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Title

Breathing resistance in automated metabolic systems is high in comparison to the Douglas Bag method and previous recommendations

Subtitle

Breathing resistance in metabolic systems

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Abstract

The purpose of this study was to investigate the resistance (RES) to breathing in metabolic systems used for the distribution and measurement of pulmonary gas exchange. A mechanical lung simulator was used to standardize selected air flow rates ($\dot{V}$, L/s). The delta pressure (Δp, Pa) between ambient air and the air inside the

equipment was measured in the breathing valve's mouthpiece adapter for four metabolic systems and four types of breathing valves. RES for the inspiratory and expiratory sides was calculated as RES = Δp / $\dot{V}$, Pa/L/s. The results for RES showed significant (p $\leq$ 0.05) between-group variance among the tested metabolic systems, breathing valves, and between most of the completed $\dot{V}$. The lowest RES among the metabolic systems was found for a Douglas Bag system which had approximately half of the RES compared to the automated metabolic systems. The automated systems were found to have higher RES even at low $\dot{V}$ in comparison to previous findings. For the hardware components, the highest RES was found for the breathing valves while the lowest RES was found for the hoses. The results showed that RES in metabolic systems can be minimized through conscious choices of system design and hardware components.

Keywords

Automated metabolic systems, breathing resistance, breathing valve, delta pressure, Douglas Bag system, flow meter, hose, mixing chamber, oxygen uptake

Introduction

Indirect calorimetry is a method that determines aerobic energy metabolism via the measurement of pulmonary gas exchange[1]. This method can be applied to various exercise modes and used to measure maximal oxygen uptake in athletes in various

sport-specific performances. The traditional gold standard for measuring aerobic energy metabolism is the Douglas Bag method, which involves collecting the exhaled air in sealed bags followed by an analysis of the contents in terms of volume and gas fractions [2, 3]. Since the 1960s, automated electronic metabolic systems that facilitate practical measurements and the presentation of data in real time have been introduced to the commercial market. Automated metabolic systems are based on mixing chamber, breath-by-breath or hybrid methodology (through micro-sampling into a miniature mixing chamber) and are available both as stationary systems for the laboratory and portable systems for measurements in the field [4-8]. Also, custom designed portable Douglas Bag systems have been built in order to provide very accurate oxygen uptake measurements in the field [9, 10].

Automated metabolic systems have been validated against the Douglas Bag method during submaximal and maximal exercise[4-7]. However, some have not been sufficiently validated and may induce considerable errors[11, 12]. The suggestion is that automated metabolic systems should be validated against the Douglas Bag method or by means of a mechanical lung simulator designed for metabolic systems[13, 14]. The validation of automated metabolic systems using highly trained endurance athletes is rare. Most validation has been performed during submaximal exercise or in moderately trained athletes during maximal exercise[11, 12]. Only a few studies have validated automated metabolic systems using highly skilled endurance athletes with pulmonary ventilation

corresponding to nearly 200 L/min during maximal exercise[5, 6, 15]. Highly trained athletes are reported to ventilate up to 278 L/min during maximal exercise[16] and might induce further limitations in accuracy for some systems[15]. In one study, a metabolic simulator was used to validate a portable metabolic system using a simulated ventilation of 240 L/min[17]. In those cases, another factor that should be considered is the resistance to breathing found in the metabolic system's hardware. The capacity for this kind of extreme breathing is likely a challenge for many breath-by-breath systems and even for systems with mixing bag technology. Limitations would be expected in these systems due to an increase in resistance caused by the hoses, valves, flowmeters, and mixing chambers.

In order to minimize resistance, Åstrand and Rodahl [18] recommended that hoses should be 30 mm or greater in internal diameter (ID), but they did not state the hoses' maximum recommended length. Saltin and Åstrand [19] noted that in a Douglas Bag system with hose ID of 35 mm and length of 0.5 m, the pressure difference between ambient air and inside the hardware were 1, 3, 6 and 10 cmH₂O at air flow rates of 100, 200, 300 and 400 L/min, respectively. This is data from a system with hardware that is no longer used in automated metabolic systems. Today's systems also use much longer hoses. Gore et al.[20] recommended that the pressure should be less than 6 cmH₂O at flows up to 300 L/min and hoses should be greater than 30 mm in ID and no longer than 1.5 m on either the inspiratory or expiratory side. The standard lengths of hoses used by

manufacturers of modern metabolic systems are often 1.7 to 2.7 m (Hans Rudolph Inc., Shawne, USA. AMIS 2001, Innovision A/S, Odense, Denmark). Jensen and co-workers [7] investigated the pressure in an automated metabolic system (AMIS 2001, Innovision A/S, Odense, Denmark) and a Douglas Bag system by simulating minute ventilation of 120 L/min using a 3 L calibration syringe (Hans Rudolph Inc., Shawne, United States). The results showed a pressure variation between the ambient air and the inside of the hardware of 2.8 and 3.2 cmH_2O, respectively. However, use of a 3 L manual calibration syringe limits the minute ventilation to approximately half of that expected from an elite athlete in aerobic sports when performing at $\dot{V}O_2$ max[16].

Despite the given recommendations, no studies have investigated the resistance to breathing in the modern hardware contained in automated metabolic systems, or its influence on pulmonary ventilation and aerobic energy metabolism during extreme performances. Moreover, hardware such as valves, hoses, flowmeters and mixing chambers are available from different manufacturers. The various materials, volumes, and geometries of the hardware from the manufacturers would likely cause differences in breathing resistance.

This study therefore aimed to investigate the resistance to breathing in hardware of three well-known automated metabolic measurement systems and a custom-built Douglas Bag system.

Methods

Air flow rates

Pulmonary ventilation ($\dot{V}$) is the product of tidal volume (VT) and breathing frequency (f), see Eq (1).

$$\dot{V} = VT \times f \tag{1}$$

In order to provide selected standardized $\dot{V}$, the study used a mechanical lung simulator (Metabolic Simulator No 17056, Vacumed, Ventura, CA, USA) with the ability to mimic different VT and f, see Fig 1.

Figure 1. The sketch shows the mechanical lung simulator used in the study.

The $\dot{V}$ in and out from the differential cylinder was determined using Eq. (2), where $\dot{x}$ is the speed (m/s) of the piston in the cylinder and A is the area (0.033 m^2) in the cylinder. L is the length (0.385 m) of the rod between the piston rod and rotary plate. It has an eccentric function, where k is an adjustable radius (m) of the eccentric from the center

axis of the plate. β is the angle (rad) to k with k perpendicular to the piston rod. ω is the rotational speed (rad/s) of the plate which was set to the desired f by an electric motor.

$$\dot{V} = \dot{x}\,A = A\left(\left(\frac{k^2 \sin\beta \cos\beta\,\omega}{\sqrt{L^2 - k^2 \sin^2\beta}}\right) + k\cos\beta\,\omega\right) \tag{2}$$

Initially, pilot measurements were performed with simulated VT of 1, 2, 3 and 4 L, k set at 0.015, 0.030, 0.045 and 0.0625 m, f of 15, 30, 45, 60 and 75 VT/min, and ω set at $\pi/2$, π, $3\pi/2$, 2π and $5\pi/2$ rad/s, respectively. In total, $\dot{V}$ of 15-300 L/min was created using the simulator. Using Eq. (2), a given mean $\dot{V}$ in L/min provides a given peak and mean $\dot{V}$ in L/s, regardless of different combinations of VT and f. Further, the analyzed pilot results for pressure differences between the ambient air and the inside of a tested hardware showed similar values for a given $\dot{V}$ regardless of different combinations of VT and f. Therefore, the experiments were limited with the lung simulator to VT of 3 L and the different f values noted above, to provide the mean $\dot{V}$ of 45, 90, 135, 180 and 225 L/min with the corresponding inspiratory and expiratory peak and mean $\dot{V}$ of 2.36, 4.71, 7.07, 9.43, 11.78 L/s and 1.5, 3.0, 4.5, 6.0, 7.5 L/s, respectively.

Delta pressure and resistance

In order to investigate the resistance to breathing (air flow) in the metabolic systems'
hardware and components, pressure differences (Δp) were measured (-2500 to 2500 Pa,
GMSD25 MR, Swedish Thermo Instrument AB, Täby, Sweden) between the inside of
the hardware and the ambient air at a rate of 100 Hz and filtered at 8 Hz using a
Butterworth-filter in Microsoft Excel. At both inspiratory and expiratory air flow, the
Δp in the systems' hardware should be greatest near the subject's mouth. Thus, the Δp
was measured in the adapter between the mouthpiece and the breathing valve by
replacing the regular adapter with a custom-made adapter manufactured from ABS
plastic, using additive manufacturing (Mid Sweden University). The custom-made
adapter geometry was equivalent to the manufacturer's original adapter but
supplemented with connections for measuring negative and positive Δp during
inspiration and expiration, respectively, (Fig. 2). For connection to the mechanical
simulator, a simple plastic tube was used instead of the original mouthpiece. The
laboratory air pressure, temperature, relative humidity and density were 98996 Pa, 18.7°
C, 40% and 1.18 kg/m^3 during the testing.

As shown in Eq. (3), the resistance to air flow (RES Pa/L/s) was calculated by the
ratio between Δp and $\dot{V}$. Five adjacent curves of Δp and $\dot{V}$ formed the results as the
mean ± SD for the inspiratory and expiratory RES.

$$RES = \frac{\Delta p}{\dot{V}} \qquad\qquad (3)$$

Since the measured Δp is negative compared to the ambient air during inspiration and positive during expiration, a negative sign is reported before the values for the inspiratory RES.

Figure 2. Customized mouthpiece adapter with connection for measuring negative and positive pressure differences versus ambient air at different air flow rates.

System hardware

The Δp was measured in the standard hardware for a custom-built Douglas Bag system and three automated metabolic measurement systems: Jaeger Oxycon Pro (Carefusion, Germany 234 GmbH, Hoechberg, Germany), Moxus Modular Metabolic System (AEI Technologies Inc, Pittsburg, USA), and AMIS 2001 (Innovision A/S, Odense, Denmark).

The Moxus Modular and Oxycon Pro systems were mainly equipped with hardware components from a manufacturer (Hans Rudolph Inc., Shawne, USA) that supplies hardware to several manufacturers of automated metabolic measurements systems . The Moxus Modular system uses a pneumotachometer (4813, Hans Rudolph Inc., Shawne, USA) on the inspiratory side to measure gas flow and a hose (Hans Rudolph Inc.,

Shawne, USA) of length 2.7 m and ID 35 mm to transmit the ambient air into a two-way non-rebreathing valve (2700 T-shape, Hans Rudolph Inc., Shawne, USA) before entering the lungs. On the expiratory side, the same type of hose transmits the expired air from the breathing valve to a 4.2 L mixing chamber (Spelsberg, TK series, type 4x and 12k, Newark Element14, 300 S. Riverside Plaza, Suite 2200, Chicago, Il 60606 USA), where the expiratory gas fractions are measured in normal use.

The Amis 2001 system's design is similar to the Moxus Modular system with a pneumotachometer and two-way non-rebreathing valve (Innovision A/S, Odense, Denmark), inspiratory and expiratory hoses 2.0 m in length with ID of 40 mm (Flexible ducting U62, Senior Aerospace BWT, Adlington, UK), and a mixing chamber (15 L bag of rebreathing type, J Kruuse A/S, Langeskov, Denmark).

The Oxycon Pro system's standard setup in mixing chamber mode is a breathing valve of the same type as the Moxus Modular system (2700 T-shape, Hans Rudolph Inc., Shawne, USA). The Oxycon Pro's system, however, has a shorter hose of length 1.7 m and ID 35 mm (Hans Rudolph Inc., Shawne, USA) only on the expiratory side where the gas flow is measured by a turbine (707230, Carefusion, Germany 234 GmbH, Hoechberg, Germany) mounted on the outlet of the mixing chamber (4.0 L, Carefusion, Germany 234 GmbH, Hoechberg, Germany).

The Douglas Bag system was equipped with the same type of breathing valve and hose, on the expiratory side, as the Amis 2001 system and a custom-built three-way

valve[5] (Håkan Eriksson, Karolinska University Hospital, Stockholm, Sweden) to distribute the expired air, either to the ambient surroundings or for collection into a bag (130 L, PU coated fabric, C. Fritze Consulting, Svedala, Sweden). The three-way valve and bag were placed on a stand where the bag lay on a wooden board at an angle of 38° to a horizontal plane. To study the RES throughout the process of the bag being filled, the bag was filled to the volume provided by the manufacturer.

The measurements of Δp were done on the inspiratory and expiratory sides for the complete hardware systems and separately for the breathing valves and breathing valves with mounted hoses.

In recent years, development of large treadmills has made it possible to study more sports specifically than has been the case in previous experiments indoors. For example, before large treadmills entered the market, cross-country skier and biathletes' maximal oxygen uptake were measured while exercising on a bicycle ergometer or running on a small treadmill[19]. Nowadays this is done more sport specifically by roller skiing in the classical and free style techniques on a large treadmill that provides the necessary space[21]. With the introduction of large treadmills, however, the distance between the test subject on the treadmill and the automated mixing chamber system positioned at the side of the treadmill has become longer compared with similar measurements formerly made on bicycle ergometers and narrow treadmills. A larger distance between the system sensors and the subject on the treadmill requires longer hoses for distribution of

the inhaled and exhaled air, which also should result in an increased resistance to breathing. Therefore, measurements were carried out both with the systems' standard hose lengths and with extended hose lengths. In the experiments using extended hose lengths, the standard hoses were put together using short aluminum tubes with a wall thickness of 1.5 mm. The lengths of the extended hoses were 4.4 m (Jaeger Oxycon Pro), 5.4 m (Moxus Modular), and 4.0 m (Amis 2001 and Douglas Bag systems). In addition, two alternative types of breathing valves were tested; Y-Shape 2730 (Hans Rudolph Inc., Shawne, USA) and Radiax (Carefusion Germany 234 GmbH, Hoechberg, Germany). All hoses and valves were unused at the start of the experiment.

During the experiments, the hardware was hung as shown in Fig. 3, with most of the hoses hanging reasonably straight in order to standardize the forthcoming measurements and simulate the shortest path between an exercising athlete and the system sensors. After the Δp of a complete hardware system was measured, pieces were removed, starting with the system sensors (pneumotachometer, mixing chamber, three-way breathing valve with bag), and Δp was measured from the remaining system until only the breathing valve remained.

Moreover, Δp calculations were made for the hoses on the inspiratory and expiratory sides using the difference in measured Δp for the breathing valve with mounted hoses minus the measured Δp for the breathing valve. Further, the Δp for the flowmeters, mixing chambers and three-way valve with bag was calculated using the difference in

Δp for the hardware system minus the measured Δp for the breathing valve with mounted hoses.

Figure 3. The systems' hardware was hung up during the experiments, as shown in the photo.

Statistics

The statistical analyses were done in SPSS for Windows statistical software release 24.0 (SPSS Inc., Chicago, Illinois, USA). The results of RES for the metabolic system variance, breathing valve variance, and $\dot{V}$ variance were analyzed using F-test of two-way analyses of variance. The Bonferroni post hoc test was used to discern significant differences found in the F-test and to correct α ($p \leq 0.05$). Linear regression analyses were used to express RES for the hoses as a function of the two independent variables, length and $\dot{V}$.

Results

The results of RES for the four metabolic systems and breathing valves are presented in Figs. 4 and 5, respectively. There was a significant ($p \leq 0.05$) difference in RES

between all four metabolic systems at all $\dot{V}$ on both inspiratory and expiratory sides. Significant differences in RES were also noted between the different $\dot{V}$, except between the two lowest $\dot{V}$ on the systems' inspiratory side (Fig. 4).

Similarly, there was a significant ($p \leq 0.05$) difference in RES between the four tested breathing valves at all $\dot{V}$ on both inspiratory and expiratory sides. A significant ($p \leq 0.05$) difference in RES was also found between the different $\dot{V}$, except between the middle three $\dot{V}$ on the expiratory side (Fig. 5).

Figure 4. Results (mean) of resistance (RES) for the four tested metabolic systems' hardware on the inspiratory and expiratory sides. Note: SD are ≤ 1.3 and hidden behind the markers.

Figure 5. Results (mean) of resistance (RES) for the four tested breathing valves on the inspiratory and expiratory sides. Note: SD are ≤ 1.8 and hidden behind the markers.

In Figure 6, the distribution of RES for the different hardware components is presented as mean $\pm$ SD of the five $\dot{V}$ for the inspiratory and expiratory side. Converted to a relative distribution, the RES breakdown for the inspiratory side was 34 and 31% for the pneumotachometers, 12% for the hoses, and 54 and 57% for the breathing valves for the

Amis 2001 and Moxus Modular systems, respectively. Since no sensors and hoses are localized on the inspiratory side for the Douglas Bag and Oxycon Pro systems, the breathing valves for these systems represent 100% of the total RES.

A calculation of the relative distribution on the expiratory side shows that the breathing valves of the Amis 2001, Douglas Bag, Moxus Modular and Oxycon Pro systems represent, 56, 78, 71 and 53% while the hoses represent 4, 6, 15 and 13%, respectively.The two types of mixing chambers used by the Amis 2001 and Moxus Modular systems represent 40 and 15%, the 3-way valve with bag used by the Douglas Bag system represents 16%, and the Oxycon Pro system with the combined mixing chamber and turbine concept represents 34% of the total RES.

The measurements using extended hoses resulted in an increased RES of 2 to 25% within the studied range of $\dot{V}$. Within the hose lengths used in this experiment and a range of $\dot{V}$ from 3 to 7.5 L/s, the RES in the two types of hoses can be highly predicted by the following two linear regression equations: Flexible ducting U62: $RES = -13.985 \times (2.89 \times \dot{V}) + (4.05 \times length)$, $r^2 = 0.70$, p<0.001 and Hans Rudolph Inc.: $RES = -29.103 + (5.075 \times \dot{V}) + (7.357 \times length)$, $r^2 = 0.86$, p<0.001.

Figure 6. Distributions of RES for the metabolic systems' hardware components on the inspiratory and expiratory sides. Mean $\pm$ SD from the five $\dot{V}$.

Discussion

The current study has provided extensive knowledge of breathing resistance in hardware of well-known automated metabolic measurement systems for the first time. Within the range of completed inspiratory and expiratory $\dot{V}$, the RES for the metabolic systems and breathing valves range between 38 and 169 Pa/L/s and 36 and 77 Pa/L/s, respectively, (Figs. 4 and 5). Gore et al[20] recommended that the inspiratory and expiratory pressure should not exceed 6 cmH$_2$O (588 Pa) at air flows up to 300 L/min, which gives a mean $\dot{V}$ of 10 L/s and RES of 59 Pa/L/s for each side, respectively. Surprisingly, the results for RES in the current study show that modern automated metabolic systems have a higher RES, even at low flow rates, in comparison to these recommendations, and that only the Douglas Bag system corresponds to this recommendation.

Jensen et al.[7] reported a Δp of 2.8 cmH$_2$O (275 Pa) for the AMIS 2001 system and 3.2 cmH$_2$O (314 Pa) for a Douglas Bag system when checked at $\dot{V}$ 4 L/s, which gives a RES of 69 and 79 Pa/L/s, respectively. The results for the Amis 2001 system in this study at similar $\dot{V}$ correspond with the result by Jensen and co-workers while the RES for the Douglas Bag system is only half as great as for Jensen et al. Saltin and Åstrand[19] reported a Δp of 1 and 3 cmH$_2$O (98 and 294 Pa) at $\dot{V}$ 3.3 and 6.7 L/s for a custom-made Douglas Bag system with a hose length of 0.5 m, which gives a RES of 30 and 44 Pa/L/s. The results of RES in this study for the tested Douglas Bag system are higher

than the results presented by Saltin and Åstrand at a similar $\dot{V}$. One reason for this is likely the significant difference in hose length between the two systems.

Due to peak Δp marginally exceeding the measuring equipment range at the highest $\dot{V}$ on the inspiratory side for the Moxus Modular system, no result is reported for this system for the $\dot{V}$ 7.5 L/s on the inspiratory side. For the Oxygen Pro system expiratory side, peak Δp is just inside the margin for the measuring equipment at the highest $\dot{V}$. Thus, RES for the Moxus Modular system at inspiratory $\dot{V}$ 7.5 L/s could be expected to slightly exceed the value obtained by the Oxycon Pro system on the expiratory side.

There is a significant ($p \leq 0.05$) difference found in RES between all four tested metabolic systems at all completed $\dot{V}$ on both inspiratory and expiratory sides. The overall highest RES was recorded from the Moxus Modular system which, compared to the other systems, was equipped with the type of breathing valve that showed the highest RES and longer hoses on both sides. The largest difference in RES between inspiratory and expiratory side was recorded from the Oxycon Pro system. This can be explained by the presence of the breathing valve only on the inspiratory side of the Oxycon Pro system while the flowmeter, unlike in the other two automated metabolic systems, is placed on the expiratory side on the outlet of the mixing chamber.

The Douglas Bag system has the lowest RES among the four tested metabolic systems. This system has approximately half of the total RES compared to the three automated systems, likely due to the following reasons: a sensor and hose was not used

on the inspiratory side and a very low total resistance exists on the expiratory side from the hose, 3-way valve and bag. If the RES from the inspiratory and expiratory side are summarized, the breathing valve represents 89% of the total RES in the Douglas Bag system. During the complete filling of a bag, a trend toward a higher Δp is observed in the beginning and final phase of filling, particularly at the two lowest $\dot{V}$. Figure 7 shows raw data for the measured Δp during a complete filling of the bag with 130 L, obtained from VT of 3 L and f of 30 VT/min. As can be seen, the Δp is slightly higher at the beginning and the end of sampling on the expiratory side, which is likely due to the separation between the bag's inner surfaces and the difficulty of further expansion when the bag begins to reach its full volume. Thus, it seems that the bags can be filled almost to the maximum volume before an increase in RES occurs.

Figure 7. Δp measured at 100 Hz during the complete filling of a 130 L Douglas Bag.

There are also significant ($p \leq 0.05$) differences in RES between all tested breathing valves at all $\dot{V}$ on both inspiratory and expiratory sides. The T-shape 2700 valve, with inlet and outlet air flow perpendicular to the mouthpiece, shows the highest RES. The smaller angle and fewer direction changes in the air flow in and out of the Y-shape 2730 (45°) and AMIS (60°) valves are likely one reason for the lower RES from these breathing valves. The Radiax breathing valve shows, unlike the other measured valves,

a large difference in resistance between the inspiratory and expiratory sides, which relates to the design of the valve. While the other three investigated breathing valves have a design with identical inlets and outlets, the Radiax valve has a different configuration. The Radiax breathing valve consists of a tube with an expiratory air flow straight out via a one-way valve at the end of the tube, while the inspiratory flow is made possible via very small valves located around the tube's circumference. At very high air flow rates, this design seems to be an advantage for minimizing expiratory RES while creating an apparent disadvantage for the inspiratory RES.

Surprisingly, the hoses play a relatively small role in the total RES among the systems' components. An average from the completed $\dot{V}$ is less than 15% for any of the metabolic systems on either the inspiratory or expiratory sides. With approximately doubled hose lengths, this increases the RES from less than 15% to 27%.

The breathing valves, on the other hand, constitute the largest RES among the components. When summarizing the RES from both inspiratory and expiratory sides, the breathing valves constitute between 55 and 89% of the total RES for the metabolic systems. If the RES in metabolic systems is found to influence an athlete's pulmonary ventilation and oxygen uptake, then product development should be focused on breathing valve hardware to minimize RES.

Significant ($p \leq 0.05$) differences exist in RES between most of the completed $\dot{V}$, except between the two lowest $\dot{V}$ on the metabolic systems' inspiratory side and

between the middle three $\dot{V}$ on the breathing valves' expiratory side. Generally, for the metabolic systems, an increase in RES was found for increased $\dot{V}$, which means that the measured Δp increases more than is proportional to $\dot{V}$. Among the different breathing valves, some difference in RES can be discerned, but in general, Δp increases fairly proportionally to an increase in $\dot{V}$. The only valve that shows a trend similar to the metabolic systems is the AMIS breathing valve, while the Radiax valve shows a trend with an inverse relationship for RES as a function of $\dot{V}$.

The RES in the metabolic systems' hardware is defined as the ratio of delta (driving) pressure to the rate of air flow. In this study, the driving pressure during simulated inspiration and expiration was achieved by means of a differential cylinder that served as a human lung with the advantage of achieving standardized air flow rates. Even though the mechanically created flow curves, which have some similarity to a sine curve, differ from the dynamic flow curves achieved by human breathing, the results of measured mean Δp and RES may be considered relatively similar in terms of the mean air flow rates of human breathing.

The RES depends on the dimensions for gas passage and the properties and velocity of the gas. Also, for turbulent flow, a larger driving pressure is required to produce the same air flow rate. A calculation often used in fluid mechanics to investigate flow characteristics is the Reynolds number[22] (Re) as shown in Eq. (4). Re is a unitless number of the ratio of inertial forces to viscous forces,

$$Re = \frac{\rho U L}{\mu} \tag{4}$$

where ρ is the air density (kg/m^3), U is the characteristic velocity (m/s) of the flow, L is the characteristic length (m) of an object and μ is the dynamic viscosity (Pa s) of the gas. In a pipe, the ID is used as characteristic length (L=ID), and the average speed is used as characteristic velocity ($U=$ V). A Re above 2300 is considered to be critical Re, where laminar flow transitions to turbulent flow. With ρ set at 1.18 and μ set at 1.8×10^{-5}, a Re of approximately 3100 to 15600 and 3600 to 17900 is obtained for the flexible ducting U62 and Hans Rudolph hoses, respectively. Due to different ID, the velocities and Re will be different for the two types of hoses. Thus, the air flow in the hoses is well above the critical Re for typical air flow rates. Increased turbulence requires greater driving pressure, likely causing the larger than proportional increase in Res compared to the air flow rate (Fig. 4) for an elongated system of circular and rectangular components, such as the metabolic systems' hardware. Further, changes in air flow direction within and between transitions for valves, sensors, and hoses are also expected to contribute to a rather turbulent flow.

Conclusion

In summary, the highest RES among the tested systems is found for the automated systems, while the Douglas Bag system has the lowest RES. The results of this study

show unexpectedly large differences in RES between the tested metabolic systems' hardware. Among the hardware components, the breathing valves show the highest RES, while the hoses show the lowest RES.

Although two of the tested automated metabolic systems at time of writing are no longer available on the market, manufacturers of mixing chamber systems often use the same type of hoses, valves and flow meters as were tested in this study.

Future research should investigate whether RES in metabolic systems, similar to those included in this study, has an influence on elite athletes' ventilation and aerobic energy expenditure. Similarly, follow-up work should explore whether a difference or similarity between inspiratory and expiratory RES has an influence on athletes. Thus, how different resistance to breathing affects ventilation, submaximal, and maximal oxygen uptake in elite athletes remains to be investigated. The authors believe that the result of such a study should provide valuable information on the importance of RES to researchers, test managers, and manufacturers of metabolic systems.

and Health Sciences) for help with Microsoft Excel macros, which facilitated the

analyses of air flow rates and differential pressures, respectively.

Declaration of conflicting interests

The authors declare that there is no conflict of interest.

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Figure 1. The sketch shows the mechanical lung simulator used in the study.

Figure 2. Customized mouthpiece adapter with connection for measuring negative and positive pressures differences versus ambient air at different air flow rates.

Figure 3. The systems' hardware was hung up during the experiments, as shown in the photo.

Figure 4. Results (mean) of resistance (RES) for the four tested metabolic systems' hardware on the inspiratory and expiratory sides. Note: SD are $\leq$ 1.3 and hidden behind the markers.

Figure 5. Results (mean) of resistance (RES) for the four tested breathing valves on the inspiratory and expiratory sides. Note: SD are $\leq$ 1.8 and hidden behind the markers.

Figure 6. Distributions of RES for the metabolic systems' hardware components on the inspiratory and expiratory sides. Mean $\pm$ SD from the five $\dot{V}$.

Figure 7. Δp measured at 100 Hz during the complete filling of a 130 L Douglas Bag.

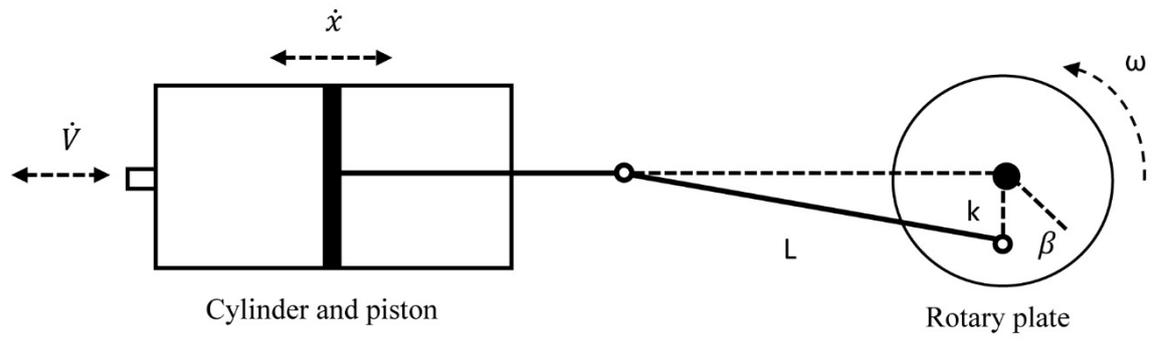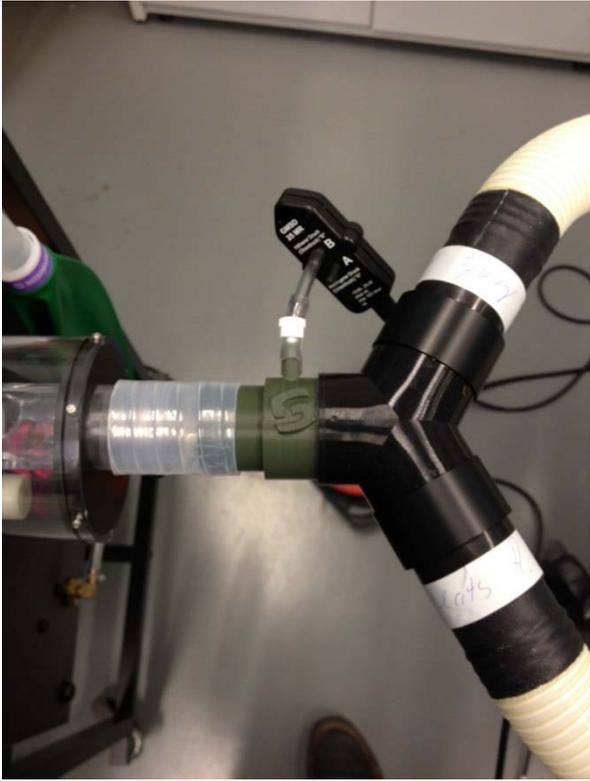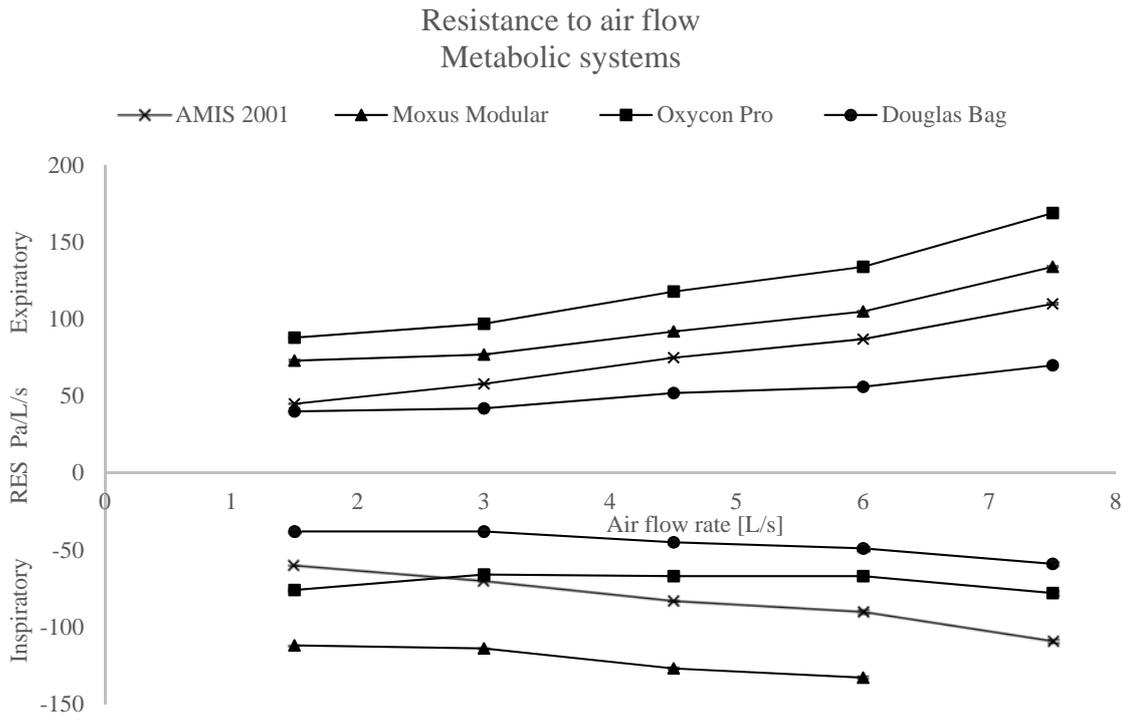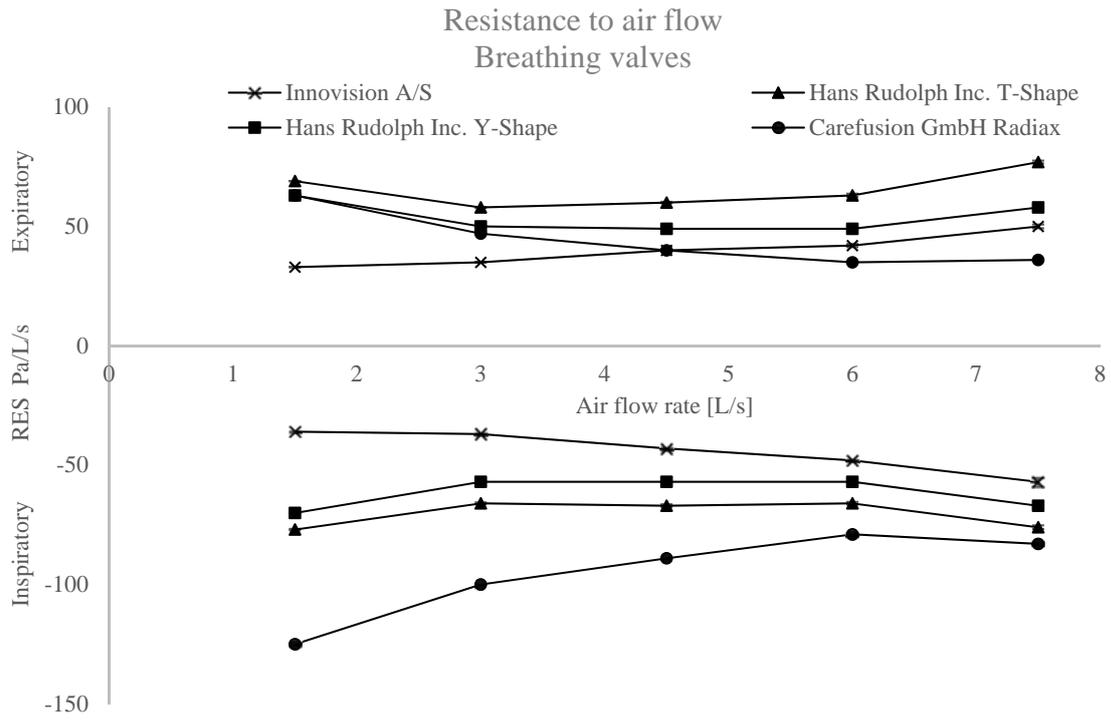$\dot{x}$

$\dot{V}$

Cylinder and piston
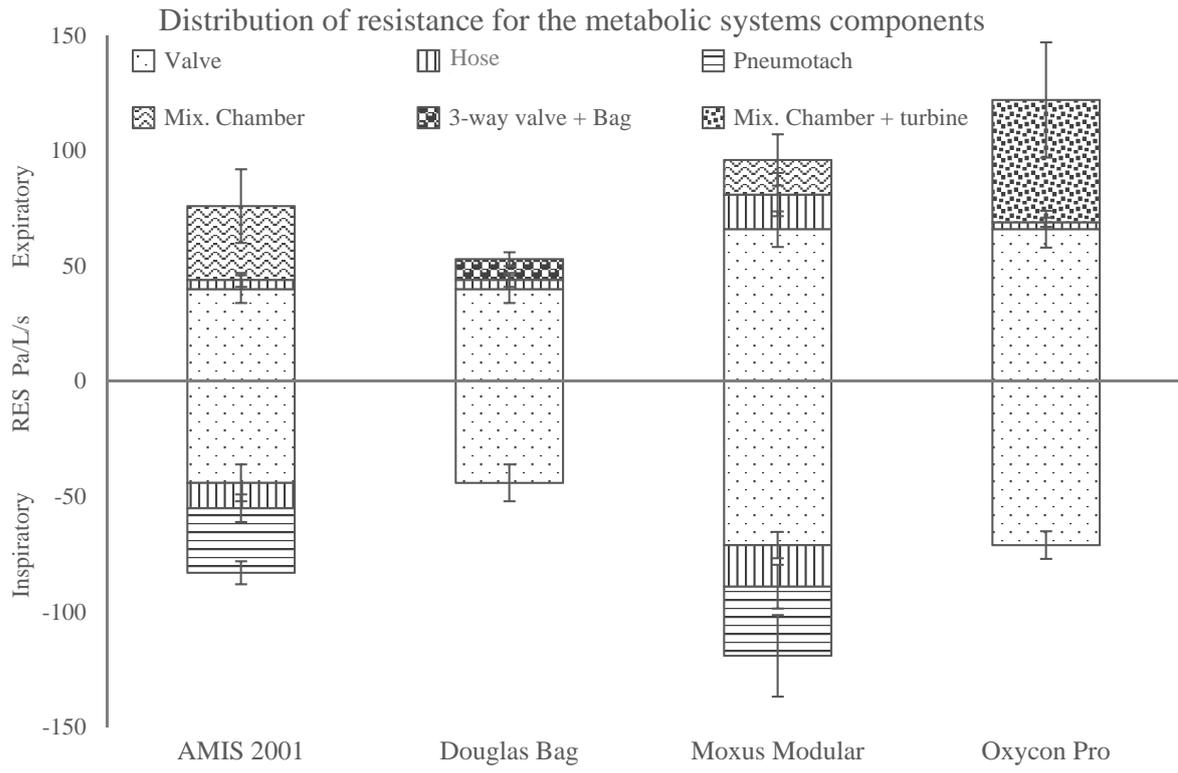
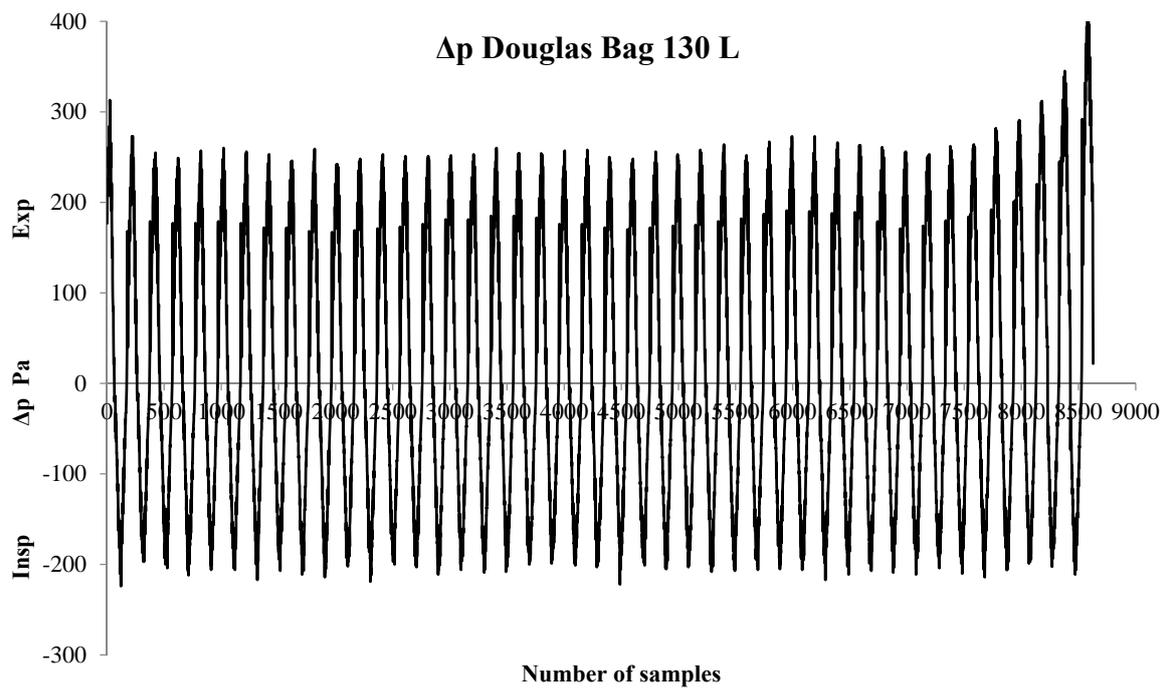ω

k

β

L

Rotary plate

Figure 1.

Figure 2

Figure 3

Figure 4

Figure 5

Distribution of resistance for the metabolic systems components

Figure 6

Δp Douglas Bag 130 L

Figure 7