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APPLICATION OF THE BIOMECHANICAL MODELS FOR THE IMPROVEMENT IN THE FUNCTIONAL DIAGNOSTICS METHODS

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Abstract: Biomechanical models are necessary for medical apparatus of functional examination. In a number of cases when the models corresponding to the conditions typical of the normal person are used, the dependences registered by the apparatus in the course of the functional examination of the patient and of the normal person are qualitatively different. It is necessary to improve the apparatus (or its software) using biomechanical model describing the definite type of pathology in order to characterize the physical properties of the object under the abnormal conditions. The above-stated theses are illustrated by an example of the examination of human respiratory tracts resistance by means of the whole body plethysmograph. The second example is the erythrocyte sedimentation rate index which is widely used in medical practice.

Key words: biomechanics of breathing, functional examination, plethysmograph, biomechanical model, complicated models of lungs, erythrocyte sedimentation rate

Introduction

The design of the functional examination medical apparatuses and their software are always based, explicitly or implicitly, upon a certain biomechanical model of the phenomenon under consideration. Models of this kind are, as usual, rather simplified and their properties correspond to those of the modelled object either on the average or under some special conditions (as usual, they are typical of the normal person). Besides, the value measured by the apparatus (or calculated from the measurements) characterizes a certain physical property of the model employed in the apparatus design. This property reflects under the corresponding conditions the analogous one of the investigated object.

The ranges of values of the measured parameter, which are typical of the norm or the pathology, are determined on the basis of the numerous functional examinations; the physical term assigned to this parameter corresponds to it in the assumed object model.

In a number of cases, when the models corresponding to the conditions typical of the normal person are used, the dependences registered by the apparatus in the course of the functional examination of the patient and of the normal person are qualitatively different. In these cases a certain system of empirical rules (which are not based upon any model) is worked out and the deviation of the «measured» parameter from that of a normal subject is estimated according to these rules. Besides, no attention is usually paid to the fact that the parameter determined in this way has no physical meaning of the corresponding value measured for the normal object because the real object does not correspond to the phenomenon model employed in the apparatus design.

It is necessary to improve the apparatus (or its software) using the biomechanical model describing the definite type of pathology in order to characterize the physical properties of the object under the abnormal conditions.

This way of identifying of the patient’s functional examination by means of the complicated biomechanical models is used rather seldom today. Nevertheless, one may expect

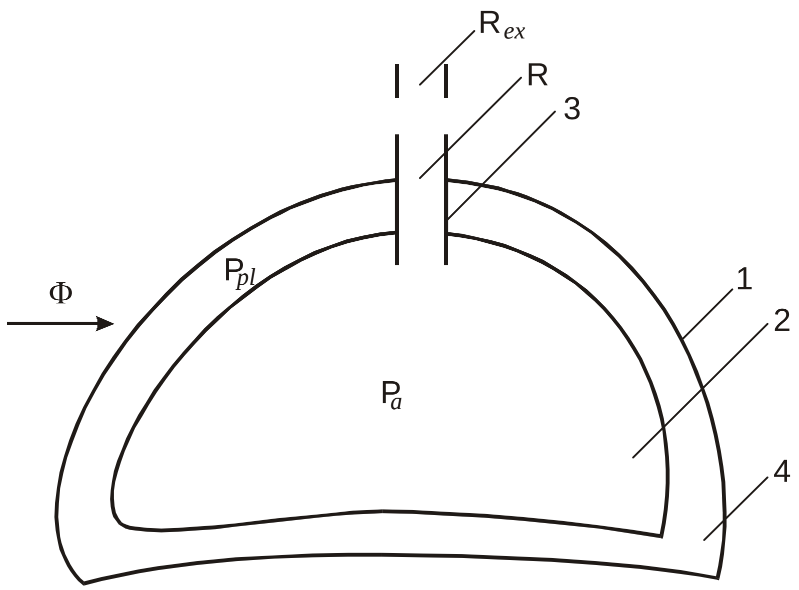

Fig. 1 The scheme of the simplest lungs model. Designations: 1 - thorax; 2 - bubble of lung; 3 - respiratory tract; 4 - pleural cavity; Φ - effort of the breathing musculature; P_a- pressure inside the bubble; P_{pl}- pleural pressure; *R* - resistance of the intrapulmonary respiratory tract; R_{ex} - resistance of the upper extrapectoral respiratory tract.

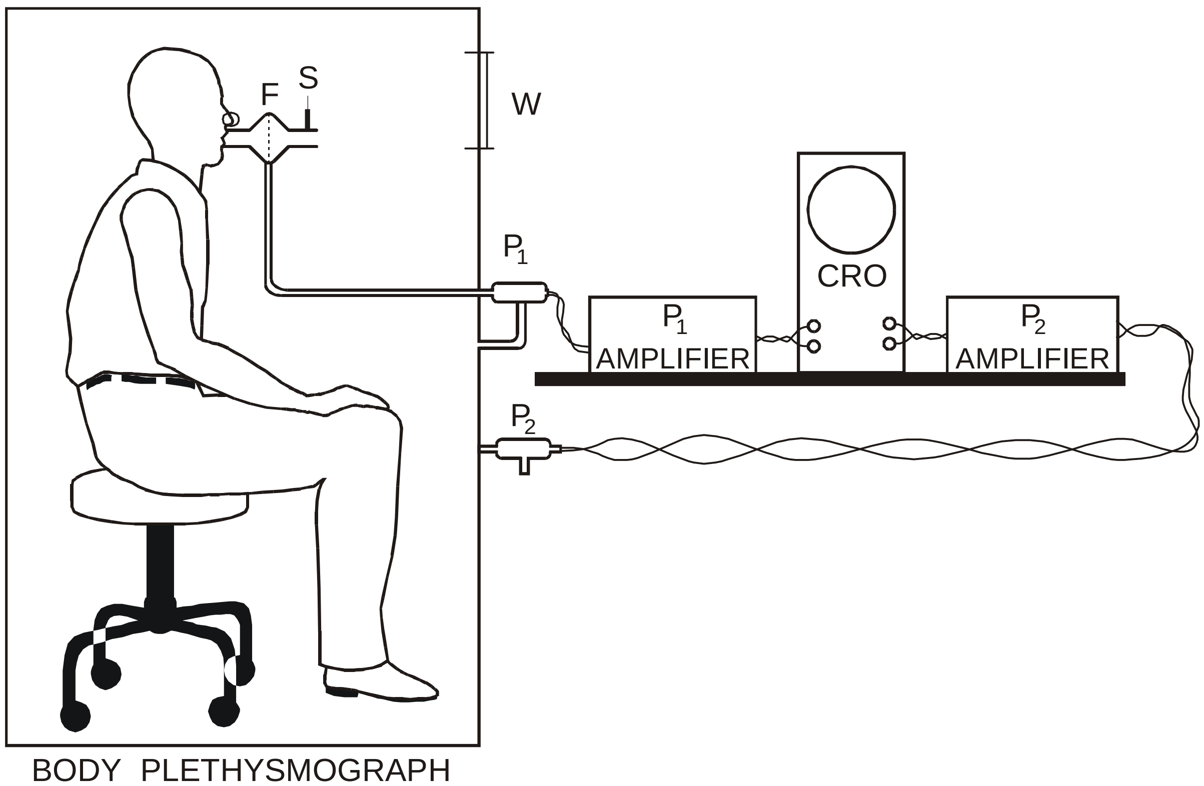

Fig. 2 The apparatus for measuring the respiratory tracts resistance. CRO - cathode-ray oscilloscope.

essential progress in the diagnostic significance of the functional examination results only on this way.

The above-stated theses will be illustrated by an example of the examination of human respiratory tracts resistance by means of the whole body plethysmograph.

The plethysmographic method of determination of the respiratory tracts resistance is based upon the simplest model of the human lungs (Fig. 1) in which the lungs represent the

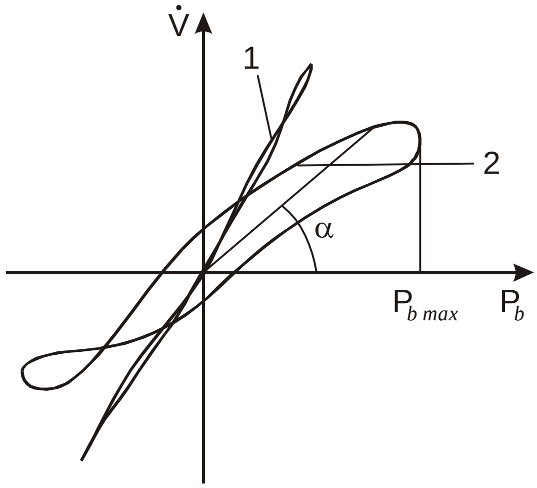

Fig. 3. The scheme of the flow vs. pressure curves and the construction for determination of the respiratory tracts resistance.

Fig. 4 The variants of flow vs. pressure loops registered at different diseases.

elastic bubble (possibly filled by the medium with the complicated mechanical properties) connected with an atmosphere by the tube of the constant hydraulic resistance R. In this model the relation of gas flow $\dot{V}$ and the pressure inside the bubble is defined as follows

$$R\dot{V} = p_a - p_b = p_A, \tag{1}$$

where p_a is the pressure inside the bubble, p_b is the pressure outside the bubble, p_A is the alveolar pressure.

It is known from the wide research experience that the lungs model shown in Fig. 1 gives the satisfactory description of a series of lungs properties for the quiet breath of a normal person (when the lungs physical properties are homogeneous all over their volume). So it is clear that the respiratory tracts resistance can be evaluated from the equation (1) if the lungs air flow and the alveolar pressure are measured simultaneously.

The plethysmograph of the whole body (Fig. 2) is the apparatus, which measures the alveolar pressure. The apparatus represents the chamber for an examinee inside it. The current pressure p_b in the closed chamber is measured while the examinee breathes. The linear dependence of p_b upon p_A corresponding to the simplest lungs model (Fig. 1) is used for the calculation of the alveolar pressure. The air flow near the examinee's mouth is measured simultaneously by means of the pneumotachometer. It is easy to draw out the dependence $\dot{V} = \dot{V}(p_A)$ (curves 1 in Fig. 3 and Fig. 4) using these measurements. The experiments indicate that the dependence $\dot{V} = \dot{V}(p_A)$ for the normal person is close to the straight line. The dependence of $\dot{V}$ upon p_A being also linear in the simplest model (Fig. 1), this fact indicates that this model gives the satisfactory description of the normal lungs properties, and the respiratory tracts resistance of a normal person can be evaluated from the ratio $R = p_A/\dot{V}$ obtained by means of the whole body plethysmograph measurements.

When the functional examinations of the patients with different lungs pathologies are carried out by means of the whole body plethysmograph, the registered curves $\dot{V} = \dot{V}(p_b)$ are qualitatively different from the curve 1 in Fig. 3 and Fig. 4. The typical shapes of such curves are shown in Fig. 4 [1]. It is necessary to define the formulae for calculating of the alveolar pressure p_A from the chamber pressure p_b in order to obtain the curves $\dot{V} = \dot{V}(p_A)$ from the above-mentioned curves and to evaluate the current resistance using (1). The different interpretations of the curves shapes shown in Fig. 1 are possible.

First of all, we may assume that the lungs pathology is connected only with the changes of the respiratory tracts resistance R, which may depend on some respiratory cycle parameters (flow, pressure, etc.). In this case the relation of the chamber and the alveolar pressures for the quiet breath remains the same (i.e. linear) as for $R = const$. Furthermore the curves in Fig. 4 would not change qualitatively if the pressure p_b in the abscissa were substituted by p_A. In the model corresponding to Fig. 1 the current respiratory tracts resistance $R(t)$ is proportional to the inclination angle of the straight line connecting the origin and the point of the curve $\dot{V} = \dot{V}(p_A)$ corresponding to the time instant t (see schematic construction in Fig. 3, curve 2). Using this situation, it is possible to construct the function $R = R(\dot{V})$ or $R = R(p_A)$ for every curve $\dot{V} = \dot{V}(p_A)$ (Fig. 4).

But for the obtained functions to be informative in the diagnostics of the diseases, it is necessary to understand what pathological processes may lead to the obtained dependences of the respiratory tracts resistance upon the flow $\dot{V}$ or pressure p_A. More general (in comparison with Fig. 1) biomechanical lungs models are necessary for this purpose. Such models can be constructed in some cases.

For example, if the pathology is connected with the distinct stationary narrowing in the extrapulmonary respiratory tracts (tumour, the fixed heterologous object, etc.) the modelling of such narrowings by a diaphragm will give the curves analogous to the curve 2 (Fig. 4) [2]. The validity of this modelling is corroborated by the fact, that in the practical functional examinations the curves of type 2 in Fig. 4 are usually connected with the stationary stenosis in the extrapulmonary respiratory tracts [1].

It should be noted that the described interpretation of the cause for curve shape change from 1 to 2 in Fig. 4 is not unique even within the limits of the model shown in Fig. 1. The appearance of the linear dependence of the intrapulmonary respiratory tracts resistance upon the flow $\dot{V}$ leads to the same qualitative changes [3]. This dependence may be connected with the decrease in the parenchyma elasticity caused, for example, by the pulmonary emphysema if the decrease is homogeneous all over the lungs volume (it is natural to model the lungs as one bubble only in this case).

We are not informed of the situations in which the curves of type 3-8 in Fig. 4 could be explained within the limits of the homogeneous lungs model (Fig. 1) by the reasonable change of the respiratory tracts resistance. On the other hand, the complicating of the pathological lungs mechanical model allows advancing in this direction.

The changes of lungs (parenchyma and respiratory tracts) physical properties as a result of a disease usually occupy a limited part of lungs. Hence, it is natural to use the inhomogeneous model for the description of the inhomogeneous lungs. The simplest inhomogeneous model is the two-component model shown in Fig. 5. Two parts of the lungs with different physical properties represent in this model two bubbles connected with an

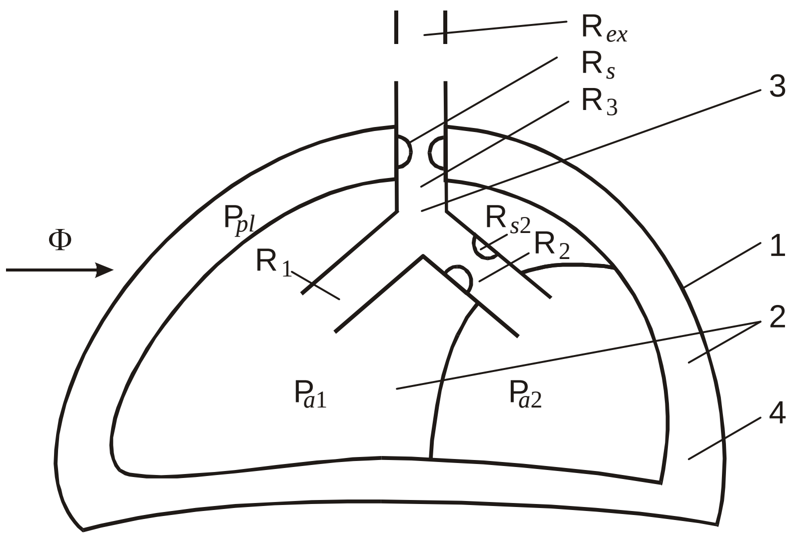

Fig. 5 The scheme of the two-component inhomogeneous lung model. Desigtnations: 1 – 4, Φ, P_{pl}, R_{ex}, as in Fig. 1; R_1, R_2 - resistances of the lung components 1, 2; P_{a1}, P_{a2} - pressure inside the components 1,2; R_s, R_{s2} - resistances of the pliable segments; R_3 - resistance of the respiratory tract.

atmosphere by the branching pipes which model both the intrathoracic and extrapectoral respiratory tracts.

The numerous calculations (partially published in [4, 5]) indicate that it is possible to describe all types of flow vs. temperature curves shown in Fig. 4 within the limits of the model shown in Fig. 5 if the modelling of different lungs components and resistance at different points of pneumatic tract is physically justified. But this qualitative description can be carried out for different versions of physical properties and model parameters, as it was shown in the above-mentioned example. This uncertainty indicates that the identical flow vs. pressure curves shapes obtained in the plethysmographic examination may correspond to the different lungs pathologies or different levels of pathology complication.

This conclusion throws a new light upon the diagnostic value of the flow vs. pressure curves obtained in the plethysmographic examinations.

First of all, the statement declaring that the respiratory tracts resistance could be someway simply estimated on the basis of the curves 3-8 (Fig. 4), should be rejected. The methods of functional examinations, recommended today [1], suggest that the patient's respiratory tracts resistance should be evaluated by the inclination angle of the straight line connecting the origin in the plane $\dot{V}, p_b$ with the point of maximum p_b (see the scheme in Fig. 3). Furthermore the formulae to calculate the alveolar pressure p_A from the chamber pressure remain the same (i.e. linear) as for the data processing for the normal person.

According to the physical meaning of the inhomogeneous lungs model (Fig. 5) the alveolar pressures in the components are different and hence

a) the alveolar pressure value evaluated by means of the standard formulae makes no sense at all;

b) the conception of the common respiratory tracts resistance value makes no physical sense for the inhomogeneous model. This model is characterized by the resistance distribution in the different branches of the respiratory tracts model (this distribution determines the dependence of the air flow at the exit of the model upon the pressure values in its components and other parameters).

Of course, the parameter suggested by the above-mentioned methods can be considered as empirical and the diagnostic conclusion can be based on this parameter value. But the dignifying of this parameter by the physical term «resistance» may only mislead the doctors because they will try to search for the causes for the respiratory tracts resistance growth where it makes no sense to search for them.

Secondly, the introduction of more general inhomogeneous biomechanical lungs model and the possibility of the qualitative description of the observed flow vs. chamber pressure curves 3-8 (Fig. 4) by means of this model, allows making a fundamental conclusion that the pathology, leading to such curves is connected with the inhomogeneous physical properties of parenchyma and respiratory tracts of the lungs.

Introduction of the inhomogeneous lungs model allows formulating a problem of determining the parameter values and the types of functions, which characterize the properties of parenchyma and respiratory tracts. Such determining is based on the quantitative accordance of the calculated flow vs. pressure curves with the measured ones. In particular, the alveolar pressures in the model components and the resistance distribution along the pneumatic tract will be determined. This procedure can be carried out either by the parameters fitting or in some automatic manner (this problem is not considered today). This approach essentially extends the possibilities of the plethysmographic method for the functional examination because this method will give not only one parameter («resistance») typical of the lungs, but the distributions (within the limits of the two-component model) of the physically defined lungs parameters over the lungs volume for the given examinee.

Thirdly, the idea of the definite relation of the flow vs. pressure curve shapes and the certain lungs disease, should be rejected. The lungs as the mechanical system are determined by a number of parameters and functions, which characterize the physical properties of their parts (parenchyma, extrapulmonary and intrapulmonary respiratory tracts, thorax, etc.). Therefore the same qualitative shapes of the flow vs. pressure curves may be expected to correspond to different sets of parameters typical of lungs and hence to different lungs pathology types. This fact is corroborated by our calculations.

The purpose of the functional examination is to obtain enough information for the definite diagnostics of the disease. Therefore, in the case of inhomogeneous lungs the additional measurements and tests for the different breath conditions are required along with the plethysmographic examination.

The complete set of the functional examinations and the corresponding methods, which will allow to determine all the physical parameters of the lungs model on the basis of the inhomogeneous lungs model, is not finally substantiated today. Although a series of approaches is investigated and they possibly will allow to solve this problem or, at least, to determine the limits of uncertainty in it.

In conclusion, it should be noted that the introduction of the inhomogeneous lungs biomechanical model into the plethysmographic examination data processing will require a great deal of joint investigations carried out by mechanicians, physiologists and doctors, and also the improvement of the plethysmograph as a physical apparatus. But the expenses will be compensated because the doctor’s conclusion as a result of such functional examination will be based not upon the empirical average values of the parameters but upon the concrete parameters distributions in the model of the investigated lungs, i.e. this conclusion will be individual but not statistical.

The given example of the functional examination contents change by means of the application of more complete biomechanical model of the investigated object does not require the development of a new apparatus for its realization but requires only the perfection of a software and possibly the improvement of some technical characteristics of some apparatus units. In the other cases the application of the more complete biomechanical models of the investigated object or physical phenomenon will lead to the necessity of the development of the new apparatus because the new parameter, which characterize the phenomenon or

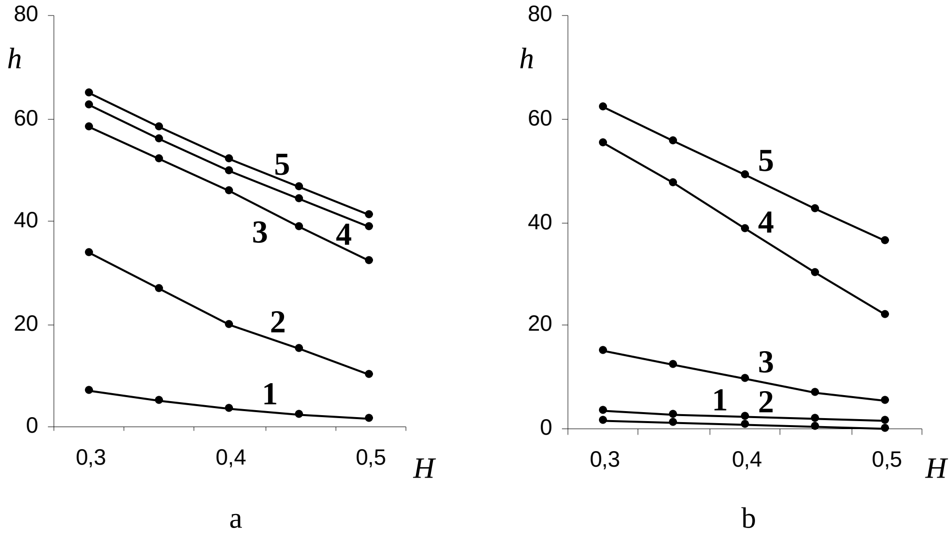

Fig. 6 The ESR index (*h*) dependence upon the erythrocyte concentration (*H*) and the parameter determining the erythrocyte agglutination (the curves 1-5 correspond to the increase in the agglutination parameter from the norm up to the grave pathology): a – the standard ESR index (erythrocyte sedimentation in an hour), b – erythrocyte sedimentation in half an hour. This figure is borrowed from [6].

pathology under consideration more completely will be revealed. Let us dwell upon such an example.

The erythrocyte sedimentation rate (ESR) index is widely used in medical practice. The change of ESR is connected with the changes of erythrocytes properties, which determine their aggregation ability. This method is physically based upon the idea that the increase in the erythrocytes aggregation ability resulted from a disease will lead to the formation of bigger aggregates with higher sedimentation rate in the liquid phase compared with that under the normal conditions.

The ESR index is used today as the non-specific index and its value is connected with the general complication of the disease. However it does not allow carrying out the differential disease diagnostics because its value essentially depends not only on the physical phenomena governing the erythrocytes agglutination process but also on the blood viscosity, erythrocytes concentration (haematocrit), etc. This leads to the situation when the same changes in the ESR index (at certain measurement precision and the lack of haematocrit data for the individual examinee) may correspond to the different diseases. It could be said on the analogy of the previous example that the same changes in the ESR index correspond to different sets of physical parameters characterizing the blood properties, which are connected with the different diseases.

It is necessary to construct the biomechanical model of erythrocytes sedimentation process for more profound understanding of the ESR index connection with the blood properties. Such model has been constructed in [6] and it leads to the following conclusions.

a) The standard ESR index, which is the height of the blood column without erythrocytes measured in an hour after the sedimentation process beginning, becomes low informative at the high aggregation rates.

This fact is illustrated by Fig.6a [6] showing the calculated dependence of the standard ESR index upon the haematocrit H and the constant, which characterizes the probability of erythrocytes agglutination (the value of this constant for the curves 1-5 varies from the norm up to the grave pathology). One may see that the ESR index is low informative in the grave pathology region because the corresponding curves form a dense strip, hence the little error in the measurements causes the large error in the agglutination constant estimate. Besides, the

ESR index strongly depends upon haematocrit, which is not always measured simultaneously with the ESR index.

b) The ESR index for 0.5 hour sedimentation (it differs from the standard index for an hour) is low informative in the light pathology region and also strongly depends, as a standard index, upon the haematocrit (see Fig. 6b).

c) It is possible to analyze another indices, such as sedimentation in the intervals of 15 min, the maximum sedimentation rate, etc. The joint application of the different indices may produce more definite value of the agglutination constant. But in any case there is the large uncertainty in its determination if the erythrocytes concentration (haematocrit) is unknown.

Thus biomechanical model of the sedimentation process allows to understand its details and to make a reasonable choice of the indices which will be more informative than the standard ESR index. The calculations indicate that the time required for the sedimentation rate to reach its maximum is one of the effective indices. This value slightly depends upon the initial erythrocytes concentration while the dependence upon the agglutination constant is expressed distinctly in all the region of its values.

However the increase in the functional method informativity is connected not only with the improvement of methodology and software (if only the sedimentation parameters for various time intervals are used) but also with the development of the new apparatus (if the time required for the sedimentation rate to reach its maximum is used as an index) which allow to continuously register the sedimentation rate or other values characterizing the sedimentation process.

In conclusion it should be emphasized that the modern biomechanics development allows constructing rather complete models of the biomechanical processes and phenomena, which are of interest from the point of view of the functional diagnostics. The analysis of the functional diagnostics methods and methodologies in existence is of present interest thereby. The purpose of this analysis is to determine the degree of accordance of these methods with the biomechanical models and the improvement of the methods by means of more complete biomechanical models compared with those used in the development of the methodologies and their software and hardware. It should be realized that it is the extensive and heavy work, especially taking the commercial items concerning the apparatus production into account.

Of course, the empirical indices and the methods of their estimation admitted to the medical practice have the right to exist. But even if they are employed, it is rather useful to apply the biomechanical models for clearing up the physical meaning of these indices and for estimation of their informativity for the differential disease diagnostics.

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ИСПОЛЬЗОВАНИЕ БИОМЕХАНИЧЕСКИХ МОДЕЛЕЙ ДЛЯ СОВЕРШЕНСТВОВАНИЯ МЕТОДОВ ФУНКЦИОНАЛЬНОЙ ДИАГНОСТИКИ БОЛЬНЫХ

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При проектировании медицинских приборов для функционального исследования и их программного обеспечения всегда явно или неявно опираются на некоторую биомеханическую модель рассматриваемого явления. При этом измеряемая прибором (или вычисляемая с помощью этого измерения) величина характеризует некоторое физическое свойство модели, использованной при проектировании прибора, которое при соответствующих условиях отражает аналогичное свойство объекта исследования.

В ряде случаев, когда используемая модель соответствует условиям, характерным для здорового человека, регистрируемые прибором зависимости при функциональном исследовании больных качественно отличаются от тех, которые регистрируются у здорового человека.

Для того, чтобы характеризовать физические свойства объекта в иных по отношению к норме условиях, необходимо совершенствовать прибор (или его программное обеспечение), используя биомеханическую модель, соответствующую той или иной форме патологии.

Сейчас такой путь идентификации функционального исследования больных с помощью усложненных биомеханических моделей используется крайне редко. Тем не менее только на этом пути можно ожидать существенного прогресса в диагностической значимости результатов функциональных исследований.

В данной работе изложенные положения проиллюстрированы на примере исследования сопротивления дыхательных путей человека с помощью плетизмографа всего тела, а также дается анализ показателя СОЭ, изменение которого связывается с изменением свойств эритроцитов крови, определяющих их агрегационную способность

Плетизмограф всего тела представляет собой прибор для измерения альвеолярного давления, кроме того с помощью пневмотахометра измеряется объемная скорость воздуха у рта испытуемого. В результате строятся кривые зависимости объемного расхода воздуха, истекающего из легких, и альвеолярного давления. Анализируются формы соответствующих кривых у здорового человека и у больных с различной патологией легких. Отмечается, что одна и та же форма кривых расход - давление, получаемая при плетизмографическом исследовании, может в принципе соответствовать различным формам патологии легких или нескольким уровням тяжести патологических изменений.

На основании этого вывода обсуждается ряд аспектов проблемы, позволяющих по-новому оценить диагностическую ценность кривых расход - давление, получаемых при плетизмографическом исследовании (введение более общей неоднородной биомеханической модели легких, определение альвеолярного давления в компонентах модели и распределения сопротивлений вдоль воздухоносного тракта и др.).

Ключевые слова: биомеханика дыхания, функциональная диагностика, плетизмограф, биомеханическая модель, усложненная модель легких, скорость оседания эритроцитов

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