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Study of Respirator Effect on Nasal-Oral Flow Partition

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Factors affecting worker tolerance of respiratory personal protective devices are inadequately understood. This study evaluates whether respirator-type loads affected the switch from nasal to oral breathing. Eleven healthy subjects were studied under progressive exercise conditions, using a respirator full-face mask with inspiratory resistance (I), pressure breathing (P) (10 cm H_2O end-expiratory pressure), or no load (N). A rapid-response thermistor was used to determine whether flow was predominantly oral or nasal. Both P and I increased the percentage of time that breathing was predominantly oral. The effect was most pronounced at higher exercise levels. The percentage of mouth breathing appeared to be closely related to the expiratory time. This study suggests that nasal-oral flow partitioning should be considered as a possible determinant of respirator tolerance. Am. J. Ind. Med. 32:408–412, 1997. © *1997 Wiley-Liss, Inc.*

KEY WORDS: respirator; nasal airflow; oral-nasal partition; industrial respirator

INTRODUCTION

Respirators (respiratory personal protective devices) are used by many workers for protection against inhaled toxins. Recent analyses have suggested that tolerance is multifactorial [Harber et al., 1991; Beckett and Billings, 1985]. An understanding of the factors leading to respirator tolerance is likely to improve the design of respirators, help establish appropriate medical certification procedures, and provide insight into causes for workers who are particularly intolerant. Several studies have suggested that the respiratory pattern, rather than just respiratory work to overcome resistance of the respirator, may be important as a determinant of the effect of respirators [Harber et al., 1988]. This study evaluated the switching of airflow from the nasal route to the oral route. This can affect respiratory sensation directly, either by changing inspired air conditions or by changing total airway resistance.

METHODS

The study was performed on 11 normal volunteers who gave informed consent to participate in a protocol approved by the UCLA Human Subjects Protection Committee. After a screening medical examination and full explanation of the study, each was introduced to the experimental apparatus. The subjects included six males and five females. The age range was 21–43 years, with a mean of 29 years. During the exercise protocol, subjects exercised on a calibrated bicycle ergometer (Monarch model 818, Varberg, Sweden). Starting from unloaded cycling, the exercise level was increased by 30 watts (W) every 60 sec, until the subject was too fatigued to continue or until 150 W was reached. The exercise regimen was repeated four times, with a minimum of a 10-min break between each run.

Each run was conducted with a different experimental load in place, with the order of the loads randomized among subjects. The loads were as follows:

No load (N): The subject breathed through the full circuit without any added resistance or end-expiratory pres-

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sure. However, he/she did breathe through the slight resistance of the pneumotachograph and the circuitry hosing.

Disconnected (D): The subject breathed through the respirator mask, but this was completely disconnected from the circuit.

Inspiratory resistance (I): An inspiratory resistance composed of a single acid-mist cartridge (MSA, Pittsburgh, PA) was placed in the inspiratory limb of the circuit. The resistance was approximately 6 cm H_2O/L/sec measured at 1–2 L/sec flow.

Pressure-biased breathing (P): End-expiratory pressure was introduced by the use of a positive end-expiratory pressure (PEEP) valve (Vital Signs, Totowa, NJ). This valve, commonly used in association with ICU mechanical ventilators, is designed to keep the end-expiratory pressure 10 cm H_2O above atmospheric. It was used to simulate the effect of a self-contained breathing apparatus (SCBA) in pressure-demand mode.

During the protocol, the subject wore a full-face mask (Scott Aviation 65, Lancaster, NY). This mask is commonly used with a canister on the inspiratory limb. For this study, the flexible hose connector for the mask was instead attached to the inspiratory limb of the research apparatus. Under normal circumstances, the mask vented exhaled air to the outside, but it was modified by attaching another flexible hose to the expiratory port. The one-way valves normally incorporated in the mask were employed for this study (and therefore the effect of the mask dead space is likely to be similar to that of the actual industrially used masks).

A pneumotachograph (Fleisch No. 3) was placed in the inspiratory limb. Flow was measured using a differential transducer (Validyne, MP-5, Northridge, CA) and carrier demodulator/amplifier. In addition, a small tap for pressure measurement was drilled through the faceplate of the respirator, and mask pressure near the mouth was measured with a transducer (MP-45, Validyne) and carrier demodulator. Signals were digitized at 50 Hz (Metrabyte, Taunton, MA). Data were analyzed with programs previously described [Harber et al., 1988], using flow criteria to define breathing cycle points.

Separation of nasal versus oral route of breathing was determined using a rapid-response thermistor (YSI model 46TUC; transducer YSI Model 520, Yellow Spring, OH). The time constant for this thermistor is 0.1 seconds. After considerable experimentation, a method was devised to allow this to operate effectively. The thermistor was passed through a small orifice in the mask face piece and placed near the oral airstream. A small cardboard cutout (constructed from a 3 $\times$ 5-inch card) was fabricated for each individual and placed within the mask approximately between the upper lip and nose in order to shield the thermocouple from the nasal exhaled air. The signal from the thermocouple amplifier was recorded on a strip chart recorder (Microscribe 4500, San Marcos, TX). Each subject was asked to ''calibrate'' this by intentionally breathing through the oral or nasal route.

The stripchart recording was analyzed for the last 30 seconds of each experimental exercise level. The laboratory technician marked the stripchart recording on a continuous basis to indicate whether breathing at that point in time was predominantly nasal or oral. In some instances, prior to initiation of exercise, it was necessary to adjust the thermocouple or 3 $\times$ 5 card baffle to obtain clearly differentiable tracings. Once this was successfully accomplished for each subject, there was little difficulty in such grading. Mouth-breathing percentage (MB%) was graded as the percentage of time in an experimental period during which breathing was predominantly by the oral route.

Statistical analyses were performed using BMDP [Dixon, 1983]. Because some subjects reached their maximal exercise sooner than others, the analysis was performed in two ways. First, only actual data points from the subject were used, producing different subject numbers at the higher exercise levels than at the lower. Second, the MB% from the highest level achieved by the subject was used for the subsequent (unaccomplished) exercise periods. This method was employed because the MB% generally reached a plateau prior to the terminal exercise periods (i.e., it did not change with added exercise levels). Results obtained by both methods were quite similar. Analyses were performed by examination of graphical data and by analysis of variance (ANOVA), considering effect of period and load type. In addition, analysis of covariance was done, using treadmill workload (watts) as a linear covariate.Results

Results are shown for the analysis in which the MB% for the highest exercise level achieved by each subject was projected for the remaining levels. Comparable results were obtained with the other method of analyzing only the data actually acquired.

Figure 1 and Tables I and II summarize the data concernning mouth-breathing percentage (MB%) at various exercise levels under the four different experimental conditions. It is shown that at low levels of exercise, breathing is predominantly nasal. As the exercise level increases, the proportion of mouth breathing increases, so that at the highest levels, the regimen is primarily oral. Loaded conditions I and P are associated with higher proportions of mouth breathing. Analysis of covariance was performed to determine whether the load type had an effect, adjusting for exercise level as a covariate. Load type had a statistically significant ($P < 0.05$) effect, and there was a statistically significant relationship between MB% and exercise level ($P < 0.1$), whether represented by workload or ventilation. For example, analysis of covariance results is shown in Table I.

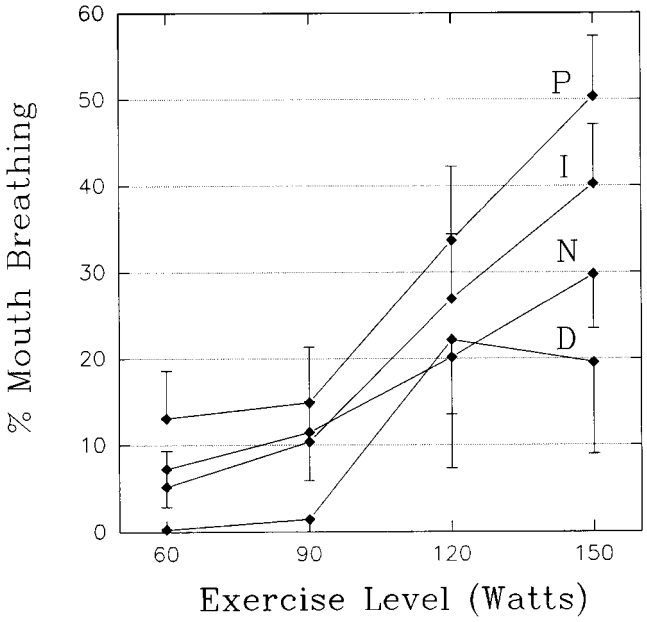

FIGURE. 1. Percentage of mouth breathing by period. Average percentage mouth breathing (%MB) for each period. Vertical bars show standard error of mean (SEM) for each period. Exercise level (in watts) is on the x-axis. Experimental conditions: D, disconnected from apparatus (mask only); N, no load added; I, inspiratory resistance; P, pressure-biased breathing.

DISCUSSION

The nose is a very important part of the respiratory system, yet its role in adaptation to respirator use has not been studied previously. This study has shown that two respirator-type loads significantly affect the partition of airflow between the oral and nasal routes, increasing the diversion of airflow from the nasal to the oral route. It is quite possible that this factor may be one determinant of respirator tolerance or intolerance.

The nose is a high-resistance component of the respiratory system. In normal individuals, the resistance to airflow through the nose is typically greater than through the oral route [Wheatley et al., 1991a], and the difference between oral and nasal resistance increases with exercise [Wheatley et al., 1991b; Forsyth et al., 1983].

Despite the higher nasal resistance, normal nasal breathing may serve three useful purposes [Witek, 1993]. First, the resistance is a consequence of the narrow, intricate passage through which inspired air must pass, allowing extensive contact with mucosal surfaces. This is important for ''conditioning'' the inspired air, heating it and adding humidity. A lower-resistance, nonturbulent system would not permit adequate contact for this purpose. In a similar manner, expiratory air also passes through the same high mucosal contact nasal system, allowing recovery of heat and moisture. Second, nasal resistance may provide an important braking mechanism for expiratory airflow. Third, the intricate air passages through the nose, with their many sharp turns, are also important in the filtering action of the nose by facilitating inertial impaction of inhaled particulate. A study of miners with silicosis suggested the importance of nasal filtering [Lehmann, 1935]. The silicotic miners had much less nasal breathing (and hence less efficient filtering) than those without, suggesting a hypothesis that nasal breathing is somewhat protective. The nose also serves to scrub soluble gases such as SO_2 [Witek, 1993].

Although the oral route provides lower resistance than does the nasal route, it does not allow the benefits of air ''conditioning,'' expiratory braking, and air filtering described above. Furthermore, since the ''natural'' respiratory path is often nasal, switching may in itself induce some adverse sensation. Mouth breathing also leads to drying of the oral mucosa. Oral cooling may also be a problem in certain environments; the nose is an effective heat exchanger, recovering heat from air as it is exhaled, but the mouth is not. The drying and cooling of the oral mucosa may be particularly a problem with supplied air respirators using cold, dry air and in powered air purifying respirators used in cold, dry environments.

This study demonstrated that the use of respirator-type loads increased the proportion of oral versus nasal breathing.

TABLE I. Percentage of Mouth Breathing by Period in Experimental Study of Respirator Use[a]

Exercise level	Load			
	D	N	P	I
60	0.3% (0.8)	7.3% (21.5)	13.1% (28.0)	5.2% (20.4)
90	1.4% (3.8)	11.5% (28.4)	14.9% (32.7)	10.4% (24.3)
120	22.1% (39.1)	20.1% (33.4)	33.7% (42.8)	26.9% (39.1)
150	19.5% (35.0)	30.0% (38.5)	50.4% (40.5)	40.2% (42.1)

[a]Mean (with the standard deviation in parentheses) of the percentage of time with mouth breathing at several exercise levels (expressed in watts). Loads: D, disconnected from apparatus; N, no load added; I, inspiratory resistance; P, pressure-biased breathing (end-expiratory pressure).

TABLE II. Analysis of Covariance: Effect on Percentage Mouth Breathing[a]

	df	F	*P*	b
Respirator load type	3,519	3.79	0.0105	—
Work rate (W)	1,519	89	0	18.92

[a]df, degrees of freedom; F, F-test statistic; b, regression coefficient for covariate.

Exercise normally leads to a switch from nasal to oral routes [Wheatley et al., 1991a,b; Forsyth et al., 1983; Niinimaa et al., 1981]. However, the two types of respirator loads made the transition from nasal to oral route occur at lower exercise levels than usual. This may significantly affect the subjective and, perhaps, the physiologic effects of respirator use.

There are several mechanisms by which the respiratory loading could theoretically affect the flow partitioning. First, it may simply represent an added respiratory load, increasing the existing tendency to use the oral route when the load increases. Therefore, the respirator load limits the ability to compensate for the increased burden of exercise, since the respirator itself induces flow switching.

Respirators may also markedly increase the nasal resistance by the mechanism of closing a flow-limiting segment (FLS). A FLS of the respiratory system commonly has a ''Starling resistor,'' a collapsible segment of the airway, such that highly negative intraluminal pressures will collapse the airway if the transluminal pressure gradient exceeds the counteracting tissue elastic forces, which would otherwise maintain patency. The inspiratory resistance imposed by the respirator requires that the thorax generate a greater negative pressure. This, in turn, is transmitted through the nasal airway, increasing the tendency of the flow limiting segment to collapse. Nasal tissue has been shown to include such Starling resistor features [Pertuze et al., 1991]. The nose is in the mask; hence, at constant flow, the net transnasal pressure would not be affected. However, transients (very brief increases in driving pressure) during initiation of flow or to overcome threshold value resistance are likely to produce net increases in the transnasal pressure gradients. Hence, since adequate airflow cannot be obtained via the nasal route, preferential switching to oral breathing may become necessary at lower exercise levels.

PEEP, such as that imposed by pressure-demand respirators, may lead to increased nasal airflow obstruction by two additional mechanisms. First, this may lead to prolongation of expiratory time with consequent shortening of inspiratory time [Harber et al., 1991b]. Consequently, the average inspiratory flow rate must increase to maintain constant tidal volume. This in turn is associated with an increased pressure gradient, again possibly collapsing the Starling resistor flow-limiting segment. Second, the PEEP in the mask may cause compression of the alae of the nose, leading to added resistance as well.

Three factors affecting nasal resistance may be particularly relevant to respirator use in the occupational setting. First, the respirator mask itself might distort facial configuration to affect the nasal alae. Neural control of their tone is a normal adaptation to exercise. This response may be limited by physical mask pressure, particularly with half face mask respirators with direct nasal contact. Second, the major determinant of nasal resistance is vascular tone [Cole et al., 1985], and the cold dry air typically provided by supplied air respirators or the presence of environmental chemical agents may affect nasal vasculature. In addition, the external inspiratory resistance of air purifying respirators will lead to greater intranasal negative pressures also affecting nasal mucosal edema because of a greater vessel–tissue fluid pressure gradient. Third, the respirator mask may limit the ability to open the mouth widely. This significantly affects the resistance of the oral route [Cole et al., 1982].

This study did not directly determine whether differences in airflow rates are associated with reported subjective effects. The influence of the switch from nasal to oral airflow was shown by Niinimaa [1980], who found that the switching point was closely associated with a rating of perceived exertion of breathing. Furthermore, asthmatics may be sensitive to the cold dry air provided by any supplied air respirators if nasal conditioning is bypassed.

The nose itself may be affected significantly by flow characteristics, particularly with cold, dry air [Naclerio et al., 1995]. Although this study did not differentiate inspiratory from expiratory partitioning, studies suggest that nasal effects are similar for inspiratory and expiratory flow [Naclerio et al., 1995].

This study employed a thermistor to determine airflow partitioning. More complex methods have been used by other investigators to directly quantify airflow via the oral and nasal routes [Wheatley et al., 1991a; Chowanetz et al., 1987]. Such methods are, however, not directly applicable to the respirator situation because such instrumentation would interfere with the direct impact of the respiratory personal protective devices.

This study demonstrated that respirators may significantly affect the oral-nasal partitioning. Measurement of flow partitioning with actual respirators should be considered in evaluating new designs. Furthermore, the normal inter-individual variability in nasal resistance and in flow regimen switchpoint may partially explain differences in respirator tolerance. For example, clinicians evaluating workers with possibly poor subjective tolerance of respirators should carefully assess nasal patency as an explanation. Designs which minimize the tendency to switch respiratory routes or minimize its impact may be better tolerated. Lower resistance respirators might theoretically be needed for persons with nasal obstruction. Designers of supplied air respirators with cool dry air may consider incorporating a cup to allow heating and humidifying inhaled air if exercise levels will lead to bypassing the nose. Thus, information from other studies indicates that nasal/oral partitioning is a significant physiologic occurrence.

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