STATISTICAL NATURE OF BLOOD PRESSURE AND FLOW WAVES*

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Introduction

As it was shown earlier, statistical methods of control engineering might be properly applied for studying dynamics of the cardiovascular system (CVS). In our previous experiments system analysis of the adrenal circulation was performed on the basis of the slow, third-order pressure and flow waves [1—5]. Then we turned to the study of dynamics of the fast, first-order pulsatile waves in the circulatory system [6, 7].

Recently, integration of measuring and data processing techniques is aimed at, likely to be convenient

1. for simultaneous and comparative analysis of first-order and third-order blood pressure and flow waves in the same experiment from the point of view of signal structure and system dynamics;
2. for quantitative analysis of the nonlinear properties of CVS;
3. for analysis of pathological changes in haemorrhagic shock from side of the signal structure and system dynamics.

The present paper offers a short survey of studies in point 1 and of the problem of stationarity of pulsatile waves.

Methods

The experiments were performed on 12 dogs. Chloralose anaesthesia and Flaxedil immobilisation were used with artificial respiration. The experiments were divided into two groups in respect to type of haemorrhage: a) graded hypotension by steps of 20 mmHg; b) standardized haemorrhagic shock.

Four circulatory variables were observed in both cases. The blood pressure was measured in the ascending aorta, right iliac artery and right atrium with Statham inductive transducers. For measuring the velocity of the blood flow in the left iliac artery a Ward ultrasonic flow meter was used. The analogue electrical signals were recorded by a Hottinger instrument tape-recorder and by

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an Alvar polygraph. The mean pressure levels were stabilized by a buffer erservoir system. The schematic diagram of experimental set-up is presented in Fig. 1. At each mean pressure level an observation period of 30 min duration was applied after the transient elicited by the bleeding off.

Based upon general properties of the measured signals in the frequency domain, every single circulatory variable was automatically decomposed into three components during playback from the magnetic tape. As it is shown in Fig. 2, the power density spectrum can be divided into the following frequency ranges: the pulsatile component above 2 Hz, the respiration waves with frequency of 0.4 Hz and the Traube-Hering-Mayer waves below 0.2 Hz.

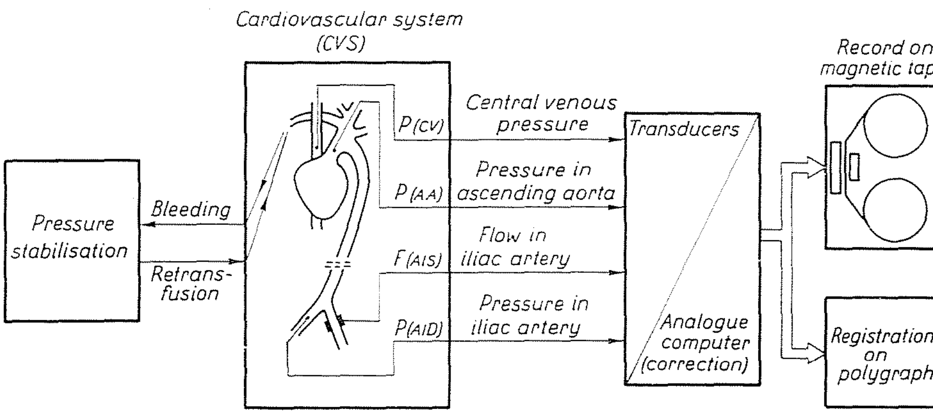

Fig. 1. Schematic diagram of measurement and registration of the circulatory variables

Finally, the mean value of the variables also belongs to the spectrum (at $f = 0$) but it is not shown in Fig. 2 because of the logarithmic frequency scale.

The signal decomposition was performed by means of a Solartron analogue computer according to the flow chart in Fig. 3. The damped respiratory waves were indicated both at the first- and third-order components. The primary data reduction was extended to the determination of auto- and cross-correlation functions, variance, trajectories and amplitude spectrum of the pulsatile waves, and that of auto- and cross-correlation functions and power density spectrum of the Mayer-waves recorded at several arterial mean pressure levels (normotension; stabilized levels at 150, 130, 110, 90 and 70 mmHg; retransfusion).

The actual state of CVS was characterized by statistical parameters derived from further processing of results of the primary data reduction (about 800 correlation functions, power density spectra, etc.). Various signal components of about 80 000 heart cycles were processed in the computations. The detailed discussion of final statistical parameters, appropriate to draw physiological conclusions too, exceeds the limits of this paper.

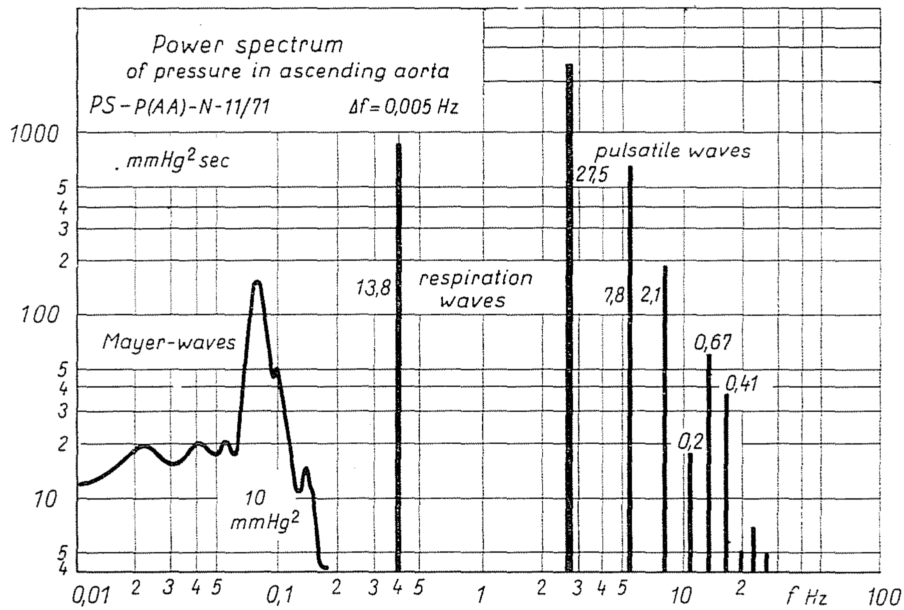

Fig. 2. Power density spectrum of pressure waves measured in the ascending aorta (Dog No. 11, normotension, filter bandwidth calculated for real-time: 0.005 Hz). Numbers at the spectrum lines indicate the variances of the given components. Mean value: 153 mmHg

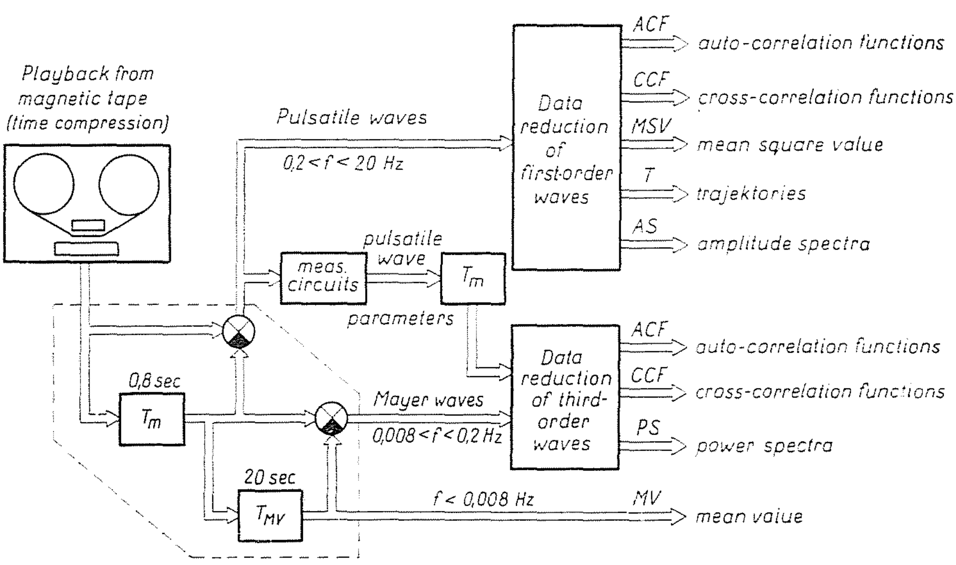

Fig. 3. Schematic diagram of signal decomposition and primary data reduction during time compressed playback of the circulatory variables

Stationarity in practice

According to the available stochastic methods of control engineering the waves — serving as input and/or output signals — must be stationary: that is, the basic statistical characteristics of the signals under study must not change during the period of registration.

In theoretical statistical investigations the stationarity of the processes is generally supposed. But in practice, the statistical characteristics of signals of technical and biological systems can undergo essential alterations.

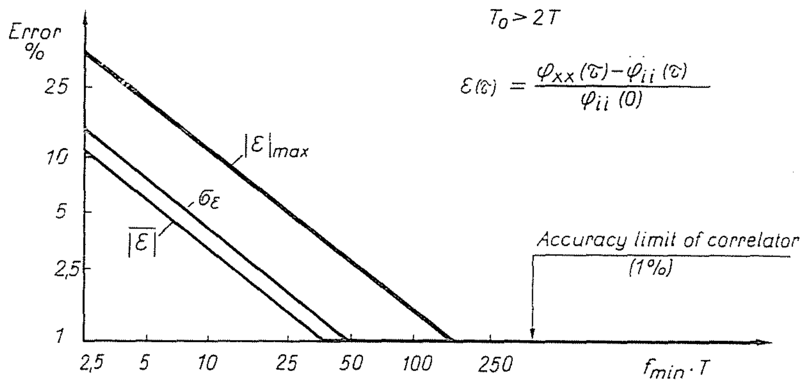

Fig. 4. Error relations derived from computed and ideal correlation functions in dependence of averaging time constant and fundamental signal frequency

The changes of statistical characteristics (correlation functions, spectra, means and mean square values, etc.) determined for real processes by computation are due not only to the instationarity of the process or signal under examination but also to the shortness of the observation period (OP). The shortening of OP is accompanied by increasing deviations in the statistical characteristics computed for different sections of a stationary signal with the same OP. It follows that the OP used in practical studies of stationary signals must at least be increased up to the value, where the relative changes of the measured statistical characteristics will be less than the specified relative accuracy of the computing device. The above minimal OP value can be called necessary OP.

For strictly stationary signals a simple approximate connection can be given to determine the necessary OP [8]. Some kinds of relative errors of correlation functions (CF), φ_{xx}, computed from square wave signals in comparison with theoretical CF, φ_{ii}, are shown in Fig. 4. The change of errors is given in dependence of the multiplication of the fundamental frequency (f_{min}, Hz) in the signal and the averaging time constant (T, sec). The lower horizontal curve shows the limit determined by the specified accuracy (1%) of the correlator.

On the basis of the desired maximal error, mean absolute or mean square error, the averaging time constant (integration time) can be determined in dependence of the low boundary frequency of the signal to be investigated. The necessary OP, T_0 should be at least double of T.

If an averaging time constant ensuring the desired accuracy of the computation is applied, the instationarity of the signal during an essentially longer OP than necessary can be quantitatively described by the value of the observed changes in the computed CF and in other statistical characteristics.

In the case of simpler systems optional statistical characteristics can be chosen for the stationarity test. In the study of complex processes and/or multivariable systems it is more suitable to simultaneously examine the formation of some statistical characteristics. It is to be noted that the sensitivity of stationarity tests is influenced by the averaging method used in forming the statistical parameters. Based upon analysis of the variance of a stochastic signal $x(t)$ with zero mean value, the I- and T-averaging methods, generally applied in practice, will be demonstrated.

The variance computed by *I-avercging*

$$\sigma_x^2(t_b, t_0) = \frac{1}{t_0} \int_{t_b}^{t_b + t_0} x^2(t)\, dt = \varphi_{xx}(\tau, t_b, t_0)\Big|_{\tau=0}$$

which is independent of beginning time t_b of computation if $x(t)$ is a stationary signal, and which gives an unvaried quantity inside the error limits determined by the necessary observation period T_0 if the integration is performed for an optional $t_0 > T_0$ value.

In the case of *T-averaging* method the square of $x(t)$ is led to a low-pass filter described by the transfer function

$$Y(s) = \frac{1}{1 + sT}, \quad \text{where} \quad T < T_0/2$$

As a result, an output signal

$$\sigma_{xT}^2(t_0, T, t_b) = \frac{1}{T} \int_{t_b}^{t_0} x^2(t) \exp\left(-\frac{t_0 - t}{T}\right) dt$$

is generated which represents the mean square value averaged by T for $t_0 > T_0 + t_b$.

For stationary signals, σ_{xT}^2 approaches σ_x^2 from below and the relative deviation between them for $T_0 = 4T$ is less than 2%. In the case of instationary processes the real changes in the mean square value can be followed more closely and sensitively by the T-averaging method than by the I-averaging one.

Stationarity in CVS

The stationarity of circulatory variables mentioned earlier was examined by T-averaging techniques. As it is seen in Fig. 2, the components of circulatory waves can be found in a frequency range of several decades, and the formation

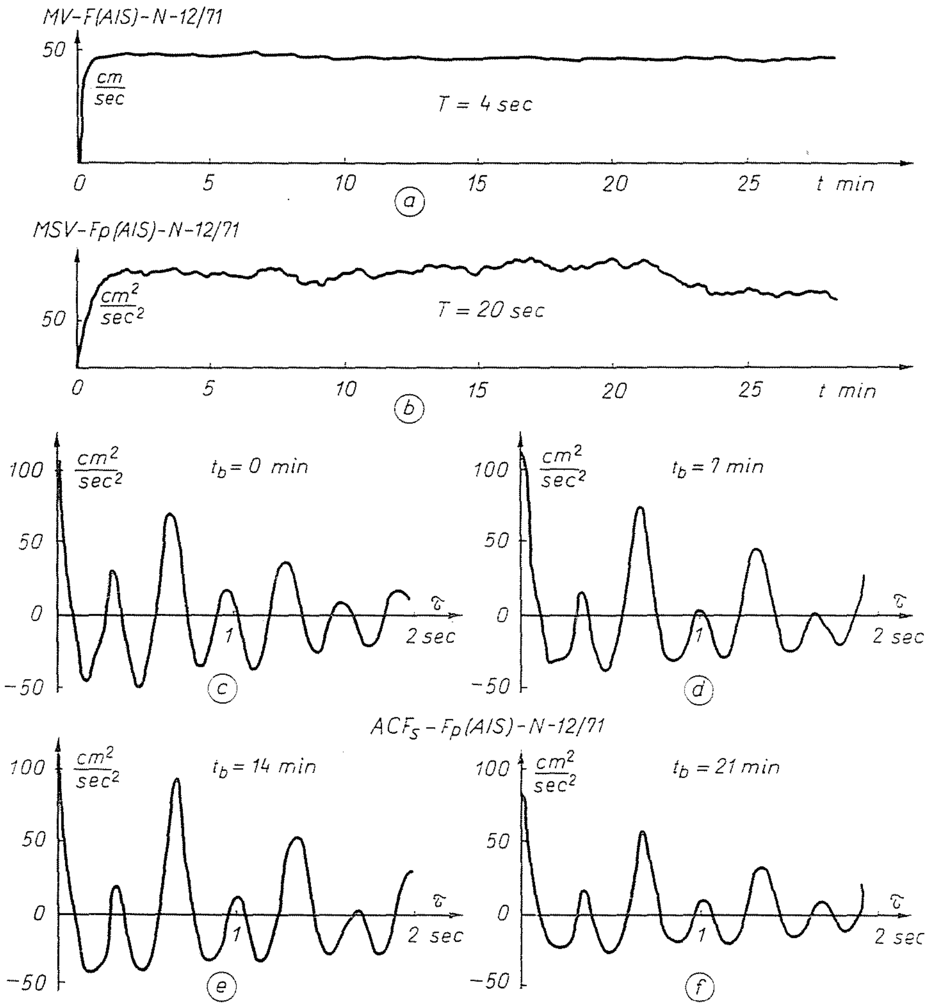

Fig. 5. Diagrams for comparison of some statistical characteristics derived from the blood flow signal in left iliac artery (Dog. No. 12. normotension. T: averaging time constant. T_0: observation period). (a) Mean value changes of the complete signal. (b) Mean square value changes of the pulsatile component. (c)—(f) Autocorrelation functions of the pulsatile component, obtained for different starting times t_b of computation ($T = 100$ sec. $T_0 = 7$ min) of the individual components is expected to be influenced by effects originated from different parts of the organism. Therefore the mean value of the circulatory variables and the variance of the pulsatile waves were simultaneously computed and recorded. The formation of the mean value during the experiments is likely to characterize the stationarity of the Mayer-waves in the first place, and the mean square value to demonstrate the changes in statistical structure of the pulsatile components.

As an example, the diagrams obtained from measuring series of blood flow in normotension are shown in Fig. 5. The mean value of blood flow does

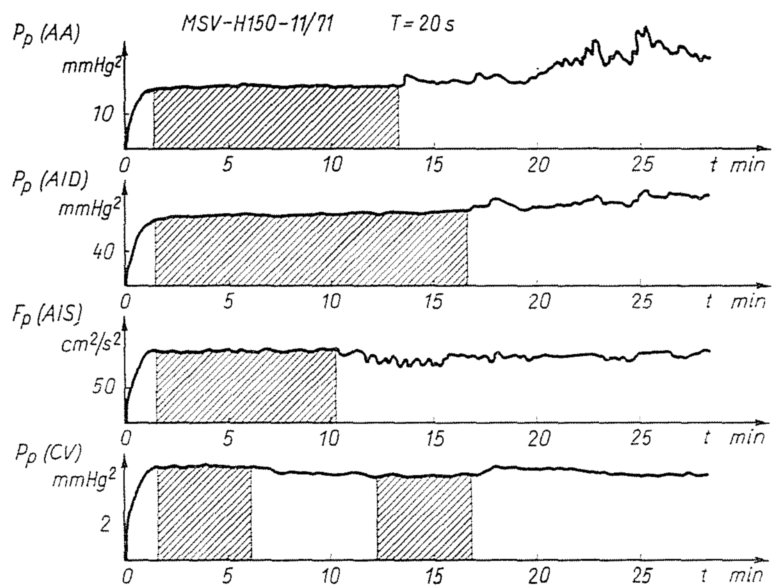

Fig. 6. Variance curves of pulsatile circulatory components (Dog No. 11, controlled haemorrhage at 150 mmHg)

not essentially change, although the averaging time is the smallest in this case. But the variance of the pulsatile component has decreased by about 25% in the last quarter of the observation time. (Based upon curves in Fig. 4, deviations by 4% are maximally permitted for the given multiplication $f_{min} \cdot T$, where $f_{min} = 1.5$ Hz, i.e. the average pulse.) The same change can be read off the autocorrelation functions determined for quarters of the OP. The autocorrelation functions permit a more distinguished analysis of the statistical structure of the pulsatile blood flow signal. Fig. 5 demonstrates the facts that the process may be regarded as a stationary one (except the last quarter) and that the individual statistical characteristics of the same signal may change in different manner.

Similarly, the changes of a given statistical characteristic, derived from different, simultaneously observed signals of the system under test can demonstrate various tendencies as it is shown in Fig. 6. The variance of pulsatile pressures measured in the ascending aorta, iliac artery and right atrium and that of pulsatile flow obtained in the iliac artery exhibits different kinds of changes. In this experiment, the periods marked by shaded areas (Fig. 6) may be regarded as stationary.

As a conclusion, pulsatile pressure and flow waves can be regarded at a good approximation as stationary for periods of about 10 min. It is concluded that the statistical characteristics of the circulatory parameters have to be checked during application of the methods of control engineering. The pulsatile processes of the CVS do not seem be invariably stationary, not even in anaesthetized animal under standard circumstances.

Summary

A complex statistical study of the cardiovascular system in normo- and hypotensive states is presented. Signals derived from ascending aorta, iliac artery and right atrium were analysed in anaesthetised dogs during observation periods of 30 min. Circulatory waves decomposed by frequency analysis were statistically reduced by correlation functions, power density spectra, etc.

A practical view of obtaining the necessary length of observation period and that of stationary test is given.

Pulsatile pressure and flow waves can be regarded at a good approximation as stationary for periods of about 10 min. The pulsatile processes of the CVS are likely not to be invariably stationary, not even in anaesthetized animal under standard circumstances.

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