Is the New AquaTrainer® Snorkel Valid for VO_2 Assessment in Swimming?

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Key words
- respiratory valves
- K4b^2
- oxygen consumption
- energetics

Abstract

The Cosmed AquaTrainer® snorkel, in connection with the K4b^2 analyzer, is the most recent instrument used for real time gas analysis during swimming. This study aimed to test if a new AquaTrainer® snorkel with 2 (SV2) or 4 (SV4) valves is comparable to a standard face mask (Mask) being valid for real time gas analysis under controlled laboratory and swimming pool conditions. 9 swimmers performed 2 swimming and 3 cycling tests at 3 different workloads on separate days. Tests were performed in random order, at constant exercise load with direct turbine temperature measurements, breathing with Mask, SV4 and SV2 while cycling, and with SV2 and SV4 while swimming. A high agreement was obtained using Passing – Bablok regression analysis in oxygen consumption, carbon dioxide production, tidal volumes, pulmonary ventilation, expiratory fraction of oxygen and carbon dioxide, and heart rate comparing different conditions in swimming and cycling. Proportional and fixed differences were always rejected (95% CI always contained the value 1 for the slope and the 0 for the intercept). In conclusion, the new SV2 AquaTrainer® snorkel, can be considered a valid device for gas analysis, being comparable to the Mask and the SV4 in cycling, and to the SV4 in swimming.

Introduction

The analysis of oxygen uptake (VO_2) during exercise is a common practice in sport physiology. Historically, the Douglas bag method was used to analyze gas exchange, collecting exhaled air in impermeable canvas later analyzed as gas fraction [7]. Until the 1990s, the VO_2 during swimming, in the flume, with pulley system, or freely swimming in a pool, was assessed directly using a Douglas bag or a mixing chamber analyser [6,15,16,31] or indirectly using a backward extrapolation method [19]. At the beginning of the 1990s, the portable Cosmed K2 telemetry gas analyzer (Cosmed K2, Italy) allowed direct gas analysis through the use of a face mask, a flow meter, and an O_2 gas analyzer. The system was considered accurate for cardiopulmonary analysis compared to the Douglas bag method (showing a measurement error less than 2%) [17] and to the conventional stationary gas analyzer [4,24]. A few years later, the Cosmed K4 was designed, and later upgraded to the K4b^2 portable telemetry system to obtain BxB measurement (Cosmed K4b^2, Italy) of cardiopulmonary parameters including both O_2 and CO_2 analysis. The instruments revealed a good accuracy at different exercise intensities, thus proved to be a valid measurement for gas exchange [8,9,14,21]. In fact, K4b^2 has been frequently used in swimming, in connection with a snorkel device, to assess VO_2 on-kinetics in rectangular and graded protocols [26,27].

To evaluate the energetic cost of swimming, snorkel devices had been used to collect O_2 and CO_2 in the swimming pool [15,25,30]. Toussaint et al. [29] firstly validated a snorkel and a valve system, with reduced drag and a dead space of 30 ml, to collect expired air in Douglas bags during swimming. A few years later, Dal Monte et al. [5] designed a snorkel and valve system in carbon fibre with a frontal single tube improving the hydrodynamics in flume conditions. The authors reduced the dead space by 15 ml and connected this apparatus to a miniaturized telemetry system for VO_2 measurements. More recently, Keskinen et al. [18] upgraded the snorkel of Toussaint et al. [29] adapting it to the K4b^2 (Cosmed S.r.l., Rome, Italy) for real time measurements. They claimed it was a valid instrument for breath-by-breath (BxB) analysis being in line with the standard face mask, but reporting a moderate

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difference (3–7%) in the respiratory and gas exchange values [21]. Later, Rodriguez et al. [28] drew similar conclusions testing a smaller and a larger volume snorkel in comparison with the direct turbine connected to a gas exchange simulator. In fact, both devices were considered valid to measure pulmonary BxB gas exchange parameters, but the regression analysis reported a somewhat larger deviation in VO_2 (7%) and VCO_2 (3%). Similar results were obtained by Gayda and colleagues [11] who by comparing the snorkel AquaTrainer® and $K4b^2$ system to the standard face mask during a cycling test, observed a difference in VO_2 of ~15%. Therefore, they categorized the AquaTrainer® system as not acceptable for field-testing when compared to the standard face mask; this study rose a debate about the validity of the instrumentation, pointing out the necessity to take into account some technical notes when the AquaTrainer® device is used in conjunction with the $K4b^2$ [3,12].

To improve the measurement of VO_2 assessment in swimming field condition, a new Cosmed AquaTrainer® snorkel was developed. This prototype presents some upgrades aiming to reduce gas mixtures, resistances and air turbulence while breathing, by means of a diminished dead space, 2 flexible but not stretchable tubes with larger diameter and shorter length, Hans-Rudolf valves with a larger diameter, and a smooth internal valves assembly surface. Moreover, to improve comfort during swimming, structural modifications including a soft and oval mouthpiece, a flexible head connection, and flexible but underwater stable tubes were utilized.

The main purpose of the present study was 2-fold: a) to establish if the new Cosmed AquaTrainer® system is proper for VO_2 assessment, comparing it to the commonly used standard face mask; b) to compare the standard 2 valves AquaTrainer® with a 4 valves configuration in order to detect the agreement between systems.

Materials and Methods

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9 active swimmers (4 male and 5 female, age 24.3±6.2 and 25.2±5.3 years, respectively) voluntary participated in this study. All the subjects were healthy athletes regularly exercising at least 3 times a week in the last year and occasionally or regularly competing in regional events. Anthropometric measures (height and body mass) of males and females were 180±2 and 165±4 cm and 72.8±2.5 and 57.8±3.6 kg, respectively. Written informed consent was obtained from all subjects and the protocol was approved by the local Ethic Committee. This study has been performed in accordance with the ethical standards of the International Journal of Sports Medicine [13]. All subjects had previous experience of VO_2 measurements in swimming using different types of snorkels, and were encouraged to subjectively compare the comfort offered through the new prototype when compared to past models. After swimming with the new AquaTrainer® snorkel, subjects were individually interviewed to ask if there were any differences in comfort in comparison with the models previously experimented, and then invited to describe eventual perceived differences.

Study design

On different days, subjects underwent 2 exercise protocols: one in a 25 m swimming pool (depth 1.90 m, water temperature 27 °C, constant ambient temperature 28 °C, 50% humidity, and ventilated environment), and the other on a cycle ergometer (Monark 928E testing ergometer). The swimming and cycling protocols consisted of 2 and 3 exercise sessions, respectively, separated by 24–48 h. Each session was composed of 3 constant exercise bouts: the first 2 performed at low or moderate intensity with a brief interval in between, and the third, after 15 min of complete recovery, was performed at high intensity (▶ **Fig. 1**). Each exercise bout was performed in a different condition: with the AquaTrainer® prototype with 2 (SV2) and 4 valves (SV4), and with a standard face mask (Mask). During the swimming test subjects performed 2 exercise sessions in 2 conditions (SV2 and SV4) (▶ **Fig. 1a**), and during cycling 3 sessions and all 3 conditions were used (▶ **Fig. 1b**). Conditions were randomly assigned between, and within, each exercise session. Subjects were asked to abstain from smoking and consuming alcohol or caffeine, 48 h prior to exercise testing, and to avoid strenuous exercise 12 h prior to exercise testing.

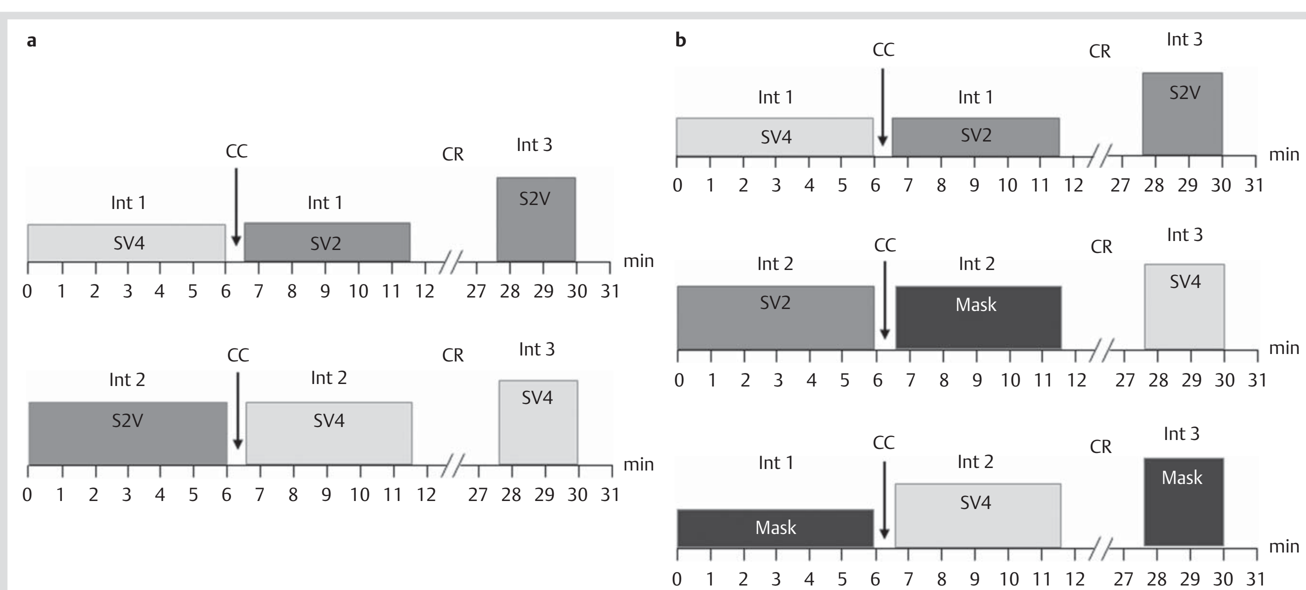

Fig. 1 Exercise protocol **a** swimming pool and **b** on a cycle ergometer performed with an AquaTrainer prototype with 2 (SV2) and 4 valves (SV4), and with a standard mask (Mask) at 3 different intensities (Int 1: low intensity, Int 2: moderate intensity, Int 3: high intensity). CC, Change Condition; CR, Complete Recovery.

Exercise tests

Before the first test session, subjects were familiarized with the instruments and underwent a test to establish the swimming velocity at the individual lactate threshold using a single-session 7×200 m (30 s rest interval) intermittent incremental protocol [10]. Therefore the moderate exercise intensity was the step velocity immediately before the individual lactate threshold, and the low exercise intensity was the velocity 15 % lower than individual moderate velocity. To identify the high exercise intensity, the step velocity corresponding to maximal oxygen consumption was used to test the subjects in a 250 m bout. The individual low, moderate and high intensities of the cycling test were established extrapolating from the modified Astrand-Ryhming nomogram [1] the power value (in W) corresponding to the VO_2 of each individual exercise intensity in swimming. During the swim tests, subjects swam using the front crawl technique at a constant velocity at either an individual low intensity (ranging from 0.7 to 1.0 m/s), moderate intensity (ranging from 0.8 to1.1 m/s), or high intensity (ranging from 0.95 to 1.33 m/s). During the cycle tests, subjects pedalled at a constant frequency of 60 rpm at 50–100, 100–150 and 175–275 W for the low, moderate and high intensities, respectively. To keep the exercise intensity constant, subjects used a visual pacer which was placed on the bottom of the pool (TAR. 1.1, GBK-electronics, Aveiro, Portugal) when swimming, or the cycle ergometer display when cycling. The exercise intensity during both swimming and cycling tests was further controlled between and within exercise bouts through blood lactate (Lactate Pro, Arkay, Inc, Kyoto, Japan), VO_2 and HR.

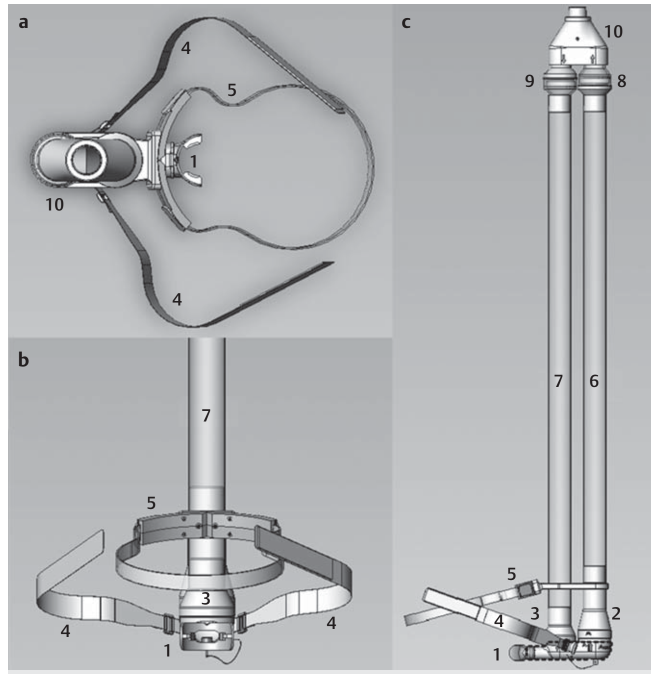

Fig. 2 Upper **a**, frontal **b** and lateral **c** (dead space delimited in dotted line) representation of the AquaTrainer® prototype system. 1 = Mouthpiece, 2 = lower expiration valve, 3 = lower inspiration valve, 4 = neck connection, 5 = head connection, 6 = expiration tube, 7 = inspiration tube, 8 = upper expiration valve, 9 = upper inspiration valve, 10 = connection tubes unit.

Gas analyzer, calibration and setting

To obtain valid and accurate data, standardized turbine (3 L), gas (ambient air with 20.94 % O_2 and 0.03 % CO_2, and reference gas mixture with 16.0 % O_2 and 5.0 % CO_2) and delay calibration procedures were performed before each test according to the manufacturer's recommendations (see "$K4b^2$ user manual" Cosmed Ltd., 2011: 44–47), and a dry gas sampling line was used for each test. Atmospheric pressure and ambient temperature were measured by the $K4b^2$ portable unit and relative humidity was measured and manually reported to the $K4b^2$ before each test. At the end of each exercise bout, temperature at the turbine was measured with an infrared thermometer (infrared thermometer, Kramer, Med.Ico). Temperature was sampled 3 times and averaged to obtain the final value. Respiratory gas exchange was detected BxB with a portable telemetric gas analyzer (Cosmed $K4b^2$, Cosmed, Italy) in both swimming and cycling conditions. Heart rate (HR) was detected by a polar HR belt, and transmitted to the $K4b^2$ portable unit. Expired gases were sampled at the turbine through a semipermeable Nafion sampling line (0.75 m in length), and analyzed into the Cosmed $K4b^2$ portable unit through O_2 and CO_2 analyzers. All data were also transmitted by telemetry from the Cosmed $K4b^2$ portable unit to a personal computer and controlled in real time.

AquaTrainer® system

The new AquaTrainer® prototype (▶ **Fig. 2**) presented many structural upgrades to improve accuracy of measurements and comfort in usage. This device was developed with the cooperation of the Fast Prototyping Unit of the Engineering Faculty of the University of Porto (INEGI), Portugal. Differences between this prototype and the model of Keskinen et al. [18] include upgrades such as: 1) more flexible but not stretchable canalization tubes (constant distance and volume between the mouthpiece and the turbine); 2) smoother inner surfaces of the inspiratory and expiratory tubes (intending to improve internal flow dynamics); 3) shorter expiratory and inspiratory tubes; 4) a system to balance both tubes in a underwater stable position was included; 5) the dead space at the valves assembly, considered by other authors as the space between the mouthpiece and the lower inspiratory and expiratory valves [5,28,29], was reduced to 11.3 ml; 6) the mouthpiece shape is oval instead of circular for better adjustment to the conformation of the mouth, 7) the valves (Hans-Rudolf) are of different configuration and dimension (35 mm in diameter compared to the previous 28 mm); 8) shorter canalization tubes (from 128 cm to 86 cm); 9) the head connection support is softer, flexible and better anatomically oriented, and 10) a system to drain the internal fluids accumulated into the valves assembly during tests was included. The AquaTrainer® prototype has been designed to add or remove the upper valves to test the snorkel device with 2 and 4 valves. The SV2 model includes only the inspiration and expiration lower 2 valves while the SV4 model includes also the upper inspiration and expiration ones to prevent mixtures between inspiratory, expiratory and ambient air. Different from the old AquaTrainer®[11], the new model presents some upgrades: a) the tubes of canalization are convoyed in a unique connector attached to the turbine so that the $K4b^2$ software automatically discerns the in/ex by the shift of the turbine spin; b) in order to reduce the internal resistances, the expiratory tube is shorter (from 196 cm to 86 cm) and the inspiratory tube is longer (from 55 cm to 86 cm), being now of the same length, and both were enlarged (from 28 mm to 35 mm) counting a volume of 847 ml from the mouthpiece to the turbine; c) it uses an open support instead of a closed briefcase to contain the $K4b^2$ portable unit (see "Tips and suggestion on how to use AQUATRAINER" Cosmed Ltd., 2005: 9–11), which prevents from overheating and samplings of stale air if auto-calibration is used; d) the HR receiver is now waterproof and positioned at the mouthpiece level attached to the tubes of canalization being within the HR detection area, reducing the risk of signal interferences; e) the internal surface of the snorkel valves assembly (which includes the mouthpiece and the first set of valves) is more smooth in order to reduce turbulence of the air while breathing (data not reported in this paper); f) to improve the comfort in usage, the mouthpiece shape is oval instead of circular for better adjustment to the conformation of the mouth, and the head connection support is more soft and flexible.

Treatment of data

BxB data of each test were reduced by excluding errant breaths caused by swallowing, coughing or signal interruptions once they were considered too different from the real kinetics. Values greater and lower than 4 standard deviations from the local mean were omitted [22]. The last 3 min of each step were smoothed at 6 breaths, and then averaged at 30 s for low and moderate exercise intensities, and at 15 s for the high intensity, using the averaging function of the Cosmed analysis software. The temperature of the expired air detected at the snorkel turbine was reported a posteriori to the Cosmed software to adjust volumes. Different from the standard procedure, which requires the use of the ambient temperature, we used the temperature of the expired gas instead of the ambient air.

Statistical analysis

Agreement between different conditions in swimming (SV2 vs. SV4) and cycling (SV2 vs. Mask, SV4 vs. Mask, SV2 vs. SV4) was evaluated for VO_2, carbon dioxide production (VCO_2), tidal volumes (V_T), pulmonary ventilation (V_E), expiratory fraction of oxygen (F_EO_2) and carbon dioxide (F_ECO_2), and HR by Passing-Bablok regression analysis (MedCalc Software, ver. 11.6, Mariakerke, Belgium). The agreement between couples of conditions within each test was performed with Bland-Altman analysis using an ancillary software. Pearson's coefficient of determination (R^2) was computed. For the Passing-Bablock regression equations, regression parameters (slope and intercept), and 95 % confidence intervals (95 % CI), were calculated to determine the degree of association between 2 methods. Accuracy was quantified as the mean of the differences (bias) between 2 conditions, one of them used as reference or criterion condition. A 95 % CI that includes the 0 for the intercept and the 1 for the slope allow to reject the hypothesis of fixed and proportional differences, respectively.

Results

The R^2 values, Passing-Bablok regression equation parameters (slope and intercept), and the mean difference of the cardiorespiratory parameters measured with the new snorkel AquaTrainer® with 2 and 4 valves in swimming (SV2 vs. SV4), and also with the standard mask in cycling (SV2 vs. SV4, SV2 vs. Mask, SV4 vs. Mask), are reported in **Table 1**. Cardiorespiratory values obtained with the 2 or 4 valves AquaTrainer® and with the standard mask were highly correlated in all conditions with an R^2 >0.99 in VO_2, VCO_2, and V_E parameters. Passing-Bablok regression analysis [23] of all parameters (VO_2, VCO_2, V_E, V_T, F_EO_2, F_ECO_2, and HR), comparing the standard mask with the 2 and 4 valves snorkel conditions in cycling and the 2 and the 4 valves in both swimming and cycling, reported slope and intercept values that include the 1 and the 0, respectively.

The Passing-Bablok regression analysis and the Bland-Altman [2] plots of the averaged VO_2, VCO_2 and V_E values obtained during swimming and cycling tests between the standard mask, the 2 and the 4 valves are graphically shown in **Fig. 3, 4, 5** respectively.

Discussion

This study demonstrated that the new snorkel AquaTrainer® system with 2 or 4 valves connected to the K4b^2 telemetric device is comparable with the standard face mask under controlled laboratory conditions for gas analysis. Moreover, the 4 valves AquaTrainer® configuration has shown to have a high correlation with the 2 valves system, both in ground and aquatic exercise.

Previous studies reported a VO_2 overestimation (~15 %) and systematic differences (3–9 %) in ventilatory parameters when comparing the snorkel with the standard mask [11,18]. Different from those, our results did not report any systematic differences in ventilatory parameters when the new snorkel AquaTrainer® with 2 or 4 valves was compared to the Mask. In fact, contrary to data reported by Keskinen et al. [18] who found a 5–7 % difference for VO_2 (mean absolute difference was −174 mL·min^{-1} with 95 % CI: −198 to −151 mL·min^{-1}), our difference was below 1 % (from −0.81 to 0.03; 95 % CI always included 0) with mean absolute difference in VO_2 ranging from 0.9 mL·min^{-1} (95 % CI: −66.0 to 67.7, for Mask vs. SV4, cycling) to −18.7 mL·min^{-1} (95 % CI: −180.0 to 143.5, for SV4 vs. SV2 swimming). In the present study, an upgrade of the old snorkel AquaTrainer® model and a more painstaking research protocol was used in order to improve the accuracy of data. As previously reported by other authors [3,18,28], the new AquaTrainer® now has the expiration and inspiration tubes that join at the apex before the turbine, allowing the use of the flowmeter in the standard mode (in/ex hardware configuration for face mask use). Moreover, different from the previous model, in which a closed support for the K4b^2 was used (see "Tips and suggestion on how to use AQUATRAINER" Cosmed Ltd., 2005: 9–11), the new AquaTrainer® provides an open support system in order to prevent from overheating and samplings of stale air if the auto-calibration is used. In addition, the reduction of the dead space by 11.3 ml and the use of 2 supplementary valves (SV4), tend to reduce mixtures of gases at the valves assembly which might alter the O_2 and CO_2 expiratory fractions. Moreover, in order to reduce resistances and air turbulence while breathing, the new AquaTrainer® prototype uses, in comparison with the snorkel of Keskinen et al. [18], a smooth internal valves assembly surface, 2 flexible but not stretchable tubes 35 mm in diameter and 86 cm long and larger sized Hans-Rudolf valves 35 mm in diameter, presenting a similar internal volume (847 ml compared to the 825 ml of the previous one). In resting condition the internal volume exceeds the tidal volume, running the risk of sampling a mixture of 2 successive expirations. This problem does not persist during exercise as the expired volume detected at the lower affordable exercise pace in our athletes (data not reported in this paper) was higher than 1 000 ml. Some other structural modifications that included a soft and oval mouthpiece, a flexible head connection, and flexible – but underwater stable – tubes were

Table 1 Agreement values obtained by the snorkel AquaTrainer® with 2 (SV2) and 4 (SV4) valves and the standard mask (Mask) in swimming and cycling assessed by Passing-Bablok regression analysis. Pearson's determinant coefficient (R^2), slope and intercept of the regression equations, and mean difference are reported.

SV4 vs. SV2 (N = 27, Swimming)				
Parameters	**R^2**	**Slope**	**Intercept**	**Mean difference**
VO_2 (mL · min^{-1}, STPD)	0.991	0.995 (0.950 to 1.040)	−12.705 (−119.201 to 81.186)	−18.7 (−180.0 to 143.5)
VCO_2 (mL · min^{-1}, STPD)	0.996	0.992 (0.965 to 1.022)	8.227 (−53.300 to 61.519)	−13.9 (−128.8 to 101.1)
V_E (L · min^{-1}, BTPS)	0.992	0.992 (0.957 to 1.023)	−0.514 (−2.382 to 1.817)	−0.47 (−4.49 to 3.55)
V_T (L, BTPS)	0.920	1.068 (0.911 to 1.230)	−0.122 (−0.443 to 0.182)	0.01 (−0.25 to 0.26)
F_EO_2 (%)	0.826	0.940 (0.783 to 1.155)	0.984 (−2.515 to 3.564)	−0.02 (−0.49 to 0.44)
$F_{EC}O_2$ (%)	0.894	1.000 (0.844 to 1.258)	0.020 (−0.996 to 0.641)	0.01 (−0.28 to 0.31)
HR (beats · min^{-1})	0.991	1.000 (0.941 to 1.015)	0.500 (−2.015 to 8.765)	0.19 (−4.49 to 4.86)
Mask vs. SV2 (N = 27, Cycling)				
Parameters	**R^2**	**Slope**	**Intercept**	**Mean difference**
VO_2 (mL · min^{-1}, STPD)	0.994	1.001 (0.967 to 1.043)	−6.126 (−90.863 to 56.145)	−2.8 (−124.9 to 119.3)
VCO_2 (mL · min^{-1}, STPD)	0.996	1.012 (0.978 to 1.044)	−42.292 (−104.030 to 23.499)	−11.3 (−126.3 to 103.7)
V_E (L · min^{-1}, BTPS)	0.992	1.008 (0.960 to 1.044)	−0.252 (−2.283 to 2.098)	0.14 (−3.68 to 3.96)
V_T (L, BTPS)	0.947	1.000 (0.864 to 1.132)	0.009 (−0.246 to 0.288)	0.01 (−0.20 to 0.22)
F_EO_2 (%)	0.837	0.950 (0.785 to 1.146)	0.884 (−2.404 to 3.626)	0.04 (−0.28 to 0.37)
$F_{EC}O_2$ (%)	0.869	0.922 (0.774 to 1.132)	0.259 (−0.613 to 0.843)	−0.06 (−0.31 to 0.18)
HR (beats · min^{-1})	0.990	1.000 (0.942 to 1.024)	−1.000 (−3.857 to 9.154)	0.03 (−5.68 to 5.74)
Mask vs. SV4 (N = 27, Cycling)				
Parameters	**R^2**	**Slope**	**Intercept**	**Mean difference**
VO_2 (mL · min^{-1}, STPD)	0.998	1.006 (0.987 to 1.026)	−1.628 (−44.755 to 27.139)	0.9 (−66.0 to 67.7)
VCO_2 (mL · min^{-1}, STPD)	0.998	1.020 (0.995 to 1.043)	−27.075 (−62.093 to 7.944)	−5.1 (−88.8 to 78.5)
V_E (L · min^{-1}, BTPS)	0.996	1.017 (0.987 to 1.044)	− 1.239 (−2.952 to 0.828)	−0.10 (−2.98 to 2.77)
V_T (L, BTPS)	0.914	1.009 (0.850 to 1.204)	−0.025 (−0.367 to 0.327)	0.01 (−0.26 to 0.28)
F_EO_2 (%)	0.839	0.995 (0.822 to 1.220)	0.059 (−3.702 to 2.962)	−0.04 (−0.37 to 0.29)
$F_{EC}O_2$ (%)	0.904	0.958 (0.836 to 1.141)	0.177 (−0.622 to 0.680)	−0.01 (−0.22 to 0.19)
HR (beats · min^{-1})	0.990	1.000 (0.944 to 1.019)	−1.000 (−3.111 to 7.889)	−0.22 (−5.83 to 5.38)
SV4 vs. SV2 (N = 27, Cycling)				
Parameters	**R^2**	**Slope**	**Intercept**	**Mean difference**
VO_2 (mL · min^{-1}, STPD)	0.997	1.000 (0.972 to 1.028)	−5.000 (−63.961 to 64.083)	−5.7 (−94.4 to 83.0)
VCO_2 (mL · min^{-1}, STPD)	0.998	0.994 (0.970 to 1.017)	−2.130 (−38.621 to 59.186)	−6.1 (−89.2 to 77.0)
V_E (L · min^{-1}, BTPS)	0.997	0.988 (0.956 to 1.018)	1.062 (−0.348 to 2.654)	0.24 (−2.32 to 2.81)
V_T (L, BTPS)	0.938	0.949 (0.818 to 1.100)	0.097 (−0.191to 0.317)	0.00 (−0.24 to 0.23)
F_EO_2 (%)	0.856	0.996 (0.829 to 1.156)	0.129 (−2.552 to 2.926)	0.09 (−0.22 to 0.39)
$F_{EC}O_2$ (%)	0.836	1.000 (0.808 to 1.196)	−0.060 (−0.856 to 0.729)	−0.05 (−0.32 to 0.22)
HR (beats · min^{-1})	0.987	1.000 (0.941 to 1.042)	1.000 (−6.375 to 9.000)	0.22 (−6.13 to 6.57)

VO_2, oxygen uptake; VCO_2, carbon dioxide production; V_E, pulmonary ventilation; V_T, tidal volume, F_EO_2; expiratory fraction of oxygen; F_ECO_2, carbon dioxide; HR, heart rate

made to improve comfort during swimming. At last, the use of a hand-cart that moves the snorkel and K4b^2 system on a suspended wire along the swimming pool increases the freedom of movement of the swimmer and facilitates the control of the operator. In order to prevent loss of data during tests and obtain accurate data, the auto-calibration was removed from the K4b^2 settings, and an accurate calibration procedure (that included volumes, gases and delay calibrations) was conducted before each test. Moreover, contrary to previous studies, the real temperature at the turbine (27 °C) was measured and then reported into the K4b^2 software, instead of ambient air of 28 °C. In previous studies, a temperature adjustment was not applied when a snorkel device was used in connection with the K4b^2 [11, 18, 28], 2 of these reporting the existence of a temperature sensor inside the turbine. In this condition the face mask default temperature of 34 °C is automatically assumed by the K4b^2. In our study we observed an average 6.0 °C difference between face mask and the temperature at the turbine when at the snorkel (34.6 °C and 27.0 °C, respectively); a similar temperature difference could have been responsible for the ~15 % VO_2 overestimation [11] and the 3–9 % systematic error of respiratory values reported in previous studies [18, 28].

Ventilatory parameters (VO_2, VCO_2, V_E, V_T,) and expiratory fraction of O_2 and CO_2 reported no differences between conditions in our study. The R^2 coefficient was very high ($R^2 \geq 0.991$) in VO_2, VCO_2, V_E, and high in V_T ($0.947 \geq R^2 \geq 0.914$), F_EO_2 and F_ECO_2 ($0.904 \geq R^2 \geq 0.826$). With respect to previous studies, these values are higher than reported by Keskinen et al. [18] on humans while VO_2, VCO_2 and V_T were only slightly lower and V_E higher compared to the study of Rodriguez et al. [28], where a gas exchange simulator system was used. Moreover, the current results reported, for each parameter, a 95 % CI that contains the value 1 for the slope and the 0 for the intercept. According to these results, this is the first study that rejects both proportional and fixed difference hypotheses when validating a snorkel device, in connection to the K4b^2 analyzer. In fact, Keskinen et al. [18] and Rodriguez et al. [28] obtained a good R^2 in ventilatory parameters, but both proportional and fixed differences were rarely validated. These results, regarding the previously mentioned 3–9 % systematic error in volumes comparing the snorkel and the standard conditions, are in line with our hypothesis of a mistake in reporting the temperature of the expired gas. Therefore, temperature measurement at the turbine is recommended, since it does not have any temperature sensors. In fact, the manufacturer recommends adjusting the temperature with the

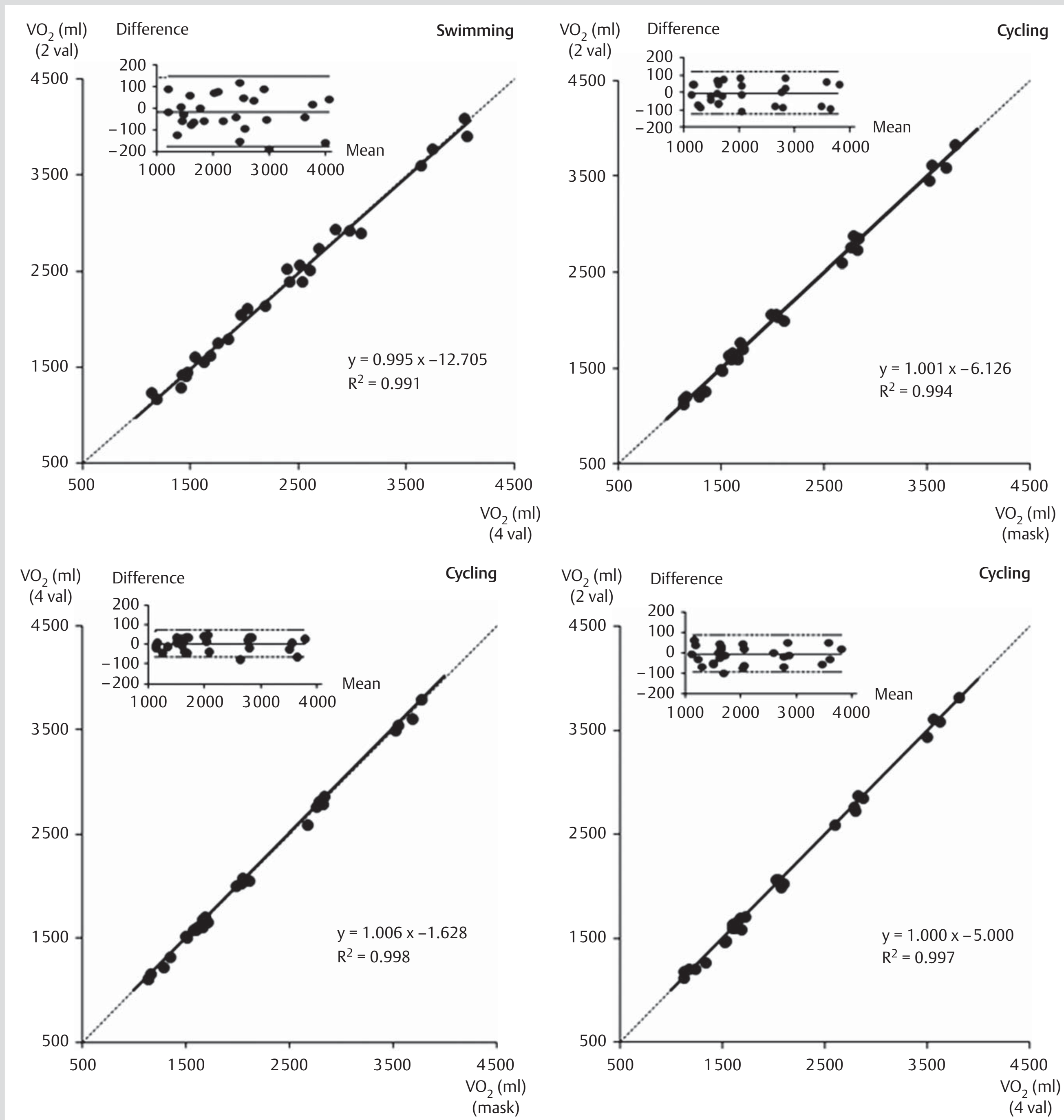

Fig. 3 Passing-Bablok regression and difference of oxygen consumption (VO_2) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. Reported for each one of the 4 main graphs is the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95% CI (dashed lines).

ambient value when a snorkel is used. Our results demonstrate that, in order to have more accurate gas exchange values, data should be adjusted to the real temperature of expired gas, in indoor swimming pools with controlled environment it may, however, not be necessary.

The use of 4 valves to prevent mixture between expired and ambient air has been shown to be irrelevant since a high agreement between SV4 and SV2 was reported in both conditions and for all studied parameters. No studies have previously analyzed the difference between a 2 and a 4 valve snorkel thus making necessary the control of this variable using a snorkel with removable valves. The R^2 coefficient was between 0.920 and 0.996 in ventilatory parameters, and 0.826, 0.894 and 0.991 in F_EO_2, F_ECO_2 and HR, respectively, when cycling; in swimming, R^2 was between 0.938 and 0.998 in ventilatory parameters, and equal to 0.856, 0.836 and 0.987 in F_EO_2, F_ECO_2 and HR, respectively. Furthermore, the 95% CI in all parameters reject the proportional and the fixed difference hypotheses. Therefore, since the addition of 2 additional valves does not affect cardiorespiratory parameters, the 2 valves model is preferred.

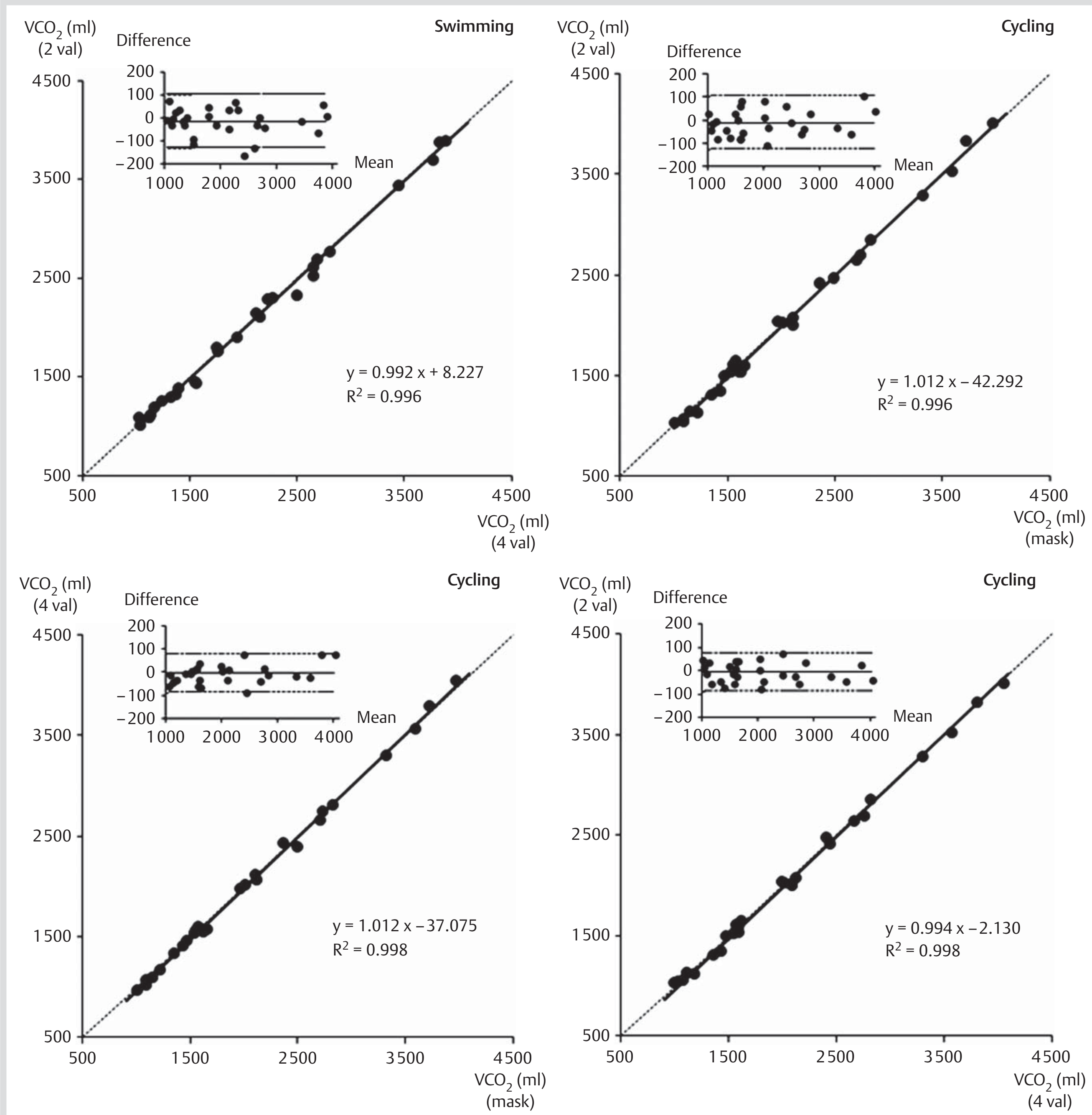

Fig. 4 Passing-Bablok regression and difference of carbon dioxide production (VCO_2) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. Reported for each one of the 4 main graphs is the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95 % CI (dashed lines).

The new AquaTrainer® system was reported by all subjects to be more comfortable in comparison with the previous systems mainly because of: a) the softer and more comfortable mouthpiece and head connection, b) the underwater stability of the tubes, c) a higher ductility of the system, in terms of freedom of movements and, when comparing the SV2 to the SV4 AquaTrainer® prototype, d) subjective better comfort using the 2 valves model.

Practical notes

The new AquaTrainer® snorkel will allow trainers and researchers to perform VO_2 assessment in swimming with high precision and comfort. However, as in all the previous models, swimmers need a familiarization period in order to feel comfortable with the device. To have more accurate gas exchange values, trainer should control and use the ambient temperature or, if possible, the temperature at the turbine as reference value. Thanks to its flexible and anatomic structure the new AquaTrainer® snorkel can adapt to swimmers in different positions. In a preliminary test which we conduced, no evident limits nor subjects' relevant

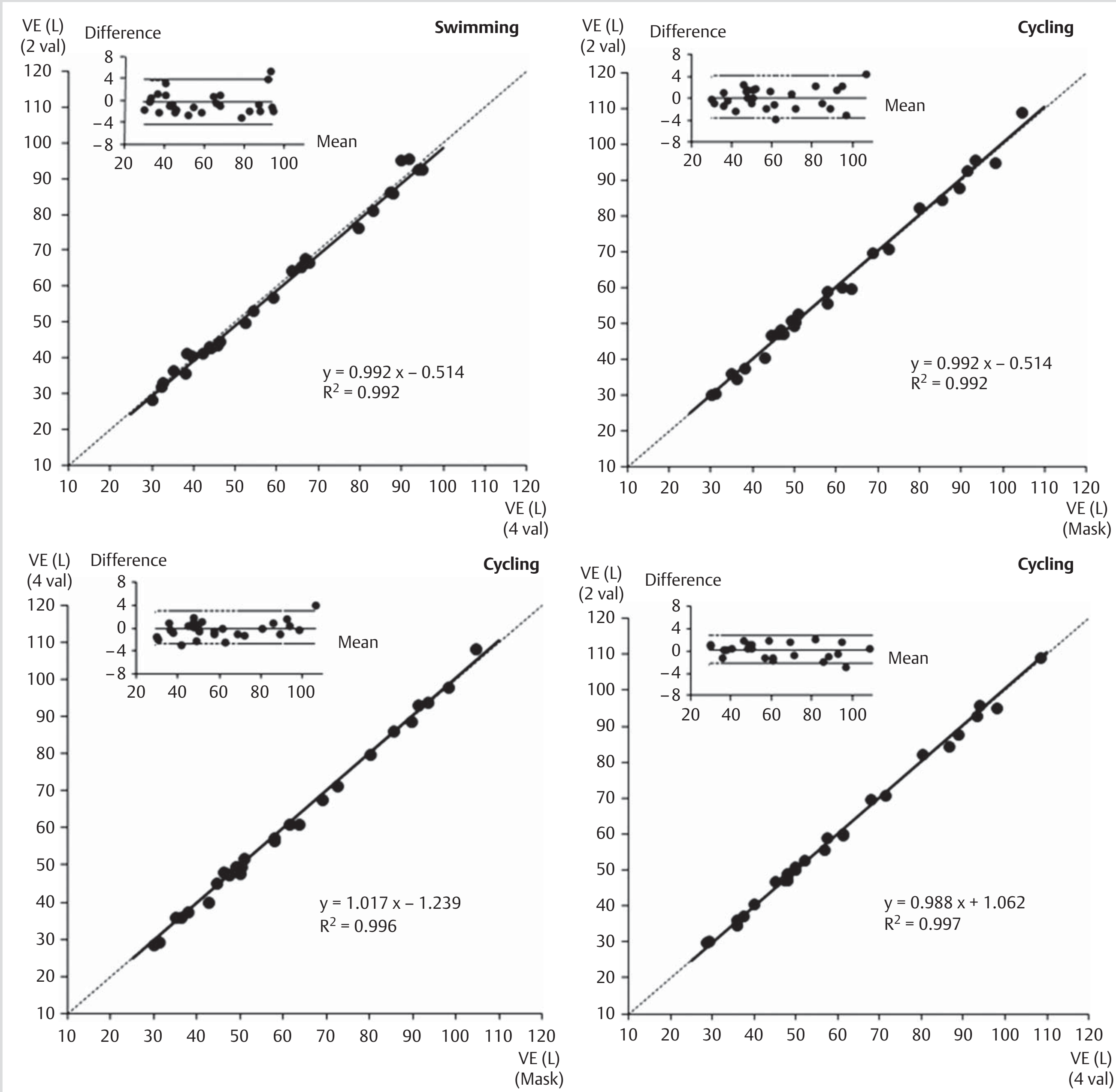

Fig. 5 Passing-Bablok regression and difference of Pulmonary ventilation (V_E) obtained during swimming and cycling tests between the standard mask (Mask), the 2 (SV2) and 4 (SV4) valves. Reported for each one of the 4 main graphs is the Passing-Bablok regression plot (the outside panel), with the linear regression (solid line), the identity (dashed line) and the equation with the Pearson's determinant coefficient (R^2), and the Bland-Altman plot (upper-left panel) with the mean difference (solid lines) and the 95 % CI (dashed lines).

discomforts while using the new AquaTrainer® prototype with different techniques were reported. However, further studies are needed to test the validity of this device when different swimming techniques are used.

Conclusion

The absence of systematic and proportional errors between SV2, SV4 and Mask in cycling, and SV2 and SV4 in swimming led us to conclude that the new AquaTrainer® prototype is suitable for collecting respiratory gases during exercise. Moreover, thanks to the improvements made in contrast to previous available systems it constitutes a flexible and comfortable device for collecting expired gas in real swimming conditions.

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