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Qualitative analysis of pulsograms by fractility indices

[1]Tatyana N. NIKITCHUK, [1]Oksana L. KORENIVSKA,
[2]Dmytro SHTOFEL, [3]Jamalbek A. TUSSUPOV, [1]Vasyl B. BENEDYTSKYI,
[1]Tetiana A. VAKALIUK, [4]Iryna M. KOBYLIANSKA
[1]Zhytomyr Polytechnic State University
[2]Vinnytsia National Technical University
[3]L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan
[4]Vinnitsa National Technical University

ABSTRACT

The article explores the possibility of applying modifications to the R/S- analysis method for pulsogram processing under conditions where the noise level is unknown. It is shown that a fast algorithm for calculating the Hirst coefficient can be used to estimate the noise level in a pulse signal. The R/S-analysis method for pulsogram processing has been improved by optimizing the initial conditions, which makes it possible to select the required pulse wave registration interval.
Key words: pulse signal, pulsograms, R/S-analysis method, noise, Hirst index.

INTRODUCTION

Information about pulse signals has been accumulated by doctors throughout the existence of pulse diagnostics, and the development of computer science today allows the processing of pulse signals by many available methods using a wide range of technical means. The amplitude, time, phase and frequency characteristics of the pulse signal can be considered as basic in the problems of modern pulse diagnostics, and methods of digital processing of pulsograms are aimed at computer filtering and selection of useful signal (spline approximation, Fourier analysis, different types of wavelet - conversion) and to determine changes in diagnostic parameters. Any registration of biological signals under real conditions is accompanied by several third-party factors that impose some additional components on the main signal. Therefore, it is important to find a method that will allow the identification of informative components of the heart rate monitor in conditions where the noise level is an unknown value.

KEY RESEARCH MATERIALS

Qualitative information about the system can be obtained by analyzing the evolution of the system parameters using the Poincare section [1]. The Poincare section is obtained when the trajectory in a three-dimensional phase space intersects some arbitrary plane described by the equation $x + y + z = d$.

For the study of pulse signals [2, 3], such a trajectory of motion represents consecutive rotations of a point of a trajectory in a twisted or untwisted spiral, near some mean position, with the time of one revolution being equal to the duration of the current RR-interval or the duration of one period of the pulse wave. In the Poincare section, some set of points of intersection of the trajectory lines with the plane is formed. This set of points can create a characteristic pattern that is characteristic of the heart or the reflective state of the individual's vascular system.

In the case of self-organizing systems, the trajectories of the reflecting points often do not end up over time, gathering near special points or closed curves. The described features are called attractors, that is, they are points in the phase space that attract the trajectory of a dynamic system. It turned out that the structure of the attractors (and hence the finite state of the system) can be analyzed without solving the whole set of nonlinear equations describing the self-organizing system [1]. The analysis of attractors at an early stage can predict the behavior of the dynamic system under study.

To be able to compare the fractal properties of pulse oscillations in the analysis of time series, we can use a dimensionless index in the form of the ratio of the magnitude R of the accumulated deviation from the mean to the standard deviation $S - R / S$ method [4,5,6]. The dependence of the parameter (R / S) on the duration of the measurement, constructed on a double logarithmic scale, represents the process understudy in the form of a fractal function. When approximating a fractal function by a straight line, the angular coefficient called the Hirst index is determined. The Hirst index is used to determine the fractal parameter of the process – the Haustdorf-Bezikovich

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dimension or the fractal dimension, which is an integral characteristic of the process [7,8,10]. The cognitive concept of the value of the fractal dimension is that it can be used to organize the processes under study by the properties of randomness and complexity and, thus, to classify (separate) them. Therefore, there is a need to consider the above indicators in more detail and to illustrate the possible integral characteristics for the phase portraits of pulsograms on model data [16].

STAGES OF THE RESEARCH IMPLEMENTATION

Selection of the method of RS-analysis with the purpose of qualitative analysis of pulsograms

The signal received at the output of the registration block is a typical example of physiological chaos, which is an irregular signal [11,17]. Chaotic systems are characterized by an attractor having a fractal structure. Physiological signals such as cardiogram, stabilogram [11,28], heart rate are not correlated noise and cannot be represented as a chaotic process and can, therefore, be represented as a stochastic process [12, 13,18].

Such time series can be characterized using the Hirst index, which is a measure of self-similarity of the process and is calculated from the known formula of dimension D

$$D = 2 - H$$

The indicator H can be found through the normalized scale R/S [8, 9]. For time series of different natural processes R/S is described by an empirical equation

$$R/S = (\tau/2)^H \quad (1)$$

Where $R(t)$ – is the span of the time series over the period,

S – the standard deviation for the period.

The Hirst index S can take values from 0 to 1. Thus, for the values of the Hirst coefficient $0 < H < 0{,}5$, the studied series is anti-persistent [8], characterized by a high level of noise. The value $H = 0{,}5$ describes white Gaussian noise. Persistent data without noise are characterized by values of the Hirst coefficient $0{,}5 < H < 1$ [8]. To calculate the Hirst index, modifications of the R/S-analysis method described in [12, 13] are used. The essence of the R/S-analysis method is to calculate the Hirst coefficient and compare it with the baseline values.

Qualitative analysis was performed within 200, 500, and 1000 samples for model signals [13, 14], which obtained mathematical equations within the three-phase harmonic wave model [13, 14,29] for six types of pulse (equal, uneven, slow, fast, high, low) using the methods of R/S- analysis described in [12, 13]. Namely, for classical R/S-analysis «c» by formula (1), fast R/S-analysis «f» by least squares method [12, 13,19] by formula (2)

$$\log(R/S) = \log(c) + H \log(n) \quad (2)$$

performing a simple least-squares regression on $\log(n)$ (lengths of rows n) as an independent variable and $\log(R/S)$ as a dependent variable. The segment cut off on the coordinate axis is an estimate $\log(c)$ - constant. The slope of the equation is an estimate of the Hirst index H and randomized R/S-analysis «r» [10, 12, 13] using the formula of randomized least squares method (3):

$$H = \frac{\sum (u_i - Ex_i)(v_i - Ey_i)}{N \sum (u_i - Ex_i)^2} \quad (3)$$

The new modification of the method is as follows: it is necessary to carry out researches and in each of them to randomly select a pair of numbers from a set $\{(x_i, y_i)\}_{i=1}^{k}$ [10]. Thus, we obtain $N\ \{(u_i, v_i)\}$ par.

The results of this analysis represent the calculation of the Hirst coefficient, the numerical values of which are presented in Table 1, indicating the implementation time for each of the algorithms [12,20,30,31].

An analysis of the results of Table 3.1, obtained using various modifications to the RS analysis method, shows that the classic algorithm, which is considered to be the most accurate and effective, can only be applied to a limited number of readings. When the analysis interval is increased up to 500 samples (N = 500 samples), the implementation time is increased.

Table 1 - Calculation of the Hirst coefficient for model signals using the basic algorithms of RS-analysis

Algorithm RS-analysis / Types heart rate	N=200 counts			N=500 counts			N=1000 counts		
	«c»	«f»	«r»	«c»	«f»	«r»	«c»	«f»	«r»
equal	0,8478	0,9443	0,9787	0, 5353	0,6000	1	0,3283	0,4455	0,9211
unequal	1	0,9535	0,8431	1	1	1	0,8168	0,7931	0,9567
slow	0,8241	0,8256	1	0,5289	0,5466	1	0,3083	0,3458	0,9305
fast	0,7418	0,7802	1	0,4383	0,4797	1	0,2470	0,2628	0,8607
high	0,8523	0,9968	1	0,5331	0,6223	1	0,3269	0,4739	0,976
low	0,8477	0,9456	0,9158	0,5363	0,6338	1	0,3301	0,4447	0,9241
Average implementation time, p	28	5	6	63	4	6	602	5	8

However, the fast algorithm of R/S-analysis allows obtaining the Hirst coefficients, which correlate well with the similar indices calculated by the classical method. The time costs for this method are the lowest among all presented in Table 1.

The randomized algorithm differs significantly in its results from its predecessors, which gives grounds for claiming its low accuracy in the case of model data research.

Thus, for further analysis of the pulsograms, a fast algorithm for calculating the Hirst coefficient [12] is recommended as such that can be used in estimating the noise level in the pulse signal [21,22,26].

INVESTIGATION OF THE DEPENDENCE OF THE HIRST COEFFICIENT DEPENDING ON THE INITIAL CONDITIONS

Thus, the results of the fast algorithm for the calculation of the Hirst coefficient depend on the length of the study interval and the size of the data segment d_0, which is taken as the smallest cell of R/S-analysis, presented in Fig. 1.

The numerical values of the Hirst H coefficient are plotted along the axis, along the axis the realization length (counts) for the sizes of data segments $d_0 = 10$, $d_0 = 20$, $d_0 = 50$, $d_0 = 96$.

This graph illustrates the decrease in the Hirst coefficient as the size of the initial segment increases d_0 in the algorithm for the rapid implementation of the R/S-analysis method. As the length of implementation increases, the Hirst coefficient also decreases, but the law of decrease is not linear.

To recommend the optimal length of implementation and the size of the initial segment for the fast algorithm of the Hirst method, model signals under white noise conditions were investigated.

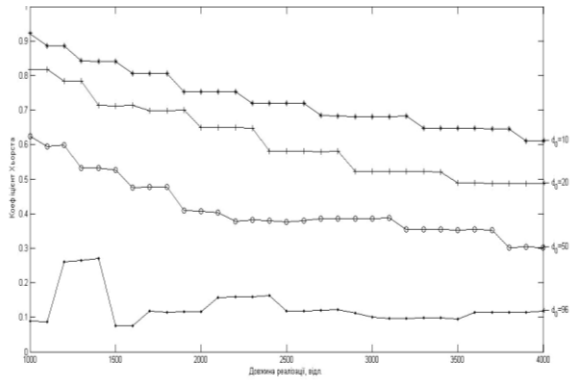


Fig. 1. The dependence of the Hirst coefficient on the length of the study interval and the size of the data segment (d_0)

The dependence of the Hirst coefficient on the length of implementation at different noise levels. Because the white noise caused by the technical implementation of electrical circuits is poorly amenable to hardware filtering, it will certainly be present in real signals, which means that it will affect the magnitude of the Hirst coefficient [23,24,31].

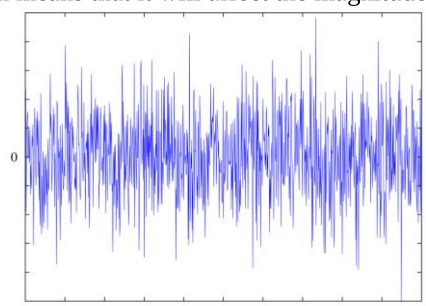


Fig. 2. An example implementation of a process with white noise properties

Therefore, during the experiment, noises were generated and a pulse signal model was applied, after which the Hirst index was calculated.

White noise with a normal distribution law has been added to the model signal of "equal" type. The noise intensity varied in the range of 1 - 5% of the useful signal amplitude (Figure 3). The result of this operation will be the appearance of five new arrays, each with a different noise component, for a different type of pulse ("even", "uneven", "high", "low", "fast", "slow").

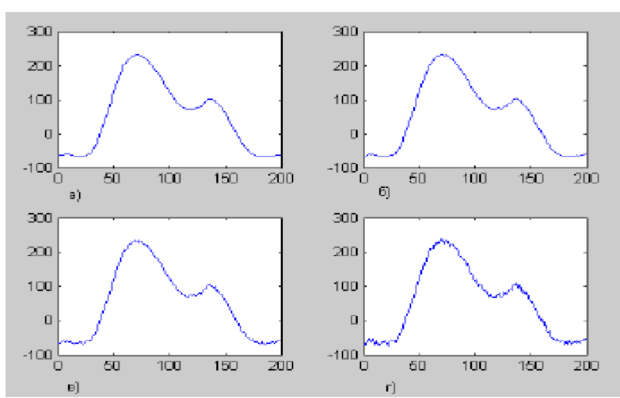
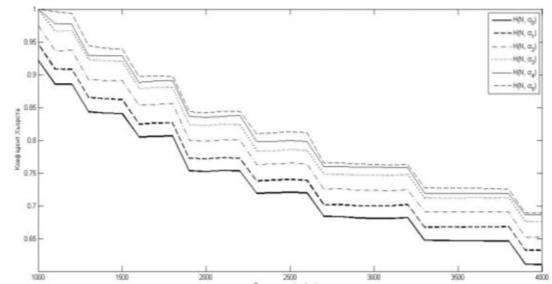
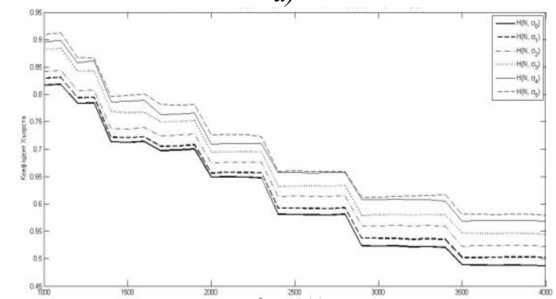


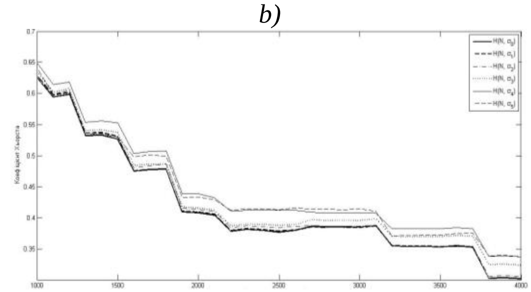
Fig. 3. Overlay of noise amplitude in the range of 1 - 5% of useful signal amplitude: a) 0% noise; b) 1% noise; c) 2% noise; d) 5% noise.



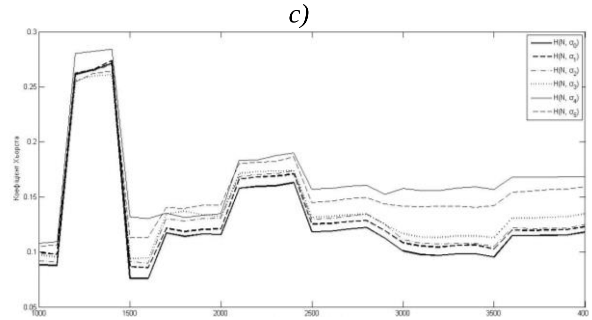
a)



b)



c)



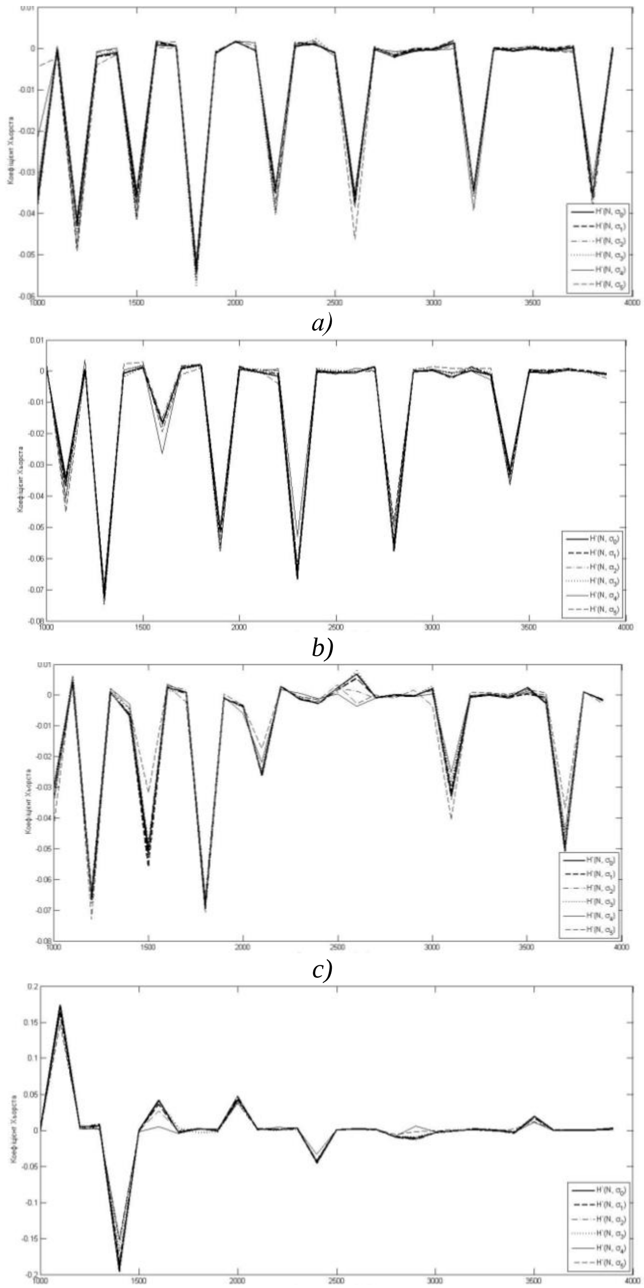
d)

Fig. 4. The values of the Hirst H coefficient at different white noise σ_j levels in model signals Graphic dependencies were used to estimate the rate of change of Hirst's indicators

$$f(H') = \frac{dH}{dN}(N, \sigma_j),$$

where is N – the number of samples;

σ_j – white noise level, represented in Fig. 5.



a) b) c) d)

Fig. 5. The value of the rate of change of the Hirst H' coefficient at different white noise levels σ_j in model signals

ESTIMATION OF THE DEPENDENCE OF THE HIRST COEFFICIENT ON THE INITIAL CONDITIONS AND THE WHITE NOISE IN THE SIGNAL

Since the curves obtained $H(N,\sigma_j)$ and $H'(N,\sigma_j)$ piecewise linear, their properties must be considered in subbands $\lfloor N_k ; N_{k+1} \rfloor$, where there $k = 1..m$ is some point of the extreme of the function $H(N,\sigma_j)$. The following criteria are proposed to quantify dependencies

$$\begin{cases} \Delta H_{N_k;N_{k+1}} = \min\limits_{N_k;N_{k+1},\, 0<j<\sigma_{\max}} \rho(H_N^j - H_N^{j+1}) \\ \Delta H'_{N_k;N_{k+1}} = \max\limits_{N_k;N_{k+1},\, 0<j<\sigma_{\max}} \rho(H'^j_N - H'^{j+1}_N) \end{cases}, \tag{4}$$

where $\rho(H_N^j - H_N^{j+1})$ – the distance between adjacent curves $H(N,\sigma_j)$ and $H(N,\sigma_{j+1})$, measured as the difference of the ordinates of points (N, H_j) and (N, H_{j+1});

$\Delta H_{N_k;N_{k+1}}$ – the minimum value of this distance in the value subband $\lfloor N_k; N_{k+1} \rfloor$;

$\rho(H_N^j - H_N^{j+1})$ – distance between adjacent curves $H'(N,\sigma_j)$ and $H'(N,\sigma_{j+1})$, measured as the difference of the ordinates of points (N, H'_j) and (N, H'_{j+1});

$\Delta H'_{N_k;N_{k+1}}$ – the maximum value of this distance in the value subband $\lfloor N_k; N_{k+1} \rfloor$.

The selected criteria are used to search within the subband of the point where the curves are $H(N,\sigma_j)$ $H(N,\sigma_{j+1})$ are located as close as possible to each other, and also points where the rate of change of the Hirst coefficient for the adjacent curves differs as much as possible. The points found will be critical, that is, at these points the most likely intersection of the curves $H(N,\sigma_j)$ and $H(N,\sigma_j)$ which is a negative factor in selecting the Hirst coefficient as a criterion for estimating the signal noise level.

$$\lfloor N_k; N_{k+1} \rfloor_{onm} = \arg\left\{\max\left(\Delta H_{N_k;N_{k+1}}\right), \min\left(\Delta H'_{N_k;N_{k+1}}\right)\right\}. \tag{5}$$

After calculating $\Delta H_{\min}$ and $\Delta H'_{\max}$ it is obtained that the numerical indices $\Delta H'_{\max}$ at the interval $(N_k - N_{k+1})$ equal to the interval 1000 - 3900 samples intersect.

Using the graphical optimization method [15], dependence $\Delta H_{\min}(\Delta H'_{\max})$ (Fig. 6) was constructed, which established that equation (5) fully corresponds to the range of points $N = 3500 - 3900$ with the size of the data segment $d_0 = 20$.

Thus, when calculating the Hirst coefficient on the specified range $F_S = 100\ Hz$, it is possible to perform a qualitative analysis of the pulsograms, using the value of the Hirst coefficient as a criterion when removing the signal from the noise components. Then, depending on the quantitative indicator of the Hirst coefficient, which is estimated by the signal-to-noise ratio, it is possible to adjust the range of registration of the signals with their subsequent digital processing and representation in the phase plane [24, 25, 27].

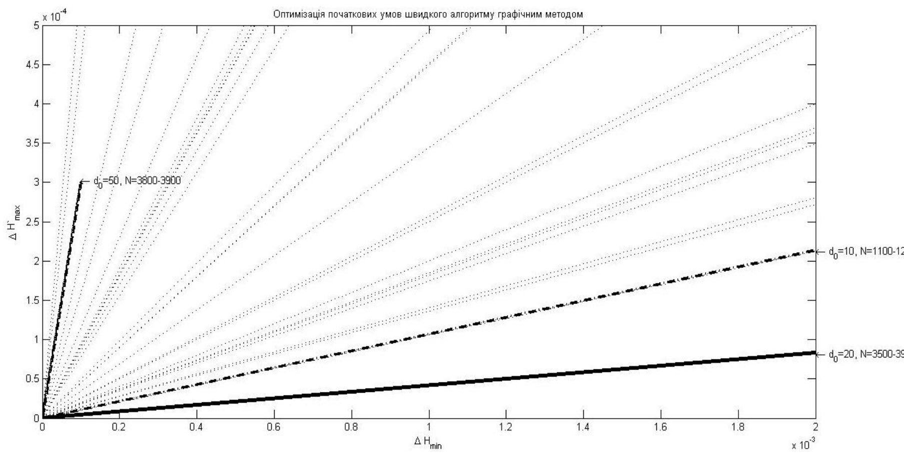


Fig. 6. Optimization of initial conditions of the fast algorithm by graphical method

CONCLUSIONS

Since any registration of biological signals under real conditions is accompanied by several third-party factors that impose some additional components on the main signal, the possibility of applying modifications to the R/S-analysis method to process pulsograms under conditions where the noise level is unknown is investigated. As a result of the experiment, it is shown that to estimate the noise level in the pulse signal, a fast algorithm for calculating the Hirst coefficient can be used. The R/S-analysis method for pulsogram processing has been improved by optimizing the initial conditions, allowing you to select the required pulse wave registration interval.

Authors: *PhD. Docent of Science (Engineering) Tatyana N. Nikitchuk, Head of the Department of Biomedical Engineering and Telecommunications, Zhytomyr Polytechnic State University, Zhytomyr, Chudnivska str., 103, E-mail: tnikitchuk@ukr.net, PhD. Docent of Science(Engineering) Oksana L. Korenivska, docent of the Department of Biomedical Engineering and Telecommunications, Zhytomyr Polytechnic State University, Zhytomyr, Chudnivska str., 103, E-mail: o.l.korenivska@gmail.com, D. Techn. Sc., Sergii M. Zlepko, Vinnytsia National Technical University, Khmelnytske shose street, 95, Vinnytsia, 21021 Ukraine, e-mail:smzlepko@ukr.net; PhD. Techn. Sc.,Dmytro Kh. Shtofel, Vinnytsia National Technical University, Khmelnytske shose street, 95, Vinnytsia, 21021 Ukraine, e-mail: striks@ukr.net, Doctor of Physical and Mathematical Sciences, professor Jamalbek A. Tussupov, L.N. Gumilyov Eurasian National University, Nur-Sultan, Kazakhstan, Satpayev str.,2, E-mail: tussupov@mail.ru, Vasyl B. Benedytskyi, Senior Lecture, Department of Biomedical Engineering and Telecommunications, Zhytomyr Polytechnic State University, Zhytomyr, Chudnivska str., 103, E-mail: vslbened@gmail.com, Professor, Doctor of Pedagogical Sciences, Tetiana A. Vakaliuk, Professor of the Department of Software Engineering, Zhytomyr Polytechnic State University, Zhytomyr, Chudnivska str., 103, E-mail: tetianavakaliuk@gmail.com, Candidate of Pedagogical Sciences, Iryna M. Kobylianska, Vinnitsa National Technical University, Khmelnytsky highway, 95, Vinnitsa, 21000, Ukraine, irishakobilanska@gmail.com*

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