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Exercise Breathing Reserve in Cross-Country Skiers: Ventilatory Capacity vs. Ventilatory Demand

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Abstract. Breathing reserve (BR), defined as the difference between ventilatory capacity and ventilatory demand during exercise, is an indicator of respiratory limitations. However, it is unclear which of the two factors has the greatest impact on BR in cross-country skiers during cardiopulmonary exercise testing on a bicycle ergometer (CPET). The **purpose** of this study is to investigate how ventilatory capacity and ventilatory demand influence BR during CPET in highly-trained cross-country skiers. **Materials and methods.** Current members of the Komi Republic national cross-country skiing team ($n = 46$; aged 22.6 ± 4.7) underwent spirometry and CPET at the beginning of the preparatory training period. BR was calculated at rest and during CPET – at the anaerobic threshold and at peak exercise. The athletes were divided into two groups with low BR (≤20%) and normal BR (>20%) at peak exercise. **Results.** The two groups showed no lung function differences. However, at peak exercise, the low BR group demonstrated statistically significant higher breathing frequency, minute ventilation, ventilatory equivalent for carbon dioxide, respiratory exchange ratio, and lower end-tidal carbon dioxide partial pressure. BR directly correlated with forced vital capacity, forced expiratory volume in the first second and the Tiffeneau index at peak exercise. BR demonstrated an inverse correlation with breathing frequency and minute ventilation throughout the test, as well as with oxygen consumption (except at peak exercise). Thus, in cross-country skiers, exercise intensity significantly influences the relationship between ventilatory capacity and BR, while the relationship between ventilatory demand and BR remains constant. Importantly, low BR at peak exercise, even with comparable exercise capacity in the groups of skiers, is associated with increased ventilatory demand.

Keywords: *breathing reserve, highly-trained cross-country skiers, exercise, bicycle ergometry test, lung function, ventilation*

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Научная статья

Дыхательный резерв при физической нагрузке у лыжников-гонщиков: вентиляционная емкость и вентиляционный запрос

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Аннотация. Дыхательный резерв (ДР) – показатель респираторных ограничений, определяемый как разница между вентиляционной емкостью и вентиляционным запросом во время физической нагрузки. Однако неясно, какой из этих двух факторов оказывает наибольшее воздействие на ДР у лыжников-гонщиков при велоэргометрическом максимальном ступенчатом нагрузочном тесте (ВЭМ). **Цель** работы – изучить, как вентиляционные емкость и запрос влияют на ДР в ВЭМ у высокотренированных лыжников-гонщиков. **Материалы и методы.** Действующие члены национальной сборной Республики Коми по лыжным гонкам (n = 46; возраст 22,6±4,7 года) проходили спирометрию и ВЭМ в начале подготовительного этапа тренировочного цикла. ДР рассчитывался в покое и во время ВЭМ – на анаэробном пороге и при пиковой нагрузке. Спортсмены были разделены на группы с низким (≤20 %) и нормальным (>20 %) ДР при пиковой нагрузке. **Результаты.** Выделенные группы не различались по показателям функции внешнего дыхания. Однако у группы с низким ДР при пиковой нагрузке выявлены: статистически значимо более высокие частота дыхания, минутный объем дыхания, вентиляционный эквивалент по углекислому газу, дыхательный коэффициент и статистически значимо более низкое парциальное давление углекислого газа в конце выдоха. ДР имел прямые корреляции с форсированной жизненной емкостью легких, объемом форсированного выдоха за первую секунду и индексом Тиффно при пиковой нагрузке. Наблюдалась обратная связь ДР с частотой и минутным объемом дыхания на протяжении всего теста, а также с потреблением кислорода (кроме пиковой нагрузки). Таким образом, у лыжников-гонщиков интенсивность физической нагрузки существенно влияет на связь между вентиляционной емкостью и ДР, в то время как связь между вентиляционным запросом и ДР остается постоянной. Важно отметить, что низкий ДР при пиковой нагрузке, даже при сравнимой физической работоспособности между группами лыжников, ассоциирован с повышенным вентиляционным запросом.

Ключевые слова: *дыхательный резерв, высококвалифицированные лыжники-гонщики, физическая нагрузка, велоэргометрический тест, функция внешнего дыхания, легочная вентиляция*

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Introduction

In endurance sports, achieving maximal athletic performance requires optimal cardiovascular and respiratory function. While cardiovascular conditioning is often considered the primary determinant of success, emerging evidence suggests that the respiratory system can also impose significant limitations on functional capacity [1–3]. Specifically, the ability to maintain an adequate breathing reserve may be critical for preventing respiratory muscle fatigue and ensuring sufficient oxygen delivery.

Breathing reserve (BR) reflects the difference between an individual's maximum ventilatory capacity (maximum voluntary ventilation (MVV)) and the ventilatory demand (minute ventilation, Ve) required during exercise. Ventilatory capacity is influenced by the respiratory system structure and mechanics and potential pathological conditions, while ventilatory demand is driven by the need for increased breathing rate and tidal volume in response to exercise [1]. In clinical settings, a BR of 20% or less is often used as a threshold to identify individuals with potential ventilatory limitations [1, 3–7]. Cross-country skiing is a particularly demanding endurance sport, characterized by exceptionally high metabolic rates and ventilation requirements [8]. While a definitive threshold for ventilatory limitation in athletes remains undefined, an average BR of 20.1% has been reported in young male endurance-trained athletes at peak exercise [3], with some studies reporting that elite athletes routinely exhibit BR values below 20% during maximal exertion [5, 6]. This makes cross-country skiers potentially susceptible to exercise-induced respiratory limitations, which could cause reduced exercise tolerance [9, 10]. Some studies suggest that higher BR correlates with higher maximal oxygen uptake (VO_{2max}) and forced expiratory volume in 1 s (FEV_1) in untrained individuals [11], and that BR decrease below threshold is induced by higher Ve rather than lower MVV [11]. Also, in older adults with obesity, a low BR group (BR ≤ 30%) is characterized by higher VO_{2max} and peak exercise capacity compared to a high BR group (BR ≥ 45%) [12]. However, it is unclear whether the same conclusions apply to highly-trained cross-country skiers. In this research, we investigate which of the two factors – ventilatory capacity or ventilatory demand – has the greatest impact on breathing reserve in cross-country skiers at peak exercise.

Materials and methods

Study population. The study included qualified athletes, active members of the national Komi Republic cross-country skiing team (males, n = 46). Qualification criteria for the athletes included membership in the national team, training consistently with a qualified coach following a sport-specific program, and regular participation in both official regional and national competitions. The exclusion criteria were the presence of personal history of cardiovascular diseases, chronic or acute diseases, taking medications known to affect lung function or exercise test parameters at the time of the examination. The examination was conducted at the beginning of the preparatory training period (June), on days when the athletes did not participate in training or competitions. The athletes were advised to minimize physical activity the day prior to the test.

Ethics approval. All athletes provided a voluntary informed consent to participate in the study. The study protocol was approved by the Ethics Committee of the Institute of Physiology of Komi Science Center of the Ural Branch of the Russian Academy of Sciences (November 15, 2021). The study was conducted in accordance with the Ethical Principles of the World Medical Association (Declaration of Helsinki).

Lung function. Before the testing, body mass and height of the athletes were measured. All tests were carried out indoors: air temperature, relative air humidity and atmospheric pressure were 22.2±1.8 °C, 65.0±7.4% and 726.3±106.8 mm Hg, respectively. Lung function was assessed using a portable microprocessor-based spirometer (SMP-21/01-R-D, Russia). The device was calibrated according to the manufacturer's instructions with a 3-liter calibration syringe. The examination was performed by an experienced spirometry technician. The lung function was measured prior to the exercise test at rest in a sitting position. The following parameters were

determined by selecting the maximum values achieved in one of three successful maneuvers: forced vital capacity (FVC, L), FEV_1 (L/min), peak expiratory flow (PEF, L/s), forced expiratory flow at 25% and 75% of FVC (FEF_{25} and FEF_{75}, L/s), and the ratio of forced expiratory volume in 1 s to vital capacity (FEV_1/VC, %). Repeatability criterion was set as FVC±0.150 L. Reference values for spirometry were calculated according to ECCS93 [13].

Exercise test. The athletes performed "maximal effort" cardiopulmonary exercise testing on a bicycle ergometer (CPET) (Ergoselect 100, Ergoline GmbH, Germany). The test included the following stages: 1) baseline measurements, without load in a sitting position on a bicycle ergometer (3 min); 2) cycling without load (1 min); 3) incremental load stage, starting from 120 W with an increase in load by 40 W every 2 min (rotation speed: 60 rpm); 4) recovery stage (3 min after load completion). The following parameters were measured by an automated gas analysis system (Jaeger Oxycon Pro, VIASYS Healthcare GmbH, Germany) during the test: heart rate (HR, bpm), Ve (L), respiratory frequency (BF, 1/min), inspiratory tidal volume (VTin, L), expiratory tidal volume (VTex, L), oxygen consumption (VO_2, mL/min), carbon dioxide output (VCO_2, mL/min), respiratory exchange ratio (RER), and end-tidal carbon dioxide pressure ($P_{ET}CO_2$, kPa). The test involved sequential recording of data in breath-by-breath mode, averaging over 15-second intervals.

The anaerobic threshold (AT) was detected using the V-slope method, with the additional criterion being that the respiratory exchange ratio (RER) reached and surpassed 1.0 [14–16]. Maximum voluntary ventilation (L/min) was calculated using the formula $MVV = FEV_1 \cdot 40$ [1]. Breathing reserve (%) was calculated as $BR = (1 - Ve/MVV) \cdot 100$ [3]. The ventilatory equivalent for carbon dioxide (Ve/VCO_2) was calculated. All parameters were recorded or calculated at rest, at AT and peak exercise (maximal oxygen consumption) stages. Based on the calculated BR value, depending on the extent of BR use, the athletes were divided into two groups: the group with low BR at peak exercise (BR ≤ 20%) and the group with normal BR at peak exercise (BR > 20%).

Statistics. Statistical analysis was performed using Statistica 8.0 (StatSoft Inc, 2007). The Shapiro-Wilk test was used to assess normal distribution of the parameters. The Mann-Whitney *U* test was used for comparing variables with non-normal distribution, and the Student's *t*-test for variables with normal distribution. Robust strictly standardized mean difference (SSMD) was used to measure the effect size. Spearman correlation was used for analyzing the relationship between variables. Significance level was set at $p < 0.05$. The results are presented as median (*Me*) and percentiles [Q_1; Q_3].

Results

The athletes with low BR (≤20%) comprised 26.1% (95% CI 13.41–38.77) of the total group. The groups did not differ significantly in height, age, or body mass ($p > 0.05$) (*Table 1*).

No significant differences in lung function parameters were observed between the BR ≤ 20% and BR > 20% groups (except for FEV_1 and MVV, as these values are inherent components of BR calculation).

No significant differences were observed between the groups in the graded exercise test parameters or BR values at rest and AT ($p > 0.05$). Differences between groups emerged at peak exercise stage (*Table 2*).

The group with low BR demonstrated higher Ve ($p = 0.001$), BF ($p = 0.018$), RER ($p = 0.001$), Ve/VCO_2 ($p = 0.040$), and lower $P_{ET}CO_2$ ($p = 0.004$) at peak exercise. The groups did not exhibit significant differences in inspiratory and expiratory tidal volumes, heart rate, and oxygen consumption at peak exercise ($p > 0.05$). A non-significant trend towards higher values of carbon dioxide output ($p = 0.068$) and power output ($p = 0.072$) at peak exercise was observed in the group with low BR.

The BR fell below the threshold, on average, 41.8 s before reaching VO_{2max}. On average, BR decreased by 61.37% in the normal BR group

Table 1

Baseline characteristics of athletes with normal (BR > 20%) and low (BR ≤ 20%) breathing reserve at peak exercise, *Me* [Q_1; Q_3]
Исходные характеристики спортсменов с нормальным (>20 %) и низким (≤20 %) дыхательным резервом при пиковой нагрузке, *Me* [Q_1; Q_3]

Parameter	BR > 20% (*n* = 34)	BR ≤ 20% (*n* = 12)	SSMD robust	*p*
Age, years	20.0 [19.0; 25.0]	21.5 [19.0; 26.0]	0.231	0.745
Body mass, kg	71.8 [67.0; 75.0]	71.3 [69.8; 72.8]	–0.100	0.863
Height, cm	178.0 [175.0; 181.0]	174.0 [171.8; 178.3]	–0.640	0.066
FVC, % predicted	107.4 [96.5; 122.5]	104.6 [89.7; 119.9]	–0.096	0.232
FEV_1, % predicted	114.1 [106.6; 123.9]	96.6 [87.9; 117.0]	–0.755	0.012$^+$
FEV_1/VC, % predicted	95.0 [89.7; 104.1]	85.0 [77.1; 100.0]	–0.537	0.070
PEF, % predicted	109.9 [96.8; 118.9]	112.4 [88.5; 129.2]	0.079	0.857
FEF_{25}, % predicted	112.4 [99.3; 125.3]	112.0 [83.3; 134.3]	–0.011	0.597
FEF_{75}, % predicted	132.4 [109.7; 173.6]	141.2 [98.9; 176.4]	0.124	0.822
MVV, L/min	207.0 [191.2; 218.4]	168.6 [157.4; 200.6]	–1.091	0.002$^+$

Note: Values expressed as percentages of predicted values were calculated relative to reference values (ECCS93); + indicates statistically significant differences between parameters according to the Student's *t*-test.

Table 2

Results of the graded exercise test in cross-country skiers with normal (BR > 20%) and low (BR ≤20%) breathing reserve at peak exercise, *Me* [Q_1; Q_3]
Результаты ступенчатого нагрузочного теста у лыжников-гонщиков с нормальным (>20 %) и низким (≤20 %) дыхательным резервом при пиковой нагрузке, *Me* [Q_1; Q_3]

Parameter	BR > 20% (*n* = 34)	BR ≤ 20% (*n* = 12)	SSMD robust	*p*
Load, W	320 [320; 360]	340 [320; 380]	0.400	0.402
BR, %	28.9 [25.0; 38.4]	8.7 [3.8; 14.0]	–1.714	<0.001$^\#$
Ve, L/min	142.0 [122.0; 152.0]	154.0 [145.0; 176.5]	0.390	<0.001$^+$
BF, 1/min	45.5 [39.0; 53.0]	52.0 [48.5; 59.0]	0.531	0.018$^+$
VTex, L	3.04 [2.74; 3.51]	2.89 [2.70; 3.48]	–0.201	0.658
VTin, L	2.88 [2.61; 3.41]	2.82 [2.61; 3.23]	–0.084	0.739
VO_2, mL/min	4286.0 [4025.0; 4540.0]	4188.0 [3998.0; 4649.5]	–0.168	0.899
VCO_2, mL/min	4631.5 [4166.0; 4981.0]	5071.0 [4368.0; 5555.0]	0.439	0.163
Ve/VCO_2, %	30.1 [28.4; 31.0]	31.8 [29.4; 35.2]	0.397	0.040$^+$
$P_{ET}CO_2$, kPa	3.92 [3.73; 4.03]	3.57 [3.40; 3.88]	–0.899	0.004$^+$
RER, %	1.12 [1.07; 1.15]	1.19 [1.14; 1.21]	0.867	<0.001$^\#$
HR, bpm	180.0 [175.0; 182.0]	181.0 [174.0; 187.5]	0.098	0.568

Note: + indicates significant differences according to the Student's *t*-test; # indicates significant differences according to the Mann-Whitney *U* test.

and by 83.86% in the low BR group compared to initial levels.

Table 3 presents the results of a correlation analysis investigating the relationship between BR and lung function and parameters measured during the graded exercise test stages.

BR positively correlated with FEV_1 and FEV_1/VC at AT and peak exercise ($p < 0.01$) and with FVC only at peak exercise ($p < 0.01$), and did not correlate with other lung function parameters (PEF, FEF_{25}, FEF_{75}). A negative correlation was found between BR and BF, Ve, Ve/VCO_2 along the

Table 3

Correlation of breathing reserve with lung function and graded exercise test parameters in cross-country skiers (n = 46) at rest, anaerobic threshold, and peak exercise

Корреляция дыхательного резерва с функцией внешнего дыхания и параметрами ступенчатого нагрузочного теста у лыжников-гонщиков (n = 46) в состоянии покоя, на анаэробном пороге и при пиковой нагрузке

Parameter	Statistical parameter	Test stage		
		At rest	Anaerobic threshold	Peak exercise
FVC, L	*R* *p*	0.159 0.291	0.267 0.072	**0.380** **0.009**
FEV_1, L/min	*R* *p*	0.263 0.077	**0.552** **<0.001**	**0.627** **<0.001**
FEV_1/VC, %	*R* *p*	0.023 0.878	**0.363** **0.013**	**0.432** **0.003**
PEF, L/s	*R* *p*	0.042 0.782	0.029 0.851	0.081 0.594
FEF_{25}, L/s	*R* *p*	–0.099 0.511	–0.041 0.785	0.103 0.495
FEF_{75}, L/s	*R* *p*	–0.066 0.664	0.002 0.987	0.050 0.740
BF, 1/min	*R* *p*	**–0.371** **0.011**	**–0.492** **<0.001**	**–0.460** **0.001**
Ve, L/min	*R* *p*	**–0.891** **<0.001**	**–0.607** **<0.001**	**–0.545** **<0.001**
VTex, L	*R* *p*	–0.160 0.290	–0.001 0.998	0.169 0.262
VTin, L	*R* *p*	**–0.392** **0.007**	–0.074 0.624	0.167 0.269
VO_2, mL/min	*R* *p*	**–0.760** **<0.001**	**–0.372** **0.011**	–0.101 0.505
VCO_2 , mL/min	*R* *p*	**–0.544** **<0.001**	**–0.307** **0.038**	–0.247 0.099
Ve/VCO_2	*R* *p*	**–0.324** **0.279**	**–0.305** **0.039**	**–0.383** **0.009**
$P_{ET}CO_2$, kPa	*R* *p*	–0.039 0.799	0.248 0.096	**0.416** **0.004**
RER	*R* *p*	–0.049 0.748	–0.249 0.097	**–0.548** **<0.001**
HR, bpm	*R* *p*	–0.023 0.881	–0.252 0.091	–0.100 0.508

Note: Peak exercise – moment of maximal oxygen consumption; statistically significant correlations are given in bold (*R* – Spearman correlation coefficient, *p* – significance level).

test ($p < 0.01$). BR was associated with VTin at rest ($p = 0.007$) and was not associated with VTex. A negative correlation was found between BR and both VO_2 and VCO_2 at rest and AT ($p < 0.001$). However, these relationships were not significant at peak exercise. BR showed no significant correlation with HR, but was associated with $P_{ET}CO_2$ and RER at peak exercise ($p < 0.01$).

Discussion

Firstly, although 26.1% of the athletes showed their BR decrease below the 20% threshold at peak exercise, they did not demonstrate superior lung function. Instead, the group with low BR showed increased ventilatory demand, evidenced by higher values of RER, BF, Ve, Ve/VCO_2 and lower $P_{ET}CO_2$ at peak exercise. Secondly, while lung function impact on BR was sufficient only at peak exercise, BR correlation with Ve and BF was continual throughout all stages of the test. At the same time oxygen consumption was negatively associated with BR only until AT, making BR independent of VO_{2max}.

Our study demonstrated that approximately a quarter of the athletes experienced a decrease in BR below the 20% threshold at peak exercise. B.J. Petek et al. [6] established that this level of breathing reserve is frequently observed in endurance athletes of all ages. The breathing reserve in our study (26.2±13.5% at peak exercise) was similar but slightly higher to that reported in B.J. Petek et al. (20.1±13.8%) [6] in a group of endurance-trained male athletes aged 18–30 years.

Athletes demonstrate high capacity of the respiratory system and the absence of respiratory function limitations in resting conditions [17, 18]. In our study, differences were found between low and normal BR athletes in terms of FEV_1 (MVV). A decrease in BR along with low values of FEV_1 and PEF indicates a restrictive role of respiratory function during exercise [4]. However, since FEV_1 is a component of the BR calculation formula, differences between the groups in this parameter were expected.

Ventilatory work is recognized as a significant contributor to cardiovascular responses during high-intensity exercise. Specifically, a primary mechanism involves the introduction of inspiratory reserve volume [17]. Given the lack of differences in inspiratory and expiratory depth between the groups, it can be assumed that utilization of ventilatory capacity reserves might not be a determining factor for reaching the BR threshold at peak exercise.

The results (*Table 3*) indicate that significant correlations were found between BR and FVC, FEV_1, and FEV_1/VC at peak exercise. These findings suggest that individuals with high ventilatory capacity may better manage BR at high exercise intensities. This confirms the findings of J. McNeill et al. [11], who observed a negative association between low lung function and low peak BR. Since FVC reflects the strength and functional power of respiratory muscles, athletes with greater muscle mass tend to exhibit higher FEV_1 and FVC values [19]. Also, in endurance sports greater respiratory muscle endurance is observed [17]. In the work of M.T. Opina et al. [12], the authors found that untrained individuals with greater muscle mass exhibited lower peak exercise breathing reserve. Resting BR was positively associated with resting VTin, suggesting that inspiratory volume reserve is a key determinant of BR in this context. Given that professional athletes often exhibit increased resting tidal volumes [20], this relationship highlights the potential influence of inspiratory muscle adaptation on respiratory mechanics.

No significant differences were found in HR between the groups at any stage of the test. This suggests that breathing reserve in athletes primarily reflects ventilatory response, statistically not correlating significantly with cardiovascular activity.

It is known that achieving VO_{2max} in highly skilled athletes during exercise test occurs within the increased anaerobic metabolism (anaerobic training zone) [21]. In this zone, breathing intensity increases sharply due to evolving metabolic acidosis. This is a compensatory mechanism aimed at removing carbon dioxide from the blood [5, 21, 22]. At peak exercise, the athletes with low BR exhibited the following characteristics: higher RER, hyperventilation/dyspnea, driven by increased breathing frequency, enhanced carbon dioxide elimination (lower $P_{ET}CO_2$), and reduced

breathing efficiency (higher Ve/VCO_2). It is shown that BF serves as a marker of the athlete's physical effort to overcome the load [23]. Notably, the influence of breathing frequency on minute ventilation growth was more pronounced than that of the depth of inspiration or expiration (tidal volume).

In our study similar exercise test parameters and BR were maintained by both groups from rest to the anaerobic threshold, indicating comparable performance at submaximal intensities. Peak exercise did not differ within the groups, however, only 19.6% of the athletes in the BR > 20% group were able to overcome or start performing the 400 W load, while in the BR ≤ 20% group this value was 46.7%. In skilled athletes, when performing high-intensity loads, increased intrathoracic and abdominal pressure may be observed, which hinders an increase in the volume of inhalation, even with increased ventilatory demand and activation of the respiratory muscles [24]. Achieving complete utilization of breathing reserve during exercise is considered energetically suboptimal due to the increased oxygen demands of the respiratory muscles [24]. This can lead to shortness of breath and muscle fatigue [25], as well as a decrease in venous blood return and cardiac output, a key indicator of athlete fitness [20, 26]. It is likely that the lack of association between BR and VO_2 at peak exercise stage is explained by a significant, disproportionately to oxygen consumption, increase in minute ventilation. Thus, the complete mobilization of BR appears to be the ultimate mechanism for maintaining the ability to perform at high-intensities.

Limitations. This study involved a relatively small, but homogeneous group of male cross-country skiers during early preparation training, limiting extrapolation to other populations. Inspiratory and expiratory reserve volumes were indirectly assessed via breathing depth dynamics due to incomplete data. While calculating MVV and BR is debatable (similar to actual MVV tests), its applicability is supported by research [27]. The 20% BR threshold effectiveness for assessing ventilatory limitation in skilled athletes requires further research. The AT was identified using a combined approach: the V-slope method complemented by the criterion that RER should reach and surpass 1.0 [14–16]. We emphasize that there is no universal agreement on how to determine the AT, however this approach ensures that the test achieved a submaximal intensity [28], and minimizes errors that may appear during noninvasive AT identification, especially in athletes [3]. To overcome these constraints, future research should employ a more comprehensive gas-exchange analysis validated by blood lactate concentrations [14, 15] in different groups of athletes.

Conclusion. The obtained data emphasize the significance of ventilatory capacity in determining BR at peak levels of a graded exercise test in cross-country skiers. Moreover, the sustained ventilatory demand proves to be a key influence on BR dynamics during the exercise test. Thus, a low BR (≤20%) in athletes might be a result of a greater ventilatory demand at peak exercise, rather than superior lung function.

Conflict of interest. The authors declare no conflict of interest.
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References

1. Staes M., Gyselinck I., Goetschalckx K., Troosters T., Janssens W. Identifying Limitations to Exercise with Incremental Cardiopulmonary Exercise Testing: A Scoping Review. *Eur. Respir. Rev.*, 2024, vol. 33, no. 173. Art. no. 240010. https://doi.org/10.1183/16000617.0010-2024

2. Barron A., Francis D.P., Mayet J., Ewert R., Obst A., Mason M., Elkin S., Hughes A.D., Wensel R. Oxygen Uptake Efficiency Slope and Breathing Reserve, not Anaerobic Threshold, Discriminate Between Patients with Cardiovascular Disease over Chronic Obstructive Pulmonary Disease. *JACC Heart Fail*., 2016, vol. 4, no. 4, pp. 252–261. https://doi.org/10.1016/j.jchf.2015.11.003

3. Petek B.J., Gustus S.K., Wasfy M.M. Cardiopulmonary Exercise Testing in Athletes: Expect the Unexpected. *Curr. Treat. Options Cardiovasc. Med.*, 2021, vol. 23, no. 7. Art. no. 49. https://doi.org/10.1007/s11936-021-00928-z

4. Guazzi M., Arena R., Halle M., Piepoli M.F., Myers J., Lavie C.J. 2016 Focused Update: Clinical Recommendations for Cardiopulmonary Exercise Testing Data Assessment in Specific Patient Populations. *Circulation*, 2016, vol. 133, no. 24, pp. e694–e711. https://doi.org/10.1161/CIR.0000000000000406

5. Herdy A.H., Ritt L.E., Stein R., Araújo C.G., Milani M., Meneghelo R.S., Ferraz A.S., Hossri C., Almeida A.E., Fernandes-Silva M.M. et al. Cardiopulmonary Exercise Test: Background, Applicability and Interpretation. *Arq. Bras. Cardiol*., 2016, vol. 107, no. 5, pp. 467–481. https://doi.org/10.5935/abc.20160171

6. Petek B.J., Tso J.V., Churchill T.W., Guseh J.S., Loomer G., DiCarli M., Lewis G.D., Weiner R.B., Kim J.H., Wasfy M.M. et al. Normative Cardiopulmonary Exercise Data for Endurance Athletes: The Cardiopulmonary Health and Endurance Exercise Registry (CHEER). *Eur. J. Prev. Cardiol*., 2022, vol. 29, no. 3, pp. 536–544. https://doi.org/10.1093/eurjpc/zwab150

7. Rasch-Halvorsen Ø., Hassel E., Brumpton B.M., Jenssen H., Spruit M.A., Langhammer A., Steinshamn S. Lung Function and Peak Oxygen Uptake in Chronic Obstructive Pulmonary Disease Phenotypes with and without Emphysema. *PLoS One*, 2021, vol. 16, no. 5. Art. no. e0252386. https://doi.org/10.1371/journal.pone.0252386

8. Sandbakk Ø., Holmberg H.C. Physiological Capacity and Training Routines of Elite Cross-Country Skiers: Approaching the Upper Limits of Human Endurance. *Int. J. Sports Physiol. Perform*., 2017, vol. 12, no. 8, pp. 1003–1011. https://doi.org/10.1123/ijspp.2016-0749

9. Neder J.A., Berton D.C., Marillier M., Bernard A.C., O'Donnell D.E. Inspiratory Constraints and Ventilatory Inefficiency are Superior to Breathing Reserve in the Assessment of Exertional Dyspnea in COPD. *COPD J. Chronic Obstruct. Pulm. Dis.*, 2019, vol. 16, no. 2, pp. 174–181. https://doi.org/10.1080/15412555.2019.1631776

10. Berton D.C., Plachi F., James M.D., Vincent S.G., Smyth R.M., Domnik N.J., Phillips D.B., de-Torres J.P., Nery L.E., O'Donnell D.E. et al. Dynamic Ventilatory Reserve During Incremental Exercise: Reference Values and Clinical Validation in Chronic Obstructive Pulmonary Disease. *Ann. Am. Thorac. Soc.*, 2023, vol. 20, no. 10, pp. 1425–1434. https://doi.org/10.1513/AnnalsATS.202304-303OC

11. McNeill J., Chernofsky A., Nayor M., Rahaghi F.N., Estepar R.S.J., Washko G., Synn A., Vasan R.S., O'Connor G., Larson M.G. et al. The Association of Lung Function and Pulmonary Vasculature Volume with Cardiorespiratory Fitness in the Community. *Eur. Respir. J*., 2022, vol. 60, no. 2. Art. no. 2101821. https://doi.org/10.1183/13993003.01821-2021

12. Opina M.T.D., Brinkley T.E., Gordon M., Lyles M.F., Nicklas B.J. Association of Breathing Reserve at Peak Exercise with Body Composition and Physical Function in Older Adults with Obesity. *J. Gerontol. Ser. A Biol. Sci. Med. Sci.*, 2019, vol. 74, no. 12, pp. 1973–1979. https://doi.org/10.1093/gerona/gly276.

13. Quanjer P.H., Tammeling G.J., Cotes J.E., Pedersen O.F., Peslin R., Yernault J.C. Lung Volumes and Forced Ventilatory Flows. Report Working Party Standardization of Lung Function Tests, European Community for Steel and Coal. Official Statement of the European Respiratory Society. *Eur. Respir. J. Suppl.*, 1993, no. 16, pp. 5–40.

14. Solberg G., Robstad B., Skjønsberg O.H., Borchsenius F. Respiratory Gas Exchange Indices for Estimating the Anaerobic Threshold. *J. Sports Sci. Med*., 2005, vol. 4, no. 1, pp. 29–36.

15. Zagatto A.M., Miyagi W., Sakugawa R.L., Kaminagakura E.I., Papoti M. Aerobic Endurance Measurement by Respiratory Exchange Ratio During a Cycle Ergometer Graded Exercise Test. *J. Exerc. Physiol. Online*, 2012, vol. 15, no. 5, pp. 49–56.

16. American Thoracic Society, American College of Chest Physicians. ATS/ACCP Statement on Cardiopulmonary Exercise Testing. *Am. J. Respir. Crit. Care Med*., 2003, vol. 167, no. 2, pp. 211–277. https://doi.org/10.1164/rccm.167.2.211

17. Hackett D.A. Lung Function and Respiratory Muscle Adaptations of Endurance- and Strength-Trained Males. *Sports (Basel)*, 2020, vol. 8, no. 12. Art. no. 160. https://doi.org/10.3390/sports8120160

18. Bernhardsen G.P., Stang J., Halvorsen T., Stensrud T. Differences in Lung Function, Bronchial Hyperresponsiveness and Respiratory Health Between Elite Athletes Competing in Different Sports. *Eur. J. Sport Sci.*, 2023, vol. 23, no. 8, pp. 1480–1489. https://doi.org/10.1080/17461391.2022.2113144

19. Komici K., D'Amico F., Verderosa S., Piomboni I., D'Addona C., Picerno V., Bianco A., Caiazzo A., Bencivenga L., Rengo G. et al. Impact of Body Composition Parameters on Lung Function in Athletes. *Nutrients*, 2022, vol. 14, no. 18. Art. no. 3844. https://doi.org/10.3390/nu14183844.

20. Holmberg H.C. The Elite Cross-Country Skier Provides Unique Insights into Human Exercise Physiology. *Scand. J. Med. Sci. Sports*, 2015, vol. 25, no. S4, pp. 100–109. https://doi.org/10.1111/sms.12601

21. Poole D.C., Rossiter H.B., Brooks G.A., Gladden L.B. The Anaerobic Threshold: 50+ Years of Controversy. *J. Physiol.*, 2021, vol. 599, no. 3, pp. 737–767. https://doi.org/10.1113/JP279963

22. Collins S.E., Phillips D.B., Brotto A.R., Rampuri Z.H., Stickland M.K. Ventilatory Efficiency in Athletes, Asthma and Obesity. *Eur. Respir. Rev.*, 2021, vol. 30, no. 161. Art. no. 200206. https://doi.org/10.1183/16000617.0206-2020

23. Nicolò A., Massaroni C., Passfield L. Respiratory Frequency During Exercise: The Neglected Physiological Measure. *Front. Physiol.*, 2017, vol. 8. Art. no. 922. https://doi.org/10.3389/fphys.2017.00922

24. Dempsey J.A., La Gerche A., Hull J.H. Is the Healthy Respiratory System Built Just Right, Overbuilt, or Underbuilt to Meet the Demands Imposed by Exercise? *J. Appl. Physiol. (1985)*, 2020, vol. 129, no. 6, pp. 1235–1256. https://doi.org/10.1152/japplphysiol.00444.2020

25. Oueslati F., Berriri A., Boone J., Ahmaidi S. Respiratory Muscle Strength Is Decreased after Maximal Incremental Exercise in Trained Runners and Cyclists. *Respir. Physiol. Neurobiol.*, 2018, vol. 248, pp. 25–30. https://doi.org/10.1016/j.resp.2017.11.005

26. Lundby C., Montero D., Joyner M. Biology of $\dot{V}O_{2max}$: Looking under the Physiology Lamp. *Acta Physiol. (Oxf.)*, 2017, vol. 220, no. 2, pp. 218–228. https://doi.org/10.1111/apha.12827

27. Korzan S., Mclellan N., Sharma A., Kaiser T., Datta D. Comparison of Breathing Reserve Obtained from Measured and Estimated Maximal Voluntary Ventilation in Cardiopulmonary Exercise Testing. *Chest*, 2018, vol. 154, no. 4S. Art. no. 970A. https://doi.org/10.1016/j.chest.2018.08.882

28. Balady G.J., Arena R., Sietsema K., Myers J., Coke L., Fletcher G.F., Forman D., Franklin B., Guazzi M., Gulati M. et al. Clinician's Guide to Cardiopulmonary Exercise Testing in Adults: A Scientific Statement from the American Heart Association. *Circulation*, 2010, vol. 122, no. 2, pp. 191–225. https://doi.org/10.1161/CIR.0b013e3181e52e69

Список литературы

1. *Staes M., Gyselinck I., Goetschalckx K., Troosters T., Janssens W.* Identifying Limitations to Exercise with Incremental Cardiopulmonary Exercise Testing: A Scoping Review // Eur. Resp. Rev. 2024. Vol. 33, № 173. Art. № 240010. https://doi.org/10.1183/16000617.0010-2024

2. *Barron A., Francis D.P., Mayet J., Ewert R., Obst A., Mason M., Elkin S., Hughes A.D., Wensel R.* Oxygen Uptake Efficiency Slope and Breathing Reserve, Not Anaerobic Threshold, Discriminate Between Patients with Cardiovascular Disease over Chronic Obstructive Pulmonary Disease // JACC Heart Fail. 2016. Vol. 4, № 4. P. 252–261. https://doi.org/10.1016/j.jchf.2015.11.003

3. *Petek B.J., Gustus S.K., Wasfy M.M.* Cardiopulmonary Exercise Testing in Athletes: Expect the Unexpected // Curr. Treat. Options Cardiovasc. Med. 2021. Vol. 23, № 7. Art. № 49. https://doi.org/10.1007/s11936-021-00928-z

4. *Guazzi M., Arena R., Halle M., Piepoli M.F., Myers J., Lavie C.J.* 2016 Focused Update: Clinical Recommendations for Cardiopulmonary Exercise Testing Data Assessment in Specific Patient Populations // Circulation. 2016. Vol. 133, № 24. P. e694–e711. https://doi.org/10.1161/CIR.0000000000000406

5. *Herdy A.H., Ritt L.E.F., Stein R., Araujo C.G.S., Milani M., Meneghelo R.S., Ferraz A.S., Hossri C., de Almeida A.E.M., Fernandes-Silva M.M. et al.* Cardiopulmonary Exercise Test: Background, Applicability and Interpretation // Arq. Bras. Cardiol. 2016. Vol. 107, № 5. P. 467–481. https://doi.org/10.5935/abc.20160171

6. *Petek B.J., Tso J.V., Churchill T.W., Guseh J.S., Loomer G., DiCarl M., Lewis G.D., Weiner R.B., Kim J.H., Wasfy M.M. et al.* Normative Cardiopulmonary Exercise Data for Endurance Athletes: The Cardiopulmonary Health and Endurance Exercise Registry (CHEER) // Eur. J. Prev. Cardiol. 2022. Vol. 29, № 3. P. 536–544. https://doi.org/10.1093/eurjpc/zwab150

7. *Rasch-Halvorsen Ø., Hassel E., Brumpton B.M., Jenssen H., Spruit M.A., Langhammer A., Steinshamn S.* Lung Function and Peak Oxygen Uptake in Chronic Obstructive Pulmonary Disease Phenotypes with and Without Emphysema // PLoS One. 2021. Vol. 16, № 5. Art. № e0252386. https://doi.org/10.1371/journal.pone.0252386

8. *Sandbakk Ø., Holmberg H.C.* Physiological Capacity and Training Routines of Elite Cross-Country Skiers: Approaching the Upper Limits of Human Endurance // Int. J. Sports Physiol. Perform. 2017. Vol. 12, № 8. P. 1003–1011. https://doi.org/10.1123/ijspp.2016-0749

9. *Neder J.A., Berton D.C., Marillier M., Bernard A.C., O'Donnell D.E.* Inspiratory Constraints and Ventilatory Inefficiency Are Superior to Breathing Reserve in the Assessment of Exertional Dyspnea in COPD // COPD J. Chronic Obstruct. Pulm. Dis. 2019. Vol. 16, № 2. P. 174–181. https://doi.org/10.1080/15412555.2019.1631776

10. *Berton D.C., Plachi F., James M.D., Vincent S.G., Smyth R.M., Domnik N.J., Phillips D.B., de-Torres J.P., Nery L.E., O'Donnell D.E. et al.* Dynamic Ventilatory Reserve During Incremental Exercise: Reference Values and Clinical Validation in Chronic Obstructive Pulmonary Disease // Ann. Am. Thorac. Soc. 2023. Vol. 20, № 10. P. 1425–1434. https://doi.org/10.1513/AnnalsATS.202304-303OC

11. *McNeill J., Chernofsky A., Nayor M., Rahaghi F.N., Estepar R.S.J., Washko G., Synn A., Vasan R.S., O'Connor G., Larson M.G. et al.* The Association of Lung Function and Pulmonary Vasculature Volume with Cardiorespiratory Fitness in the Community // Eur. Respir. J. 2022. Vol. 60, № 2. Art. № 2101821. https://doi.org/10.1183/13993003.01821-2021

12. *Opina M.T., Brinkley T.E., Gordon M., Lyles M.F., Nicklas B.J.* Association of Breathing Reserve at Peak Exercise with Body Composition and Physical Function in Older Adults with Obesity // J. Gerontol. Ser. A. 2019. Vol. 74, № 12. P. 1973–1979. https://doi.org/10.1093/gerona/gly276

13. *Quanjer P.H., Tammeling G.J., Cotes J.E., Pedersen O.F., Peslin R., Yernault J.C.* Lung Volumes and Forced Ventilatory Flows. Report Working Party Standardization of Lung Function Tests, European Community for Steel and Coal. Official Statement of the European Respiratory Society // Eur. Respir. J. Suppl. 1993. № 16. P. 5–40.

14. *Solberg G., Robstad B., Skjønsberg O.H., Borchsenius F.* Respiratory Gas Exchange Indices for Estimating the Anaerobic Threshold // J. Sports Sci. Med. 2005. Vol. 4, № 1. P. 29–36.

15. *Zagatto A.M., Miyagi W., Sakugawa R.L., Kaminagakura E.I., Papoti M.* Aerobic Endurance Measurement by Respiratory Exchange Ratio During a Cycle Ergometer Graded Exercise Test // J. Exerc. Physiol. Online. 2012. Vol. 15, № 5. P. 49–56.

16. *American Thoracic Society, American College of Chest Physicians.* ATS/ACCP Statement on Cardiopulmonary Exercise Testing // Am. J. Respir. Crit. Care Med. 2003. Vol. 167, № 2. P. 211–277. https://doi.org/10.1164/rccm.167.2.211

17. *Hackett D.A.* Lung Function and Respiratory Muscle Adaptations of Endurance- and Strength-Trained Males // Sports (Basel, Switzerland). 2020. Vol. 8, № 12. Art. № 160. https://doi.org/10.3390/sports8120160

18. *Bernhardsen G.P., Stang J., Halvorsen T., Stensrud T.* Differences in Lung Function, Bronchial Hyperresponsiveness and Respiratory Health Between Elite Athletes Competing in Different Sports // Eur. J. Sport Sci. 2023. Vol. 23, № 8. P. 1480–1489. https://doi.org/10.1080/17461391.2022.2113144

19. *Komici K., D'Amico F., Verderosa S., Piomboni I., D'Addona C., Picerno V., Bianco A., Caiazzo A., Bencivenga L., Rengo G. et al.* Impact of Body Composition Parameters on Lung Function in Athletes // Nutrients. 2022. Vol. 14, № 18. Art. № 3844. https://doi.org/10.3390/nu14183844

20. *Holmberg H.C.* The Elite Cross-Country Skier Provides Unique Insights into Human Exercise Physiology // Scand. J. Med. Sci. Sports. 2015. Vol. 25, № S4. P. 100–109. https://doi.org/10.1111/sms.12601

21. *Poole D.C., Rossiter H.B., Brooks G.A., Gladden L.B.* The Anaerobic Threshold: 50+ Years of Controversy // J. Physiol. 2021. Vol. 599, № 3. P. 737–767. https://doi.org/10.1113/JP279963

22. *Collins S.E., Phillips D.B., Brotto A.R., Rampuri Z.H., Stickland M.K.* Ventilatory Efficiency in Athletes, Asthma and Obesity // Eur. Respir. Rev. 2021. Vol. 30, № 161. Art. № 200206. https://doi.org/10.1183/16000617.0206-2020

23. *Nicolò A., Massaroni C., Passfield L.* Respiratory Frequency During Exercise: The Neglected Physiological Measure // Front. Physiol. 2017. Vol. 8. Art. № 922. https://doi.org/10.3389/fphys.2017.00922

24. *Dempsey J.A., La Gerche A., Hull J.H.* Is the Healthy Respiratory System Built Just Right, Overbuilt, or Underbuilt to Meet the Demands Imposed by Exercise? // J. Appl. Physiol. (1985). 2020. Vol. 129, № 6. P. 1235–1256. https://doi.org/10.1152/japplphysiol.00444.2020

25. *Oueslati F., Berriri A., Boone J., Ahmaidi S.* Respiratory Muscle Strength Is Decreased after Maximal Incremental Exercise in Trained Runners and Cyclists // Respir. Physiol. Neurobiol. 2018. Vol. 248. P. 25–30. https://doi.org/10.1016/j.resp.2017.11.005

26. *Lundby C., Montero D., Joyner M.* Biology of $\dot{V}O_{2max}$: Looking under the Physiology Lamp // Acta. Physiol. (Oxf.). 2017. Vol. 220, № 2. P. 218–228. https://doi.org/10.1111/apha.12827

27. *Korzan S., Mclellan N., Sharma A., Kaiser T., Datta D.* Comparison of Breathing Reserve Obtained from Measured and Estimated Maximal Voluntary Ventilation in Cardiopulmonary Exercise Testing // Chest. 2018. Vol. 154, № 4S. Art. № 970A. https://doi.org/10.1016/j.chest.2018.08.882

28. *Balady G.J., Arena R., Sietsema K., Myers J., Coke L., Fletcher G.F., Forman D., Franklin B., Guazzi M., Gulati M. et al.* Clinician's Guide to Cardiopulmonary Exercise Testing in Adults: A Scientific Statement from the American Heart Association // Circulation. 2010. Vol. 122, № 2. P. 191–225. https://doi.org/10.1161/CIR.0b013e3181e52e69

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