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Synchronization of physiological signals of patients after orthodontic correction

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This paper considers changes in the synchronization of physiological signals such as ECG, PPG and respiratory rhythm after orthodontic correction. The synchronization of signals was determined by calculating cross-recurrent and joint recurrent indices. Records obtained before orthodontic correction, immediately after, and two weeks after correction were evaluated. It was shown that both synchronization parameters (cross-recurrent and joint recurrent indices) get decreased after orthodontic correction. In addition, statistical patterns of the joint recurrent index change slightly after orthodontic correction.

Keywords: physiological signals, recurrent analysis, living systems, inclusion.

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One of the urgent tasks of modern practical medicine is solving the problems of inclusion during long-term treatment of various types [1]. If treatment is painful or stressful, or involves prolonged bed rest, the patient's condition may directly affect the treatment quality. One of examples of long-term treatment when problems of this kind may arise is orthodontic correction with braces or aligners [2]. Practical-dentistry treatment of this type needs developing some objective methods that allow assessing the patient's pain feelings and stresses during orthodontic correction in order to ensure an optimal and personalized treatment trajectory. One of the promising ways to create such a method may be assessing the dynamics of interrelation between the circulatory and respiratory systems during treatment, since long-term orthodontic treatment may significantly affect synchronization of physiological signals generated by these systems [3].

In order to analyze peculiar features of the circulatory and respiratory systems synchronization during orthodontic treatment, a series of experiments was conducted in the scope of this work on simultaneous detection of physiological signals: electrocardiograms (ECG), photoplethysmograms (PPG) and respiratory rhythm (RR). The patients' physiological signals were recorded three times during the cognitive tests: prior to orthodontic correction, a day after installing the orthodontic appliance, and two weeks after correction. A total of eight patients who underwent orthodontic correction took part in the experiment: their age was 19 to 39 years, average age was 25.1 years, gender ratio was 5/3. To exclude the possibility of statistical anomalies, among the panel of patients with orthodontic correction there was selected a reference group of eight people without fixed health problems whose physiological signals were recorded in the same way once during the cognitive test: their age was 22 to 31 years, average age was 24.7 years, gender ratio was 4/4. Criteria for the exclusion from participation in the examination were as follows: age under 15 or over 45 years; identified maxillofacial anomalies requiring additional surgical treatment; need for tooth extraction prior to orthodontic treatment; depression with ((BDI-II $\leqslant 8$) according to Beck scale); severe cognitive impairment (< 24 points according to the Mini-Mental State Examination scale); concomitant diseases (chronic obstructive pulmonary disease, malignant pathology, thyroid dysfunction, etc.); diseases of the central nervous system.

To evaluate synchronization between physiological signals, recurrent analysis was used; this is a method well suited for processing complex signals, since the method itself is easy to implement and does not require a large number of complex calculations [4]. This method may be fluently applied to any type of physiological signals, which is especially valuable [5] since in this study signals of three different types are being compared. In addition, recurrent indices are statistically stable [6], which allows working even with small statistical samples.

Both cross-recurrent and joint recurrent indices are important metrics of recurrent analysis that has found application in a wide range of problems of processing various-nature complex signals [7]. The calculation algorithm itself is simple [8], which makes it promising for working with big data and real-time signal processing. Below is illustrated the algorithm for calculating the given indices for signals $x(t)$ and $y(t)$ whose values are known at the same time moments t_i, where $i = 1, \ldots, n$. Thus, the cross-recurrent index may

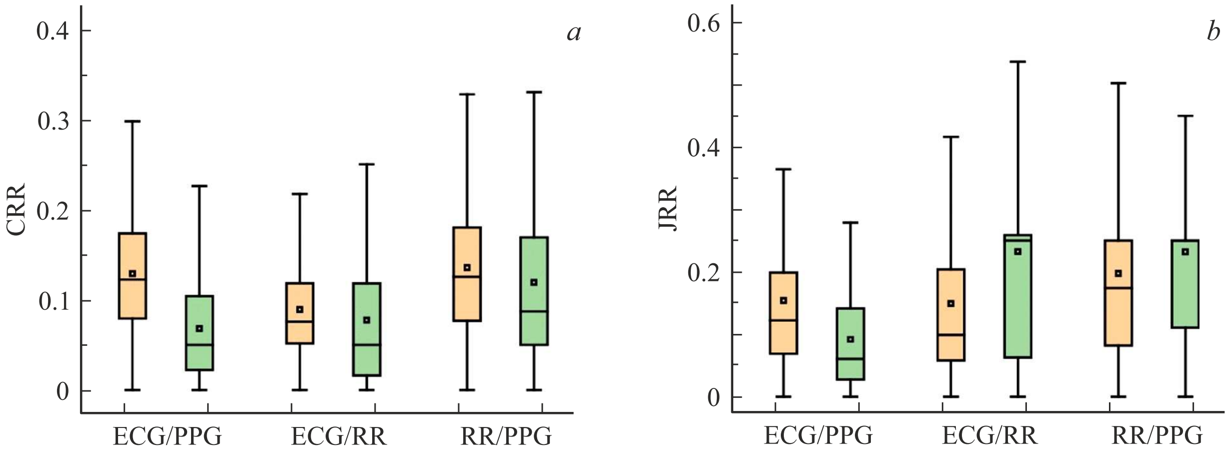

Figure 1. Variations in cross-recurrent (*a*) and joint recurrent (*b*) indices for the reference group (left panel) and patients prior to orthodontic correction (right panel) for three pairs of channels. The rectangles demonstrate the within-sample scatter from 25 to 75 %. Lines indicate the remaining values from minimum to maximum. Horizontal lines in the rectangles represent medians, squares are for mean values.

be calculated as

$$\mathrm{CRR} = \frac{1}{N^2}\sum_{j=1}^{N}\sum_{i=1}^{N}\theta\big(\varepsilon - \| y(t_i) - x(t_j) \|\big). \quad (1)$$

The joint recurrent index is defined somewhat differently:

$$\mathrm{JRR} = \frac{1}{N^2}\sum_{j=1}^{N}\sum_{i=1}^{N}\theta\big(\varepsilon - \| x(t_i) - x(t_j) \|\big) \times \theta\big(\varepsilon - \| y(t_i) - y(t_j) \|\big). \quad (2)$$

Here $\varepsilon = 0.02$ is the empirically determined threshold value ensuring the necessary accuracy of the method. It is to be selected in advance based on the tightness of recurrent diagrams of the signals under consideration [9]. $\theta(\ldots)$ is the Heaviside function in both formulas.

Cross-recurrence and joint diagrams have fundamentally different meanings. For instance, the cross-recurrent index increases if at time moments t_i and t_j the values of two signals appear to be in the same ε-neighborhood. The joint recurrent index may increase provided the pairs of signal values $(x(t_i), x(t_j))$ and $(y(t_i), y(t_j))$ are close to each other (within the ε-neighborhood). Therewith, signals $x(t_i)$ and $y(t_i)$ may differ greatly from each other.

In this study, both indices were used to compare the physiological signal dynamics in the patients after orthodontic correction. The cross-recurrent index is expected to reflect the complete synchronization of signals when their values coincide in view of normalizations. As for the joint recurrence index, it is expected to reveal a deeper signal interconnection when dynamics of both signals change simultaneously.

To evaluate the recurrent indices, in this work the frequency range of 0.01 to 1 Hz was considered. It was chosen because a number of studies [10,11] have shown that synchronization of cardiovascular system signals in heart and vascular diseases is largely affected at the frequencies close to 0.1 Hz. However, since this paper considers not only ECGs and PPGs but also RDs, it was decided to expand the range by including in it the entire low-frequency and high-frequency ranges of respiratory waves [12]. To use recurrent analysis, preliminary statistical processing of the data was carried out in order to remove the trend and bring the mean signal value to zero. In addition, all the signals were then normalized to range [-1;1] in order to ensure correct application of the cross-recurrent analysis.

Fig. 1 illustrates the comparison of scattering of recurrent indices for the reference group and for patients prior to installing the orthodontic appliance. The Mann–Whitney U-criterion did not reveal for this data strict separation of samples, $P < 0.05$.

It is evident that, in general, the indices for these two groups differ statistically only scarcely. Thus, initially the group of patients did not exhibit any statistically significant deviations from the reference group; therefore, subsequent comparison of indices after orthodontic correction is justifiable.

For the patients of the main group, the cognitive test was performed three times. Fig. 2 demonstrates the scatter of cross-recurrent and joint recurrent indices over three experiments for three pairs of channels. Cross-recurrent indices exhibit mainly variations in the scatter of values. Mutual position of the median and mean values, as well as that of the minimum and maximum values, remains almost unchanged from experiment to experiment for all the channel pairs. At the same time, the difference between the maximum and minimum values changes quite significantly. Hence, synchronization of channels in the second experiment gets reduced compared to that in the first cognitive test; in the third experiment, it decreases even more.

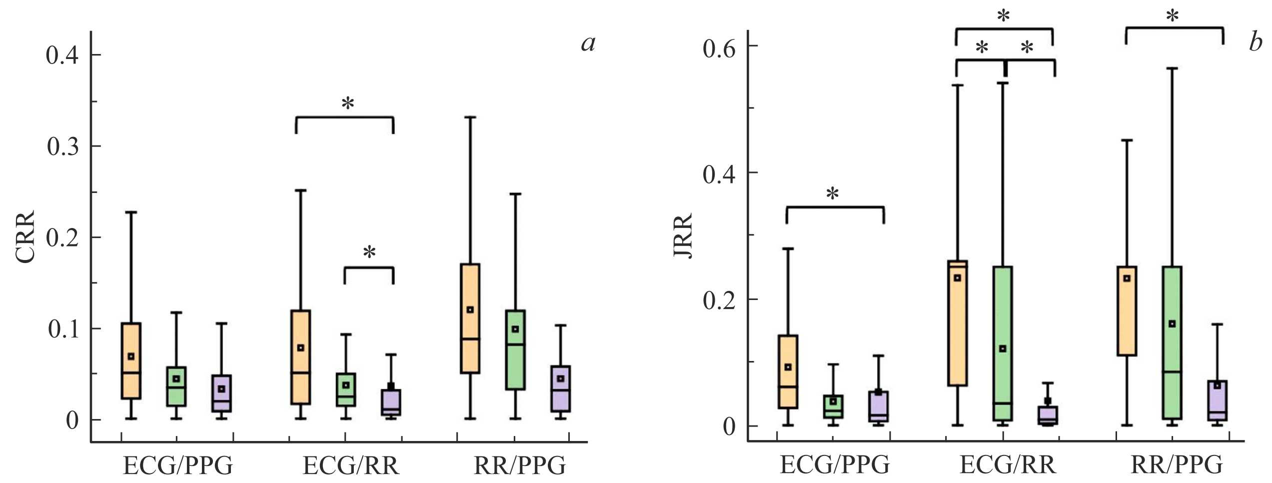

Figure 2. Variations in cross-recurrent (*a*) and joint recurrent (*b*) indices for patients prior to orthodontic correction (left panel), a day after correction (central panel), and two weeks after correction (right panel) for three pairs of channels. Rectangles demonstrate the within-sample scatter from 25 to 75 %. Lines indicate the remaining values from minimum to maximum. Horizontal lines in the rectangles represent medians, squares are for mean values. Asterisks with shelves represent pairs of recurrent-index samples that are statistically different according to the Mann−Whitney U criterion, $P < 0.05$.

As for the joint recurrent indices, their mean value noticeably tends, in general, to approach the maximum (relative to the median). This effect is especially prominent in the third experiment. In contrast to sequential reduction in scattering of cross-recurrent indices, joint indices for the ECG/PPG pair from the first experiment differ greatly from those from the second and third experiments. At the same time, the third experiment for the ECG/RD and PPG/RD pairs differs strongly from the first and second ones. The result of applying the Mann−Whitney U criterion showed which of the samples could be reliably separated statistically, $P < 0.05$.

Thus, analysis of cross-recurrent and joint recurrent indices of physiological signals during cognitive tests after orthodontic corrections has revealed significant differences in patients' conditions. Statistical patterns of the pre-correction indices do not differ significantly from those in the reference group of healthy people. Records of cognitive tests performed immediately after orthodontic intervention and after a long time of wearing the orthodontic appliance demonstrate statistical patterns different from those in the first experiment. The obtained results show that synchronization between physiological signals significantly decreases during orthodontic treatment when both the cross-recurrent indices and joint recurrent indices are assessed. It is assumed that analysis of recurrent indices will further allow development of a technique for determining the acceptable impact level, which is necessary to adjust the orthodontic treatment. In this regard, especially promising is using the joint recurrent analysis or combination of both methods enabling one to compare the electrocardiogram and respiratory rhythm.

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Compliance with Ethical Standards

All the first-in-human trials performed in the framework of this study comply with Ethical Standards of the institutional and/or national research ethics committee, as well as with Declaration of Helsinki (1964) and its subsequent amendments or matched ethical norms. All clinical data and design of the clinical study on recording physiological signals were approved by the Research Ethics Committee of the N.G. Chernyshevsky Saratov State University. All the trial subjects participated in the experiment on the voluntary and free basis, signed the informed voluntary consent to participate in the clinical study, received all the necessary explanations regarding the study, and gave consent for the subsequent publication of the study results. The collected experimental data were processed taking into account requirements for confidentiality and anonymity of the trial participants.

Conflict of interests

The authors declare that they have no conflict of interests.

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