Face Masks and the Cardiorespiratory Response to Physical Activity in Health and Disease

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Abstract

To minimize transmission of severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the novel coronavirus responsible for coronavirus disease (COVID-19), the U.S. Centers for Disease Control and Prevention and the World Health Organization recommend wearing face masks in public. Some have expressed concern that these may affect the cardiopulmonary system by increasing the work of breathing, altering pulmonary gas exchange and increasing dyspnea, especially during physical activity. These concerns have been derived largely from studies evaluating devices intentionally designed to severely affect respiratory mechanics and gas exchange. We review the literature on the effects of various face masks and respirators on the respiratory system during physical activity using data from several models: cloth face coverings and surgical masks, N95 respirators, industrial respirators, and applied highly resistive or high–dead space respiratory loads. Overall, the available data suggest that although dyspnea may be increased and alter perceived effort with activity, the effects on work of breathing, blood gases, and other physiological parameters imposed by face masks during physical activity are small, often too small to be detected, even during very heavy exercise. There is no current evidence to support sex-based or age-based differences in the physiological responses to exercise while wearing a face mask. Although the available data suggest that negative effects of using cloth or surgical face masks during physical activity in healthy individuals are negligible and unlikely to impact exercise tolerance significantly, for some individuals with severe cardiopulmonary disease, any added resistance and/or minor changes in blood gases may evoke considerably more dyspnea and, thus, affect exercise capacity.

Keywords: face mask; SARS-CoV-2; pulmonary limitations to exercise

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Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2), the novel coronavirus responsible for coronavirus disease (COVID-19), has infected millions of individuals worldwide, resulting in over two million deaths. There is evidence for airborne transmission via both droplets and aerosols that contact mucosal surfaces and are inhaled directly into the upper airway (1), potentially infecting many people (2).

To minimize the risk of transmission of SARS-CoV-2, both the U.S. Centers for Disease Control and Prevention (3) and the World Health Organization (4) recommend wearing masks or face coverings in public, especially when physical distancing is impossible. Because any potentially negative effects of face masks are believed to be exacerbated by exercise, face masks are not universally required during exercise, even in indoor environments such as gyms and fitness centers, where the risk of a superspreading event increases (5). Purported reasons for not wearing a face mask include concerns about increased dyspnea and work of breathing (Wb) as well as about alterations in pulmonary gas exchange associated with reduced ventilation and rebreathing of exhaled carbon dioxide (4).

The purpose of this review is to synthesize the available literature on the effects of various masks and face coverings on the cardiorespiratory system during physical activity/exercise. Although more high-quality data from well-designed studies are needed, there is a substantial body of literature evaluating various effects on the cardiopulmonary system caused by the following types of face masks: low-resistance face coverings (i.e., cloth and surgical masks); N95 respirators; industrial respirators, such as self-contained breathing apparatuses (SCBAs); and applied external resistors, which generate high resistive loads or added dead space and are used in research studies.

Exercise and the Cardiopulmonary System

The healthy cardiopulmonary system is overbuilt for sedentary life but is challenged by physical activity. As exercise intensity increases, ventilation rises through an increase in breathing frequency and tidal volume. The increase in ventilation is approximately linear until the ventilatory threshold at about 60–70% of maximal exercise capacity is reached, after which it rises at a faster rate as carbon dioxide (CO_2) production increases and arterial pH falls. In contrast, oxygen consumption ($\dot{V}O_2$) and cardiac output increase linearly with workload until maximal exercise (*see* Reference 6 for review). The arterial O_2 partial pressure (Pa_{O_2}) is unchanged in most healthy subjects but may decrease in some patients and some highly trained athletes (reviewed in Reference 7). In the discussion that follows, we categorize the intensity of physical activity/exercise as light (20–40% of maximal $\dot{V}O_2$ [$\dot{V}O_2$max]), including activities such as yoga, walking, or daily activities; moderate (40–60% of $\dot{V}O_2$max), including activities such as brisk walking; vigorous (60–85% of $\dot{V}O_2$max), including activities such as jogging; and high and/or maximal ($>$85% of $\dot{V}O_2$max) (8).

Mask Filtration and Resistance

A wide range of face masks are available, including loose-fitting handkerchiefs, homemade fabric masks, surgical masks, tight-fitting industrial and healthcare-standard respirators (e.g., N95) (9), and SCBAs (e.g., for firefighting use). Factors influencing filtration ability include the material, structure (e.g., knit, woven or fused), number of layers, shape (surgical style, conical, or duckbill), and facial fit (10). Well-fitted respirators are required to achieve $>$95% filtration of aerosols under standardized testing conditions. Medical-type surgical masks with an adjustable nose wire attain 50–90% filtration when used as designed, with most of the variability resulting from the quality of fit (11). When made either commercially or at home from tightly woven cotton, cloth face masks provide variable particle filtration when properly worn, ranging from $<$30% to up to ~90% (11). Thus, the filtering protection conferred by masks is variable, although typically stable, over time and across flow rates of 30–85 $L \cdot min^{-1}$ (12). Moisture exerts only minimal influence on filtration effectiveness, likely without practical consequence (13). The filtering effects of face masks appear to be less effective in children (11, 12), likely because of problems with achieving adequate fit.

Resistance to airflow is a key element of face-mask function, as it reduces forward particle velocity and, potentially, the risk of infection among people in the vicinity of an infected individual (14). As shown in Figure 1, the National Institute for Occupational Safety and Health guidelines require that for standardized respirators (e.g., N95 respirators), the pressure drop across the mask cannot exceed 3.5 and 2.5 cm H_2O for inspiration and expiration, respectively, at a standardized constant flow of 85 $L \cdot min^{-1}$ (9). Importantly, these limits represent maximal allowable values, and reported pressure drops are often significantly lower. For N95 respirators, the observed pressure drop is ~0.4 cm H_2O at a flow rate of at least 30 $L \cdot min^{-1}$ and no higher than 1.7 cm H_2O at 85 $L \cdot min^{-1}$ (11, 15) (*see* Figure 1). Given that humans do not breathe at a constant flow rate, 85 $L \cdot min^{-1}$ of constant flow is comparable with an exercise ventilation of ~30–50 $L \cdot min^{-1}$ (16), such as would occur during moderate-to-vigorous activity for healthy untrained individuals.

Higher-intensity exercise necessitates higher ventilation. This results in greater airflow resistance, which does not necessarily increase linearly with increasing ventilation or flow rate. As expected, N95 respirators provide the greatest amount of protection but also have greater resistance than surgical masks/face masks. However, even at a ventilation $>$100 $L \cdot min^{-1}$, breathing simulation studies have shown that the resistance imposed by N95 respirators is $<$2 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ (17) and remains low after prolonged simulated use (18). This resistance is similar to the resistance observed with the mouthpiece and tubing used during a standard cardiopulmonary exercise test (CPET) (19) (Figure 1). Surgical face masks have a mean pressure drop of $<$1 cm H_2O at 85 $L \cdot min^{-1}$ of constant flow, with no difference observed when tested with inspired versus expired flow (11). The pressure drop with a handkerchief or two-layer cotton face mask at 85 $L \cdot min^{-1}$ has also been shown be $<$1 cm H_2O (10), which is within the limit recommended by the World Health Organization for a nonmedical face mask (11). The testing described previously does not include extremely high minute ventilations and flow rates (e.g., $>$150 $L \cdot min^{-1}$) that can be achieved by exceptional aerobic athletes. The pressure drop across masks may be somewhat larger in such athletes at these high minute ventilations, and further research will be helpful to elucidate the precise effects of cloth and surgical masks on

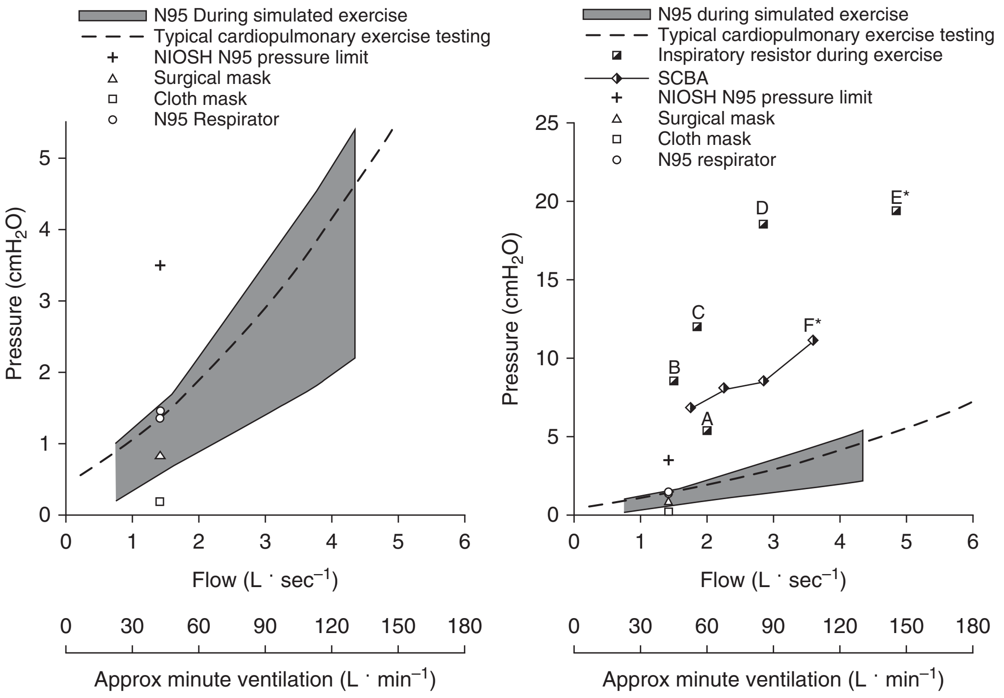

Figure 1. Pressure difference across various masks, respirators, and resistors relative to flow ($L \cdot s^{-1}$) and measured or estimated minute ventilation ($L \cdot min^{-1}$) (16). Pressure difference/flow = resistance. The plot on the left displays data up to 5 cm H_2O, whereas the graph on the right displays data up to 25 cm H_2O. Minute ventilation was directly measured in human trials (16) or estimated on the basis of the reported flow in simulation trials (17) and extrapolated back to human data (16). The dashed line represents the reported pressure of a typical mouthpiece setup used in a cardiopulmonary exercise test (CPET) (19). The shaded area represents the reported pressure difference of an N95 respirator across various simulated flow rates (17). The + displays the peak inspiratory pressure allowed under National Institute for Occupational Safety and Health (NIOSH) guidelines at a standard flow of 1.4 $L \cdot s^{-1}$ (i.e., 85 $L \cdot min^{-1}$) (77). Surgical (triangle), cloth (square), and respirator (circle) data are reported resistances at 85 $L \cdot min^{-1}$ (11). The split square represents experimental resistors (17, 41), and the split diamond represents self-contained breathing apparatuses (SCBAs) (21). Surgical and cloth masks and respirators all have a mouth pressure/resistance that is well below NIOSH guidelines (9). When tested up to a minute ventilation of ~120 $L \cdot min^{-1}$, N95 respirators have an airflow resistance that is similar to what is observed with a standard CPET mouthpiece setup (17, 19). External resistors provided a resistance that is 5–10 times the resistance of a typical mask. When these resistors are used, no change in dyspnea (points "A" and "B") (19, 41) or metaboreflex (points "C" and "D") (37) activation has been observed up to a ventilation of ~90 $L \cdot min^{-1}$. It is only during intense exercise, when ventilating at ~150 $L \cdot min^{-1}$ with a resistor, that the metaboreflex is initiated (point "E*") (38). The SCBA provides a resistance that is 3–5 times greater than that of an N95 respirator, and only at a minute ventilation of >110 $L \cdot min^{-1}$ is the work of breathing greater than that observed with a standard a CPET mouthpiece (point "F*") (21). *Indicates measurable changes. Approx = approximate.

the cardiorespiratory system in highly trained athletes. However, it should be noted that the pressure drop across such masks would still be substantially less than that observed with applied external resisters as discussed below.

Wb

In healthy adults, the Wb at rest and during light exercise is minimal (1–3% of whole-body $\dot{V}O_2$) and is almost exclusively the result of inspiratory elastic work (reviewed in Reference 20). As ventilation increases during exercise, the Wb rises in a curvilinear manner, primarily because of increased resistive work secondary to increased airflow, reaching 20–30 times resting levels during high-intensity exercise (Figure 2).

Anything covering the mouth/nose has the potential to increase the resistive Wb. The majority of published data on Wb during physical activity have evaluated respirators such as N95 respirators and SCBAs used in industrial applications and firefighting. The SCBA provides ~3 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ of resistance (21) during exercise (*see* Figure 1), but the Wb is not greater during vigorous/high-intensity exercise when compared with a standard CPET system. It is not until exercise ventilation exceeds 110 $L \cdot min^{-1}$—which is very high and unlikely to be attained by most untrained individuals—that a significant increase in Wb with the SCBA is observed (21) (*see* Figure 1).

As mentioned previously, N95 respirators produce a pressure drop of <1.7 cm H_2O at a minute ventilation of ~30–50 $L \cdot min^{-1}$ (11). The added resistance at this ventilation is estimated to increase total Wb by ~5 $J \cdot min^{-1}$ (i.e., 7–13%) and $\dot{V}O_2$ by a trivial amount of ~4 $ml \cdot min^{-1}$ (i.e., ~0.25% of whole-body $\dot{V}O_2$) (*see* Figure 2). As shown in Figure 1, the pressure drop from an N95 respirator is also similar to that of a CPET system and is well below the threshold at which increases in Wb are observed with a SCBA (Figure 1). With a mean pressure drop of <1 cm H_2O at a constant flow of 85 $L \cdot min^{-1}$, the airflow resistance of surgical masks is less than that of a CPET system (Figure 1) (16, 20). In keeping with this, face masks with resistances similar to those of

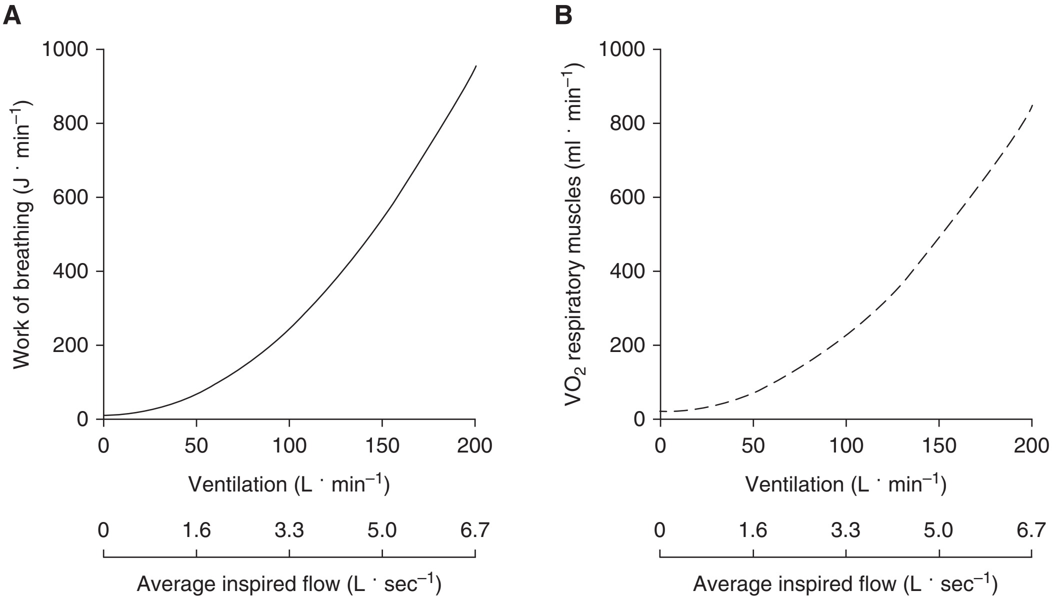

Figure 2. Average (*A*) work of breathing and (*B*) $\dot{V}o_2$ of the respiratory muscles across a range of minute ventilation and flow rates in healthy young males and females (16). The average inspired flow values were calculated on the basis of composite flow-volume loops from the same subjects. $\dot{V}o_2$ = oxygen consumption.

surgical and cloth masks have not been shown to significantly alter ventilation, breathing frequency, or tidal volume after 1 hour of light-to-moderate–intensity treadmill exercise (22). Importantly, healthy individuals have undertaken several weeks of high-intensity exercise training while wearing face masks that are specifically designed to cause a substantial load on the respiratory muscles (23) without reported adverse events, further suggesting that wearing a face mask/respirator during exercise is unlikely to cause harm in healthy individuals.

Arterial Blood Gases

Under normal unmasked conditions, inspired fresh air mixes with the previously exhaled air contained within anatomical dead space and is warmed and humidified before reaching the alveoli where gas exchange occurs, lowering O_2 and increasing CO_2 partial pressure. The net result is that the fractional concentration of O_2 falls from 21% in ambient air (i.e., inspired partial pressure of O_2 of ∼160 mm Hg at sea level) to a mean of ∼14–15% (P_{O_2} of ∼100 mm Hg) in the alveolar space, whereas the fractional concentration of CO_2 rises from essentially zero to ∼5–6% (alveolar CO_2 partial pressure [$P_{A_{CO_2}}$] of ∼40 mm Hg). In addition to the small added inspiratory and expiratory resistance to breathing discussed earlier, another potential issue with face masks is the inspiration of some fraction of the previously exhaled tidal volume that is partially depleted of O_2 and enriched with CO_2 (i.e., increased dead space). It is important to recognize that the concentrations of O_2 and CO_2 measured inside a face mask in published studies do not represent the gas concentrations delivered to the airways because these measurements represent the average of expired and inspired values. Thus, the true inspired fractions of O_2 and CO_2 will be higher and lower, respectively, and dependent on the metabolic rate and the amount of inspired fresh ambient air. The relative contributions of increased respiratory frequency and increased tidal volume to the increase in ventilation with exercise is also important: increasing tidal volume will result in the inspiration of more fresh ambient air (i.e., less dead space) than will increasing frequency. As both ventilation and inspiratory flow increase with exercise, there will be more entrainment of ambient air so that the effective inspired O_2 concentration will rise, whereas the concentration of CO_2 will fall (17, 24).

Generally at sea level, any fall in the inspired O_2 fraction and the corresponding decrease in Pa_{O_2} does not stimulate increased ventilation via peripheral chemoreceptors until Pa_{O_2} is <60 mm Hg (25); this extent of hypoxemia is not expected with face masks (see below). With some degree of hypercapnia, the threshold for hypoxic stimulation moves to a higher Pa_{O_2}. Nevertheless, it is the reinspiration of CO_2 that would be the driving force for any increases in ventilation when breathing through a face mask. In normoxia, even a 1-mm Hg rise in Pa_{CO_2} will stimulate ventilation (26). Importantly, any changes in ventilation will be greater with exertion because the higher metabolic rate with exercise itself increases the ventilatory responsiveness to CO_2 and O_2 (27, 28).

There are limited data reporting arterial blood gases during exercise while wearing a face mask. Arterial saturation remains above 97% while wearing a surgical mask or N95 respirator while exercising at moderate intensity for 60 minutes (29, 30), indicating that changes in Pa_{O_2} sufficient to affect ventilation are unlikely. When breathing through a full-face industrial respiratory mask, the inspired fraction of CO_2 was 1.5% at rest and decreased to 1.0% during heavy exercise (24). Of note, talking while exercising through a mask generally increased the inspired fraction of CO_2 by ∼0.5% over not talking (24). A recent study examined the exercise responses with surgical masks and N95 respirators (31). Capillary Pa_{O_2}, CO_2, and pH at peak exercise did not differ among users of surgical masks, N95 respirators, and standard CPET face masks, suggesting that alveolar ventilation/gas exchange are not significantly impacted by face masks (31). Work using applied external dead-space loading as a means to stimulate the respiratory system generally shows little change in the end-tidal or arterial CO_2 until the applied dead space is greater than 100–200 ml (32–34), a value that is larger than that expected with most face masks, other than some industrial respirators. However, studies measuring transcutaneous CO_2 as a proxy for Pa_{CO_2} in young healthy adults show small increases of 1–2 mm Hg during moderate-intensity treadmill walking with an N95 respirator compared with being unmasked (29). The reason for the differences between these studies are unclear, but when viewed together, the studies suggest that these respirators may increase ventilation with exercise depending on an individual's ventilatory response to CO_2, with only limited effects on the Pa_{O_2}.

Sympathetic Nervous System, Muscle Blood Flow, Cardiac Output, and Cerebral Blood Flow

During exercise, reflexes from limb skeletal muscle mediate increased sympathetic outflow to the systemic circulation to ensure adequate perfusion of a large active muscle mass and maintain arterial blood pressure. These reflexes originate in nerve endings (groups III–IV) in skeletal muscle and are activated by mechanical deformation, venous distention, and metabolite accumulation. Similar phenomena occur with the respiratory musculature (35).

Muscle Blood Flow and Fatigue

Studies designed to unload the respiratory system demonstrate that the normal work done by respiratory muscles affects vascular conductance, sympathetic vasomotor outflow, diaphragmatic fatigue, locomotor muscle fatigue, dyspnea, leg discomfort, and exercise performance during maximal exercise (*see* Reference 36 for review). These reflex effects are minor or absent during submaximal exercise (37).

The effect of increasing Wb during exercise has been studied by adding external resistors to markedly increase airflow resistance. For example, increasing inspiratory resistance by 3–10 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ (*see* point "D" in Figure 1) during submaximal exercise elicits a 50–70% increase in the Wb, with no change to leg blood flow or sympathetic activity. Moreover, an increase in inspiratory resistance of this magnitude is not associated with changes in heart rate, blood pressure, arterial blood gases, lactate, or pH (37). Thus, given the low resistance of face coverings and surgical masks, they are unlikely to alter sympathetically mediated vascular control and limb fatigue.

Cardiac Output

Cardiac output during exercise is largely unaffected by increased Wb, even when Wb is experimentally increased by 50% during maximal exercise (38). At those high airflow resistances, there is a redistribution of blood flow from other working muscles toward the respiratory muscles to facilitate the increased Wb. This only occurs to a substantial degree, however, when the exercise intensity (>90% of $\dot{V}O_2max$) and ventilation (~150 $L \cdot min^{-1}$) are all very high and airway resistance is well in excess of resistance due to any mask or respirator (>3–7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$) (38) (Figure 1). At lower exercise intensities and with lower airway resistance (i.e., face mask or N95 respirator), $\dot{V}O_2$ (and thus cardiac output and/or oxygen extraction) increases minimally above values measured under conditions of normal airway resistance (37), whereas at maximal exercise, cardiac output is not changed by surgical masks or N95 respirators (31).

Cerebral Blood Flow

Cerebral blood flow is tightly regulated and remains relatively constant under a variety of physiological conditions. Changes in Pa_{O_2} and Pa_{CO_2} alter cerebral blood flow, with marked increases seen when the Pa_{O_2} falls below 50 mm Hg (39) or with slight increases in Pa_{CO_2} and accompanying decreases in brain-tissue pH (40). These are protective mechanisms that maintain constant cerebral blood flow and oxygen delivery under conditions far more abnormal than those experienced with the minimal alterations in Pa_{O_2} and Pa_{CO_2} when wearing a cloth mask or N95 respirator, as discussed above.

Dyspnea

Some individuals may be reluctant to exercise with masks because of increased dyspnea, a complex symptom defined as "a subjective experience of breathing discomfort that consists of qualitatively distinct sensations that vary in intensity" (28). Well-controlled laboratory experiments in healthy participants show that dyspnea-intensity ratings are not increased by low, externally imposed respiratory resistance (i.e., 2.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$) during high-intensity exercise (41). This was also true of higher applied resistances (i.e., 5.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$) during moderate-intensity exercise, despite a ~40–50% increase in the Wb (19). Importantly, the amount of resistance in these studies far exceed resistance values in N95, cloth, and surgical face masks (*see* Figure 1).

It is possible that rebreathing a small volume of exhaled gas (i.e., ~50–100 ml of added dead space) while wearing a face mask during exercise would increase dyspnea because of the effect of CO_2 (42). During exercise with large applied additional dead space (i.e., 600 ml), healthy adults and those with chronic obstructive pulmonary disease (COPD) have higher end-tidal P_{CO_2}, higher minute ventilation, and more dyspnea than they have during exercise without additional dead space; however, the relationship between minute ventilation and dyspnea remains unaltered (43). Indeed, ventilatory stimulation with inhaled CO_2 during incremental exercise has no effect on dyspnea at a given absolute ventilation in healthy adults (44). Thus, if wearing a face mask increases dyspnea during exercise as a result of CO_2 rebreathing, this effect is attributable to the perception of increased ventilation rather than the increased Pa_{CO_2}.

Although controlled laboratory experiments provide valuable insight into the relationship between externally imposed respiratory resistance and exertional dyspnea, they do not fully replicate the sensory experience of wearing face masks, which has resulted in conflicting findings. Several studies have been conducted to evaluate the effects of different face masks on dyspnea during light-to-moderate exercise intensities. Despite the varying experimental protocols, mask types, amount of resistance, and language used to evaluate dyspnea (e.g., "breathing resistance," "breathing discomfort," "inspiratory/expiratory effort," etc.), most studies demonstrate increased dyspnea with face masks compared with controls (15, 45, 46), although this is not a universal finding (22). The discrepancy between studies on face masks (15, 45, 46) and studies adding external resistance to a breathing apparatus (41, 47) may be related, at least in part, to the type of resistance used (i.e., inspiratory vs. combined inspiratory + expiratory resistance), challenges associated with blinding participants, moisture- and temperature-related factors with face masks versus mouthpieces, and flexibility of soft face masks that may collapse and potentially increase dyspnea during exercise. The mechanisms of increased dyspnea with face masks are complicated by the fact that several studies fail to show changes in most physiological variables, despite increased dyspnea (15, 45). However, this also suggests that people may adapt to mask-wearing over time, as has been observed in patients who initially report symptoms of claustrophobia with continuous positive airway pressure devices (48).

Although this is speculative, some posit that increased facial skin temperature, face-mask moisture/heat, or temperature of the inhaled air could contribute to increased dyspnea when wearing a face mask (15). Of these possibilities, increased temperature of the ambient air has been shown to have a larger effect than humidity on participant-reported mask comfort, with increased humidity only affecting participant-reported face-mask comfort when the ambient air was above 25°C (49). Increasing facial airflow using a fan, which reduces the temperature and humidity of the air near the face, decreases dyspnea in healthy adults and those with COPD (50), suggesting that face masks may increase dyspnea by raising facial temperature/humidity.

Special Populations

Older Adults

The impacts of aging on the physiological and perceptual responses to exercise are well characterized (*see* Reference 51 for review). There is a need for further data on the effects of face masks on the cardiopulmonary response to exercise in this population. However, on the basis of current understanding of the effects of aging, it is unlikely that wearing a face mask during exercise would differentially affect younger and older adults for four main reasons. First, although aging increases the ventilatory cost of exercise at a given absolute intensity (47), older adults are likely to exercise at relative (rather than absolute) intensities similar to those of their younger counterparts. In this context, older and younger adults have a similar absolute ventilation for a given relative submaximal exercise intensity (47), meaning that any additional load on the respiratory muscles imposed by a face mask would also be similar. Second, the negative intrathoracic pressure swings associated with small elevations in the Wb while wearing a face mask during exercise are likely similar in older and younger adults and are too small to have a meaningful effect on stroke volume (52). Third, during work-related tasks, men over 45 years old are able to tolerate respiratory resistances well in excess of those caused by N95 respirators or cloth and surgical masks (i.e., ranging from 3.1 to 14.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ at a constant flow of 1.67 $L \cdot s^{-1}$) to an extent similar to that of younger men (53). In fact, the addition of a respiratory resistance (i.e., 5.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$) does not affect dyspnea during moderate-intensity exercise in older men and women (19). Fourth, added ventilatory stimulation (via dead-space loading) has a similar effect on the mechanical ventilatory, gas-exchange, and perceptual responses to exercise in older and younger men, and the associated reduction in peak exercise capacity does not differ on the basis of age (54).

Pediatrics

There are important differences in respiratory physiology in infants and young children as compared with adults (*see* Reference 55 for review). Infants and young children have underdeveloped accessory muscles of respiration and thus rely more on the diaphragm for most of the Wb. An increase in respiratory muscle work is largely accomplished by an increase in the respiratory rate, and the diaphragm can become fatigued more quickly than in adults. Children under the age of 6 years have proportionally more extrathoracic anatomical dead space owing to the larger ratio of head size to body size (56). These anatomical differences combined with an inherently higher basal metabolic rate place infants and young children at greater risk of respiratory failure than adults from various significant health threats. These differences decrease as children age, and other than in children younger than 2 years and those with significant respiratory or neurological conditions, there are no significant differences in respiratory physiology for older children and adolescents that are expected to substantially alter the effects of masks as described above, but additional data are needed to clarify this issue.

Sex-based Differences

Compared with males, females have smaller lungs and rib cages and disproportionally smaller large conducting airways (57). These sex differences in respiratory system morphology affect the integrative response to exercise by influencing Wb, dyspnea, blood-gas homeostasis, and cardiovascular function (57). For example, narrower airways in females result in a greater resistive (~50% greater) and total Wb (~20% greater) during exercise when ventilation exceeds ~60 $L \cdot min^{-1}$ (16, 58).

Males typically have a higher minute ventilation and generate greater air flow at a given relative, but not absolute, exercise intensity. Because the external resistance offered by a face mask is flow dependent, males may have a greater increase in Wb because of higher absolute flows while wearing a face mask. However, the additional Wb associated with a face mask during exercise is small (*see* Figure 1), and the associated physiological and perceptual consequences are likely correspondingly minor. The addition of external resistance (i.e., 5.7 cm $H_2O \cdot L^{-1} \cdot s^{-1}$) to increase Wb during moderate-intensity exercise in older (i.e., 60–80 yr) adults increases the absolute Wb to a greater extent in males than in females, but the relative increase in Wb is similar between sexes. Importantly, the external resistance used in this study had no effect on dyspnea in either sex (19). However, in one study of standardized simulated work tasks while wearing an N95 respirator, females reported higher symptom scores than males (59).

Patients with Cardiopulmonary Disease

On the surface, the addition of a small increase in the Wb and reinspiration of low concentrations of CO_2 with any type of face mask would appear to pose more problems for individuals with underlying cardiopulmonary disease. Other drawbacks for such individuals with face-mask wearing may include anxiety and greater dyspnea (60, 61), reduced fine-motor performance (62), possible cognitive effects as a result of slight CO_2 retention and mildly increased hypoxemia, and increased Wb (63).

Increased temperature around the face (64) and a 0.5°C body-temperature elevation with loss of normal respiratory heat dissipation (65) may also have effects. Patients with mild-to-moderate pulmonary disease will likely tolerate cloth/surgical masks with an acceptable extent of discomfort, but with advanced disease, this may become more burdensome because of the effects of mask wearing described above (66, 67). More efficient filtering masks will be difficult for almost anyone with severe nonasthmatic lung disease and may warrant closer monitoring of symptoms and arterial saturation with oximetry. Patients with altered ventilatory control and blunted drives to breathe, such as those with obesity hypoventilation syndrome, may also warrant monitoring for greater hypoxemia and increased CO_2 retention, resulting from potential small increases in dead space with a face mask.

Data regarding face-mask use with exercise in cardiopulmonary disease are very limited. Patients with COPD and high dyspnea scores or markedly impaired pulmonary function (forced expiratory volume in 1 s [FEV_1] < 30% predicted) may be less likely to tolerate moderate exercise, such as a that within a 6-minute walk test, while wearing an N95 respirator, with a 1.5–mm Hg greater rise in end-tidal CO_2 and a 1% greater fall in O_2 saturation as measured by pulse oximetry (Sp_{O_2}) (68) when compared with performing the test without a mask. However, a recent study demonstrated no changes in Sp_{O_2} and end-tidal CO_2 in patients with severe COPD (mean $FEV_1 = 44\%$) at rest while wearing a surgical mask for up to 30 minutes (69). Furthermore, when these patients performed a 6-minute walk test while wearing a surgical mask, Pa_{CO_2} increased by <1 mm Hg, indicating that significant alveolar hypoventilation and CO_2 retention is unlikely to be induced by surgical masks during self-paced exercise.

The addition of 5 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ of inspiratory resistance and 1.5 cm $H_2O \cdot L^{-1} \cdot s^{-1}$ of expiratory resistance during exercise at a $\dot{V}O_2$ of 0.8 $L \cdot min^{-1}$ resulted in declines in respiratory rate and ventilation and increases in tidal volume, end-tidal CO_2, and mouth-pressure swings in individuals with various forms of parenchymal restrictive lung disease (70). However, with the exception of the larger mouth-pressure swings, there were no significant differences in the magnitude of these changes when compared with healthy control subjects (70). Importantly, these external resistances are greater than would be expected from surgical or other face masks. Although expiratory loading improves the stroke volume index and cardiac index during semirecumbent exercise at 60% of maximal exercise capacity in individuals with heart failure (71), no studies have examined the specific effects of respirator masks on exercise in heart failure or other forms of cardiac disease. Given the lesser amounts of expiratory resistance with a more loosely fitting face mask, it is unlikely that patients with heart failure will experience these benefits.

For at least one particular form of lung disease, however—exercise-induced bronchoconstriction—face masks may have beneficial effects with exercise. Multiple studies (72–74) have demonstrated that wearing a face mask is associated with a smaller decline in FEV_1 with exercise in cold and/or dry air compared with control conditions. Although most studies used face masks with heat and moisture exchangers—masks that would not likely be widely used as part of COVID-19–prevention protocols—similar benefits have also been demonstrated with standard surgical face masks (75) or woolen scarves (76), which have been used widely during the current pandemic.

Conclusions

This review has examined the effects of various face masks and on the physiological and perceptual responses to physical activity. Although the body of literature directly evaluating this issue is evolving, for healthy individuals, the available data suggest that face masks, including N95 respirators, surgical masks, and cloth face masks, may increase dyspnea but have small and often difficult-to-detect effects on Wb, blood gases, and other physiological parameters during physical activity, even with heavy/maximal exercise. There is currently no evidence to suggest that wearing a face mask during exercise disproportionally hinders younger or older individuals, and significant sex-based differences are not expected. Depending on the severity of their underlying illness, individuals with cardiopulmonary disease are more likely than healthy individuals to experience increased exertional dyspnea with a face mask because of small increases in resistance and reinspiration of warmer and slightly enriched CO_2 air. Such problems may serve as a basis for seeking exemptions from mask regulations, but the benefits of decreased dyspnea will need to be weighed against the risks of contracting the SARS-CoV-2 infection. ■

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