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Noninvasive Monitoring of Cerebrovascular Autoregulation Response to Resistance Exercises

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Key words: *cerebrovascular autoregulation; noninvasive monitoring; resistance exercises.*

Summary. *Background and Objective. A novel noninvasive monitor is presented by demonstrating its capabilities to perform the real-time estimation of dynamics in cerebrovascular autoregulation in athletes during their training. The aim was to explore the characteristics of human cerebrovascular autoregulation by performing the monitoring of cerebrovascular autoregulation responses to resistance exercises in healthy volunteer athletes.*

Material and Methods. Cerebrovascular autoregulation status was monitored in 20 amateur and 20 elite male athletes (weightlifters and bodybuilders) in the supine position at rest during and after the resistance exercises by using a novel noninvasive monitor "Vittamed." Blood pressure and heart rate were also measured noninvasively. During the exercises, the athletes lifted 50 kg and 80% of 1RM (repetition maximum) weights in a dynamic and static manner in separate tests.

Results. The cerebrovascular autoregulation reactivity index showed a temporal improvement in the cerebrovascular autoregulation status for almost all sportsmen after the exercises. No disturbances of cerebrovascular autoregulation response occurred in the weightlifters and amateur athletes after the static and dynamic exercises. However, an unstable status of cerebrovascular autoregulation was observed for the elite bodybuilders during the interval of 400 to 600 s after the exercises.

Conclusions. The data of this study demonstrated significant differences in cerebrovascular autoregulation response to the resistance exercises between the elite bodybuilders and other subjects (amateurs and weightlifters) – a temporarily unstable status of cerebrovascular autoregulation was observed in the group of elite bodybuilders. This study also demonstrated the applicability of the noninvasive device for exploring the physiology of cerebrovascular autoregulation mechanism in elite athletes and healthy volunteers.

Introduction

Cerebrovascular autoregulation (CA) is the ability of the brain to modulate its blood supply, while maintaining cerebral blood flow (CBF) relatively constant when the cerebral perfusion pressure (CPP) or arterial blood pressure (ABP) are changing within physiological ranges (1–3). CA is one of the most important physiological mechanisms responsible for retaining a stable milieu within the brain. A temporary CBF response to spontaneous changes in blood pressure is defined as a dynamic CA (4). CA controls the tone of distal resistance blood vessels in the brain, thus not only maintaining the constant CBF at rest, but also minimizing temporary changes in CBF (5–7). During the physical exercise, increases in the resistance raise blood pressure and heart rate, as well as brain perfusion. Rapid and pronounced variations in blood pressure are a challenge for CA. High sympathetic activity levels and altered oxygen and carbon dioxide partial pressures in blood (Po_2, Pco_2) also affect brain perfusion, because the increases in muscle metabolism result in higher blood Pco_2 levels. CA maintains the balance between these cardiovascular and metabolic responses to physical exercises (8, 9).

The exercises alter ABP due to a long-term effect on the autonomic control mechanisms and the remodeling of blood vessels (10). The resistance exercises, such as bench press, increase the resistance of peripheral blood vessels and the left ventricle afterload (11), and CBF increases at the beginning of the exercise (12).

The strenuous weight lifting triggers the Valsalva maneuver (13, 14), which can lead to a rise in intrathoracic pressure from normal to >150 mm Hg in healthy individuals (13). As a result, blood pressure (15) and CBF (13, 16, 17) decrease. This increase in the intrathoracic pressure with the Valsalva maneuver is directly transmitted to the cerebrospinal fluid so that the cerebrospinal pressure increases to match that in the thorax and abdomen (18). This may represent an important protective mechanism by reducing transmural pressures across the cerebral vessels,

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thus reducing the risk of vascular damage under the extremes of the pressure encountered with this form of exercise (18). CA response during the Valsalva maneuver may be disturbed by the existing sympathetic activation, which can be induced by a potent baroreceptor response during the Valsalva maneuver (19) or the increased intracranial pressure (20).

The athletes who perform strenuous resistance exercises during their training continuously encounter the changes in many physiological parameters influencing the CA status. However, safe physiological limits of the CA status in the trained athletes under the physical load condition are not known. The aim of this study was to explore the characteristics of a human CA by performing experimental investigation of CA responses to the resistance exercises in healthy athletes. A novel noninvasive CA measurement technique was used in this study. Therefore, the additional aim was to explore the applicability of the new noninvasive CA measurement technique for performing a real-time estimation of the CA status in healthy athletes.

Material and Methods

A total of 40 male athletes participated in this study. The participants were divided into 3 groups. The first group (amateur athletes, group A) comprised 20 healthy men practicing in gyms 3–4 times a week according to conventional exercise programs. The sportsmen able to perform bench press exercise 10 times with 50-kg weight (or a little greater) and not preparing for any kind of power sports competition were included into the amateur athletes' group. The second and third groups comprised elite weightlifters (group W, 10 participants) and elite bodybuilders (group B, 10 participants), respectively. All these elite athletes were Lithuanian, European, or world record holders and medalists. The athletes' data (age, weight, and experience in sport) are shown in Table 1.

The ethical approval for biomedical research was obtained from the Kaunas Region Ethics Committee.

The study was conducted under everyday conditions for each athlete – in their gyms, during workouts. The studies usually started in the afternoon. The study followed a preset protocol. All the participants were introduced to the aim and the methods of the study, their questions were answered upon their arrival, and then they were asked to sign the participation agreement form. All the participants were questioned about the use of anabolic steroids before the study, and all of them answered negatively. During the study, each volunteer was laid down on his back on a horizontal weight training bench with his knees bent at the right angle, his feet flat on the ground, and hands positioned on his chest. In order to equalize the breathing rate among all the volunteers, they had to breathe as signaled via a 0.2-Hz vibrator held in their hands. The volunteers performed dynamic resistance (bench press, i.e., lifting the weight 10 times during 30 s) and static resistance (isometric, i.e., holding the lifted weight above their chest for 30 s) exercises. All the exercises were performed under the supervision of a physical trainer; the hands on the barbell were positioned with the thumbs 80 cm apart.

It was expected that such exercises could raise the changes of blood pressure significantly and, consequently, influence different reactions of CA dynamics for different athletes' groups (20, 21). To get a better influence on CA, the duration of exercises was chosen several times longer (30 s) than a transient time of a healthy human's CA mechanism, which is about 5–10 s (22).

During the investigations, the CA status was monitored in two sessions: 600 s before the exercise at rest (first session) and 1200 s after the exercises (second session). The second session included CA reaction monitoring of 600 s after the dynamic resistance exercise (DRE), during the static resistance exercise (SRE), and 600 s after the SRE.

All the investigations in the athletes were performed before the trainings after a light warm-up. To avoid the occurrence of traumas, all the amateur athletes lifted the weight of only 50 kg. The amateur athletes who were not able to lift 50 kg 10 times and those who were able to lift much heavier weights 10 times (e.g., 100 kg) were not included in the study. All the elite athletes lifted the weight of 50 kg and 80% of 1RM (1-repetition maximum) in separate tests. The 80% weight of 1RM instead of 1RM was chosen for the elite athletes to enable them to lift the weight 10 times and to hold the weight for 30 s, thus lowering the risk of injury.

The novel noninvasive real-time CA status monitor "Vittamed" (developed in the Telematics Science Laboratory, Kaunas University of Technology, Lithuania) was used for the investigation of CA dynamics in athletes (Fig. 1). This fully noninvasive CA monitor is based on the ultrasonic measurement of the cerebral blood volume (CBV) pulsation (slow, respiratory, and pulse waves) within the brain pa-

Table 1. Characteristics of Study Population

Athletes' Group	No. of Volunteers	Mean Age, Years	Experience in Sports, Years	Body Weight, kg
Amateur athletes	20	22.4 (3.1)	4.9 (2.8)	84.2 (9.1)
Weightlifters	10	22.1 (5.4)	9.8 (6.5)	111.6 (25.0)
Bodybuilders	10	25.0 (5.4)	8.15 (3.62)	99.3 (11.5)

Values are mean (standard deviation).

renchyma, extraction of informative and the reference slow and respiratory volumetric waves, and the calculation of pressure-reactivity indices (PRx) as a parameter for the evaluation of CA status (23).

The ultrasonic measurement method for real-time monitoring of CA is based on the transmission of short ultrasonic pulses within the brain parenchymal acoustic path from one side of the skull to the other and dynamic measurements of the time-of-flight of ultrasonic pulses. The time-of-flight measured noninvasively depends on the acoustic properties of the pulsating intracranial blood within the small parenchymal arterioles, which are responsible for the cerebral blood flow autoregulation (24). The light and convenient head frame is mounted on the athlete's head in order to fix the ultrasonic transducers in a proper position for transmitting ultrasonic pulses through the brain parenchyma (Fig. 1).

The noninvasive CA monitor provides the estimated PRx (index representing the status of the CA) data plotted on the device window as the results of monitoring. The limits of PRx are −1...1. The mechanism of cerebral blood flow autoregulation functions normally (intact CA), when PRx is negative. When the mechanism of cerebral blood flow autoregulation is disturbed, PRx becomes positive and the critical value is 1, which means the total impairment of the CA status (24–27).

A noninvasive sphygmomanometer (digital automatic blood pressure monitor Model M6 Comfort, brand "Omron," Japan) was also used for measuring ABP and heart rate (HR) during the investigation. ABP and HR were measured immediately after the athletes were positioned on the bench, after 600-s lying at rest, immediately after the DRE, after 600 s following the DRE, and 600 s after the SRE (at the end of the study). The cuff of the sphygmomanometer was removed after each measurement.

All the measurement data (CA, ABP, and HR) were processed by performing statistical analysis. For the statistical estimation of differences of CA data among the athletes' groups, the recorded CA data were split into a nonoverlapping time window with the duration of 100 s, and for each window, the hypothesis about the equal means of two comparable groups was estimated by the *t* test. The assumption that CA data have a normal distribution was accepted after averaging the PRx indexes within 100-s interval. For the estimation of the differences of ABP and HR among the study groups, the Kruskal-Wallis test was used after the assessment of the normal distribution of data. The Friedmann test was used to evaluate the changes of ABP and HR within the groups. Each variable was tested for normal distribution, and the *t* test was used if a variable was normally distributed. If a variable did not have a normal distribution, the Wilcoxon signed rank test was used instead. *P* value <0.05 was considered statistically significant.

Results

All volunteers tolerated the exercises without any side effects. During the second test, elite athletes performed submaximal resistance exercise by lifting 80% 1RM weight. The mean value of 80% 1RM weight was 87 kg (SD, 36.5) for the weightlifters and 96 kg (SD, 10.8) for the bodybuilders. The data of CA reactivity index (PRx) for each group of athletes before and after the exercises are presented in 2 sessions (Fig. 2). The steady CA status and similar values of PRx were observed in all groups of athletes at rest (Fig. 2A). Immediately after the DRE, the improvement of the CA status was observed for all athletes due to the temporal increase of the heart rate. However, in 400...600 s after the DRE, an unstable CA status was detected in the group of bodybuilders (Fig. 2B), but after the SRE (at 650 s in Fig. 2B), the CA status returned to the steady state.

The estimated differences in the CA reaction between the groups are shown in Table 2. Regular and statistically significant differences can be observed only by comparing the mean reactions of CA after the exercises between the following groups of athletes (Table 2):

– B_{w1}; W_{w1}: bodybuilders and weightlifters after lifting the weight w1=50 kg in time 200...1000 s,
– B_{w1}; A_{w1}: bodybuilders and amateur athletes after lifting the weight w1=50 kg in time 100...1100 s,
– B_{w2}; A_{w1}: bodybuilders after lifting the weight w2=80% 1RM and amateurs after lifting the weight w1=50 kg in time 400...800 s,
– B_{w2}; W_{w2}: bodybuilders and weightlifters after lifting the weight w2=80% 1RM in time 400...500 s.

However, by comparing the CA status among different athletes groups at rest or by comparing the changes of CA status before and after the exercises, regular and significant differences were not observed.

A statistically significant difference in the CA reaction was also observed for the group of bodybuilders by comparing the CA reactions in time 100...200 s after the DRE and SRE, when the weight w2=80% 1RM was lifted (Table 3 and Fig. 2B).

The results of ABP and HR measurements are presented in Table 4 (lifting of the weight w1=50 kg) and in Table 5 (lifting of the weight w2=80% 1RM). Immediately after the lie-down on the bench, no significant differences of ABP and HR data between the pairs of different athletes groups were found. While recording ABP 600 s after rest, the only significant difference was found for the diastolic ABP between the bodybuilders and amateurs (Table 4). After the DRE and SRE with the weight w1=50 kg, higher systolic ABP values were observed for the bodybuilders' group. The significant systolic ABP differences were found between the bodybuilders and amateurs (after the DRE) and between the bodybuilders and weightlifters (at the end of the study).

When lifting 80% 1RM, significant differences in

Table 2. The Results of the Hypothesis Testing About the Equal and Nonequal Means of the CA Reaction Between two Different Groups (Pairs) After the Exercises

Time, s	Hypothesis	B_{w1}; B_{w2}	B_{w1};W_{w1}	B_{w1}; A_{w1}	B_{w2}; W_{w2}	W_{w1}; W_{w2}	W_{w1}; A_{w1}	B_{w2}; A_{w1}	W_{w2}; A_{w1}
0...100	H	0	0	0	0	0	0	0	0
	P	0.203	0.729	0.091	0.533	0.548	0.163	0.982	0.431
100...200	H	0	0	**1**	0	0	0	0	0
	P	0.239	0.244	**0.013**	0.581	0.723	0.393	0.259	0.284
200...300	H	0	**1**	**1**	0	0	0	0	0
	P	0.427	**0.040**	**0.008**	0.963	0.156	0.916	0.137	0.083
300...400	H	0	0	**1**	0	0	0	0	0
	P	0.413	0.091	**0.006**	0.171	0.577	0.450	0.086	0.846
400...500	H	0	0	**1**	0	0	0	**1**	0
	P	0.604	0.073	**0.004**	0.112	0.841	0.481	**0.024**	0.598
500...600	H	0	**1**	**1**	0	0	0	**1**	0
	P	0.314	**0.002**	**0.000**	0.103	0.426	0.932	**0.006**	0.319
600...700	H	0	**1**	**1**	**1**	0	0	**1**	0
	P	0.720	**0.008**	**0.010**	**0.029**	0.702	0.490	**0.023**	0.782
700...800	H	0	**1**	**1**	0	0	0	**1**	0
	P	0.853	**0.045**	**0.006**	0.102	0.986	0.417	**0.010**	0.450
800...900	H	0	0	**1**	0	0	0	0	0
	P	0.869	0.052	**0.018**	0.498	0.289	0.878	0.080	0.164
900...1000	H	0	**1**	0	0	0	0	0	0
	P	0.804	**0.016**	0.099	0.738	0.062	0.315	0.166	0.319
1000...1100	H	0	0	**1**	0	0	0	0	0
	P	0.895	0.052	**0.034**	0.431	0.383	0.860	0.090	0.301

B_{w1} and B_{w2}, bodybuilders after lifting weights w1 and w2; W_{w1} and W_{w2}, weightlifters after lifting weights w1 and w2; A_{w1}, amateur sportsmen after lifting weight w1; H, hypothesis; *P*, probability; A, amateur athletes; W, weightlifters; B, bodybuilders.
The significance level of the hypothesis of "means are equal" rejection is 5%. The hypothesis about "nonequal mean" is accepted when H=1 ($P \leq 0.05$). The null hypothesis about "mean are equal" is accepted when H=0 ($P>0.05$). The bolded numbers in the table cells indicates the accepted hypothesis of "different means."

Table 3. The Results of the Hypothesis Testing About the Equal Means of the CA Reaction in the Same Group Between the CA Reactions After the Static and Dynamic Exercises

Time, s	Hypothesis	B_{w1}	B_{w2}	W_{w1}	W_{w2}	A_{w1}
100...200	H	0	**1**	0	0	0
	P	0.104	**0.025**	0.591	0.273	0.289
200...300	H	0	0	0	0	0
	P	0.806	0.756	0.232	0.995	0.758
300...400	H	0	0	0	0	0
	P	0.424	0.972	0.151	0.508	0.306
400...500	H	0	0	0	0	0
	P	0.362	0.801	0.483	0.559	0.685

B_{w1} and B_{w2}, bodybuilders after lifting weights w1 and w2; W_{w1} and W_{w2}, weightlifters after lifting weights w1 and w2; A_{w1}, amateur sportsmen after lifting weight w1; H, hypothesis; *P*, probability.
The bolded number indicates the accepted hypothesis of "different means."

systolic ABP between the bodybuilders and weightlifters were observed after 600 s following the DRE and at the end of the study (i.e., 600 s after the SRE). In all the phases of ABP measurement, the systolic ABP was higher for the bodybuilders (Table 5).

In analyzing the ABP data within each group of the athletes, significant changes were found only in the bodybuilders' group (Tables 4 and 5):

for the systolic ABP data: after 600 s at rest and after the DRE with w1=50 kg,

for the diastolic ABP data: immediately and 600 s after the DRE with w1=50 kg and 600 s after the DRE with w2=80% 1RM.

In analyzing the HR data within each group, significant changes were found mainly for the group of weightlifters: after 600 s at rest and 600 s after the DRE. The changes of HR data were also found for the bodybuilders: 600 s at rest (before the exercises with w2=80% 1RM).

No significant changes in blood pressure and heart rate within the group of amateur athletes were found.

Discussion

In this study, the CA changes during the static and dynamic resistance exercises were investigated, and the ABP and HR in healthy volunteers of different athletic background were monitored by using the noninvasive techniques. Figs. 2A and 2B present the mean data of CA reactions of the athletes groups at rest and after the weight lifting exercise. Immediately after the DRE, an improvement in CA status was observed for all athletes due to a temporary increase in the heart activity: the heart rate increased insignificantly after the DRE as compared to the state of rest. According to literature (28, 29), heavy resistance exercises cause a 15%–30% increase in cerebral blood flow, which is explained as an adaptive process to the increased brain activity during the exercise, while CA prevents the brain blood flow from rising beyond control. The disorders of CA response were observed after a heavy resistance exer-

Table 4. The Results of Measured Systolic and Diastolic Blood Pressure and Heart Rate of the Studied Volunteers (lifting 50 kg)

Measuring Time	Group	ABPs, mm Hg	ABPd, mm Hg	HR, bpm
Primary state	A	145.5 (16.9)	76.8 (8.8)	86.3 (19.3)
	W	147.2 (14.8)	82.1 (6.2)	67.3 (11.1)
	B	156.2 (14.7)	82.8 (10.0)	71.1(12.5)
600 s at rest	A	138.3 (16.0)	74.5 (7.3)†	77.9 (16.7)
	W	143.1 (18.2)	79.4 (9.7)	68.9 (11.6)
	B	151.1 (14.4)*	80.4 (11.3)†	70.8 (11.2)
After DRE	A	147.9 (20.6)†	76.8 (7.1)	81.6 (17.7)
	W	145.4 (13.1)	76.9 (8.4)	68.5 (9.4)
	B	162.7 (14.3) *†	75.0 (12.7)*	72.0 (10.3)
600 s following DRE	A	137.4 (12.7)	77.2 (8.1)	82.0 (15.5)
	W	141.1 (7.1)	80.6 (8.0)	67.6 (7.4)
	B	156.4 (20.4)	85.5 (17.5)*	70.1 (10.9)
600 s following SRE	A	141.9 (12.6)	77.8 (8.2)	77.1 (13.5)
	W	136.5 (13.2)†	78.6 (11.01)	65.3 (9.3)
	B	157.0 (22.7)†	81.8 (14.8)	70.3 (11.4)

A, amateurs; W, weightlifters; B, bodybuilders; ABPs, systolic arterial blood pressure; ABPd, diastolic arterial blood pressure; HR, heart rate; DRE, dynamic resistance exercise; SRE, static resistance exercise.
*Statistically significant changes within the group; †statistically significant difference in pairs between groups.

Table 5. The Results of Measured Systolic and Diastolic Blood Pressure and Heart Rate of the Studied Volunteers (Lifting 80% 1RM)

Measuring Time	Group	ABPs, mm Hg	ABPd, mm Hg	HR, bpm
Primary state	W	149.3 (14.7)	82.1 (8.7)	64.1 (8.7)
	B	158.8 (16.0)	84.3 (18.3)	67.3 (9.2)
600 s at rest	W	144.4 (16.9)	91.2 (21.0)	66.0 (11.5)
	B	159.9 (22.0)	81.4 (12.4)	67.3 (8.8)
After DRE	W	146.3 (12.6)	74.0 (9.8)	72.4 (9.8)*
	B	164.1 (25.6)	82.1 (17.6)	73.5 (10.2)
600 s following DRE	W	139.6 (11.3)†	82.6 (10.3)	71.0 (10.2)
	B	162.6 (20.9) *†	83.1 (12.5)	77.1 (23.1)*
600 s following SRE	W	140.4 (10.5)†	80.7 (6.5)	68.3 (11.3)
	B	165.3 (27.5)†	83.1 (18.1)	69.9 (8.2)

Values are mean (standard deviation). A, amateurs; W, weightlifters; B, bodybuilders; ABPs, systolic arterial blood pressure; ABPd, diastolic arterial blood pressure; HR, heart rate; DRE, dynamic resistance exercise; SRE, static resistance exercise.
*Statistically significant changes within the group; †statistically significant difference in pairs between groups.

cise in the early recovery period (up to 25 s) by using transcranial Doppler devices (28). The authors of this study (28) agreed with the results of some previous studies that the CA disorders might be a result of the increased vasomotor sympathetic tonus and that the cerebral blood flow velocity changes are dependent on the sudden ABP changes and not on the absolute systemic ABP values (29). According to our data, the indices of CA status showed a normal CA status for all the athletes and a slight enhancement of CA after the DRE; however, significant changes in the mean CA values were observed in the bodybuilders' group, which showed a temporary instability in their CA responses (Fig. 2).

After comparing the mean CA response values in the athletes' group during rest with the values after the exercise, no consistent and significant differences were observed, except a significant difference in a short interval between 200 and 300 s after the DRE in the bodybuilders' group. A similar study performed by using a transcranial Doppler device reported that the mean cerebral blood flow velocity in the middle cerebral artery during 10 submaximal weight lifts did not differ from the initial value (29). Fluctuations in the mean blood flow velocity in the middle cerebral artery during the submaximal resistance exercises correspond to mean arterial pressure (MAP) fluctuations; however, the mean blood flow velocity in the middle cerebral artery remains stably enhanced due to the effective CA response, as opposed to MAP, which increases in a sine curve after each resistance exercise (29). The cerebrovascular system functions as a powerful filter – it replaces great MAP fluctuations with changes in brain bloodstream velocity that are harmless to the brain (29).

The CA reaction of each athlete has an individual behavior and may depend on the training level, the athletes' health condition, and other individual parameters. To represent an individual variation in the CA reaction within the athletes' groups, the probability distribution of individual CA monitoring data within the certain time interval was plotted. The time interval of the 400...600 s at rest and after the exercises was chosen in order to compare

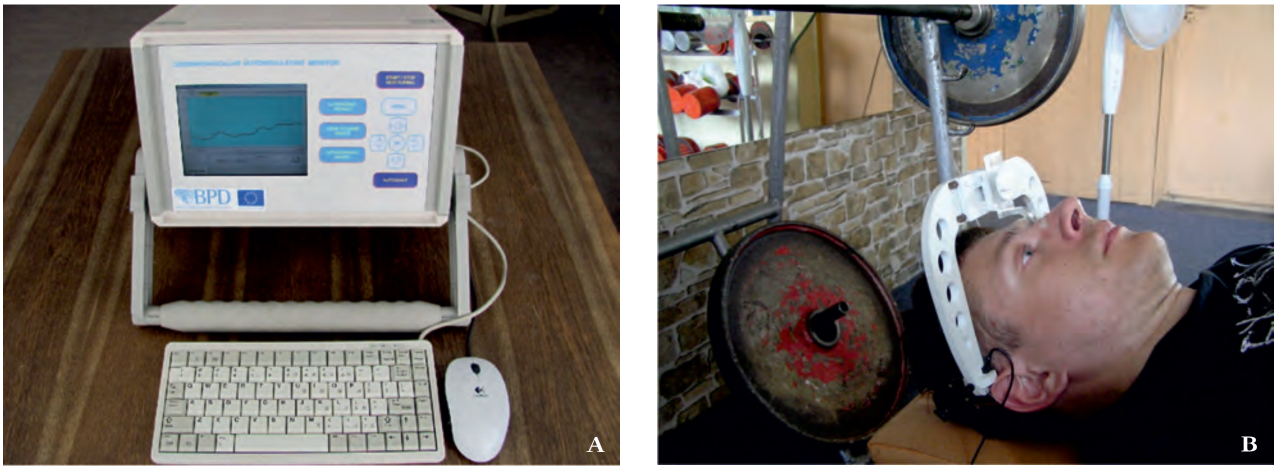

Fig. 1. The noninvasive device for continuous real-time monitoring of CA (A) and the mechanical frame mounted on the athlete's head in order to fix the ultrasonic transducers in a proper position (B)

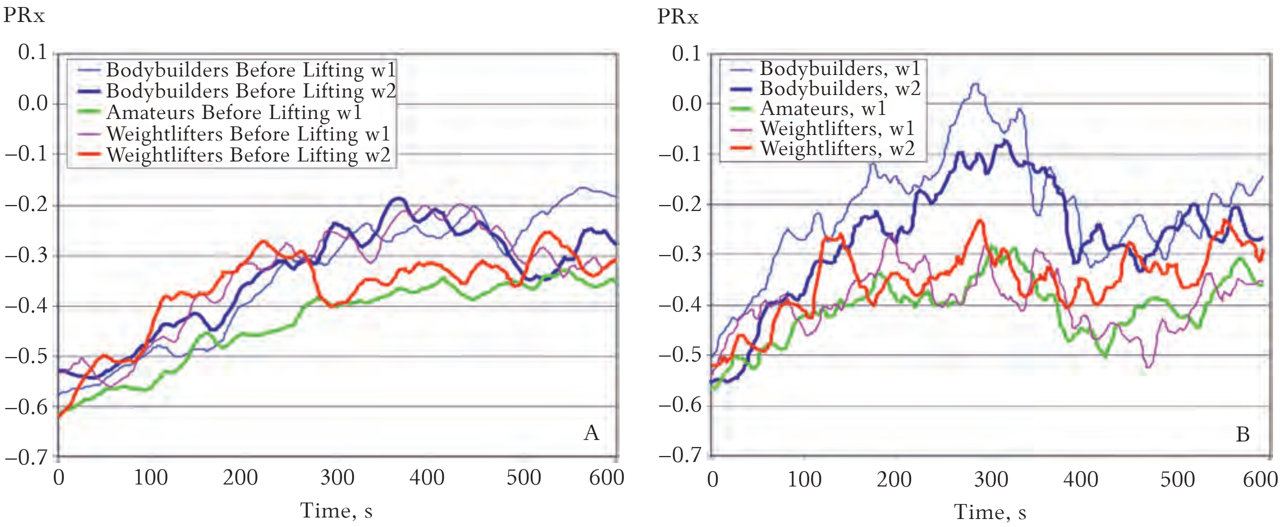

Fig. 2. The results of CA status monitoring in athletes
Mean value of CA index (PRx) in elite (bodybuilders and weightlifters) and amateur athletes at rest (A) and after the exercises (B).

the probability distributions of the CA reactions for different groups (Fig. 3). From these distributions, it is seen how the mass center of PRx probability functions changes after the dynamic exercises and how the distribution of the CA reaction varies for different athletes' groups. The highest variation and transformation of the probability functions were seen for the group of bodybuilders: at rest the mass center of the distribution function was μ=–0.25, but 600 s after the DRE, the mass center shifted to μ=–0.17. However, such changes for the weightlifters and amateur athletes were not clearly seen either from the distribution functions or from the calculation of the hypothesis of different means between the groups.

While analyzing the ABP changes influenced by the exercises with different weights, only a small fluctuation in the ABP (systolic, diastolic) and HR data within each group can be seen (Tables 4 and 5). However, in other works (14, 30–33), it was found that during the submaximal or maximal resistance exercises, an increase in systolic and diastolic ABP up to 4 times was observed. Such an increase is temporal and lasts only during the exercises (31, 32). After the exercises, the ABP returns to the previous state in ~10 s. In our investigation, the measurement of ABP took 30...40 s, and therefore, no extreme increase of ABP and HR data was observed.

For the bodybuilders' group, it was also found that the diastolic ABP peaked after 600 s of rest following the DRE and significantly differed from the diastolic ABP recorded immediately after the DRE. However, there were no significant changes in the diastolic ABP in other groups. We hypothesize that the explanation of this phenomenon is possible by interpreting the blood flow regimes in the muscles. When the muscles are in a static contraction, the intramuscular mechanic compression eventually rises to the level that stops the blood flow in the mus-

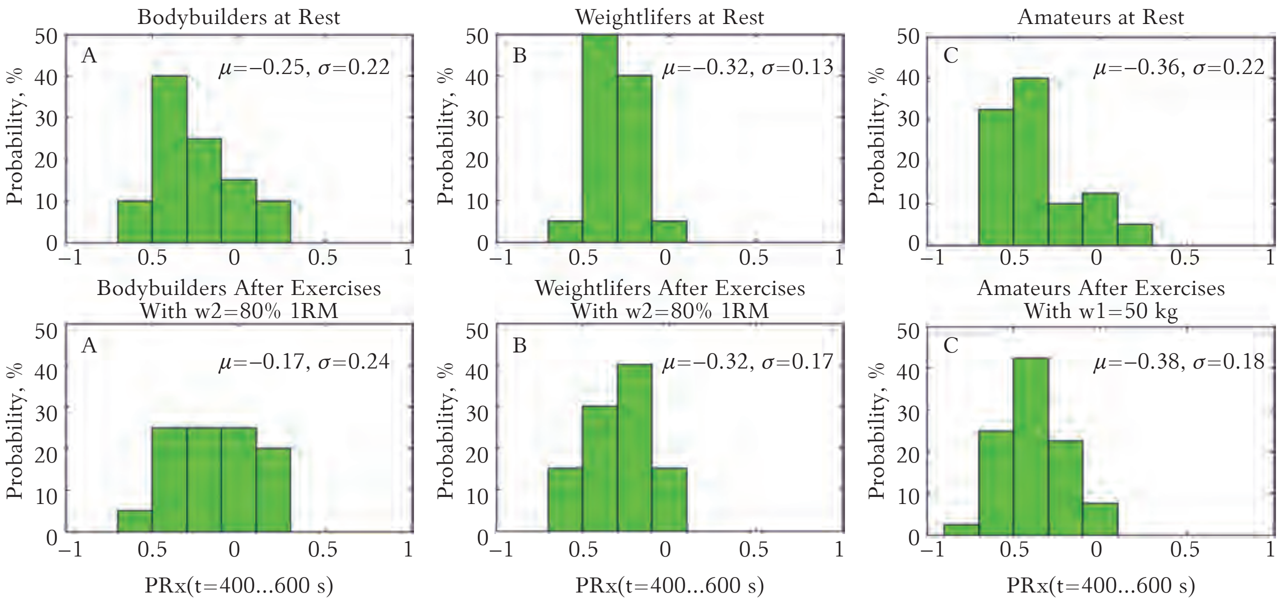

Fig. 3. Distributions of PRx indexes in time 400...600 s at rest (above) and after the exercises (below): elite bodybuilders (with w2=80% 1RM) (A), elite weightlifters (with w2=80% 1RM) (B), and amateurs (with w1=50 kg) (C)

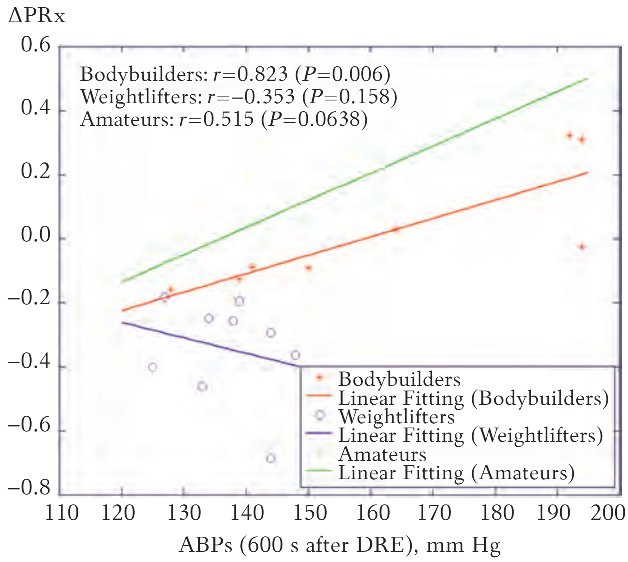

Fig. 4. The temporarily appeared relationship between changes in the cerebrovascular autoregulation status and the systolic arterial blood pressure (ABP) data in 600 s after the dynamic resistance exercise (DRE)

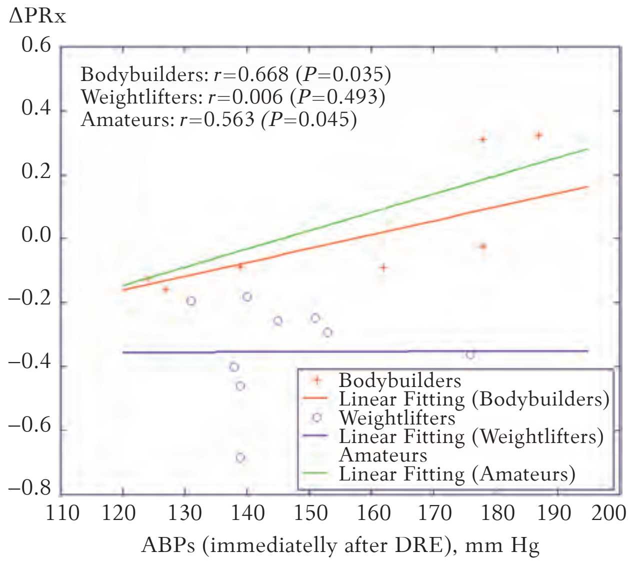

Fig. 5. The temporarily appeared relationship between changes in the cerebrovascular autoregulation status and the systolic arterial blood pressure (ABP) data immediately after the dynamic resistance exercise (DRE)

cles (31). The local blood flow is hindered or slowed down if the contraction is between ~40% to 60% 1 MVC (maximum voluntary contraction) (31). The bodybuilders have a large and prominent muscle mass; therefore, lying still on the bench with their arms crossed on their chests is hard. Lying still acts as an isometric resistance exercise, during which the muscles are constantly contracted, the mechanical blood vessel wall compression occurs (31) and peripheral resistance increases. Moreover, the additional blood volume gathers in the lowered legs due to gravity, while venous blood return is hindered (30, 31, 33), and consequently, the diastolic blood pressure should decrease. Some authors also explain this phenomenon referring to biomechanical inconvenience of the body position (29). This was observed in our study, too. However, the authors who explored the CA reactions after heavy resistance exercise by using the transcranial Doppler devices reported that the CA immediately after the exercise (during the first 25 s) is temporarily disturbed, but shortly afterward, the CA returns to a normal state (28, 29). In our study, the CA returned to the previous normal state after 650 s (shortly after SRE).

However, the increase in the diastolic blood pressure in our bodybuilders' group might be explained by other, non–volume-related blood flow changes, i.e., neural or metabolic changes. The studies showed (even though these data were acquired by using the invasive methods) (14, 31) that the HR increased maximally to 166 beats per minute (bpm) (14) during the exercise and significantly differed from the state of rest (81±12 bpm and 91±10 bpm) (33). It was proved that heart contractility increases during the resistance exercise (30, 33). In our study, the HR in the weightlifters' group after the DRE with 80% 1RM weight was significantly higher than the HR at rest (Table 5). There was also a significant HR increase in the bodybuilders' group after 600-s rest following the dynamic resistance exercise as compared with lying for 600 s before the resistance exercises (Table 5). In our opinion, a large muscle mass, isometric muscle stress while lying still, and gravity hinder the related venous blood return, which causes a reduced heart systolic volume and increases the heart rate as a compensation mechanism.

Analysis of the CA status and ABP changes for the athletes revealed that a strong correlation exists between the distinguishing data of the systolic ABP values after the DRE and the changes of the CA status in the indexes (by comparing PRx changes after the DRE with PRx at rest). These relationships are shown in Figs. 4 and 5. A high correlation coefficient was found between ΔPRx(after DRE/at rest) and systolic ABP (after DRE) data for elite bodybuilders: $r(\Delta PRx;\ ABPs_{600\ s\ after\ DRE})=0.823$ ($P<0.05$) for the systolic ABP data 600 s after the DRE and $r(\Delta PRx;\ ABPs_{after\ DRE})=0.668$ ($P<0.05$) for systolic ABP immediately after the DRE (Figs. 4 and 5). A moderate correlation of borderline significance was documented for amateur athletes: $r(\Delta PRx;\ ABPs_{600\ s\ after\ DRE})=0.515$ ($P=0.063$) and $r(\Delta PRx;\ ABPs_{after\ DRE})=0.563$ ($P=0.045$). However, these dependences were weak and not significant for the elite weightlifters (Figs. 4 and 5).

The temporarily appeared relationship between the changes of CA status and the systolic ABP values might be as a symptom of the CA status disturbance for the elite bodybuilders. The ideal case of the autoregulatory reaction was found for the elite weightlifters when the CA status was not dependant on the ABP values. An additional hypothesis for the interpretation of these data might be based on different techniques of weight lifting. It was observed that the training methodology of weightlifters was oriented to the development of a lifting technique, which allowed them to lift heavier weights with the consumption of less power. However, mostly, the bodybuilders lifted the weight in slow movements, which required more power. The same reason might explain the difference of the CA reaction after the static and the dynamic resistance exercises, which was observed only for the group of elite bodybuilders (Table 3). This difference illustrates that lifting of a heavier weight (w2=80% 1RM) in a static manner appears to be more disturbing for the cerebral autoregulatory mechanism than a dynamic lifting. This phenomenon was observed only for the elite bodybuilders who lifted heavier weights w2 than the weightlifters and, therefore, influenced the stability of the autoregulatory mechanism during the SRE more than the weightlifters or the amateurs did. Moreover, the SRE, applied as a weight holding, acts similarly as the Valsalva maneuver, because mostly the athletes expire and hold breathing during the weight holding.

Sader et al. carried out the study that demonstrated the association of the elite bodybuilding athletes with the impaired vascular reactivity and the increased carotid intima-media thickness (34). The authors of that study analyzed the influence of steroids on the arterial and the cardiac dysfunction in the bodybuilders; however, no significant associations were found (34). In our study, the relation between the athletes' diet and the stability of their CA status was not analyzed. We hypothesize that different behavior of the CA reaction in the group of the elite bodybuilders could be explained by the disturbance of blood flow mode in the muscle mass of the bodybuilders and different training methodology.

Our study has several limitations. Firstly, the control of the substances used (e.g., steroids) was limited only to questioning the studied individuals and the reviewing the previous records of substance checks; thus, the possibility that some athletes might have used these substances and that it might have influenced the results cannot be fully excluded. Secondly, the study was limited to only male Lithuanian athletes, and there are various factors, such as age, race, gender, nutrition, training regimen, etc., that might have an impact on CA response throughout this population group.

Conclusions

By exploring the characteristics of cerebrovascular autoregulation responses to the resistance exercises, the symptoms of temporal unstable cerebrovascular autoregulation status were detected for the group of elite bodybuilders. The unstable status of cerebrovascular autoregulation was also seen from the temporal dependencies between the changes in cerebrovascular autoregulation status and the systolic ABP data. However, the impairment of the cerebrovascular autoregulation status was not observed for the elite weightlifters and amateur athletes.

The instability of the cerebrovascular autoregulation mechanism in the group of elite bodybuilders might be explained by the disturbed or hindered blood flow in the contracted muscle mass of the bodybuilders during their quiet lying in the supine position after the exercises. An additional reason might be a different technique of weight lifting used by bodybuilders, because they lifted the weight in slow movements with more power consumption than the weightlifters or amateurs did.

The performed investigation also allowed us to demonstrate for the first time the capabilities of the noninvasive monitor "Vittamed" to perform a real-time and continuous evaluation of cerebrovascular autoregulation. The provided information about the dynamics of cerebrovascular autoregulation in the athletes can help better understand the brain physiology of healthy human beings and elite athletes.

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Statement of Conflict of Interest

The authors state no conflict of interest.

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