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Nitrous Oxide Control in the Dental Operatory: Auxiliary Exhaust and Mask Leakage, Design, and Scavenging Flow Rate as Factors

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APPLIED STUDIES

Nitrous Oxide Control in the Dental Operatory: Auxiliary Exhaust and Mask Leakage, Design, and Scavenging Flow Rate as Factors

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Two new local exhaust systems, intended primarily to control patient mouth emissions of N_2O, were installed in a dental operatory, and resulting exposure concentrations to dental personnel were observed. The exposures were found to be typically unaffected by the presence and operation of these new controls. Laboratory testing on a head form, in conjunction with the operatory observations, established that mask leakage due to poor fit was the primary cause of N_2O emissions. An improved mask fit and the addition of a slotted skirt around the outer mask shell individually resulted in greatly reduced leakage rates in the laboratory tests. Also, exhaust systems placed on the chin, on the chest, or in the mouth proved effective in capturing mouth emissions simulated by a breathing machine and head form.

Keywords: dental operatory, local exhaust systems, nitrous oxide

In the United States there are over 424,000 dental workers, including dentists, dental assistants, and dental hygienists.[1] Thirty-five percent of all dentists use nitrous oxide (N_2O) for psychosedation.[2] Usage of N_2O by pediatric dentists increased from 65% in 1980 to 88% in 1988.[3] Although the N_2O is administered with a mask placed over the patient's nose, often dentists and other dental workers are exposed. In addition, there are many administrative, secretarial, maintenance, and other nondental personnel who may regularly be exposed to N_2O at relatively low concentrations in the dental operatory or in other parts of the building, if it is served by a common ventilation system using return-air.

Occupational exposure to N_2O causes adverse health effects[4,5] including reduced fertility, spontaneous abortions, and neurologic, renal, and liver disease. The current National Institute for Occupational Safety and Health (NIOSH) recommended exposure limit (REL) for N_2O is 25 ppm as a time-weighted average (TWA) concentration over the period of administration.[6] The REL is based on the results of a study showing adverse behavioral effects such as decreased performance, cognition, audiovisual ability, and dexterity during exposures to N_2O.[7,8] The Occupational Safety and Health Administration does not have a standard for N_2O exposure.

Because dental workers must be in close proximity to the source of N_2O, general ventilation cannot effectively reduce exposures to below the REL.[9–11] Although other control measures, such as scavenging devices added to the mask, maintenance, monitoring, leak detection, and work practices have reduced exposures significantly,[12,13] these also have not succeeded in consistently achieving exposures below the REL. While supplemental local exhaust ventilation (LEV) can reduce N_2O exposures to below the REL, other considerations such as excessive noise, intrusion on the space required to carry out the dental procedure, and aesthetic acceptability have made LEV difficult to implement practically.[9,14,15] A summary of the NIOSH position on exposure limits and controls for N_2O is available,[16] as is a review of NIOSH and other efforts to control N_2O exposures.[17]

In this NIOSH study, the authors initially attempted to redesign the supplemental LEV system. An approach was sought that would not only control N_2O exposures to below the NIOSH REL but also would improve on or

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avoid the above-noted detractions. These early efforts focused on reducing mouth emissions, since other N_2O sources were thought to be less significant when a modern scavenging mask was used. A modern scavenging mask has an integral exhaust system intended to control the emission of leakage of anesthetic gases outside the mask. Tests of these new LEV systems suggested that mask redesign might prove more effective, as mask leakage was not eliminated by any of the control methods evaluated. A better-fitting prototype mask with a slotted skirt was then designed and tested as a final step in these experiments.

EXPERIMENTAL DESIGN

Control of mouth emissions was the original goal of this effort. The approach to this goal involved the following three steps. First, a series of supplemental LEV systems was constructed and tested qualitatively in the laboratory. Systems were tested using the apparatus shown in Figure 1 to determine which had the basic ability to capture mouth emissions. If this test was successful, the second step was to obtain an initial opinion of the system's acceptability in dental practice. The director of the dental operatory in which the field evaluation was accomplished provided this opinion. The third step was a field evaluation in the operatory of those systems that had acceptably met the criteria of the first two steps. With controls in place and operating, personal sampling of the dentist and dental assistant was carried out for N_2O exposure concentrations.

N_2O concentration measurements were intended to demonstrate the effectiveness and acceptability of two new controls designed primarily to capture emissions from the patient's mouth. The first control, an auxiliary exhaust (Figure 2), rested on the patient's chest so that the inlet to the tubing was 3 to 6 inches from the patient's chin. It was connected to a blower with flexible and rigid sections of vacuum cleaner hose and pipe. The blower was exhausted outside the building in which the operatory was located. The exhaust flow was 100 ft^3/min.

The second control tested in the operatory was based on a modification of a mouth-prop commonly used in dental operations (Figure 3). The modification involved cutting off the two portions of the mouth-prop normally located in the patient's mouth. Welded in their place were two pieces of ¼-inch diameter stainless steel tubing, bent to the shape of the removed pieces and connected outside the mouth by plastic tubing to a vacuum source. The total airflow rate through the mouth-prop control was 80 L/min. In this manner mouth emissions could be captured at their source.

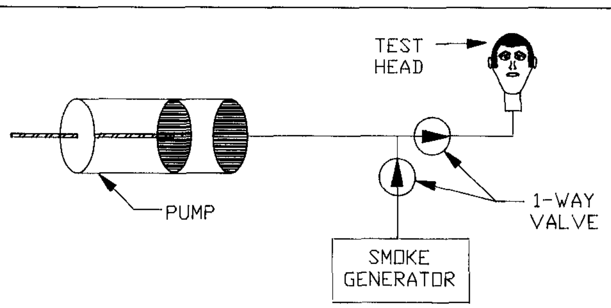

FIGURE 1. Breathing simulator for qualitative mask leakage testing

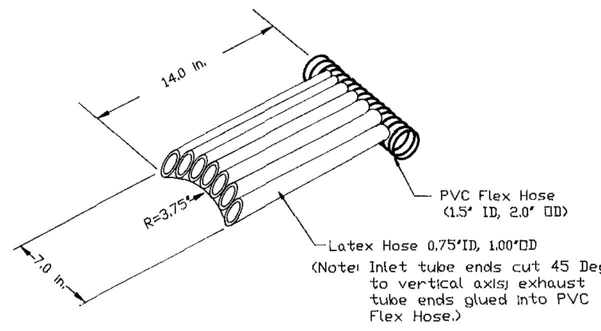

FIGURE 2. Diagram of auxiliary exhaust

METHODS AND MATERIALS

Research activity alternated between the dental operatory and the laboratory. Three mask systems were studied, one in the operatory and all in the laboratory leak-testing facilities. The three mask systems are referred to as follows: (1) unmodified mask—the latest available Porter-Brown mask (Porter Instrument Co., Hatfield, Pa.) as received from the manufacturer; (2) skirted mask—A Porter-Brown mask with a flexible slotted skirt added to the outer shell; (3) Medicvent mask—a recently introduced mask[18] (Model Anevac-D, Medicvent AB, Umeå, Sweden) that includes a supplementary chin-mounted exhaust (Figure 4) and has a much higher scavenging flow than the Porter-Brown masks.

Field Location

The operatory was located in the pediatric ward of a teaching hospital. The patients ranged in age from 8 to 17 years. A series of eight operations was observed in the dental operatory, using different combinations of the mouth-prop (Figure 3) and chest-mounted (Figure 2) controls. The unmodified masks were used to administer N_2O. The scavenging flow rate of the unmodified masks was measured for each of the flow controllers. The inlets to the personal sampling system for N_2O in the operatory were located on the dentist's and assistant's lapels, a typical location used by industrial hygienists. N_2O concentration measurements made in the operatory were carried out in October and November 1992.

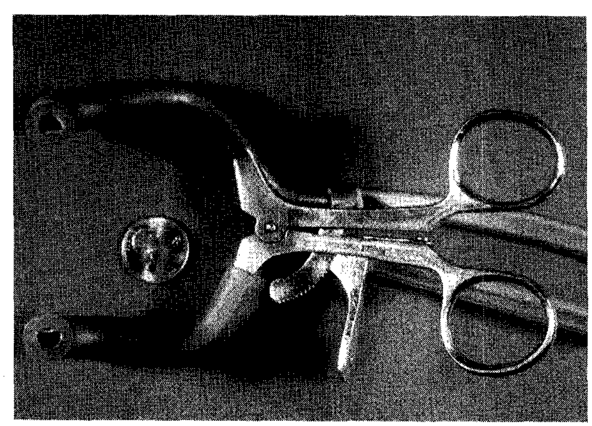

FIGURE 3. Mouth-prop exhaust

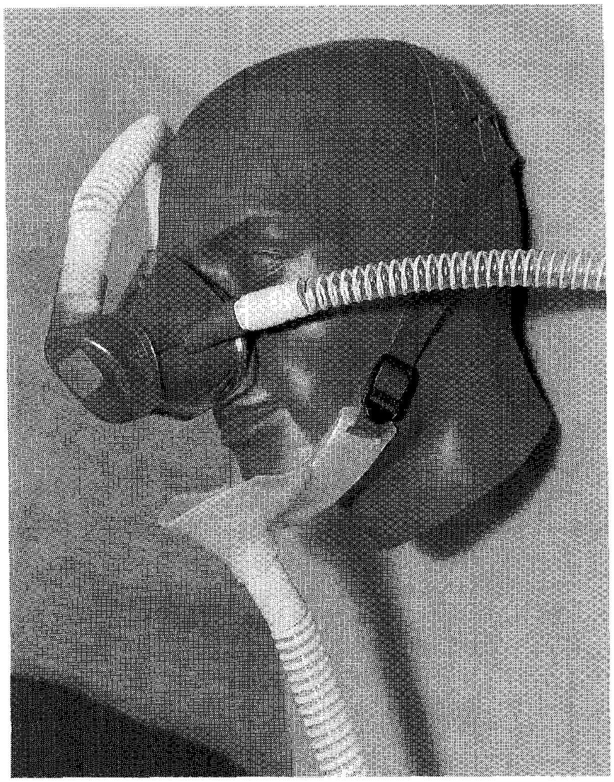

FIGURE 4. Medicvent scavenging mask in place on head with supplementary chin exhaust

The high-speed drill (Midwest Model 8000, Gendex Midwest, Des Plaines, Ill.) used in this operation was driven by an air turbine. It consumed 24 ±1 L/min of air, as measured in a free-running state *in situ* with a bubble meter. The drill had a supply port for the compressed air and an exhaust port for the air exiting the turbine. However, a jet of air escaped from both ends of the bearing in the drill head, apparently an unavoidable feature of the drill design.

N_2O exposure concentrations were measured in a dental operatory using two MIRANs (the infrared analyzers used in both the laboratory and the field work were MIRAN® Models 1A and 1B2, The Foxboro Co., East Bridgewater, Mass.) continuously sampling the breathing zones of the dentist and the dental assistant. One end of plastic tubing with an inside diameter of ¼ inch was fastened to the lapels of the dental personnel and run first to a diaphragm pump and then to a MIRAN. The flow rates of the sampled air were each about 17 L/min. Analog data produced by these MIRANs were digitized and stored in data loggers (Rustrak Ranger I, Model RR 400, Rustrak Instruments, East Greenwich, R.I.), then downloaded to a portable personal computer for later analysis. Also, a video recording was made of most of the operations in which N_2O exposure concentrations were measured. The video was synchronized with the digitized N_2O concentration data for later use in correlating events in the dental operation with features of the concentration data.

The speed of unconfined air was measured with a digital air velocity meter (Model 1440, Kurz Instruments, Inc., Monterey, Calif.). Ambient air velocities in the laboratory were adjusted to the same range as those found in the operatory.

Laboratory

Qualitative laboratory testing of the various mask configurations and supplementary controls used a head form connected to a breathing machine and a smoke generator (Figure 1). This same breathing machine and head form, along with the later addition of another apparatus—Infrared Analyzer 1 and Infrared Analyzer 2 (Figure 5)—was used to locate and quantitatively test the leakage of N_2O administration and control equipment used.

The breathing machine was driven by a variable speed motor. The travel of the piston also was adjustable. For the data reported here, the breathing machine was set for 15 cycles/min, and the volume per inhalation (exhalation) was 580 cm^3, which corresponds to a resting breathing rate.[19] The smoke was delivered by tubing to the head form, either to its nose to simulate normal breathing, or to its mouth to simulate mouth breathing, or to both the mouth and the nose. Qualitative evaluation of the performance of the equipment under test was based on visual observations of smoke capture.

For quantitative testing, breathing gas was supplied from a regulated compressed gas tank of air, containing 2% of either N_2O or SF_6, the tracer gases. The breathing bag, shown in Figure 5, was a plastic bag of about 1-L capacity. A breathing bag is a normal part of the anesthesia machines used in the dental operatory. Its function is to supply any sudden large demands by the patient for air. The breathing gas was maintained at a flow rate of 10.27 L/min.

Infrared Analyzer 1 (Figure 5) measured the concentration, c, of tracer gas released into the hood where the head form and equipment to be tested were located. The flow rate, f, of tracer gas entering the hood was determined by the following equation, using the tracer gas concentration, c, and measurements of the flow rate, Q, of air entering the hood and traveling down the duct:

$$c\left[\frac{\text{volume tracer gas}}{\text{volume air}}\right] \times Q\left[\frac{\text{volume air}}{\text{time}}\right] = f\left[\frac{\text{volume tracer}}{\text{time}}\right]$$

where c was measured with Infrared Analyzer 1,
Q was measured in the duct with a Pitot tube, and
f was the flow rate of tracer gas in the duct that was not captured by the equipment under test.

Infrared Analyzer 2 allowed measurement of the sum of the flow rates of tracer gas captured by the test equipment and by the hood and provided assurance that tracer gas was not escaping from

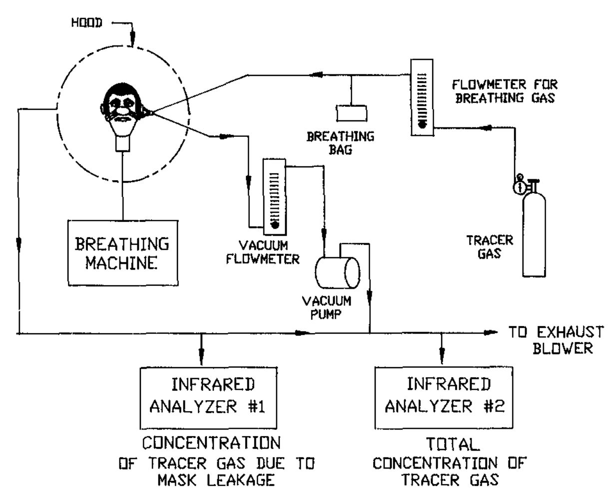

FIGURE 5. Quantitative mask leakage test facility

the test system. Each MIRAN sampled air in the exhaust duct using a diaphragm pump, operating at 17 L/min, located between the duct and the MIRAN. The air was extracted from the exhaust duct through ¼-inch diameter stainless steel tubes inserted into the duct along its diameter. Air entered the steel tubes through five 1/16-inch diameter holes drilled in the tube and spaced evenly across the duct diameter. The exhaust of Infrared Analyzer 1 was routed back into the exhaust duct between the two MIRAN inlets. The exhaust of Infrared Analyzer 2 was routed back to the exhaust duct downstream of its inlet, preventing tracer gas contamination of the laboratory, which supplied fresh air for the hood.

The flow rates of the breathing gas and the vacuum pump were measured with calibrated rotameters. The flow rate to the exhaust blower was determined by two 10-point pitot tube traverses made at right angles in the 14-inch diameter exhaust duct. The flow characteristics of the breathing machine were determined using a Medistor Pulmonary Function Analyzer (Model M-010, Cybermedic, Boulder, Colo.).

Calibration of the MIRANs was accomplished with the arrangement shown in Figure 5. By turning off the scavenging exhaust flow, a known concentration of tracer gas was generated at the sampling points of both MIRANs, since the tracer gas and hood flow rates were measured. This measured concentration agreed well with the concentration determined using the internal library of the 1B2.

In conjunction with the above quantitative leakage measurement system, an infrared (IR) imaging system (Thermovision 782, AGEMA Infrared Systems, Secaucus, N.J.) was later used to locate leaks in the systems under test. The source of IR energy was a square panel 18 inches on a side maintained at 120°F. The apparatus under test was placed between the IR camera and the hot panel. Leaking tracer gas strongly absorbed the IR radiation generated by the panel and was visible as a flowing plume or cloud on the IR system's video display.

RESULTS

Field Testing Results

Originally, seven of the eight flow controllers, when set as directed by the manufacturer, actually produced a scavenging flow rate below the recommended minimum of 40 L/min. When informed of the problem, the manufacturer replaced all eight of the original units. The replacements also flowed less than 40 L/min. A third set of flow controllers supplied by the manufacturer all flowed at least 40 L/min, with an average of 41.3 L/min. N_2O exposure data reported here were obtained with the original set of flow controllers in operation. However, several subsequent measurements of N_2O exposure concentrations showed no noticeable improvement in exposures when the scavenging flow rates were set to 40–45 L/min.

Average exposure data for the dentist and the assistant are given in Figure 6 for the dental operations. Although in two operations the dentist's exposures were below or near the NIOSH REL, there was very little correlation between the activity of the control to capture emissions from the patient's mouth and the resulting exposure concentrations. Turning a control on or off during an operation generally produced no observable change in exposure concentrations, as shown in Figure 7.

The first of the controls, the auxiliary exhaust, was not effective in controlling the dentist's exposure while the high-speed drill was on. Figure 7 shows the concentration of N_2O in the dentist's breathing zone versus time for one operation. In the time interval from approximately 1400 to 3000 seconds, with the drill off, it appears that the auxiliary exhaust did have a significant effect on the dentist's exposure. The air velocity in the operatory measured at the dentist's breathing zone with an air velocity meter ranged from 25 to 40 ft/min. Because the normal location of the auxiliary exhaust, placed on the patient's chest, occasionally interfered with the dentist's technique, it was therefore lowered for sufficient access to the patient. However, the normal placement was judged by several dentists not to be a significant interference problem.

Again, as seen in Figure 7, the operation of the mouth-prop exhaust, the second of the new controls, was ineffective in controlling the dentist's exposure, particularly during high-speed drilling.

Laboratory Test Results

In the laboratory tests, ambient air velocity in the vicinity of the head form ranged from 30 to 50 ft/min as measured with an air velocity meter. Laboratory tests conducted before the operatory tests showed that little or no smoke escaped when the mouth-prop and the auxiliary exhaust leakage controls were in place while the head form was simulating mouth breathing using the apparatus of Figure 1. Because the two controls, auxiliary exhaust and modified mouth-prop, did not pass the third step (control of N_2O in the operatory) proposed to achieve the study's goal, tests were later run to confirm the original assumption that the primary source of N_2O exposure was mouth emissions. The apparatus of Figure 5 was developed to measure mask leakage. Also, an infrared imaging system was used to locate leaks.

The unmodified mask as supplied by the manufacturer typically leaked considerably when placed on the head form with average care. Results are shown in Figure 8. Leakage with a typical loose fit was 1.6×10^3 cm^3/min. Observations of the leakage with the IR imaging system showed that during exhalation a jet of gas escaped from gaps between the mask and the head form. When the breathing machine was not operating, the mask did not leak.

Improved control of mask leakage was attempted in several ways, and leakage was again measured using the apparatus shown in Figure 5. First, increased flow of the mask's scavenger system

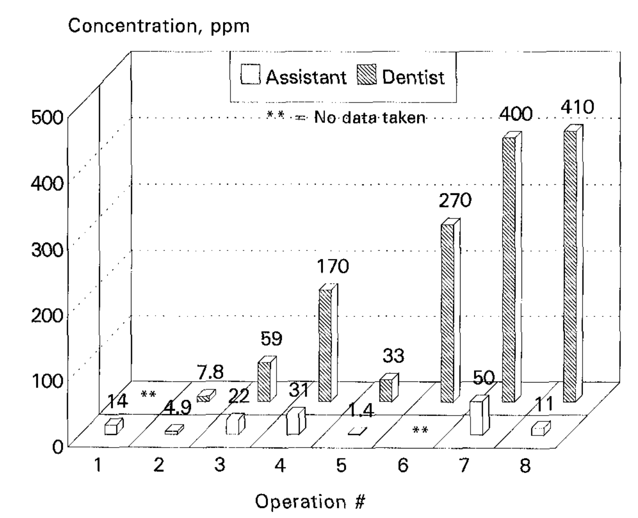

FIGURE 6. Dentist's and assistant's breathing zone concentrations of N_2O averaged over the procedure

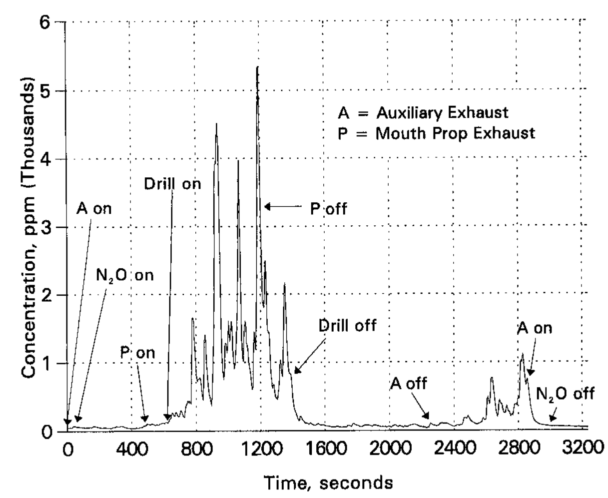

FIGURE 7. N_2O concentration versus time in the dentist's breathing zone with various combinations of the auxiliary and mouth-prop exhausts in place

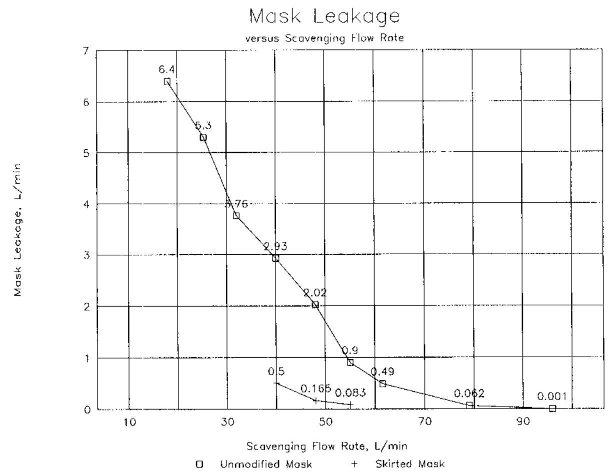

FIGURE 9. Standard and skirted mask laboratory leakage rates as a function of scavenging flow rate

was evaluated. When the scavenging flow was increased from 40 L/min to 62 L/min, the mask leakage decreased to 17% of its original value (Figure 9). The N_2O concentration inside the mask was reduced to 73% of its original value as a result of this increase in scavenging flow (Figure 10).

A second approach to better leakage control was to improve the mask fit. A good fit was achieved by increasing the pressure of the mask's inner shell against the head form, which resulted in low leakage. The leakage rate was 92 cm^3/min, about 6% of the loose-fit rate. A good-fitting, low-leakage mask resulted in an active breathing bag, whereas a poor-fitting mask resulted in a largely passive breathing bag.

The third approach was the addition of a slotted skirt to the outer shell of the mask-type used in the operatory (construction diagrammed in Figure 11). The leakage was decreased considerably as shown in Figure 12. With a loose fit the skirted mask produced a leakage rate of 60 cm^3/min and with a tight fit 6 cm^3/min.

Finally, leakage measurements were made for the Medicvent system, which includes a mask and a chin-mounted exhaust as a supplementary control for N_2O emissions (Figure 4). Leakage data obtained for various arrangements of this system are shown in Figure 13. Using the mask only, the tight fit and loose fit leakage rates are 485 and 6.46 × 10^3 cm^3/min, respectively. By adding the chin exhaust in its normal position, the tight fit and loose fit leakage rates are reduced to 121 and 893 cm^3/min, respectively. Finally, if the chin exhaust is pushed down off the chin onto the neck, as it might be during an operation to permit better access to the patient's mouth, the tight and loose fit leakage rates become 398 and 684 cm^3/min, respectively. The scavenging flow rate for the Medicvent mask was 250 L/min. Its supplementary chin exhaust also flowed at 250 L/min.

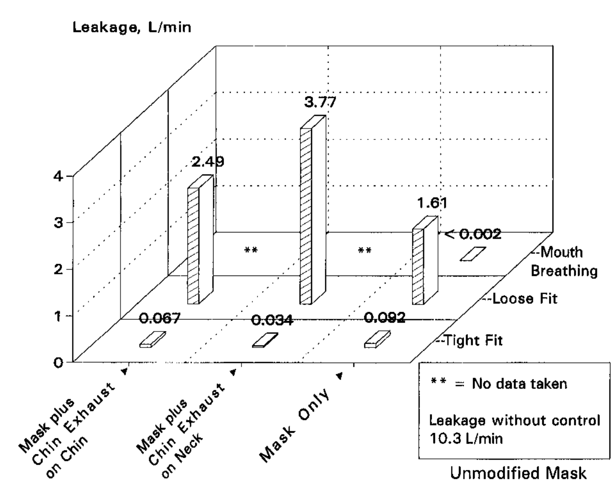

FIGURE 8. Laboratory leakage rates of an unmodified mask with tight and loose fits, nose and mouth breathing, and with a supplementary chin exhaust located on the head form's chin or neck.

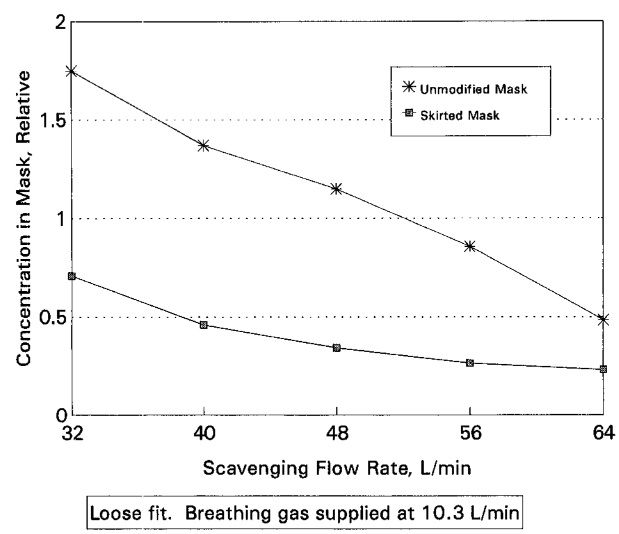

FIGURE 10. Relative concentration of breathing gas inside the mask as a function of scavenging flow rate as measured in the laboratory for the standard and skirted masks

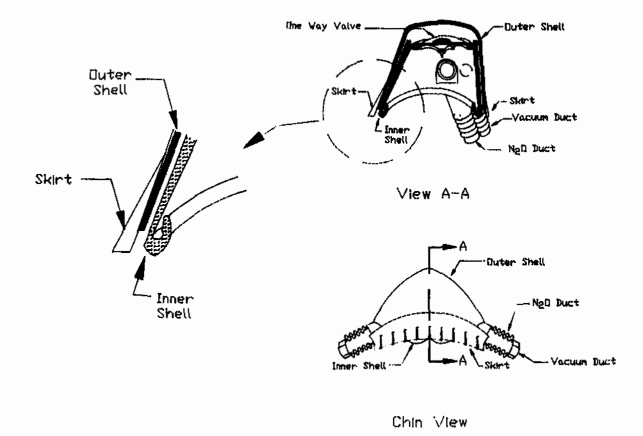

FIGURE 11. Diagram of skirted mask

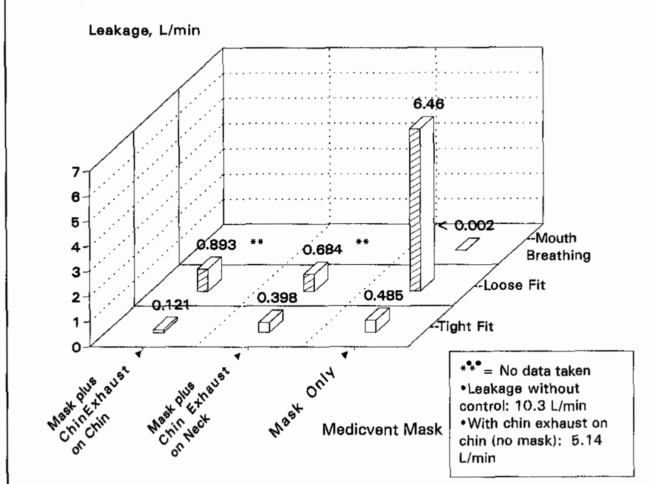

FIGURE 13. Laboratory leakage rates of the Medicvent mask with tight and loose fits, nose and mouth breathing, and with a supplementary chin exhaust located on the head form's chin or neck

DISCUSSION

As noted earlier, the high-speed drill produced two jets of air that escaped from the head of the drill. These air jets could entrain N_2O emissions from the mouth or mask, carrying them into the operatory away from potential capture points and possibly directly into the breathing zone of dental personnel. It seems likely that elimination of these jets from the high-speed drills would reduce N_2O emissions and consequent exposures to dental personnel.

If a loosely fitting unmodified or skirted mask was used, the addition of a chin-mounted exhaust increased the systems' leakage rates. However, the Medicvent mask always performed better when the chin-mounted exhaust was added (Figures 8, 12, and 13). It appears that airflow associated with the chin-mounted exhaust pulled breathing gas out of the loose-fitting masks that had relatively low scavenging flow rates, allowing the ambient airflow to carry the gas away. The Medicvent mask, with a higher scavenging rate, was less affected by external airflows in its ability to retain breathing gas.

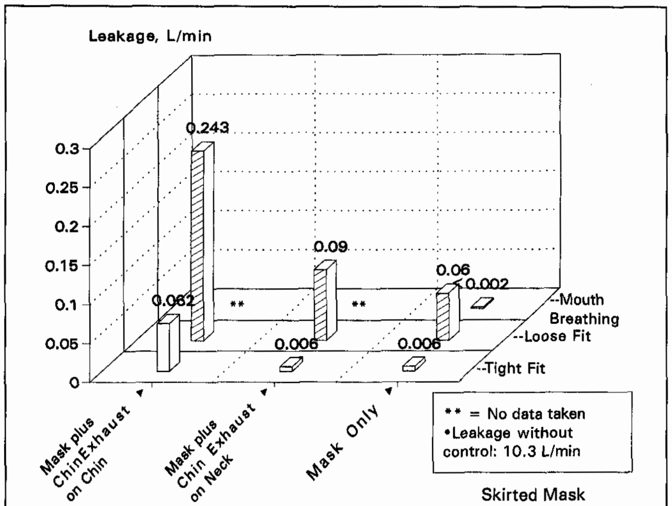

FIGURE 12. Laboratory leakage rates of a skirted mask with tight and loose fits, nose and mouth breathing, and with a supplementary chin exhaust located on the head form's chin or neck

Figures 9 and 10 show that, although mask leakage could be reduced by increasing the scavenging flow rate, the concentration of the breathing gas (N_2O) decreased if the rate at which breathing gas was supplied remained constant. Thus, to maintain a sufficient concentration of anesthetic gas in the patient's breathing zone, additional gas would have to be supplied as the scavenging rate was increased.

It is evident that simply increasing the scavenging flow rate to a reasonable degree does not eliminate mask emissions. It may be that even though mouth emissions may not escape into the environment when a control is in place, the dentist could inhale the emissions at some point on the path from the patient's mouth to the exhaust inlet.

From an engineering standpoint, it would be useful to know the maximum mask leakage rate that would still maintain worker exposures to N_2O below statutory limits. The concentration of N_2O in the mask is typically 50% or less. Also, a typical procedure takes about 25 minutes. Assuming a worker breathing rate of 10 L/min, inhalation of 12.5 cm^3 of the 50% N_2O mixture would result in an exposure at the NIOSH REL of 25 ppm. A steady leakage of 0.5 cm^3/min for 25 minutes could deliver 12.5 cm^3, or an instantaneous release of 12.5 cm^3 or more of the mixture would also be sufficient for an overexposure. It is not known what volume of ambient air combines with the 50% mixture before inhalation by the worker. Thus, a worst case estimate of the maximum acceptable steady mask leakage rate would be 0.5 cm^3/min, with a maximum total leakage volume of 12.5 cm^3.

CONCLUSIONS

The most significant observation arising from this study is that even with scavenging, a commonly used mask does not reliably control N_2O emissions to current NIOSH recommendations, because of leakage between the mask and the patient's face. Because the breathing bag was generally passive in the operatory, indicative of an ill-fitting mask, it was concluded that the mask leaked in most operations, as it had in the laboratory, and was the usual cause of overexposure to N_2O. A good-fitting mask is achieved by increasing the pressure of the mask's inner shell against the face. As shown by experiments, a quality fit resulted in low leakage. While the addition of an elastic headband to the mask improved its fit to the point of eliminating emissions, based on laboratory observations, a dentist's need to move the mask periodically would affect the reliability of this approach. Assuring a tight fit under the conditions commonly occurring in operatories may not always be feasible.

Regardless of fit and with little or no further modification of the system, a redesigned mask that incorporates a flexible, slitted skirt on its outer shell can effectively capture gas leaking from the inner shell. The slits are necessary to prevent formation of a vacuum seal between the skirt and the patient's face, which would result in direct vacuum application to the patient's lungs.

While the skirted mask alone was shown by the laboratory testing data to capture emissions occurring during mouth breathing, a supplemental LEV gave additional protection. The chin-mounted exhaust, such as the Medicvent system, or chest-mounted device, such as was constructed and tested here, show promise.

It should be noted that all of the leakage rates observed during this study were above the estimated worst case maximum acceptable described in the Discussion section above. Thus, there may be room for improvement of the N_2O administration system. In follow-up work, a mask with improved emissions control, such as the skirted mask tested here, should be constructed and evaluated in an operatory. It is hoped that the current study will provide the direction for future research into the development of control measures to decrease N_2O exposures in the dental operatory.

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