Effects of the Turbine™ on Ventilatory and Sensory Responses to Incremental Cycling

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ABSTRACT

SCHAEFFER, M. R., E. MCBRIDE, R. A. MITCHELL, K. G. BOYLE, A. H. RAMSOOK, J. H. PUYAT, M. J. MACNUTT, and J. A. GUENETTE. Effects of the Turbine™ on Ventilatory and Sensory Responses to Incremental Cycling. *Med. Sci. Sports Exerc.*, Vol. 53, No. 1, pp. 192–199, 2021. **Introduction:** The Turbine™ is a nasal dilator marketed to athletes to increase airflow, which may serve to reduce dyspnea and improve exercise performance, presumably via reductions in the work of breathing (WOB). However, the unpublished data supporting these claims were collected in individuals at rest that were exclusively nasal breathing. These data are not indicative of how the device influences breathing during exercise at higher ventilations when a larger proportion of breathing is through the mouth. Accordingly, the purpose of this study was to empirically test the efficacy of the Turbine™ during exercise. We hypothesized that the Turbine™ would modestly reduce the WOB at rest and very low exercise intensities but would have no effect on the WOB at moderate to high exercise intensities. **Methods:** We conducted a randomized crossover study in young, healthy individuals (7M:1F; age = 27 ± 5 yr) with normal lung function. Each participant performed two incremental cycle exercise tests to exhaustion with the Turbine™ device or under a sham control condition. For the sham control condition, participants were told they were breathing a low-density gas to reduce the WOB, but they were actually breathing room air. The WOB was determined through the integration of ensemble averaged esophageal pressure–volume loops. Standard cardiorespiratory measures were recorded using a commercially available metabolic cart. Dyspnea was assessed throughout exercise using the 0–10 Borg scale. **Results:** Peak $\dot{V}O_2$ and work rate were not different between conditions ($P = 0.70$ and $P = 0.35$, respectively). In addition, there was no interaction or main effect of condition on dyspnea, ventilation, or WOB throughout the exercise (all $P > 0.05$). **Conclusion:** These findings suggest that the Turbine™ does not reduce the WOB and has no effect on dyspnea or exercise capacity.
Key Words: WORK OF BREATHING, RESPIRATORY MECHANICS, ERGOGENIC AID, VENTILATION, DYSPNEA

The mechanical work of breathing (WOB) increases exponentially with minute ventilation ($\dot{V}_E$) and can account for up to 10%–15% of maximal oxygen consumption in untrained and highly trained individuals (1,2). A high WOB may influence exercise performance. For example, respiratory muscles compete with other tissues for finite metabolic resources; the higher the WOB, the fewer resources are available to fuel the locomotor muscles (3). In addition, a high WOB can contribute to increased dyspnea and to respiratory muscle fatigue, both of which can reduce the ability to sustain high ventilations and workloads (4,5). Accordingly, reducing the WOB during exercise can lead to improved exercise endurance. For example, a study that reduced the WOB by having participants breathe a low-density helium–oxygen gas mixture showed a 0.7%–1.5% improvement in cycling time trial performance (6). In addition, there is evidence that using a proportional-assist ventilator to reduce the WOB significantly decreases the degree of quadriceps fatigue following a constant load cycling test (5), which could also lead to improved exercise endurance. Although these specific interventions cannot be readily applied during training or competition, they demonstrate the importance of targeting the WOB as a strategy to enhance whole body exercise performance.

The Turbine™ (RHINOMED Ltd., Cremorne, VIC, Australia) is a stent device that sits inside the nose to dilate and support the nasal valve. The nose is a principal site of airflow resistance, which accounts for approximately 50% of total pulmonary resistance at rest (7). More specifically, the nasal valve represents the narrowest region of the entire upper airway (8). The dynamic collapse of this region with high inspiratory flows further contributes to its already high resistance (9). According to Poiseuille's law, increasing airway diameter, such as with a nasal dilator device

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Submitted for publication March 2020.
Accepted for publication June 2020.

0195-9131/21/5301-0192/0
MEDICINE & SCIENCE IN SPORTS & EXERCISE®

DOI: 10.1249/MSS.0000000000002427

(e.g., the Turbine™), should decrease the pressure needed to overcome airflow resistance and therefore reduce the total mechanical WOB for a given airflow. In addition, these devices may provide structural support to prevent the aforementioned dynamic collapse of the nasal valves, which can occur with high inspiratory airflow (9). Although the Turbine™ is endorsed by some of the world's most successful professional athletes, there is no evidence to suggest that it reduces the WOB during exercise or enhances exercise performance. Marketing materials cite an unpublished clinical trial showing that the Turbine™ increases airflow by 38% (10), with a presumed associated decrease in the WOB. However, these data were collected under resting conditions while participants breathed exclusively through their noses. No study to date has evaluated the effect of this device on the WOB during exercise.

The Turbine™ is designed for use during training and competition. Therefore, it is essential to determine whether the claimed increase in airflow during exercise, via reductions in airflow resistance and presumably the WOB, is true. Oronasal distribution is technically challenging to quantify and highly variable between individuals (8). Nonetheless, nasal ventilation has been shown to account for approximately 70% of total ventilatory airflow at rest, and ventilatory distribution typically becomes predominantly oral during exercise at relatively low ventilations, with only a 27% contribution of nasal ventilation to total airflow during high-intensity exercise (11,12). Therefore, increasing airflow through the nose may be of little benefit during moderate- to high-intensity exercise.

The purpose of this study was to evaluate the effects of the Turbine™ on the WOB, dyspnea, and standard cardiorespiratory measures during exercise in young, healthy participants. We hypothesized that the Turbine™ would modestly reduce the WOB at rest and low exercise intensities but would have no effect on the WOB at moderate to high intensities because of the shift to predominantly oral breathing. We also hypothesized that the Turbine™ would have no effect on dyspnea ratings or any other standard cardiorespiratory variable across any exercise intensity.

METHODS

Experimental Overview

This study received institutional ethical approval from the University of British Columbia, Providence Health Care Research Institute, and Quest University Canada. Participants visited the laboratory twice, separated by a minimum of 48 h, and were instructed to refrain from caffeine the day of the visit and to avoid strenuous exercise in the 24 h before each visit. They provided written informed consent and were screened for inclusion during their first laboratory visit. At both visits, participants completed an identical incremental cycling test to exhaustion with continuous assessment of cardiorespiratory responses, WOB, and dyspnea. Each participant completed the Turbine™ trial and a sham control trial in a random, counterbalanced order.

Participants

Eight young, healthy individuals completed the study. Inclusion criteria included no current or history of smoking, normal pulmonary function, no history of cardiopulmonary disease, and normal body mass index (>18 or <30 $kg \cdot m^{-2}$). General health was confirmed through a medical history questionnaire and the Physical Activity Readiness Questionnaire (PAR-Q+), and anthropometric measurements were collected for participant characterization.

Experimental Conditions

Turbine™. Participants were instrumented with the Turbine™ according to manufacturer instructions. Briefly, participants guided the device into the nostrils and expanded or contracted the paddles to achieve optimal dilation and comfort. The device remained in place for the entirety of the testing session. Throughout rest and exercise, participants breathed through a two-way non-rebreathing valve connected to a face mask and large bore tubing, which was open to room air. Participants were not instructed to primarily breathe through their nose or alter their breathing pattern in any way.

Placebo. As in the Turbine™ trial, participants breathed through an identical two-way non-rebreathing valve connected to a face mask and large bore tubing, which was open to room air. However, participants were misled to believe the tubing was connected to a large reservoir bag containing a low-density gas (heliox), which would reduce their airway resistance and WOB (6). We opted to use a sham condition that has been proven to reduce the WOB (6) rather than an external nasal dilator, which has not (13). All participants were informed of the deception following completion of the study.

Pulmonary Function

Spirometry was performed according to established recommendations (14) using a commercially available system (Vmax Encore 229; SensorMedics, Yorba Linda, CA). All measurements were expressed as percentages of predicted values (15).

Incremental Exercise Protocol

Progressive exercise tests were performed on an electromagnetically braked cycle ergometer (Velotron®; Quarq Technology, Spearfish, SD). After a 6-min resting period, exercise began with a 1-min warm-up of unloaded pedaling followed by a stepwise increase of 25 W every 2 min until volitional exhaustion. Maximal work rate was determined as the highest work rate that could be sustained for at least 30 s. No verbal encouragement was provided during the exercise tests to avoid any potential bias caused by those administering the exercise tests.

Metabolic and Cardiorespiratory Responses to Exercise

$\dot{V}_E$, oxygen consumption ($\dot{V}O_2$), carbon dioxide production ($\dot{V}CO_2$), tidal volume (V_T), and breathing frequency (F_b) were recorded throughout rest and exercise using a commercially

available metabolic cart (TrueOne® 2400; Parvo Medics, Salt Lake City, UT). Heart rate was assessed using a commercially available heart rate monitor (Polar T34; Polar Electro Oy, Kempele, FIN), and arterial oxygen saturation was estimated using pulse oximetry (Radical-7 Rainbow CO-Oximetry; Masimo Corp., Irvine, CA). Measurements are reported as 30-s averages.

Inspiratory and Expiratory Flow

Inspiratory flow was measured using a separate pneumotachograph (Series 3813; Hans Rudolph, Shawnee, KS) and amplifier (PA-1 Series 1110; Hans Rudolph) connected via large bore tubing to the inspiratory port of the two-way non-rebreathing valve. The expiratory flow signal from the metabolic cart was relayed to an external data acquisition system (PowerLab 16/35; ADInstruments Inc., Colorado Springs, CO). The combined inspiratory and expiratory flow signals were then integrated to obtain continuous inspiratory and expiratory volumes for the assessment of the WOB.

WOB

Participants were instrumented with an adult esophageal-balloon catheter (Cooper Surgical Inc., Trumbull, CT), which was connected to a calibrated differential pressure transducer (Model DP15-34; Validyne Engineering, Northridge, CA). The catheter was inserted through a nostril and guided through the esophagus after local anesthesia of the nasal mucosa (Lidodan® Endotracheal Topical Anesthetic Non-Aerosol Spray; Odan Laboratories Ltd., Montreal, QC, CAN). After insertion, participants evacuated the air in the balloon by performing a Valsalva maneuver, which was confirmed using a glass syringe. A known volume of air (1 mL) was then introduced. Appropriate positioning of the catheter was determined through sniff maneuvers, where the presence of a positive pressure deflection during inspiration indicated that the balloon was located in the stomach. The catheter was retracted 10 cm from the location where the pressure deflection switched from positive to negative to ensure that the balloon was located in the esophagus (16). An occlusion test was then used to confirm appropriate balloon position (16).

Flow, volume, and pressures from several breaths (~5–20) corresponding to rest, each stage of exercise, and peak exercise were ensemble averaged using customized software (Bibo, LabVIEW software V6.1; National Instruments, Austin, TX) (17). The WOB was calculated by integrating the area within the ensemble averaged pressure–volume loop, with the addition of a triangle that fell outside the loop (i.e., part of the elastic work) as previously described (18). The total WOB (WOB_{Tot}) and inspiratory resistive WOB (WOB_{Ires}) data were then multiplied by breathing frequency, representing a unit of power (i.e., joules per minute). However, by convention, it will be called the WOB and not the "power of breathing" in this manuscript.

Inspiratory Muscle Fatigue

Participants performed maximal sniff maneuvers at rest, immediately postexercise, and 10 min postexercise to indirectly examine global inspiratory muscle fatigue (19). Sniffs were performed from relaxed end expiration with 10 s of rest between each sniff. Participants performed 5–10 sniffs at each time point, until they achieved a plateau of pressure values (19). The three highest sniff values at each time point were averaged. The degree of inspiratory muscle fatigue was calculated as the relative change in sniff pressure from rest expressed as a percentage.

Perceptual Responses

Dyspnea (defined as "the sensation of labored or difficult breathing") and perceived leg discomfort were evaluated at rest, every minute during exercise, and at peak exercise using the 0–10 category ratio Borg scale (20). Upon exercise cessation, participants were asked to select the qualitative descriptors of their breathlessness (i.e., I feel a need for more air, my breathing feels shallow, my chest feels tight, etc.) from a modified list of 15 dyspnea descriptors (21).

Statistical Analysis

A two-way repeated-measures ANOVA was used to determine the effect of the Turbine™ on metabolic, cardiorespiratory, and ventilatory parameters as well as ratings of dyspnea and leg discomfort during standardized submaximal exercise intensities (i.e., each 25-W stage of exercise up to the highest work rate achieved by all participants on both exercise tests). A comparison of the WOB relative to $\dot{V}_E$ was provided. However, statistical comparisons were not performed because $\dot{V}_E$ was not standardized within and between participants for each work rate. A two-way repeated-measures ANOVA was also used to determine the effect of the Turbine™ on sniff pressures at rest, immediately postexercise, and 10 min postexercise. Significant main and interaction effects for each outcome variable were tested in relation to the assumption of sphericity (Mauchly). Paired *t*-tests were used to make between-condition comparisons at peak exercise. Between-condition differences in the qualitative descriptors of dyspnea at peak exercise were assessed using McNemar's exact test (RStudio, Version 1.2.1335; RStudio, Inc., Boston, MA). Statistical significance was set at $P < 0.05$. Data are presented as mean ± SD unless otherwise specified.

RESULTS

Participants. Demographic, anthropometric, and spirometry data are summarized in Table 1. Participants had a normal

TABLE 1. Participant characteristics.

Demographics/Anthropometrics	
Sex, M:F	7: 1
Age, yr	27.5 ± 4.5
Height, cm	178.6 ± 13.0
Mass, kg	72.3 ± 9.1
BMI, $kg \cdot m^{-2}$	22.7 ± 1.6
Spirometry	
FVC, l (% predicted)	5.9 (106) ± 1.2 (7)
FEV_1, l (% predicted)	4.6 (102) ± 0.9 (7)
FEV_1/FVC, % (% predicted)	79.1 (96) ± 3.7 (4)

Values are presented as mean ± SD.
M, male; F, female; BMI, body mass index; FVC, forced vital capacity; FEV_1, forced expiratory volume in 1 s.

TABLE 2. Physiological and perceptual responses to exercise.

	Rest		Isowork		Peak	
	Sham Control	Turbine™	Sham Control	Turbine™	Sham Control	Turbine™
Work rate, W	0 ± 0	0 ± 0	200 ± 0	200 ± 0	325 ± 74	319 ± 76
$\dot{V}O_2$, L·min^{-1}	0.38 ± 0.08	0.36 ± 0.11	2.63 ± 0.18	2.59 ± 0.12	3.98 ± 0.87	3.94 ± 0.81
$\dot{V}O_2$, mL·kg^{-1}·min^{-1}	5 ± 1	5 ± 1	37 ± 6	36 ± 5	55 ± 8	54 ± 8
$\dot{V}CO_2$, L·min^{-1}	0.30 ± 0.08	0.29 ± 0.10	2.43 ± 0.21	2.37 ± 0.19	4.18 ± 0.93	4.13 ± 0.91
RER	0.79 ± 0.06	0.80 ± 0.08	0.93 ± 0.06	0.92 ± 0.07	1.05 ± 0.04	1.05 ± 0.03
$\dot{V}_E$, L·min^{-1}	11 ± 3	11 ± 3	66 ± 9	63 ± 10	141 ± 36	128 ± 36
V_T, L	0.89 ± 0.26	0.90 ± 0.32	2.51 ± 0.48	2.41 ± 0.44	2.78 ± 0.56	2.89 ± 0.67
F_b, breaths per minute	12.8 ± 2.2	13.0 ± 3.0	27.6 ± 8.8	27.2 ± 8.0	50.4 ± 6.4	44.6 ± 7.6
$\dot{V}_E$/MVV, %	6 ± 1	6 ± 1	38 ± 13	36 ± 14	76 ± 10	69 ± 13
$\dot{V}_E/\dot{V}O_2$	29 ± 3	31 ± 5	25 ± 4	24 ± 4	35 ± 3	32 ± 4
$\dot{V}_E/\dot{V}CO_2$	37 ± 3	38 ± 6	27 ± 3	26 ± 3	34 ± 3	31 ± 4*
HR, bpm	61 ± 6	60 ± 9	150 ± 18	146 ± 21	182 ± 6	181 ± 8
Dyspnea, 0–10 scale	0 ± 0	0 ± 0	3 ± 2	3 ± 2	8 ± 3	8 ± 3
Leg discomfort, 0–10 scale	0 ± 0	0 ± 0	3 ± 2	3 ± 2	8 ± 2	8 ± 3

Values are presented as mean ± SD. Isowork represents the highest work rate achieved by all participants. MVV was estimated by multiplying FEV_1 by 40.
* $P < 0.05$ compared with sham control at same measurement time.
$\dot{V}O_2$, oxygen consumption; $\dot{V}CO_2$, carbon dioxide production; RER, respiratory exchange ratio; $\dot{V}_E$, minute ventilation; V_T, tidal volume; F_b, breathing frequency; MVV, maximum voluntary ventilation; HR, heart rate.

body mass index, and pulmonary function was within normal predicted values (15).

Exercise responses. Metabolic, cardiorespiratory, and ventilatory parameters with and without the Turbine™ at rest, standardized submaximal work rates, and peak exercise are presented in Table 2 and Figure 1. The highest work rate achieved by all participants (isowork) was 200 W. Peak work rate was not different between conditions ($P = 0.35$), and there was no interaction effect and no main effect of condition on any variable at rest or during submaximal exercise. However, $\dot{V}_E/\dot{V}CO_2$ was significantly lower at peak exercise with the Turbine™ compared with sham control ($P = 0.04$).

WOB. There was no interaction effect and no main effect of condition on the WOB_{Tot} or WOB_{Ires} during exercise. Figure 2 shows the WOB_{Tot} and WOB_{Ires} as a function of increasing work rate and $\dot{V}_E$.

Inspiratory muscle fatigue. There was no interaction effect and no main effect of condition on sniff pressures. In addition, there was no indication of inspiratory muscle fatigue in either condition, as sniff pressures were similar pre- to postexercise

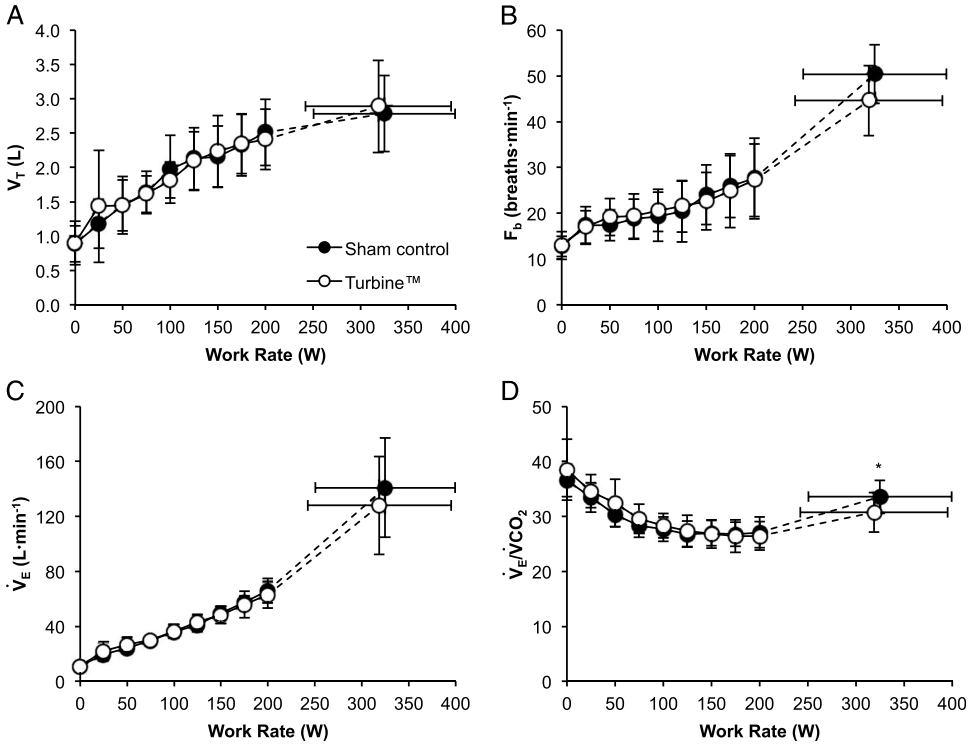

FIGURE 1—Ventilatory responses to exercise. Values are presented as mean ± SD. *Dashed lines* connect the highest submaximal work rate achieved by all participants to the peak exercise data point. (A) V_T, tidal volume; (B) F_b, breathing frequency; (C) $\dot{V}_E$, minute ventilation; (D) $\dot{V}_E/\dot{V}CO_2$, ventilatory equivalent for carbon dioxide. *$P < 0.05$ compared with sham control.

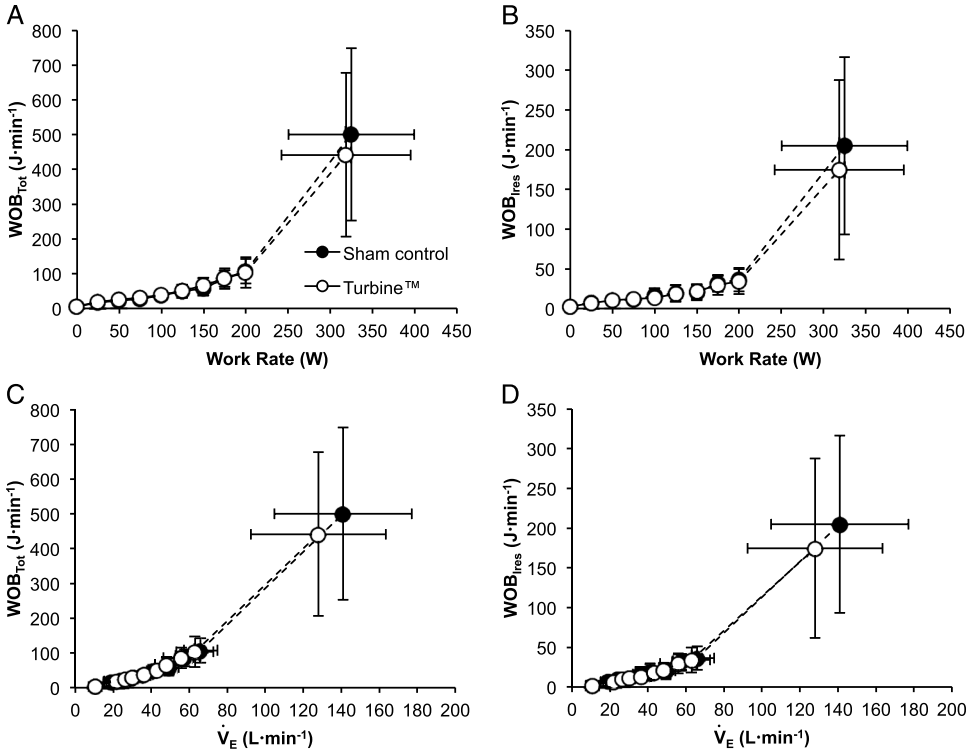

FIGURE 2—Total WOB (WOB_{Tot}) and inspiratory resistive WOB (WOB_{Ires}) for a given work rate (panels A and B) or ventilation ($\dot{V}_E$) (panels C and D) during exercise, respectively. Values are presented as mean ± SD. *Dashed lines* connect the highest submaximal work rate achieved by all participants to the peak exercise data point.

in both conditions (−89 ± 25 vs −88 ± 13 and −95 ± 23 vs −94 ± 19 cm H_2O for Turbine™ and sham control, respectively).

Perceptual responses. There was no interaction effect and no main effect of condition on perceived dyspnea or leg discomfort during exercise (Table 2; Fig. 3). Selection frequencies of dyspnea descriptors from the 15-item list administered at the end of exercise were similar between conditions (all $P > 0.05$; Fig. 4).

DISCUSSION

This study evaluated the effect of the Turbine™ on the WOB during exercise. The main findings are as follows: 1) there was no difference in the inspiratory resistive WOB or total WOB at rest or during exercise with the Turbine™ compared with sham control; 2) there were no between-condition differences in ventilatory responses at rest, during submaximal exercise, or peak exercise except $\dot{V}_E/\dot{V}CO_2$, which was significantly lower at peak exercise with the Turbine™ compared with sham control; and 3) there were no differences between conditions in sensory ratings for breathing or leg discomfort throughout exercise or qualitative descriptors of dyspnea at peak exercise. Collectively, we did not observe any meaningful physiological or sensory changes that would suggest potential for improved exercise performance with the Turbine™.

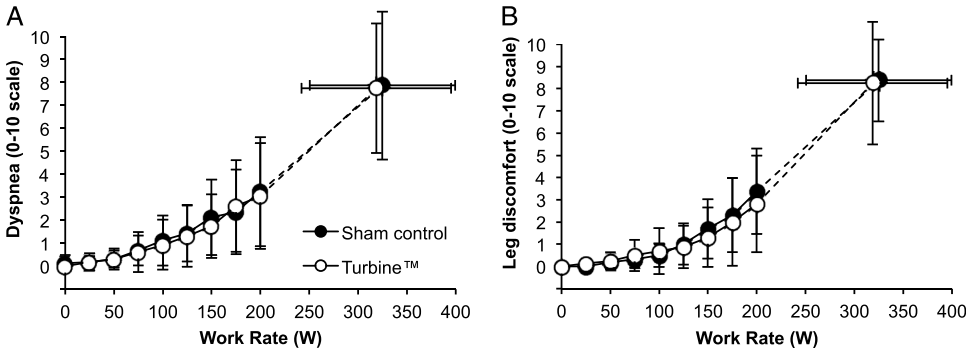

FIGURE 3—Dyspnea (A) and leg discomfort (B) ratings during exercise. Values are presented as mean ± SD. *Dashed lines* connect the highest submaximal work rate achieved by all participants to the peak exercise data point.

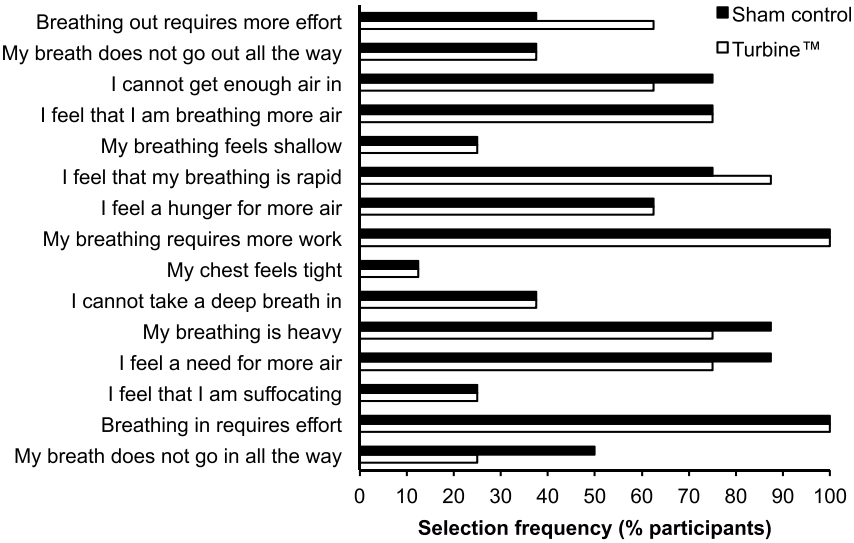

FIGURE 4—Selection frequency of qualitative descriptors of dyspnea at peak exercise.

WOB. The Turbine™ manufacturer claims to "make breathing more efficient before, during, and after exercise" to improve performance, endurance, and/or recovery. If the Turbine™ reduces airflow resistance in a meaningful way, then this should translate into a reduction in the WOB, which we measured using gold standard methods. However, we did not observe significant reductions in either inspiratory resistive or the total WOB in the present study at rest or at any time point during exercise. This is consistent with previous findings using an external nasal dilator (13). Without changes in the WOB, there is no physiological basis for improved exercise performance.

There are several possible explanations for why we did not observe a reduction in the WOB at rest or during exercise with the Turbine™ compared with sham control. At rest, 70%–80% of healthy individuals breathe primarily through the nose (8), wherein the Turbine™ has the most potential for benefit. Nonetheless, the effectiveness of nasal dilators in reducing nasal airway resistance in the literature is equivocal, and the responses to external nasal dilators in normal healthy subjects at rest are highly variable (22). During exercise, when there is an increase in ventilatory demand, the distribution of oral and nasal ventilation is adjusted such that upper airway resistance, and presumably respiratory work, is minimized (8). The ventilation at which breathing switches from a nasal to oronasal breathing pattern is highly variable between individuals, but on average, has been shown to occur at low ventilations ranging from 22 to 35 $L \cdot min^{-1}$ (12,23). At this transition point, the nasal contribution to airflow has been shown to range from 26% to 64% (23), further reducing to an average of 27% at high-intensity exercise (11). It is possible that any potential benefit of the Turbine™ compared with sham control during low-intensity exercise may have been redundant of inherent exercise-induced activation of the alae nasi muscles, which dilate and stabilize the nasal valve and reduce nasal airflow resistance (24). In addition, although we did not measure nasal versus oral contributions to breathing in the present study, it is likely that a larger proportion of the total ventilation was through the mouth during moderate- to high-intensity exercise (11), wherein the device would have little to no effect.

We did not observe a main effect of the Turbine™ on changes in sniff pressure, a crude estimate of respiratory muscle fatigue, in the present study. This is not surprising as incremental cycling tests do not typically induce diaphragm fatigue (25). Interestingly, Tong et al. (26) showed that nostril dilation with an external nasal dilator eliminated respiratory muscle fatigue, assessed via the comparison of pre- to postmaximal inspiratory pressure, which occurred during high-intensity intermittent exercise without the device. Both sniff and maximal inspiratory pressure tests are volitional tests of respiratory muscle fatigue and must be interpreted with caution. The results of the present study as well as Tong et al. (26) should be verified using gold standard methods of phrenic nerve stimulation.

Physiological responses to exercise. Cardiorespiratory responses to exercise in the present study were similar between the Turbine™ and sham control conditions, and there was no significant difference in exercise capacity. These findings are consistent with previous research with internal (27,28) and external nasal dilators during exercise (13,26,27,29–35). The only exception is one study by Griffin et al. (36) that observed a reduction in HR, $\dot{V}_E$, and $\dot{V}O_2$ with an external nasal dilator compared with a placebo condition during two standardized submaximal cycle exercise intensities. However, participants in that study were specifically instructed to "switch from nasal breathing to oronasal breathing when they felt it was necessary" (36), and it has been speculated that this awareness of breathing may have changed their breathing pattern and influenced the results (27). In addition, we did observe a significant decrease in peak $\dot{V}_E/\dot{V}CO_2$ with the Turbine™, suggesting an improvement in ventilatory efficiency at this measurement point. However, we did not observe any change in $\dot{V}_E/\dot{V}CO_2$ at any other exercise intensity,

particularly during submaximal exercise where the Turbine™ would presumably have the greatest benefit. The lower $\dot{V}_E/\dot{V}CO_2$ with the Turbine™ at peak exercise is primarily attributable to the fact that three participants achieved lower peak work rates in the Turbine™ condition relative to the sham control. These participants had markedly lower levels of $\dot{V}_E$ (range, 11–50 $L \cdot min^{-1}$) with the Turbine™ compared with the sham control. The relative decrease in $\dot{V}_E$ was disproportionally greater than the relative decrease in $\dot{V}CO_2$ in these participants, resulting in a lower $\dot{V}_E/\dot{V}CO_2$ ratio.

Perceptual responses to exercise. Although a perceived reduction in breathing difficulty in itself could have performance enhancing effects, few studies have investigated the effect of a nasal dilator on dyspnea during exercise. Chinevere et al. (29) found no significant difference in dyspnea during a maximal incremental running test when comparing nose-only breathing to nose-only breathing with an external nasal dilator. Another study by Adams et al. (27) found no difference in dyspnea during a 20-km time trial with an internal or external nasal dilator compared with control. In the present study, we did not observe any significant differences in dyspnea with the Turbine™ compared with the sham control, which supports the notion that a nasal dilator does not provide meaningful perceptual changes during exercise (27). This is also consistent with participants being unable to differentiate between active and inactive (i.e., placebo) external nasal dilators in a double-blind study while repeating 1 min running intervals to exhaustion (32). Unique to this study were our qualitative descriptive measures of dyspnea, which were also not different with the Turbine™ at peak exercise compared with sham control. By contrast, a main effect of an external nasal dilator on dyspnea at intensities above 70% of peak HR has been shown during a progressive treadmill exercise test (33). Similarly, although dyspnea was not directly measured, all participants in another study reported that an external nasal dilator seemed to open the nasal passages during a ramp cycle exercise test (30). Average ratings of the perceived magnitude of breathing effort have also been shown to be lower with an external nasal dilator during high-intensity intermittent cycle exercise compared with exercise without the device (26). Finally, 19 of 20 patients perceived an improvement in nasal breathing with an external nasal dilator during submaximal cycle exercise compared with exercise without the device when restricted to nasal breathing (37). Importantly, none of these studies were placebo-controlled (26,30,32,33) and only one demonstrated a physiological benefit (26). Therefore, the placebo effect of a nasal dilator on the sensory ratings reported in these studies cannot be ruled out, and the results are not comparable to the present study that used a sham control.

A previous study showed that when the WOB was reduced via a proportional-assist ventilator, perceived limb discomfort was lower during exercise compared with control (5). We did not observe any effect of the Turbine™ on leg discomfort ratings during exercise. Other studies have included more general RPE instead of leg discomfort. One study did report significantly lower RPE with an external nasal dilator compared with control during submaximal exercise, which was likely a reflection of a concomitant improvement in exercise economy (36), which as previously mentioned has not been replicated. However, the vast majority of previous studies did not observe an effect of a nasal dilator on central (38), local (38), or overall (28,31,35,38,39) RPE, which is consistent with our findings.

Limitations. There were some limitations to this study that should be acknowledged. First, while we did incorporate a sham control condition in our study design, it was not a regular placebo control for the experimental condition (Turbine™). We considered an alternative placebo condition, but we were ultimately unable to use an internal nasal dilator because any rigid or semirigid device would likely add support and potentially prevent any dynamic collapse during inspiration at high ventilations. In addition, if we were to have inserted a stent that did not provide any dilation, it would have potentially narrowed the nasal passage by taking up space, thus increasing airways resistance. An alternative option was to use a placebo external nasal dilator strip as done by others (32,40). We decided against this approach because, unlike heliox (6), external nasal dilators have not been proven to reduce the WOB (13). Having three conditions (e.g., Turbine™, sham, regular control) would have been a stronger design and could have potentially allowed us to determine whether there was a placebo effect of the Turbine™. Second, we placed the esophageal catheter through a nostril rather than through the mouth to minimize participant discomfort as per standard practice. It is possible that our thin catheter (1.67 mm) could have slightly increased resistance in one nostril. However, we do not believe this would influence our overall interpretation because the catheter was placed in the same nostril on both experimental visits. Finally, we acknowledge that this invasive physiological study was completed in a relatively small number of participants, and a formal sample size estimation was not performed because of the lack of knowledge about clinically important differences in our primary outcome (i.e., WOB). This increases our potential for making a type II error and, furthermore, did not permit us to make any subgroup comparisons (e.g., male vs female, responders vs nonresponders, etc.).

CONCLUSION

We did not observe any effect of the Turbine™ on respiratory mechanical, ventilatory, cardiometabolic, or perceptual responses throughout incremental cycle exercise in a small sample of young, healthy participants. These findings suggest that the Turbine™ has no physiological or sensory benefit and is unlikely to enhance exercise performance.

This work was funded by a Discovery Grant from the Natural Sciences and Engineering Research Council of Canada (NSERC). M. R. S. was supported by postdoctoral fellowships from the Michael Smith Foundation for Health Research (MSFHR) and the British Columbia Lung Association (BCLA). R. A. M. was supported by a postgraduate doctoral scholarship from the NSERC. A. H. R. was supported by an NSERC Alexander Graham Bell Canada Graduate Scholarship and a

fellowship from the BCLA. R. A. M. and A. H. R. were also supported by a 4-yr doctoral fellowship from The University of British Columbia. J. A. G. was supported by a Canadian Institutes of Health Research Clinical Rehabilitation New Investigator Award and a Scholar Award from the MSFHR.

No conflicts of interest, financial or otherwise, are declared by the authors. The results of the present study do not constitute endorsement by the American College of Sports Medicine. The results of the study are presented clearly, honestly, and without fabrication, falsification, or inappropriate data manipulation.

REFERENCES

1. Shephard RJ. The oxygen cost of breathing during vigorous exercise. *Q J Exp Physiol Cogn Med Sci*. 1966;51(4):336–50.
2. Aaron EA, Seow KC, Johnson BD, Dempsey JA. Oxygen cost of exercise hyperpnea: implications for performance. *J Appl Physiol (1985)*. 1992;72(5):1818–25.
3. Harms CA, Wetter TJ, McClaran SR, et al. Effects of respiratory muscle work on cardiac output and its distribution during maximal exercise. *J Appl Physiol (1985)*. 1998;85(2):609–18.
4. Harms CA, Wetter TJ, St Croix CM, Pegelow DF, Dempsey JA. Effects of respiratory muscle work on exercise performance. *J Appl Physiol (1985)*. 2000;89(1):131–8.
5. Romer LM, Lovering AT, Haverkamp HC, Pegelow DF, Dempsey JA. Effect of inspiratory muscle work on peripheral fatigue of locomotor muscles in healthy humans. *J Physiol*. 2006;571(Pt 2):425–39.
6. Wilkie SS, Dominelli PB, Sporer BC, Koehle MS, Sheel AW. Heliox breathing equally influences respiratory mechanics and cycling performance in trained males and females. *J Appl Physiol (1985)*. 2015;118(3):255–64.
7. Ferris BG Jr, Mead J, Opie LH. Partitioning of respiratory flow resistance in man. *J Appl Physiol*. 1964;19:653–8.
8. Dempsey JA, Adams L, Ainsworth DM, et al. Airway, lung, and respiratory muscle function during exercise. *Compr Physiol*. 2011; 448–514.
9. Schreck S, Sullivan KJ, Ho CM, Chang HK. Correlations between flow resistance and geometry in a model of the human nose. *J Appl Physiol (1985)*. 1993;75(4):1767–75.
10. Braham S. *Phase 1 'Proof of Principle' Randomised Cross-Over Study of the Effect of a New Therapeutic Device and a Marketed Device on Nasal Airflow Rates in Normal, Healthy Adults*. East Melbourne (Victoria, Australia): Royal Victorian Ear and Eye Hospital; 2003. ASAP 1–03.
11. Fregosi RF, Lansing RW. Neural drive to nasal dilator muscles: influence of exercise intensity and oronasal flow partitioning. *J Appl Physiol (1985)*. 1995;79(4):1330–7.
12. Niinimaa V, Cole P, Mintz S, Shephard RJ. The switching point from nasal to oronasal breathing. *Respir Physiol*. 1980;42(1):61–71.
13. O'Kroy JA, James T, Miller JM, Torok D, Campbell K. Effects of an external nasal dilator on the work of breathing during exercise. *Med Sci Sports Exerc*. 2001;33(3):454–8.
14. Miller MR, Hankinson J, Brusasco V, et al. Standardisation of spirometry. *Eur Respir J*. 2005;26(2):319–38.
15. Tan WC, Bourbeau J, Hernandez P, et al. Canadian prediction equations of spirometric lung function for Caucasian adults 20 to 90 years of age: results from the Canadian Obstructive Lung Disease (COLD) study and the Lung Health Canadian Environment (LHCE) study. *Can Respir J*. 2011;18(6):321–6.
16. Benditt JO. Esophageal and gastric pressure measurements. *Respir Care*. 2005;50(1):68–77; discussion 75-77.
17. Guenette JA, Querido JS, Eves ND, Chua R, Sheel AW. Sex differences in the resistive and elastic work of breathing during exercise in endurance-trained athletes. *Am J Physiol Regul Integr Comp Physiol*. 2009;297:R166–75.
18. Dominelli PB, Sheel AW. Experimental approaches to the study of the mechanics of breathing during exercise. *Respir Physiol Neurobiol*. 2012;180(2–3):147–61.
19. ATS/ERS statement on respiratory muscle testing. *Am J Respir Crit Care Med*. 2002;166(4):518–624.
20. Borg GA. Psychophysical bases of perceived exertion. *Med Sci Sports Exerc*. 1982;14(5):377–81.
21. Simon PM, Schwartzstein RM, Weiss JW, et al. Distinguishable sensations of breathlessness induced in normal volunteers. *Am Rev Respir Dis*. 1989;140(4):1021–7.
22. Gehring JM, Garlick SR, Wheatley JR, Amis TC. Nasal resistance and flow resistive work of nasal breathing during exercise: effects of a nasal dilator strip. *J Appl Physiol (1985)*. 2000;89(3):1114–22.
23. Wheatley JR, Amis TC, Engel LA. Oronasal partitioning of ventilation during exercise in humans. *J Appl Physiol (1985)*. 1991;71(2):546–51.
24. Connel DC, Fregosi RF. Influence of nasal airflow and resistance on nasal dilator muscle activities during exercise. *J Appl Physiol (1985)*. 1993;74(5):2529–36.
25. Romer LM, Miller JD, Haverkamp HC, Pegelow DF, Dempsey JA. Inspiratory muscles do not limit maximal incremental exercise performance in healthy subjects. *Respir Physiol Neurobiol*. 2007;156(3): 353–61.
26. Tong TK, Fu FH, Chow BC. Effect of nostril dilatation on prolonged all-out intermittent exercise performance. *J Sports Med Phys Fitness*. 2001;41(2):189–95.
27. Adams CM, Peiffer JJ. Neither internal nor external nasal dilation improves cycling 20-km time trial performance. *J Sci Med Sport*. 2017; 20(4):415–9.
28. Whyte DG, Whitty A, Rice VJ. The effect of a novel mechanical nasal dilator on cycling performance. *J Sports Med Phys Fitness*. 2016; 56(7–8):949–50.
29. Chinevere TD, Faria EW, Faria IE. Nasal splinting effects on breathing patterns and cardiorespiratory responses. *J Sports Sci*. 1999;17(6):443–7.
30. Trocchio M, Fisher J, Wimer JW, Parkman AW. Oxygenation and exercise performance-enhancing effects attributed to the breathe-right nasal dilator. *J Athl Train*. 1995;30(3):211–4.
31. Baker KM, Behm DG. The ineffectiveness of nasal dilator strips under aerobic exercise and recovery conditions. *J Strength Cond Res*. 1999;13(3):206–9.
32. Case S, Redmond T, Currey S, Wachter M, Resh J. The effects of the breathe right® nasal strip on interval running performance. *J Strength Cond Res*. 1998;12(1):30–2.
33. Overend T, Barrios J, McCutcheon B, Sidon J. External nasal dilator strips do not affect treadmill performance in subjects wearing mouthguards. *J Athl Train*. 2000;35(1):60–4.
34. Thomas DQ, Bowdoin BA, Brown DD, McCaw ST. Nasal strips and mouthpieces do not affect power output during anaerobic exercise. *Res Q Exerc Sport*. 1998;69(2):201–4.
35. Nunes V, Barbosa D, Damasceno W, et al. External nasal dilator strip does not affect heart rate, oxygen consumption, ventilation or rate of perceived exertion during submaximal exercise. *J Exerc Physiol Online*. 2011;14:11+.
36. Griffin JW, Hunter G, Ferguson D, Sillers MJ. Physiologic effects of an external nasal dilator. *Laryngoscope*. 1997;107(9):1235–8.
37. Portugal LG, Mehta RH, Smith BE, Sabnani JB, Matava MJ. Objective assessment of the breathe-right device during exercise in adult males. *Am J Rhinol*. 1997;11(5):393–7.
38. Pujol TJ, Langenfeld ME, Hinojosa JR, Iman WH. Effects of an external nasal dilator strip on differentiated ratings of perceived exertion. *Percept Mot Skills*. 1998;86(3 Pt 2):1153–4.
39. Bourdin M, Sallet P, Dufour AB, Lacour JR. Influence of changes in nasal ventilation on estimated workload during submaximal field running. *J Sports Med Phys Fitness*. 2002;42(3):295–9.
40. O'Kroy JA. Oxygen uptake and ventilatory effects of an external nasal dilator during ergometry. *Med Sci Sports Exerc*. 2000;32(8):1491–5.