and interactions of these variables. This information may identify an association of critical facial dimension(s) with respirator fit or facial shapes which might be accommodated by a specific respirator type or configuration.

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