

Design of Respirator Masks to Incorporate Physiological Effects: A Review

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Abstract

Once it has been ascertained that respirator masks provide sufficient protection against airborne contaminants, attention must turn to reduction of the physiological burden imposed on mask wearers. Mask designers need the design tools to produce new masks specifically meant to reduce this burden. Although masks have been used for over seventy years, there is very little basic information in quantitative form that can be used by mask designers to incorporate physiological effects into their designs. The ultimate goal, with accumulation of this type of information, is a computer-aided design process that eliminates the fabrication of prototypes that don't show promise for success in meeting design goals. This review demonstrates progress toward the ultimate goal.

The Engineering Design Process

Many products, from light bulbs to automobiles to buildings, are produced in the same general way. Each involves the steps of conceptualization, when the mental representation of the object is conceived, and calculation, where the specific workability of the object is forecasted. Modern designs are usually based on established quantitative relationships that are incorporated into computer software. These computer-aided design (CAD) programs are used to guide design decisions in order to assure that the object will fulfill its intended function. Some degree of optimization of function is usually attempted at this state.

The capital of the design organization resides primarily in the computer model, not in the prototype, since availability of the model allows each trial design to be evaluated before it is physically fabricated, thus saving the time and expense that is otherwise devoted to prototype testing. Only after the design appears satisfactory on the computer is a relatively expensive prototype built. The function of the prototype is to confirm predictions made on the computer. If any discrepancies are noted between the computer model and prototype evaluation, they must be resolved. If the faults are in the computer model, the model is modified to improve its accuracy.

The Respirator Mask Design Process

Respirator mask design is centered around contaminant removal and protection of the wearer (Bancroft et al., 1980; Bernard and Stein, 1979;

Tobey et al., 1972). This part of mask design is an absolute requirement and cannot be compromised. Mask design has thus been largely devoted to

design of the filters (Brown, 1989) and airflow paths through the mask facepiece (Burgess and Yankovich, 1972; Johnson and Cummings, 1975).

Once a mask meets protection criteria, however, it must meet other constraints incurred by the burdens imposed by the mask on the wearer. These other constraints include comfort, minimization of sensory deprivation, minimization of thermal burden, aesthetics, equipment compatibility, task performance, communications, and others. Evaluation of these types of burdens presently requires a mask prototype to be fabricated and tested before a mask design is deemed acceptable. Computer-based mathematical models are not available to examine trial mask designs before the prototype fabrication state. There is thus a large difference between the respirator mask design process and that for many other products. While the respirator mask may not normally be considered a high-technology device, mask complexity demands a high-technology design approach.

Respirator mask design is still largely based on anecdotal testimony from users or evaluators who are normally dissatisfied with some aspect of the mask. When mask designers react to accommodate this disapproval, they often incorporate other shortcomings into their mask designs. It is beginning to be realized that a mask optimized for one purpose almost always cannot be optimized for others (Johnson et al., 1992A; Johnson et al., 1992B; Johnson et al., 1993), and that someday the general purpose respirator mask will be replaced by a wide selection of masks or mask modules specialized for individual applications. While it is true that there are many different half and full facepiece respirators on the market today, each serving different respiratory protection needs, the need is to supply respirators that are optimized for various environments (for example, high temperature vs moderate), work intensity (for example, sedentary vs highly active tasks), and psychological needs.

The Need to Incorporate Physiological Effects

There is at present no published means to incorporate *quantitative* physiological information in mask design at the preprototype stage. This means that mask design will remain inefficient and at times ineffective in producing an acceptable product. The limits to achievable designs are not known because requisite information is not available.

The mask design process ultimately affects worker performance. Whereas it is generally conceded that workers wearing masks cannot work as long nor as hard as they can without masks, it is not known how much this is true. Different masks may impose different burdens, and supervisors should be aware of relative burdens imposed by different masks in order to make choices about masks to be worn. They also need to know, in more absolute terms, how much less productive their workers will be while wearing masks in order to adjust their expectations of worker productivities.

There are many steps before the ultimate goal of computer-aided design of respirator masks can be achieved. The first step that must be taken is to define the problem in such a way that answers can be obtained. There are many physiological and other effects of mask wear; so many, in fact,

that efforts to identify them all can be confusing in themselves. The answer is to define the major factors first, obtain required information, and refine the list of factors later. Engineering design requires quantitative relationships between input variables (such as mask inhalation resistance) and output variables (such as task performance time or rate). Information on physiological effects of mask wear has usually been presented in terms of qualitative comparisons of treatment effects, such as different levels of mask resistance (Zimmerman, 1991; Louhevaara, 1984; Shimozaeki et al., 1988; Hermansen et al., 1972; Raven, 1983; Craig et al., 1970; Cerretelli et al., 1969; Demedts and Anthonisen, 1973; Olgiati et al., 1986; Isayama, 1962; Bjurstedt et al., 1979; Asakanazi et al., 1980; Duggan et al., 1990; Thompson and Sharkey, 1966; Cala et al., 1991; Bartlett and Specyht, 1957; Cummings, 1968; Silver, 1993; Sharkey and Merad, 1993; Allen et al., 1992; Cummings et al., 1973; Cummings et al., 1972; Morgan, 1983; Craig and Stemler, 1975; Craig et al., 1970; Raven et al., 1981A; Raven et al., 1981B; Wilson et al., 1989; Van Huss and Heusner, 1965; Flook and Kelman, 1973). Sometimes information has been developed as acceptable levels of mask parameter values (Deno et al., 1981; Love, 1983; Morgan and Raven, 1985; Craig et al., 1971; Cooper, 1960A; Silverman et al., 1945; Stannard

and Russ, 1948; Wiley and Zechman, 1966; Bentley et al., 1972; Dodd et al., 1988; Jones et al., 1971; Cooper, 1960B; Wilson et al., 1986; Bentley et al., 1973). Neither of these is in the form required for CAD mask design; the first gives no quantitative information and the second gives no indication of the performance degradation that occurs when the acceptable levels cannot be met. It is often the case in design of a complex product that the best overall design does not result from meeting all design goals. Thus, an indication of possible design trade-offs should be available.

The next step after defining the problem is to obtain quantitative information on the factors previously identified. This requires an approach toward experimentation different from normal; results must be obtained as input-output relationships between independent and dependent variables rather than as statistical comparisons between groups of extremes.

The third step is to incorporate quantitative relationships into a mathematical model and transfer this to computer software. To accomplish this step will still require a long time to complete, but a foundation has been established (Johnson et al., 1992A; Johnson, 1992), and the computer program can be built piecemeal as quantitative information becomes available.

The result of this series of steps will be the rational design of respirator masks that are more compatible with the people who wear them. Since a major obstacle to mask wear is acceptance by wearers (Hermansen et al., 1972; Love, 1983; Bentley et al., 1991), design of respirator masks that incorporate physiological effects of mask wear should make the masks more universally acceptable and more widely worn when required, and improve worker health and worker productivity as well.

Mask Design Criteria

Setting good design goals should be the first act in respirator design. In order to set these goals, mask design engineers and mask evaluation physiologists must be able to discuss the ultimate product of the design process, as each group views it from its different vantage point. The difficulty that has often appeared is that physiologists have not understood the design process that is subject to many constraints, and engineers have not been able to translate physiological information into quantitative terms useful at the design stage. Thus, the search for useful design criteria is critical.

There are many possible criteria to use for mask design. One might be to design for maximum comfort. Designs based on comfort would use information generated from psychological scales—such as Rating of Perceived Exertion (Johnson et al., 1995; Borg, 1982), or Thermal Sensation, (Johnson et al., 1995; Gagge et al., 1967; Gagge et al., 1969,) etc.—administered during wear trials and may or may not account for differences between rest and exercise. Comfort is an important ingredient in present design procedures (Shimozaki et al., 1988; Cummings et al., 1972; Love, 1983; Bentley et al., 1972).

Another design criterion may be to reduce physiological stress, perhaps based on heart rate, feelings of dyspnea, or blood lactate levels. Such

designs would be based on physiological measurements probably made during exercise when physiological stress is greatest. Because of the difficulty in interpreting the many possible measurements and their combinations, almost no mask designs are based upon this criterion.

A third design criterion could be aesthetic appearance of the mask. These designs would not be based primarily on evaluation tests involving wearers' responses. Instead, mask designs would be based on the way they look to the designer, or perhaps to the user or the purchaser. There is a strong aesthetic component in today's mask designs.

The best design criterion is probably performance rating. As the primary mask design measure, performance rating compares performance of the wearer with a mask to performance without a mask, and performance can be defined in terms of accuracy (as in identification or reading tasks), endurance (as in exercise at a given work rate), or rate of work (when the rate is determined by the wearer and not by the nature of the task). Performance rating has work force and economic implications, since a performance rating of 0.5 could indicate that two people wearing masks were required to produce a result as great, or as fast as one person without a mask. As long as the

primary use of respirator masks is occupational, performance rating should be used as a design criterion above comfort alone, physiological stress, or aesthetics. Very likely, the mask that produces

the highest performance rating will also score well with these other measures, but the performance rating is more readily quantifiable than the others.

Performance Rating Tables

An initial attempt to define the physiological effects of mask wear resulted in the Performance Rating Table (PRT) (Johnson et al., 1992A; Johnson et al., 1992B; Johnson et al., 1993). The PRT compares effects of various mask factors on task performance of an individual wearing a mask compared to the unmasked condition.

PRT entry values are given as percentages of performance while wearing the M17 mask and hood compared to performance without the mask and hood (an example is given in Table 1). All other conditions, including work rate, are considered to be the same regardless of whether or not the mask is worn.

Overall performance rating is obtained from the individual entry values at any particular work rate as the product of all mask element values or as the product of all mask factor values (Bancroft et al., 1980). The rationale for this approach is based on the fact that all mask factor effects are assumed to be independent and that the maximum performance, including one factor, cannot be any higher than that determined by the other factors. Performance decrement is the performance rating subtracted from 100.

PRT cell entries, denoting expected performance ratings of mask wearers due to particular mask factors at different work rates, were obtained from the very few available sources in the literature, military reports, and experiences of the authors. Many experimental and most field reports are more integrated than the PRT, and results from these reports cannot be used to completely identify performance degradation due to one particular mask factor at one particular work rate. As an illustration of this point, notice that the PRT total performance rating varies with work rate, from 49% at very light work to 74% at very heavy work. These values were obtained as the product of seven mask factor entries or fifteen mask element entries (indented values), each of which varies in value depending on the conditions.

Many mask evaluation tests have been per-

formed with a graded exercise stress test wherein the rate of work progresses in steps from light to very heavy until the subject voluntarily stops (Cummings et al., 1973; Craig and Stemler, 1975). This type of test has been found to be very insensitive to differences among masks (Johnson and Cummings, 1975; Johnson and Berlin, 1974; Johnson, 1976; Johnson and Berlin, 1973) because performances while wearing masks, as seen from the PRT, are localized to particular rates of work or to the particular types of tasks to be performed. It is much better to design a mask evaluation test to be performed at one particular work rate, with the choice of work rate to highlight the mask factor of interest. The study of Deno et al., (1981) illustrates this point: at a relatively high rate of work they were able to distinguish performance times among various resistances, but at a lower work rate they were not. The higher work rate was sensitive to respiratory stress, but the lower work rate was sensitive to heat stress. The study by Stemler and Craig (1977) also illustrates this point.

The PRT is nothing more than a start toward the ultimate goal of mask CAD. The PRT, even with its complexity, oversimplifies pertinent mask organization; the PRT is intended to relate to average wearers, but isn't concerned with inevitable variability among wearers; PRT entries are reduced to constant numbers, but these should eventually be replaced by mathematical models that account for interactions with other mask elements. Nonetheless, the PRT has some advantages: 1) it helps organize knowledge about the physiological effects of mask wear on performance, 2) it gives numbers from which design decisions can be made, 3) it illustrates that one mask cannot be considered optimum for all uses, 4) it demonstrates that mask design falls in the region of diminishing returns because most performance rating entries are close to 100 (this means that performance because of these factors is close to the unencumbered performance, and that much more design effort will be needed to remove the last few percent of performance degradation), and 5) the

Table 1. Performance Rating Table for Temperate Environments^A

Mask Factor	Work Rate									
	Very Light	Light	Medium	Heavy	Very Heavy					
Vision	93	95	97	99	99					
Field size	96		97	98	100				100	
Acuity	97		98	99	99				99	
Communications	94	95	98	99	100					
Attenuation dist	99		99	99	99				100	
Intelligibility	95		97	99	100				100	
Direction	100		99	100	100				100	
Respiration	100	98	94	80	81					
Resistance	100		99	99	84				84	
Dead space	100		99	95	95				96	
Thermal Factors	100	95	95	100	100					
Moisture removal	100		100	100	100				100	
Thermal balance	100		95	95	100				100	
Personal Support	93	94	95	95	95					
Drinking/eating	93		94	95	95				95	
Medical procedures	100		100	100	100				100	
Physical Factors	64	69	87	92	97					
Physical structure	76		90	98	98				98	
Compatibility	85		78	90	95				100	
Anthropometry	99		99	99	99				99	
Psychological factors	95	95	98	100	100					
Total performance rating	49	52	69	69	74					
(Total performance degradation)	(51)	(48)	(31)	(31)	(26)					

^AValues indicate percent performance of an M-17 mask wearer compared to no-mask performance.

PRT has served as a starting point for a research program to obtain better mask design information

(Johnson et al., 1995; Johnson et al. 1994; Jones et al., 1971).

Interactions Among Respirator Elements

Respirator masks are not designed along the lines of the PRT. Some respirators are very simple, and do not include all mask elements appearing in the PRT. Design of others naturally cleaves into several design modules that comprise the finished mask (Johnson and Grove, 1993) (Table 2). Each of these modules influences levels of mask factors appearing in the PRT. Thus the task of the mask designer is made much more complex; even if performance rating dependencies on mask factors were known, these dependencies would still need to be translated (Silver et al., 1971; Johnson and Micelli, 1973) into effects on mask design modules. For instance, design of lenses, communications apparatus, nose cups, facepieces, and drinking devices can influence the level of dead volume in the mask. Design of filters, valves, and materials can affect resistance levels.

Interaction among resistances, dead volume, and other variables arises, also, though the physiology of breathing. Breathing during exercise appears to be optimized to minimize the level of energy expenditure expended by the respiratory musculature (Bartlett and Specht, 1957; Bartlett et al., 1958; Milic-Emili, 1991; Mikami and Yoshimoto, 1966). The parameters that appear to be optimized are respiration rate (Otis et al., 1950; Johnson and McCuen, 1980; Yamashiro and Grodins, 1971; Yamashiro and Grodins, 1973; Yamashiro et al., 1975; Mead, 1960), ratio of inhalation time to exhalation time (Yamashiro and Grodins, 1973; Johnson and Masaitis, 1976), respiratory airways resistance (Widdicombe and Nadel, 1963), breathing waveshape (Yamashiro and Grodins, 1973; Yamashiro et al., 1975; Johnson and Masaitis, 1976; Silverman et al., 1951; Peak and McCool, 1992; Ruttimann and Yamamoto, 1972; Hamalainen and Sipilä, 1984; Hamalainen and Viljanen, 1978; Grinman and Whitelaw, 1983; Johnson, 1993), and expiratory reserve volume (Yamashiro and Grodins, 1973; Johnson, 1993; Johnson 1995). None of these can be varied without affecting the others, and there is evidence that worn mask resistances are included in the optimization process (Johnson and McCuen, 1980).

Metabolically-produced carbon dioxide appears to be completely eliminated from the blood during exercise (Johnson, 1991) without raising arterial levels of CO₂; inhaled CO₂ appears to be incompletely eliminated, raising arterial CO₂ by small amounts (Johnson, 1991). Thus, mask dead volume can translate metabolic CO₂ into inhaled CO₂. This, in turn, stimulates breathing and raises tidal and minute volumes. The additional airflow requires more respiratory power as it is drawn through mask and respiratory airways resistances. Thus, there is a natural physiological interaction between resistance and dead volume.

Above the anaerobic threshold, additional CO₂ is removed from the bicarbonate buffering system of the blood plasma (Johnson, 1991). This additionally stimulates breathing and exacerbates the interaction between dead volume and resistance.

Respirator mask design modules that influence wearer psychology are also involved indirectly in respiration. Hyperventilation accompanies anxiety (Morgan, 1983). Responsiveness to CO₂ is linked to anxiety and thus many mask elements can relate to breathing difficulties if the environment, the wearer, or the mask conditions cause anxiety.

Because of these interactions, experimental testing performed on breathing resistance or dead volume alone can give only partial answers to mask designers. Testing of this type should be performed with a mask rather than with any other type of apparatus because there are as yet unknown or uncontrollable influences of the mask and testing conditions on performance results (Johnson and Cummings, 1975; Craig et al., 1971; Stemler and Craig, 1977; White et al., 1983; Sébert, 1983; Hummer et al., 1991; Borkan and Reis, 1991; Watkins et al., 1993; Bridger and Proctor, 1970; Berger and Burki, 1982; Barnett and Rasmussen, 1988; Bennett and Fordyce, 1988; Tawfik and Chang, 1988; Milic-Emili, 1989; Cole et al., 1982; Nunn et al., 1959; Raine and Bishop, 1963; Salvini and Capodaglio, 1958; Navajas et al., 1988; Demediuk et al., 1992; Cauberghs and Van de Woestijne, 1992).

Table 2. Customary Mask Design Modules Affecting Mask Factors for Gas Masks.

Design Module	Mask Factor						
	Vision	Communications	Respiration	Thermal	Personal Support	Physical	Psychological
Lens Design	- Field of View - Acuity	-Size affects close communications	- Size can effect flow volume and fogging	- Radiated heat transfer thru lens	- Allows for subject identification and observation	• Size and clamping requirements affect bulk • Eye relief affects compatibility	- Better field of view and acuity improve psychological reactions
Communications Design	- Size can cause limits in field of view	-Intelligibility distance	- Size of communications systems can affect dead space	- Can add to metabolic burden	- Enhances correct medical diagnosis	- Size of communications device affects bulk - Plug-in compatibility is critical	- Better communications improves psychological reactions
Valve Design	- Size of nosecup valves can affect lens design	- Outlet valve openings help communication	- Resistances to air flow	- Valves can allow for heat transfer	- Give mouth access for medical treatment	- Size of valving can affect bulk	- Improved breathing can reduce psychological burden
Filter Design	• Size of filter can reduce field of view	- Filter can block speech projection	- Resistances to air flow	- Filter slightly reduces humidity	- Provides protection from contaminants	- Size of filter affects weight and bulk	- Labored breathing causes psychological burden
Seal Design	- Nosecup sealing can interfere with vision	- Nosecup seal can influence communications	- Nosecup seal affects dead volume	- Warm, humid air can leak into facepiece	- None	- Can affect weight comfort, and compatibility	- Improved seal and comfort can improve psychological reaction
Hood Design	- Hood can interfere with field of view	- Hood material and design affects hearing	- Pressurized mode affects breathing	- Hood material and design affect convection and conduction	- None	- Size and material affects bulk	- Good flexibility and thermal characteristics improve psychological reaction
Facepiece Design	- Shape of nose cavity affects vision	- Materials and size of nose cavity affects communication	- Ducting and dead space affect breathing	- Materials and flow patterns affect cooling	- Location of drinking system affects ease of operation - Eating inhibited	- Size and materials affect bulk - Size affects compatibility	- Improper size affects psychology - Clarity can improve feelings
Drinking Design	• Usually none	- Tubes can absorb acoustic power	- Can affect dead volume	- Improved drinking helps cooling	- Flow must be adequate	- Size can affect bulk and compatibility	- Improved drinking can improve feelings
Materials	-Materials affect physical optics	-Materials affect both output power and frequency	- Valve and filter materials affect resistance	-Materials affect heat transfer	- Materials must be impermeable and safe	- Materials greatly affect flexibility and bulk	• Softer materials help comfort

Heat stress (Sawka et al., 1983; De V. Martin and Callaway, 1974) can cause psychological difficulties for wearers of respirator masks, and these, in turn, have consequences for judgmental and motor task performances (Johnson et al., 1992B; Ramirez et al., 1988; Fleishman and Hemple, 1954). Communications difficulties can also add to the anxieties associated with mask wear, and can thus directly affect performances. Others, such as inability to eat or drink, to clear

one's nose, to scratch an itch on the face, or to clearly identify another mask wearer from a far distance can also have direct performance effects.

Indirect effects are perhaps more subtle. Each of these stresses can affect respiration as mentioned above, can affect heat stress through additional physical effort used to overcome the original sources of the difficulties, and can affect any of the other mask factors or elements.

An Example of Performance Data: Visual Acuity

Full facepiece masks interfere with many of the sensory inputs to wearers that normally occur without masks. One of these is vision, which can cloud because of: 1) moisture condensation inside lenses for cool and windy ambient conditions, 2) deposition of fine particulate matter on the outside of lenses, and 3) liquid or solid material flowing down lens exteriors.

Tests were performed (Johnson et al., 1994) to determine the effects of visual acuity level on task performance while wearing a respirator mask compared to the unmasked condition. The results showed that Performance Rating for a console monitoring task were linearly related to Snellen eye-chart score by the mathematical equation:

$$PR = 12.8 + 9.76S \quad R^2 = 0.99 \quad (1)$$

where S = Snellen eye-chart number

This result could have severe consequences. In the event of an emergency in an industry where respirator wear was required, operations, including shut-down, that required console monitoring could be seriously compromised by smoke, or lens

fogging, or a respirator that contained someone else's corrective lenses.

Economic consequences of reduced worker performance while wearing a mask may even tip the scales away from masks as the most economical solution to a contaminant problem and toward engineering controls. For a worker earning \$10/hr performing a console-monitoring task, the loss of visual acuity of one Snellen eye chart line (not very much) can cost the employer \$1/hr in lost productivity or even more in product quality. That much cost can become many thousands of dollars in a year's time, and might well pay for a contaminant removal system not dependent upon mask wear.

If mask designers can produce improved masks that don't result in as significant reductions in performance with loss of visual acuity, or if new mask designs are less prone to have fogged or scratched lenses, then there should be strong economic or regulatory support for the improved designs. In this way, the mask designer becomes an important link in the process of human performance data resulting in an improved respirator mask product.

Conclusion

Procedures to incorporate physiological information in the design of respirator masks, with the ultimate goal of predicting performance measures while wearing a mask, must be appreciated as being very complex. Nonetheless, masks will be with us for at least the foreseeable future, and

improvements in the performances of workers wearing masks will very much depend on how quickly we get on with the task of providing mask designers with the information that they need, in the form that they need it, to minimize the physiological burden of the mask.

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