SHORT COMMUNICATION

Breathing through a diving snorkel; theory and experiment of air flow resistance and cost of breathing

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ABSTRACT

The snorkel allows a surface swimmer to observe the underwater world through the face mask without being disturbed by inhaling. The effect of a snorkel on breathing resistance and cost is widely held to be substantial. This study aims to model these parameters and to measure indirectly the actual increases. Further, resistances of differing designs and dimensions were assessed and recommendations were made concerning use and choice.

Maximal voluntary ventilation in 12 seconds (MVV12) was measured in 19 volunteers seated on dry land with and without a classic J-type snorkel (inner diameter 20.5 mm). The extra and total resistances and costs were calculated using the MVV12 data and using estimated airways resistance extrapolated from subject's demography and spirometric literature data.

MVV12 measurements with snorkel showed a minute volume of 152 ± 38 $L{\cdot}min^{-1}$, 6.0±3.7% lower than without snorkel ($p = 7.0x10^{-6}$). The theoretical MVV12, calculated from snorkel and airways resistances, decreased by 3.2%. Experimental total breathing resistance (457 ± 83 $Pa{\cdot}s{\cdot}L^{-1}$) was 6.5 ± 3.2% higher than without snorkel ($p = 2.6x10^{-7}$), but the total mechanical breathing cost was unaffected by the snorkel (13.58 Watts with; 13.64 Watts without). Divers' estimations of resistance increase were exaggerated (8.8% at rest, 23% swimming). Classical J-type snorkels with an inner diameter ≥19.5 mm add 3-16% resistance . There is no risk of hypercapnia.

Scuba divers are recommended to use their snorkel to breathe more comfortably on the surface. It is recommended the snorkel be made a mandatory safety accessory. The best multipurpose snorkel (19-21 mm) has no top appendages and no water release valve.

KEYWORDS laminar; turbulent; spirometry; airways; modeling

INTRODUCTION

The side-mounted diving snorkel is a bent breathing tube with a mouthpiece used by swimmers, typically while looking though a half-facemask. In addition, swim fins are used to reduce swimming effort. The facemask allows the snorkeler to continuously observe the underwater scenery and to breathe while remaining facedown at the surface. Swimming facedown with mask but no snorkel is uncomfortable. Snorkeling is also used by scuba divers on the surface, in freediving and breath-hold diving in underwater sports (e.g., underwater hockey), in pool training and in monofin swimming.

Half a century ago the snorkel was a compulsory device of the recreational diving gear, but nowadays many divers neglect to take a snorkel. A possible explanation is the assumption that a snorkel substantially increases breathing resistance.

There is extensive literature on the respiratory effects of breathing though a tube. However, these studies – for example reference [1] – examined the tubes of clinical ventilators. Because in outdated machines these tubes add a dead space of 1-1.5 liters (L), which is about five times that of a snorkel, the findings are not relevant to this study.

Although snorkel resistance is dependent on the dimensions of the snorkel, snorkels for adults do not differ much in length or inner diameter (< 8%).

The use of a snorkel or breathing tube increases $FiCO_2$ (CO_2/carbon dioxide fraction in inhaled gas) due to its dead space, which could result in hypercapnia [2,3]. Although reducing the tube diameter reduces dead space, it also increases flow resistance which in turn increases the work of breathing. This may result in a hypercapnic effect reducing the advantage of the smaller dead space. In this study hypercapnia is addressed only in passing, the focus being on resistance, ventilatory capacity and breathing expenditure.

This study aims to quantify the snorkel's flow resistance and its effect on respiratory cost for a large range of respiratory minute volumes (RMV). This resistance and extra breathing cost were calculated using a physical model for laminar and for turbulent flow. The calculations used both hypothetical low and intermediate flows, as well as actual flows which were obtained from maximal voluntary ventilation (MVV) of volunteers measured by spirometry.

When a snorkel has a substantial resistance compared to that of the airways one would expect a substantial reduction in MVV. It is assumed that in an MVV experiment with snorkel (WiSn) and without snorkel (NoSn) the total cost of breathing is the same. Then, using the calculated snorkel resistance and an estimated airways resistance, the decrease in MVV WiSn – as opposed to NoSn – can be predicted. This prediction is tested by comparison with the actual decrease obtained by dry spirometric measurements of the subject's MVVs.

Resistances can also be measured directly in a physical experimental setup. However, this was not considered to be beneficial in terms of accuracy (see Discussion).

Since no similar study has been previously conducted it is difficult to speculate over the contribution of a snorkel to resistance and cost of breathing.

MATERIAL AND METHODS

Theory of flow resistance and cost of breathing

Laminar and turbulent flow

To calculate the resistance of a tube, the flow-dependent Reynolds number Re should first be calculated:

(1) $$Re = 4V'\rho\pi^{-1}D^{-1}\eta^{-1}$$

where V'=flow ($m^3 \cdot s^{-1}$); D=inner tube diameter (m); ρ=gas specific mass at 28°C (the estimated average of inhaled and exhaled gas) at 1 bar (dry air), being 1.17 $kg \cdot m^{-3}$; η=dynamic viscosity (18.9 x 10^{-6} $Pa \cdot s^{-1}$ at 28°C). Laminar flow happens at Re < 2300 (with our snorkel at a stationary flow this corresponds to < 16 $L \cdot min^{-1}$). Flow is fully turbulent at Re > 2900 (flow > 24 $L \cdot min^{-1}$). In between is the transition zone.

For laminar flow of a fluid through a straight tube with length L (m) and a smooth surface Poiseuille's law applies, yielding the flow resistance:

(2a) $$R_{tube} = 128\eta L/(\pi D)^4 \ (Pa \cdot s \cdot L^{-1})$$

However, often the respiratory minute volume (RMV) is so high that the airflow in the snorkel is turbulent. With MVV, the flow in the snorkel is always fully turbulent ($Re_{snorkel}$ > 15.000). For turbulent flow the resistance of the tube is (rewritten from eq. 14 of ref. [4]):

(2b) $$R_{tube} = 2^{5/2}\pi^{-7/4}LD^{-19/4}\eta^{1/4}V'^{3/4}\rho^{3/4} \ (Pa \cdot s \cdot L^{-1})$$

The basic difference between these equations is that the latter is flow-dependent (~$V'0^{.75}$).

Flow resistance of a snorkel

A snorkel can be divided into several sections, all with measurable axial lengths, diameters and curvatures. The resistance of the straight part (R_{st}) can be calculated using (eq. 2a) for laminar flow and with (eq. 2b) for turbulence. The bends result in extra resistance that can be, expressed by the Hütte correction coefficient ζ_i with i the bend number. When calculating the resistance of each bend, R_{st} was used as the reference. The resistance of a snorkel, $R_{snorkel}$ is the sum of the resistance of the straight part and the n bends:

(3) $$R_{snorkel} = R_{st} + R_{st} \cdot \sum_{i=1}^{n}(1+\zeta_i)(L_i/L_{st})$$

where L_i is the axial length of the i-th bend. It is assumed that the flow is continuous.

The one snorkel used in all the physiological experiments by all subjects was of classic J-type design, made of rubber without appendages at the top and without a water release valve. The tip-to-tip length was 36 cm with a total axial length of L= 42.3 cm, an inner diameter of 20.5 mm and a volume of 136 mL. It comprised a straight section L_{st} of 23.8 cm, followed by three bends: a gentle bend (22.5°; L_1 13 cm; ζ_1 = 0.045), a sharp bend (60°; L_2 = 2.5 cm; ζ_2 = 0.21) and finally the rubber mouthpiece (80° bend, L_3 = 2 cm; ζ_3 = 0.7). To be able to generalize our findings we also examined a similar J-type snorkel and two J-types with a water purge valve, all with different dimensions.

Extra cost of breathing

The flow-dependent mechanical work W, of the flow through a tube is:

(4) $$W = V'^2R_{tube}$$

where R_{tube} is $R_{snorkel}$, the airways resistance R_{aw} (see below) or R_{aw} + $R_{snorkel}$. (Note: metabolic W is about 4.5 times higher.) For laminar flow the mechanical cost depends strongly on the flow ($\sim V'^2$) and even more so for turbulent flow ($\sim V'^{2,75}$; eq. 2b substituted in eq. 4). In this calculation it is assumed for the sake of simplicity that flows during inhalation and exhalation are equal. However, the flow under the MMV12 protocol is more or less sinusoidal. Integration for sinusoidal flow yields correction factors of 0.974 and 1.47 for resistance and cost respectively (yielding $R'_{snorkel}$ and $W'_{snorkel}$).

Demographic model of airways resistance

To calculate R_{aw} we used a demographic model based on the functional residual capacity (FRC): FRC = 0.0021·age + 0.4) TLC, where TLC is total lung capacity; TLC = 10.67 · height (in meters) – 12.16 (L) and TLC = 7.81 · height – 7.88 (L) for males and females, respectively [5]. Finally, R_{aw} can be calculated from thoracic gas volume TGV (TGV ≈ FRC): $R_{aw,30}$ = 400TGV^{-1} Pa·s·L^{-1}, defined for RMV = 30 L·min^{-1} [6,7]. Under our conditions, the airflow in all the airways, including the mouth and glottis (excluding the smallest bronchioles which hardly contribute to R_{aw}) is always turbulent. Hence, it holds that:

$$R_{aw,V'} = R_{aw,30}\ (V'/30)^{0.75} \quad (5)$$

V' (L·s^{-1}) can have any value, e.g., MVV12 (MVV measured in 12 seconds). Applying (eq. 5) to the data of each subject and next averaging gives the mean $R_{aw,MVV12}$. For RMV < 16 L·min^{-1} (eq. 5) was corrected, since the flow in a progressively larger part of the airways becomes laminar when the flow is reduced further.

Assuming that breathing costs under both conditions (WiSn and NoSn) are exactly the same, $V'_{snorkel}$ of MVV12 can be calculated using (eq. 4) – two times – as the values of the variables on the right of the new equation are known:

$$V'^{2}_{snorkel} = V'^{2}_{without} \cdot R_{aw,without} / (R_{aw,s} + R'_{snorkel}) \quad (6)$$

where $R_{aw,s}$ is R_{aw} when using a snorkel. The results were compared with the actual measured flow (MVV12) when using the snorkel.

Applying (eq. 4) for $R_{aw,V'}$ gives the estimated mechanical cost of breathing through the airways.

Experimental methods

The study was approved by the Medical Ethical Committee of the University of Amsterdam (WMO, 2012; Project W18_022, Decision #18.033) and the subjects signed an informed consent. The experimental part of this study was performed before 2020.

Demographics of the spirometry subjects were: 13 male and six female divers; age 45 ± 16 years; height 179 ± 9 cm; BMI 25 ± 2.7 kg/m^2. All had experience with snorkeling.

A short questionnaire (Quest1) was presented to dive physicians asking them to estimate the relative difference in breathing resistance between the conditions WiSn and NoSn for a theoretical swimmer who is swimming moderately fast (turbulent flow in snorkel). The same question was asked for a resting subject (laminar flow in snorkel). In another short questionnaire (Quest2) we asked divers whether they leave their snorkel ashore while scuba diving and if so why.

MVV12 requires an optimal choice of tidal volume (TV) and breathing frequency. This was determined by one or two tryouts. The subjects (sitting, nose clip) performed MVV12 attempts (alternating WiSn and NoSn) until three of each condition were deemed acceptable by visual evaluation; individual volume-versus-time breathing cycles recorded during 12 seconds had to be similar in shape. The highest value of the three of each condition was used, which is actually the maximum RMV. The tip of the rubber snorkel (used by all subjects) was press-fitted into the spirette of an Easy PC spirometer (NDD Medical Technologies). To ensure a close fit, spirette and snorkel were held firmly together by the right hand of the subject. Any leakage would have been negligible, and none was observed (leakage area a few mm^2 at most; inner cross section of snorkel 330 mm^2).

Analysis of the data of MVV12, resistance and breathing cost was performed using the (paired) Student's t-test; p ≤ 0.05 (two-tailed) was considered significant. Normality was checked with the Shapiro-Wilk test.

RESULTS

The questionnaires

Eighteen diving physicians answered Quest1.Their estimation of the increase in flow resistance caused by the snorkel at rest was 8.8% (median, range 0-100%) and while swimming 23% (12-300%; five respondents ≥50%). Quest2 showed that 24% of the respondents leave their snorkel at home (n=23). Reasons given were: it gets in the way; it was lost; it serves no purpose. However, observation of divers in the Red Sea (Egypt) by ourselves and two instructors gave a higher estimate, approximately 75%, suggesting that Quest2 is strongly biased.

The model

According to (eq. 2b) and (eq. 3) $R'_{snorkel}$ of our snorkel with turbulent flow was (after rewriting for the dimensions and for sinusoidal flow):

$$R'_{snorkel} = 1.11 \cdot RMV^{3/4} \text{ Pa·s·L}^{-1}. \quad (7a)$$

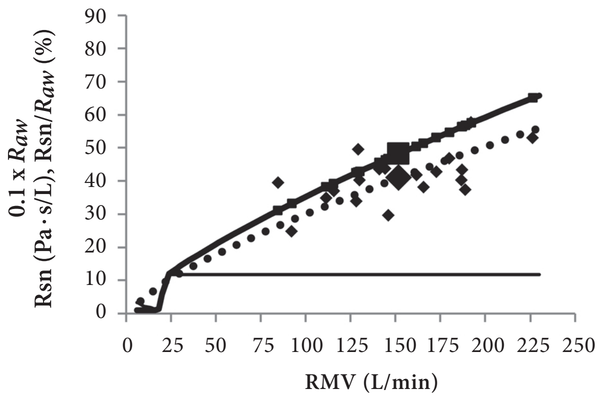

FIGURE 1

Rsn, $R'_{snorkel}$ (thick curve);
R_{aw}, airways resistance with snorkel (one tenth; stippled curve);
RMV respiratory minute volume;
Rsn/R_{aw} (thin curve) versus RMV;
small squares: individual $R'_{snorkel}$;
large square: mean $R'_{snorkel}$;
small diamonds: individual $R_{aw,s}$ with snorkel;
large diamond: mean $R_{aw,s}$

Table 1

	MVV12	air flow resistances calculated from MVV12	
	($L·min^{-1}$)	($Pa·s·L^{-1}$)	
WiSn	151.7 ± 37.5	$R_{aw,s} + R_{snorkel}$	457.1 ± 83
		$R_{aw,s}$	409.3 ± 77.3
NoSn	161.3 ± 38.7	R_{aw}	429.0 ± 75.5
difference %	-6.0 ± 3.7	difference%*	6.5 ± 3.2
p-value	7.0×10^{-6}	p-value	2.6×10^{-7}

MVV12 and airways resistance R_{aw}, R_{aw} with snorkel $R_{aw,s}$ and $R_{snorkel}$ calculated from the 19 measured MVV12s

* Between $R_{aw,s} + R_{snorkel}$ and R_{aw} (NoSn)

The bends in the snorkel appear to contribute 6% of its resistance. This small fraction allows a rough estimate of the resistance of any J-type snorkel (no top appendages) with inner diameter D:

(7b) $R'_{J\text{-type snorkel}} = 2 \cdot 10^6 \cdot D^{-4.75} \cdot RMV^{3/4}$ $Pa·s·L^{-1}$
(here D in mm).

Figure 1 shows $R'_{snorkel}$ (upper curve, (eq. 2)) and R_{aw} (middle curve; mean subject demography) as a function of RMV together with $R'_{snorkel}$ and R_{aw} of the individual subjects (data points). Their means resulted in the values given in Table 1. The MVV12 WiSn ranged from 84 to 226 $L·min^{-1}$, a ventilation much higher than during recreational snorkeling, typically some tens of liters per minute. With turbulence, the resistance increase of WiSn compared with NoSn was 6.5% (Table 1). Assuming equal breathing costs for WiSn and NoSn, applying (eq. 4) yields a theoretical flow difference of 3.2%, whereas 6.0% was measured. The mean $R'_{snorkel}$ calculated from the 19 MVV12s is 47.9 ± 9.0 $Pa·s·^{-1}$.

The other J-type snorkel yielded a 14% higher resistance than the snorkel used in the experiment, mainly due to a 1.0-mm smaller diameter. The two J-types with a purge valve had a 38% higher resistance caused by a smaller diameter, greater length and a very sharp bend near the mouthpiece due to the purge valve. A further eight other J-types, most with a purge valve, had a mean diameter of nearly 20.0 mm. Their resistances should be similar to the previous four.

For any laminar flow $R'_{snorkel}$ is the same. With RMVs at rest, $R'_{snorkel}$ is 3.4% of R_{aw} and for intermediate flows it finally increases to 11.8% (lower curve Figure 1; or 10.5% of total R) when turbulence is reached.

For laminar flow in the snorkel, the extra mechanical cost of breathing is virtually nil (< 0.001 W), but the cost progressively increases when the flow becomes turbulent (Figure 2). At RMV = 226 $L·min^{-1}$ (the highest MVV12 found) it is 5.6 W. Figure 2 gives the airways' cost (bold curve) and the cost due to the snorkel (dashed curve), both as a function of RMV. In Figure 2, both curves cover a range of a factor of 10,000. The average cost of MVV12-breathing calculated from all subjects with (eq. 4) yields 13.64 W for NoSn (illustrated by the large dot in Figure 2) and 13.58 W for WiSn, 0.4% less (p=0.90) (the thick horizontal dash). This small and insignificant difference is not surprising, since the subjects were asked to breathe with maximal effort both with and without snorkel.

Using eq.(6) the mean $V'_{snorkel}$ of MVV12 was predicted to be 155.0 L/minute, 2.1% more than the mean of the subjects (Table 1).

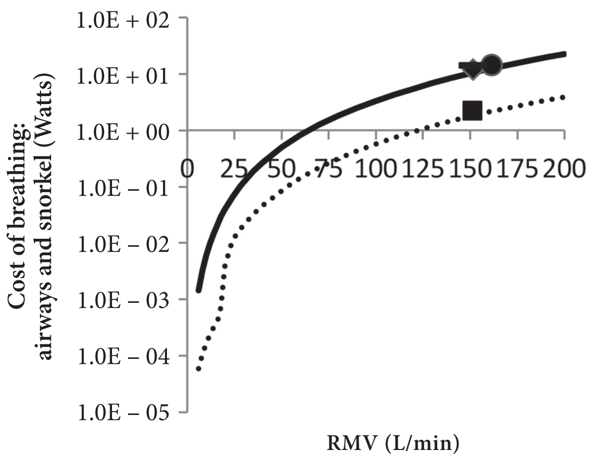

FIGURE 2

Mechanical cost of breathing of airways (drawn curve) and snorkel (stippled curve).
RMV respiratory minute volume.
Square: the subjects mean snorkel cost ($W'_{snorkel}$) at the subjects mean MVV12 with snorkel.
Diamond: similarly airways cost with snorkel.
Thick horizontal dash: sum of both.
Round spot: cost without snorkel.

DISCUSSION

Our calculations suggested that the 20.5-mm snorkel increases breathing resistance during laminar flow between 1.3 and 3.0% ($R'_{snorkel}$ constant; R_{aw} flow-dependent), and during turbulent flow by 11.7%. The actual extra resistance, as shown by the MVV12 experiments was 6.5%. In contrast, Quest1 resulted in a resistance increase of 23%. Hence, the notion that a snorkel substantially increases breathing resistance is exaggerated.

With relaxed diving in warm water, air consumption is about 15 ambient L·min^{-1} [8]. Assuming that with relaxed snorkeling the consumption is < 15 L·min^{-1}, the flow in the snorkel is laminar and the extra cost practically nil. With an RMV of 15 L·min^{-1}, the swimming speed with scuba is estimated to be ca. 7 m·min^{-1}, which amounts to a total metabolic expenditure of 140 W. (These estimates are based on theory and data in references [8-10]). Therefore, with low to moderate speed $W'_{snorkel}$ is negligible. This also holds for the other snorkels we modeled. Even with turbulent flow the total cost of breathing is always much less (<10%) than the energy expenditure of the whole body. An RMV of 30 L·min^{-1} (turbulent flow) will allow a snorkeling speed of a diver of 20 m·min^{-1}, as extrapolated from reference [8]. This is unlikely to result in fatigue of the respiratory muscles. With scuba, fatigue is likely only with a much higher ventilation, e.g., 48 L·min^{-1} (speed 34 m·min^{-1}) [9].

A number of findings suggests that theory – i.e., resistance and cost models and experiments agree.

1. **Resistance.** The WiSn versus NoSn modeled breathing resistance resulted in a theoretical MVV12 difference of 3.2% whereas the measured resistance difference from MVV12 data was 6.5% (Table 1).
2. **Flow.** The prediction of MVV12 with the snorkel (155 L·min^{-1}) was only 3.0% larger than the measured value.
3. **Cost.** The MVV12-cost of breathing with and without snorkel do not differ.

Dimensions of snorkels and other types

At present, for adults the various standards of dive organizations prescribe a minimal inner diameter of 18 mm (resistance +74% compared to 20.5 mm snorkel of same length) and a maximum of 23 mm (-39%) [11,12]. Based on a balance between resistance and dead space volume we consider 18 mm as being too narrow and 23 mm as too wide for normal use (increased force to release water; hypercapnia is addressed in the next subsection). Streamlined tubes can have even smaller diameters. Nowadays, most types have an inner diameter of 19.5-20.0 mm. For these snorkels without any top appendage the conclusions of our study remain unchanged. With turbulent flow, those with an inner diameter of 19 mm have a 28% higher resistance than a 20-mm snorkel.

Also modeled was a peculiar snorkel with a purge valve, a soft, wide and flexible lower tube (22 mm), a hard plastic upper section (17 mm) and two narrow axial slits at the top with a severe diameter reduction (to induce the Venturi effect). Its resistance was at least twice as large as the 20.5-mm snorkel, so the extra cost will be substantial. Therefore this type is advised against. Many modern snorkels have all kinds of top appendages (e.g., wave deflectors, splash guides, "dry snorkels" or slits). Nearly all have a water release valve near the mouthpiece. An experienced snorkeler does not need these attributes, but they may be helpful to novices. All these attributes increase the resistance since they disturb laminar flow or increase turbulence. The marketing of snorkels with top-appendages seems to be mainly based on commercial considerations. To open a release valve, the expiration must be quite explosive and only a small amount of the expired gas leaves the snorkel through the valve: With normal expiration all gas leaves through the tube. Valves may also leak or fail altogether, which makes the J-type without a valve more reliable. This is possibly the reason why many, for instance underwater hockey players, prefer a valve-less snorkel. Elite swimmers show superior lung function compared to controls (forced vital capacity, forced expiratory volume for one second and peak expiratory flow are larger) [13] and consequently would have lower R_{aw} and therefore need low-resistance snorkels (shorter and wider). For any J-type (no top appendages) an estimate of $R'_{snorkel}$ (RMV) can be calculated with (eq. 7b) and for R_{aw} (RMV) with (eq. 5). From laminar to turbulent flow the $R'_{snorkel}/R_{aw}$ ratios of the four modeled snorkels cover a range of 0.03 to 0.16.

Hypocapnia and hypercapnia

Use of a snorkel increases $FiCO_2$ (CO_2 fraction in inhaled gas), which in turn increases $FeCO_2$ (CO_2 fraction in exhaled gas). The latter has been measured at rest and during exercise with a tube volume of 600 mL, which is about twice the airways volume [2]. However, $FeCO_2$ increased only by 10-20% depending on the subject's experience and the conditions [2].

With our snorkel volume of 136 mL and an airways volume of 320 mL, the increase in dead space is 43%. With high tidal volumes – for instance 1.7 L as found in the MVV12 experiments and assuming a complete mixing of freshly inhaled air and end-tidal gas – the rate of refreshment is 73% with and 81% without snorkel. As a result, with a supposed end-tidal $FeCO_2$ (CO_2 fraction in exhaled gas) of 5% (50 hPa), PCO_2 of the gas entering the alveolar space will increase slightly from 9.8 (NoSn) to 13 hPa (WiSn) (0.42 hPa in atmospheric air accounted for). With a NoSn-TV of 750 mL at rest, $FiCO_2$ is theoretically 15 hPa. Surprisingly, this is 15% more than with the snorkel when tidal volume is 1.7 L. Based on material from various sources it appears that snorkeling at the surface is likely to be performed with TVs of 1-1.5 L and RMVs up to 30 $L \cdot min^{-1}$. Therefore hypercapnia will not occur and consequently RMV will be unaffected. In our MVV12 experiments, $FeCO_2$ is expected to be less than 5% since the subjects were hyperventilating heavily (low O_2 consumption; sitting). Moreover, hypercapnia is impossible, since 12 seconds is far too short for this to occur.

In conclusion, hypocapnia rather than hypercapnia can be expected in MVV12 experiments; the general belief that normal snorkeling could result in hypercapnia is questionable. Snorkelers on the surface stand no risk of clinical hypercapnia as long as they follow the rule "deep in and deep out" to maximize TV.

The use of the snorkel by scuba divers

From Quest2 and even more clearly from observations in the field, it appears that many scuba divers leave their snorkel ashore. Yet, recreational divers often have to swim extended distances on the surface before descending and again after surfacing to reach the shore or their boat. A benefit of snorkeling is that it saves gas from the tank, and this study shows that swimming with a snorkel has a low extra breathing cost.

Swimming with scuba gear at the surface while breathing ambient air without a snorkel requires the head be lifted out of the water over and over again for breathing and orientation. Quite likely, snorkeling can conserve energy by requiring the head to be lifted only occasionally for orientation, especially in surf and swell.

Limitations

Our subjects were seated. However, when in water, the total breathing cost increases, even when floating on the surface. But the cost-contribution of the snorkel remains the same: It is only a function of flow, irrespective of the conditions of the breathing subject. In a subsequent study the kinematics and hydrodynamics of a swimmer with and without snorkel will be investigated and the difference in cost between snorkeler and swimmer will be modeled and experimentally tested.

Snorkelers are in prone position. The prone position on dry land is uncomfortable and the exact body position (arms, head) is hard to control, resulting in unreliable measurements. Although in a sitting position MVV12 is slightly larger [14], absolute MVV12 values are not of primary concern.

The snorkel resistance was modeled and not measured directly. With flows from 6 to 225 $L \cdot min^{-1}$ resistances range from 1.0 to 64 $Pa \cdot s \cdot L^{-1}$. This implies pressure differences between mouthpiece and tip from 0.2 to about 490 Pa. Ultra-low differential pressure transducers have an accuracy of 0.5-10 Pa (depending on range). Low-flow transducers have errors of 2%. Together, the error in resistance would range from approximately 4% (highest flows) to >100% (lowest flows). Therefore, this method of measuring snorkel resistance is not suitable.

The accuracy of the snorkel model of (eq. 2a) (laminar flow) is intrinsically high, due to its robust physics. The exponent 0.75 of V' in (eq. 2b) (turbulent flow) is empirical and therefore less robust, but it is used to calculate both $R'_{snorkel}$ and R_{aw} (eq. 5), so does therefore not affect their ratio. A measurement error of 1% (0.2 mm) in diameter does however give an error of 5% in $R'_{snorkel}$ (turbulent), which may increase the maximal $R'_{snorkel}/R_{aw}$ ratio to 17%. The demographic R_{aw} model yielded a mean R_{aw} of 124 Pa·s·L^{-1} for an RMV of 0.5 L·s^{-1}, which is close to classical plethysmographic data (Dubois et al. [15]).

We did not examine full face masks with the integrated snorkel. The reader is referred to reference [16]. Only those masks with completely separated in- and outgoing gas-ways are generally safe, although the technology is a little vulnerable (valves, cleaning, long face seal) and a little bulky.

CONCLUSIONS

Comparison of theory and measurements shows that the resistance model of the snorkel appears to be valid. A questionnaire confirmed the general belief, that the resistance of a classic snorkel (no top appendages) is substantial. This study shows this to be incorrect regardless of the conditions.

The physics and reliability of the J-type without purge valve is superior to any other type. For observing the biotope, flows are so low that even snorkels with diameters <19 mm and all kind of appendages will work, provided the conditions are ideal (calm sea and hardly any current) since hypercapnia can reasonably be excluded. However, such snorkels are not suitable under more challenging conditions and for other purposes. A multipurpose snorkel (biotope exploration, pool training, underwater sports, diver gear) should have an inner diameter of at least 19 mm.

A snorkel allows a scuba diver to breathe with less effort while swimming at the surface, particularly under difficult conditions. In an emergency, this can be lifesaving. It is therefore recommended that the snorkel be made a mandatory piece of equipment for every scuba diver.

■

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Conflict of interest statement
The author declares that no conflict of interest exists with this submission.

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