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A multi-sensor system for the non-invasive measurement of the activity of the autonomic nervous system

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Abstract

A method using six sensors for measuring the activity of the autonomic nervous system (ANS) is presented. The measured parameters are: skin potential, skin resistance, skin blood flow, skin temperature, instantaneous heart rate, and instantaneous respiratory frequency. The multiparametric measurement of variables of different natures provides complementary information relating to ANS activity. The sensors are characterized by being non-invasive and painless and provide minimal discomfort to the subjects. The sensor's instrumentation system is portable and can be used in laboratory and in real conditions (sports field, on board a vehicle, air-traffic control room, etc.) and presents high immunity to noise. Experiments were performed on 11 marksmen during a shooting competition to study the correlation between ANS activity and shooting performance on the basis of the subjects' control of their emotional reactivity and concentration/relaxation technique.

Keywords: Autonomic nervous system

1. Introduction

The study of the response of the autonomic nervous system (ANS) provides an important asset for the estimation of the emotional reactivity, mental workload, and vigilance level.

Physiological parameters such as heart rate, electrodermal activity, or skin microcirculation are largely modulated by variations in the activity of the ANS, which in its turn depends on the psycho-physiological state of the subject.

In the described method, a set of six sensors is used for measuring autonomic activity: skin potential (SP), skin resistance (SR), skin blood flow (SBF), skin temperature (ST), instantaneous heart rate (IHR), and instantaneous respiratory frequency (IRF).

The sensors used for measurement of ANS-related physiological parameters in real conditions should satisfy several important requirements. They need to be non-invasive and painless, thus providing minimal discomfort to the subjects. They should also be recordable in real time and on a continuous basis.

The responsiveness of the subjects to external stimuli is usually obvious through one or more preferential channels of response [1,2]. The multiparametric recording of variables of different nature is thereby well adapted for accounting for inter-individual differences in automatic responses. It also provides a complementary information reflecting different aspects of ANS activity.

The described methodology was applied to study the time course of ANS activity during different situations: reaction to visual, auditory, and olfactive stimuli, sporting activity, mental imagery, car crash simulation, air-traffic control, etc. An experimentation is presented where this method was used to evaluate the emotional reactivity and the phases of concentration during a shooting competition performed by a population of 11 marksmen.

2. Experimental

The non-invasive sensors are placed on the palmar side of the subject's non-dominant hand, leaving the

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subject free to perform other tasks with the dominant hand (Fig. 1).

2.1. Skin resistance and skin potential electrodes

The exosomatic measurement of skin resistance is performed using two non-polarizable Ag/AgCl electrodes (Clark Electromedical Instruments, surface area = 30 mm^2). The electrodes are placed on the second phalanx of the forefinger and the median (Fig. 1) and are held by an adhesive tape. A 15 μA d.c. current is injected into the skin (current density = 0.5 $\mu A/mm^2$) in order to measure its electrical resistance.

The endosomatic measurement of skin potential is performed by two double-sided adhesive Ag/AgCl electrodes (Beckman, surface area = 78 mm^2). The electrodes are positioned in accordance to traditional recommendations by Fowles et al. [3]. The active electrode is placed at the hypothenar eminence on the palmar side of the non-dominant hand and the reference electrode 10 cm higher on the wrist (Fig. 1). The instrumentation is designed and optimized so that no interference occurs between skin resistance and skin potential measurements.

Special original indices have been developed for the quantification of the skin potential and skin resistance responses. Phasic skin resistance responses are analysed by the ohmic perturbation duration (OPD) [4] which is defined as the interval between the moment of stimulus onset and the moment SR starts returning to its pre-stimulus level.

Skin potential responses are quantified using the Syder Code, which permits the classification of responses into one of three elementary forms [5]: a peak with a duration less than 5 s, responses with a rapid increase followed by a slower decrease, and plateau responses. The elementary forms can be either positive or negative.

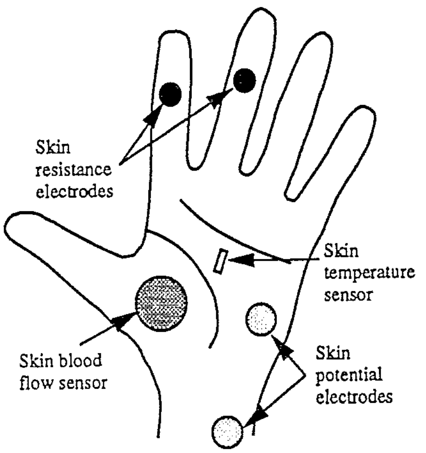

Fig. 1. Position of electrodes and sensors on the subject's non-dominant hand.

2.2. Skin blood flow sensor (Hematron)

A special sensor (Hematron) was developed by Dittmar et al. [6] for the evaluation of SBF (skin microcirculation) by the measurement of the thermal conductivity of the skin. The sensor consists of a disc in which the measuring surface in contact with the skin has two elements: one element at the centre for injecting heat into the skin and the other for measuring the temperature gradient between the centre of the sensor and its periphery resulting from the heating process.

A very low thermal inertia flat heater is located at the centre of the sensor. The amount of heat injected into the skin is regulated by a PID controller in order to maintain the temperature gradient between the centre of the disc and its periphery at a constant increment of 2 °C.

The power necessary to maintain the constant temperature gradient depends on the skin microcirculation. According to the principle of thermal clearance, heat injected into the skin is washed out by the blood flow [7]. At all times, power dissipated by the sensor is proportional to the heat evacuated by the blood and thus to blood flow. The geometry of the heating element has been designed so that the propagation of the microthermal field into the skin reaches the capillary layer of the dermis and thus gives a direct reading of the skin microcirculation (Fig. 2).

SBF measurements are characterized by slow oscillations with a period ranging from 10 to 60 s [7]. These oscillations are an indication of the state of relaxation of the subject. Following a stimulus, these oscillations are inhibited for a duration varying from 10 to 30 s and then resume their oscillatory behaviour. This duration, termed non-oscillatory duration (NOD), is an indicator of the stimulus effect.

2.3. Skin temperature sensor

Skin temperature measurements are performed at the centre of the palm of the hand by a low thermal inertia microthermistor (Betatherm 10 K2 MC D2, outer

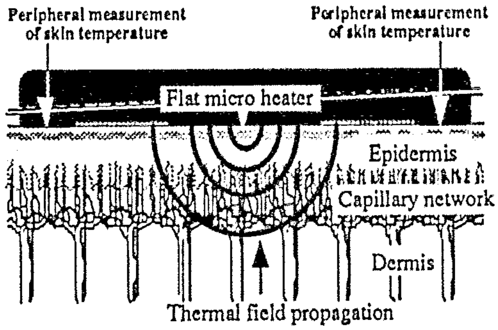

Fig. 2. The Hematron sensor for the estimation of skin blood flow, evaluated by means of the measurement of the thermal conductivity of the skin.

diameter 0.45 mm). The temperature sensor is capable of detecting, after linearization of its characteristics, temperature variations as low as a thousandth of a degree [8]. The fixing of the sensor on the hand is done by applying a non-caustic glue.

2.4. Instantaneous heart rate and respiratory frequency

Instantaneous heart rate measurements are obtained after analog processing of the electrocardiogram. The D2 derivation signal (the interval between two consecutive R waves of the ECG) is processed and delivered in the form of instantaneous heat rate. The ECG is recorded on the subject by means of three large silver electrodes placed in precordial position.

Instantaneous respiratory frequency is measured using a microthermistor placed at the entrance of the subject's left nostril. The sensor measures the difference in temperature between inhaled and exhaled air. The delivered signal is processed by a circuitry similar to that used for instantaneous heart rate and thus respiratory frequency is calculated for each respiratory cycle. This measurement permits the regularity of the respiration activity to be determined and allows the identification of apnea.

3. Results

Tests were performed on 11 marksmen during a shooting performance. These tests were performed to study the relation between the obtained scores and the emotional state of the subjects. The elaboration of objective quantitative and qualitative criteria would subsequently permit the athletes to program better their actions and optimize their performance by feedback.

Fig. 3 shows the measurements obtained as a result of a successful shot.

(i) Relaxation period (before 'Take Post'). The subject is perfectly relaxed; SR and SP indicate an increase in tonic level with no phasic responses, IHR oscillations are stable (mean = 72 beats per min) accompanied by a regular IRF; ST remains invariant.

(ii) 'Take Post'. The subject is asked to start preparing for shooting. This is accompanied by marked variations of all measured parameters.

(iii) 'Loading'. The activation of the mental state of the subject is evidenced by a marked decrease in SR. A regular increase in ST and oscillations in IHR are indicative of an excellent control of the emotional response.

(iv) Concentration period (after 'Start'). The subject starts aiming at the target. The subject's concentration is reflected by a decrease in sinus arrhythmia, a continual decrease in SR, and variations in SP. ANS responses during this concentration phase are a predictive indicator of the subject's performance.

(v) Shooting. Individualized ANS responses are observed on all recorded parameters but are of low amplitude compared with the mean value of all the subjects.

(vi) Result. The subject sees the result of the shot. A small response is observed followed by a rapid return to the relaxation state.

A recording obtained as a result of an unsuccessful shot by a different subject is shown in Fig. 4.

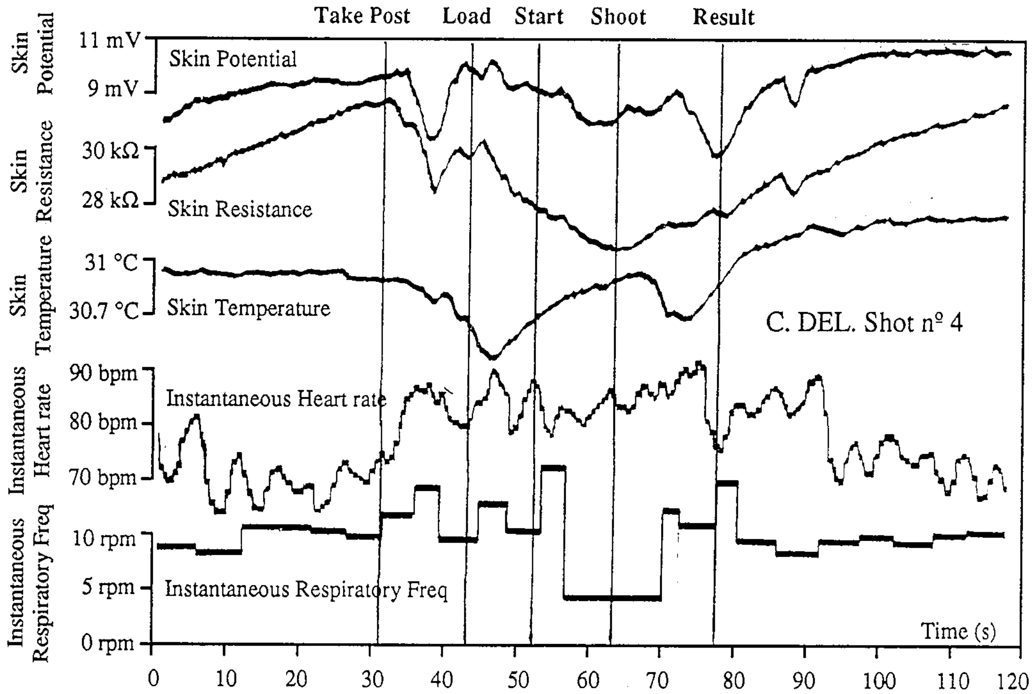

Fig. 3. Autonomic nervous system responses resulting from a successful shooting performance (result = 10).

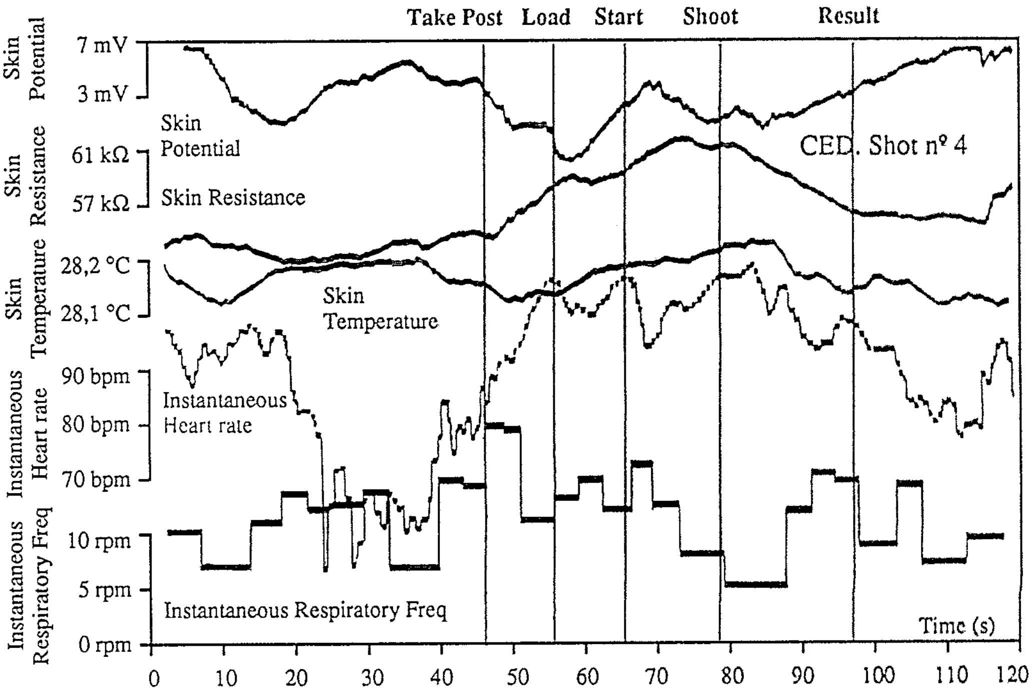

Fig. 4. Recording showing autonomic nervous system responses as a result of an unsuccessful shooting performance.

(i) Relaxation period. The subject is not relaxed. The tonic level of SR remains constant and instantaneous heart rate and instantaneous respiratory frequency are irregular.

(ii) 'Take Post'. A marked response in SP level and more particularly in IHR (110 beats per min). Paradoxically, SR increases indicating that the subject is probably conscious of his emotional state and is trying to relax.

(iii) 'Loading'. The subject responds via all measured ANS indicators, thus increasing his emotional response. The level of SR continues to increase indicating that the subject is not getting prepared for shooting.

(iv) Concentration period (after 'Start'). Additional responses and activation (decrease in SR) only 5 s before shooting. The elevated value of IHR seems incompatible with the subject's immobile state which could be probably attributed to an excessive emotional load.

(v) Shooting. Small responses are produced as a result to shooting. The subject's awaiting for his score produces a strong activation response which maintains IHR at an elevated value 40 s after the shooting. The subject is thereby not at rest.

The measurements indicate an absence of relaxation prior to action and the absence of preparatory activation preceding shooting. This reflects a strong uncontrolled emotional response.

4. Conclusions

This multiparametric measurement using six sensors offers a gateway for the exploration of ANS activity concerning emotional response, vigilance, mental workload, and cognitive processes. Additional research is presently being done for the extraction of new indices related to ANS activity and their graphical presentation in order to be directly exploited by the subjects in real time.

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