Monitoring of the Functional State of Athletes by Pupillometry

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Abstract: Method of binocular pupillometry is presented with an application to evaluation of the functional state of athletes. The method is based on synchronous registration of both pupil reactions to a light flash stimulus. Pupil reaction reflects the state of sympathetic-parasympathetic balance of autonomic nervous system and serves as an objective measurement of the body condition. The advantages of the method are: non-invasiveness, quick operation, wide spectrum of measured characteristics, and the fact that pupil reaction to light flash stimulus is an unconditioned reflex and is not controlled by the cortex and consciousness. Results of the experiments performed with various groups of athletes are presented. A possibility of using the pupillometry for evaluating athletes' state is shown. Comparison with traditional methods of functional state evaluation is done.

1 INTRODUCTION

Nowadays trainers, physicians, rehabilitation doctors who are involved in sports of high achievements face increasing negative effects of sport to the human body. Quite frequently this is connected with lack of information on functional state of the athletes in the right time. That is why it is necessary to enhance the methods of survey, diagnosis, and control in order to notice deviations of health condition in time and to prevent unwanted outcomes of training and competition loads as well as to correct training process. One of actual problems of modern sport medicine is development of new methods of examination, allowing more complete and reliable evaluation of the functional state of an athlete.

One of such methods is pupillometry that is measuring pupil response to a stimulus, typically light flash. Possibility to use pupil as an objective criterion for estimating the condition of autonomic nervous system and various connected characteristics was persuasively proven by the works (Velhover and Ananin, 1991; Apter, 1956; Shahnovich, 1964; Smirnov, 1953). Pupillometry is especially attractive since pupil reaction is unconditioned reflex, which is not driven by cortex and thus is not controlled by mind (Velhover and Ananin, 1991; Andreassi, 2000). At the same time it is sensitive indicator of wide spectrum of physiological processes connected with sympathetic-parasympathetic balance.

Despite the seeming simplicity, registration and processing of pupil reaction poses several difficulties due to its quickness and relatively small size of an object to be measured. Pupillometry as a clinical medicine method dates back more than 100 years: in the end of 19-th century Du Bois-Reymond and P. Garten made attempts to photograph the pupil for diagnostic purposes. However necessity of speedy recording and processing of vast data amount delayed the development of the method. First versions of pupillometer devices also faced problems connected with bright background illumination necessary for capturing the film, which causes strong constriction of the pupil. Due to modern means of image registration and processing these problems are now solved. Recent development of informational technology allowed to construct the systems, which register pupil image stream with high speed and process it in real time precisely and reliably. Basic informative feature of modern pupillometry systems is pupillogram, which is a graph of pupil size during its reaction.

This paper presents a method of binocular pupillometry in its application to athlete functional state evaluation. Following section describes some peculiarities of the method. In the third chapter results of experiments are presented. The tests were performed

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on several groups of athletes before and after training loads. Abilities of pupillometry in the evaluation of their conditions are shown. The presented method is compared with standard ones used for this purpose.

2 BINOCULAR PUPILLOMETRY METHOD

Method of pupil reflex registration and processing is implemented by HW/SW complex. Images of right and left eyes are registered simultaneously and synchronously during 2.5 seconds. Light flash stimulus is outputted after 200*ms* after start of registration. Light intensity of 145*lux* was used in examinations described herein. Images are registered by two CCD/NTSC cameras with interlacing. Frame rate is 60 frames per second, thus 150 pairs of frames are captured in one registration session. Frame period is $1/60 = 16.67ms$. Image resolution is $640 * 480$ pixels, grayscale 8 bit. Infrared illumination with wavelengths of 880*nm* and 940*nm* is used. Frame scan and light flash output are synchronized. Examination includes registration of three series split by 1-minute pauses for pupil recovery. Thus total duration of examination does not exceed three minutes. Apart from images age of testee is input since normal behaviour of pupil depends on the age of person.

Figure 1 shows a sample of eye images obtained in pupillometry examination. Images with maximum pupil size (before flash) and in the moment of maximum pupil constriction are presented.

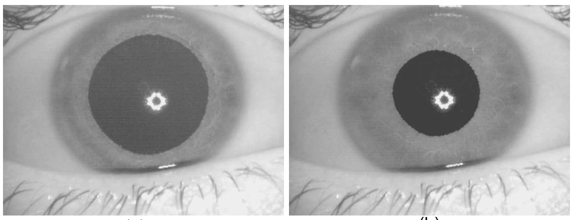

Figure 1: Sample of pupil reaction. (a) — first image in sequence, original pupil size; (b) — 55-th (from 150) image, minimal pupil size.

Pupillogram is determined as a ratio of pupil and iris sizes, dependent on time, expressed in percent:

$$R(t) = \frac{r_{pupil}(t)}{r_{iris}(t)} 100\% \ , \qquad (1)$$

where $r_{pupil}(t)$ and $r_{iris}(t)$ are measured radii or pupil and iris in the moment t. One should note that it is necessary to measure iris radius in all frames of the sequence since the testee can move and scale of image may change. Radii of pupil and iris are determined in frames by the iris segmentation algorithms (Gankin et al., 2014) that give higher precision compared to photometric methods (Shahnovich, 1964) and substantially higher speed compared to manual processing (Velhover and Ananin, 1991), which were used earlier.

First phase of pupillogram reflects the state of pupil sphincter innervated by parasympathetic nervous system. Second phase reveals the state of pupil dilator innervated by sympathetic nervous system. Hence pupillogram characterizes interaction of these two compounds of autonomic nervous system and gives an opportunity to judge about them. Figure 2 represents the typical appearance of the pupillogram. Abscissa axis uses time in milliseconds, ordinate axis gives relative pupil radius (1).

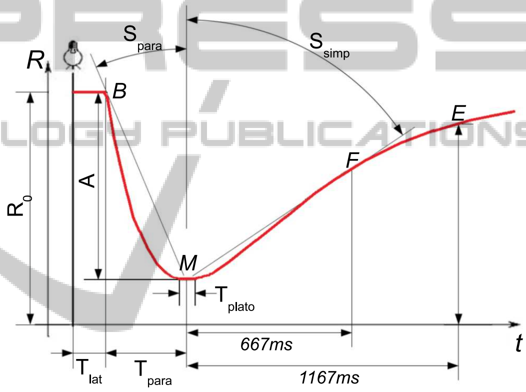

Figure 2: Scheme of the pupillogram and some of its parameters.

From mathematical point of view pupillogram is a series of 150 numbers: $\{r(t)\}_{t=1}^{150}$ each belonging to an interval from 10 to 80 (minimal and maximal possible relative pupil radius). Using time series analysis methods (Hamilton, 1994) the following characteristic points are located in pupillogram: B — moment of reaction start; M — middle of *the plateau*, which is a flat segment of minimum pupillogram values; F — control point lying in a distance of 667*ms* from M; E — control point lying in a distance of 1167*ms* from M. Various parameters describing person's functional state can be extracted from pupillogram. We present nine of them, which are used for functional state monitoring and easily interpretable.

1. R_0 — original relative pupil size, measured in percent. It is calculated as an average relative radius in several beginning frames:

$$R_0 = \frac{1}{T} \sum_{t=0}^{T} R(t) \ , \ \ T \approx 5 \ . \qquad (2)$$

2. T_{lat} — duration of latent period of pupil constriction, i.e. time elapsed from light flash till the start of pupil reaction. It is measured in milliseconds. This parameter is numerically equal to t coordinate of point B: $T_{lat} = t(B)$. It characterizes the agility of nervous processes.

3. T_{para} — duration of parasympathetic phase of pupil reaction i.e. time passed from start of pupil reaction to the middle of plateau. $T_{para} = t(M) - t(B)$.

4. S_{para} — criterion of pupil constriction activity, which is an angle between the BM segment and ordinate axis.

5. A — reaction amplitude, measured as a constriction of pupil relative to iris radius:

$$A = \frac{r_{pupil}(B) - r_{pupil}(M)}{r_{iris}(0)} \ , \quad (3)$$

where $r_{pupil}(B)$ and $r_{pupil}(M)$ are absolute pupil sizes in B and M points.

6. C_{max} — maximum speed of pupil constriction, expressed in percent per millisecond.

$$C_{max} = \max_{t \in [B_t; M_t]} \left(-\frac{dR(t)}{dt} \right) \ . \quad (4)$$

Values of T_{para}, S_{para}, A, C_{max} characterize strength and stability of nervous and muscular excitations.

7. T_{plato} — duration of latent period of recovery, time from stopping constriction till starting dilation. This is the width of the plateau. This value as well as T_{lat} characterizes agility of nervous processes, i.e. speed of switching between excitation and inhibition. For sportive achievements it is optimal to have this parameter in minimum of normal range.

8. S_{simp} — criterion of activity of pupil recovery, which is an angle between FM segment and ordinate axis.

9. V — ratio of pupil sizes after certain period of recovery (control point E). It characterizes recovery abilities of the body. It is expressed in percent:

$$V = \frac{R(E)}{R_0} 100\% \ , \quad (5)$$

If this parameter falls below 50%, chronic fatigue syndrome may take place (Ananin, 1982). With athletes it means over-training.

Average, minimal and maximal values are determined for each parameter statistically. These values vary according to age of the testee. Parameters are normalized so as to fit in range $[-100\%; +100\%]$:

$$\tilde{P} = \begin{cases} \dfrac{P - P_{norm}}{P_{norm} - P_{min}} 100\%, \ P \leqslant P_{norm} \ , \\ \dfrac{P - P_{norm}}{P_{max} - P_{norm}} 100\%, \ P > P_{norm} \ , \end{cases} \quad (6)$$

where P_{norm}, P_{min}, P_{max} are average, minimal and maximal norms of P. By this normalization parameters become dimensionless and their substantial dependence from age is eliminated.

Synchronous binocular pupillometry obtains two pupil reactions and hence gives an opportunity to reveal and examine bilateral asymmetry of nervous system, particularly hemisphere asymmetry. One of basic asymmetry manifestations is *anisocoria* i.e. relative difference in radii of two pupils, defined here as:

$$An = 2 \frac{\tilde{R}_0^{(D)} - \tilde{R}_0^{(S)}}{|\tilde{R}_0^{(D)}| + |\tilde{R}_0^{(S)}|} \ , \quad (7)$$

where $\tilde{R}_0^{(D)}$ and $\tilde{R}_0^{(S)}$ are normalized parameter R_0 (2) for right and left eyes respectively. Due to limitations of iris segmentation methods precision of anisocoria value is 2%. Thus hemisphere asymmetry is detected if $An \notin [-0.02; 0.02]$. For athletes presence of hemisphere asymmetry first of all means possible mismatch in coordination.

3 COMPARISON WITH OTHER METHODS

Pupillometry abilities were verified in comparative tests with standard methods. 30 professional volleyball players were tested. Age of the athletes ranges 22-24 years, sport experience is 5-6 years. Control group was formed from 30 healthy men of same age, not athletes. Tests were performed in natural conditions, i.e. in the sports hall. Pupillogram was registered in rest (before the load) and after the load (training or competition). Complex estimation of functional condition of the testees was done including studies of cardiovascular, somatic and autonomic nervous systems, operability, emotional and volitional qualities. Cardiovascular system was evaluated by conventional sports medicine methods: heart rate (HR), blood pressure (BP) and electrocardiogram (ECG) (Dolmatova et al., 2001). Operability was determined by a common European test PWC-170. Maximal oxygen consumption (MOC) calculated by the method (Karpman et al., 1988). State of conditioned reflex activity was determined by the latent period of the motor response (visual-motor test). Sensorimotor coordination (tremor of hands, strength and endurance of individual muscle groups hands) was determined by labyrinth tremor-meter as the number of errors made in 30 seconds. Emotional and volitional qualities and status of major organs and systems were determined by electro-puncture reflex diagnosis (Nacatani and Yarnashita, 1985). The athletes were divided into two groups according to their performance in competitions: I — high professional group, II — middle level group.

As shown in Table 1, indicators HR and BP in both groups of athletes have the same value, and the value of these indicators point to a good recovery of the cardiovascular system. However, the performance of the MOC and PWC in group I was significantly above the rate of group II and correlated with the level of professional training of athletes. Control group has significantly lower MOC and PWC, and indicators of the cardiovascular system showing that these testees are above their limits of adaptation at this test load.

Table 1: Indicators of cardiovascular and performance after the load test

Indicator	Groups		
	Group I	Group II	Control
HR, beats/min	$54-74$	$56-71$	$110-118$
BP, mm Hg	$130/60$	$130/75$	$150/90$
MOC, ml·kg/min	60 ± 1	51 ± 6.8	33 ± 5.2
PWC-170, kgm/kg	21.8 ± 1	17.3 ± 2.13	11.4 ± 1.7

The effects of exercise on the somatic nervous system and the coordination of movements are presented in Table 2. Columns 'A' and 'B' show the results in tests before and after exercise, respectively. As the table shows, the reaction rate (based on reflex-meter) and sensorimotor coordination (in terms tremor-meter) before exercise are same in both groups of athletes, but after training indicators of Group I are much better.

Table 2: Indicators of reaction speed and tremor before and after the load.

Indicator	Groups					
	Control		Group I		Group II	
	A	B	A	B	A	B
Reflex, ms	380	495	126	96	129	128
Tremor, errors	30	52	30	10	30	25

In the control group, the rate of reaction and sensorimotor coordination worsens after a load test, that indicates the deterioration of conditioned reflex activity and inadequate physical load, which led to fatigue.

Pupillometry results are presented in Tables 3 and 4. Columns 'A' and 'B' show test results before and after exercise, respectively. For athletes columns 'C' and 'D' show results before and after the competition.

As shown in Table 3, latent period of pupil reaction T_{lat} in Group I before exercise is much shorter (at 48*ms*), than in the control group. For Group I T_{lat} becomes shorter after a training and is reduced even more before compatition, that can be explained by emotion tension. After the competition T_{lat} increases to the level observed after training, but does not reach

Table 3: Dynamics of pupillometry parameters for Group I and Control.

Parameter	Groups					
	Control		Group I			
	A	B	A	B	C	D
T_{lat}, ms	283	306	235	224	216	223
T_{para},ms	408	401	441	453	483	508
A,%	8	6	12	14	15	16
V,%	65	57	76	82	84	90

the values that characterize the state of rest. Thus, the readiness of athletes in Group I, characterized by T_{lat}, increases during exercise, peaking before the competition. Observed dynamics of T_{lat} in this group of athletes is positive and indicates an adequate adaptation.

Dynamics of T_{para} for Group I is characterized by a progressive increase. It is minimum in the state of rest, grows after training, grows more before competition, reaching a maximum after competition. This demonstrates high functionality of athletes in Group I. Maintaining a high level indicator after the event shows that the functional reserves of the athletes in this group have not been exhausted by psycho-emotional and physical stress even till the end of the competition.

A similar pattern is observed for the reaction amplitude A. For Group I the indicator increases during exercise, increases even more before the competition and reaches a maximum by the end of the competition. This behavior shows that the potential performance of athletes by the end of the competition is not exhausted, but due to the inertia of energy mobilization processes remained at a high level even after the competition.

Recovery criterion V for Group I is also significantly higher than in control group. After training, V value is significantly higher than before training and remains approximately same before the competition. After the competition the recovery process is strengthened. Thus, the pupillometry study of Group I confirms a known phenomenon of overcompensation after exercise for well-trained athletes. Pupillometry analysis allows to conclude that in this group of volleyball players a high level of adaptation of the autonomic nervous system to physical activity is achieved. For these athletes psycho-emotional load during competition stimulates the adaptive mechanisms.

Table 4: Dynamics of pupillometry parameters for Group II.

Parameter	Group II			
	A	B	C	D
T_{lat}, ms	251	253	246	274
T_{para}, ms	427	432	442	421
A, %	10	10	12	9
V, %	74	77	80	68

As can be seen by comparing the tables 3 and 4, value and dynamics of pupillogram parameters of Group II significantly differ from Group I. Parameters of Group II show higher activity than that of control group, but lower than in Group I.

The latent period of the reaction T_{lat} is longer. Whereas in Group I duration of the latent period decreased after training and before the competition, indicating the improvement of readiness, no significant differences of T_{lat} is found for Group II, and after the competition the latency significantly increases. This marks a decline of starting readiness for these athletes and slower decision making.

Level of reaction revealed by duration of parasympathetic phase T_{para} generally follows the dynamics of T_{lat}. Under the influence of emotional tension before the competition, the durability of reaction increases, but after the event it becomes worse than before training. Such dynamics indicates an insufficient degree of fitness and lower potential performance of athletes in Group II compared with Group I.

Reaction amplitude A is significantly lower in Group II compared to Group I and does not change under the influence of physical load during training. Before the competition, under the influence of emotional stress, these athletes demonstrate an increase of the amplitude, but after the contest reaction strength declines.

Distinct differences between two sportsmen groups exist also in recovery. Characteristic of Group I is a positive trend of all pupillogram parameters during training and competition. Characteristic of Group II is the lack of positive dynamics after exercise compared with the resting state, the trend toward improvement in these areas before the competition and a significant decline after the competition. Apparently, in this group of athletes at the time of tests reached the limit of adaptation capabilities of autonomic regulation. This yields slight improvement in performance under the influence of emotional stress before competition, but then frustration during the competition. Evidence of this frustration is the deterioration of all pupillogram parameters after the competition.

4 COMPARISON OF SPORTS SPECIALIZATIONS

Apart from monitoring of training process pupillometry-based estimation may be applied in other aspects. One of them is evaluation of the appropriateness of the athlete to this or that sport specialization. Different specializations require different physical and psychical characteristics. A study of athletes from different sport specializations was performed in order to determine whether such differences can be revealed by pupillometry.

Male athletes were tested from three different specializations: power (boxing), game (volleyball) and endurance (skiing) in the age group under 25 years. The control group consisted of men of the same age who were not athletes. All participants in the study period were healthy. Each groups included at least 20 persons. Table 5 key indicators for groups of athletes are shown. The groups are designated as 'P', 'G', 'E' (power, game, endurance). Control group indicators are taken as 100%.

Table 5: Pupillogram parameters for athletes of different specializations.

Parameter	Groups		
	P	G	E
T_{lat}	89%	78%	87%
T_{para}	69%	72%	73%
A	164%	165%	151%
V	150%	175%	172%

In general, the reaction of athletes of different specializations differ: reduced amplitude response in a group of endurance, which is associated with the need to save power and distribute it over a longer period. The reaction time is less for the Game group that reflects the focus on making quick decisions. Degree of recovery is higher for Game and Endurance groups. These indicators are lower for Power group, and it is logical, because these sports suppose high performance in short time periods, whereas recovery may be slow.

5 CONCLUSION

Binocular pupillometry is an objective method of assessing the state of the autonomic nervous system and an important additional method for complex evaluation of the functional state of the athletes. Studies of pupil reflex in persons involved in various sports revealed a significant correlation between the time of pupil constriction and overall reactivity of human. Data obtained by pupillometry correlate with analyses of reflex-meter, tremor measurements, latent periods of somatic motor responses.

Binocular pupillometry method allows estimating the degree of athlete's adaptation to the physical and psycho-emotional stress. Absence of positive dynamics of pupillogram parameters after exercise compared with the resting level indicates tension in adaptation processes and the threat of failure of adaptation during the competition. Analysis of the dynamics pupillogram parameters allows to effectively adjust the training process of athletes, analyze their functional fitness and health, optimize and personalize training loads at various stages of preparation, as well as to identify athletes with limited reserves of adaptation and make the selection of athletes for competitions.

Method of computer binocular pupillometry is easy to use, requires no special training and can be utilized for mass screening.

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