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LACTATION CURVES AS A TOOL FOR MONITORING THE HEALTH AND PERFORMANCE OF DAIRY COWS — A MINI-REVIEW

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Abstract

According to the estimation of FAO, worldwide milk production increased from 694 million tons in 2008 to 914.3 million tons in 2020. Currently, animal breeding for high milk yield continues. However, some authors consider high milk productivity the main reasons of milk quality and health deterioration, including fertility. Therefore, monitoring of animal physiological state and productivity becomes especially important. Lactation curve modeling is one of the most effective methods for predicting component milk composition, yielding capacity and animal health. It is a tool for early diagnostics of certain diseases, which can help reduce treatment costs and improve the disease course prognosis. Thus, predicting the evolution of milk yields is an important stage of management and breeding decisions; it is widely used for diagnostic purposes. The article provides a brief overview of mathematical methods for modeling lactation curves (for milk yield, percentage of fat, fat yield and protein). Classic Wood's model (P.D.P. Wood, 1967), Ali and Schaeffer (T.E. Ali and L.R. Schaeffer, 1987), Wilmink parametric models (J.B.M. Wilmink, 1987) and models based on the machine learning algorithms are considered here. It should be mentioned that there is no universal model for describing lactation curves. Most attention is paid to Wood's model used for constructing lactation curves described by A.S. Emelyanov (1953). This equation application for prediction milk yield curves and milk components has shown good prediction accuracy. In this study, it was found that most of the models are unstable under decreasing input data that makes their use almost impossible for farms unable to accurately collect data of the lactation activity on a regular basis. It is shown that deviations of the observed milk yield from a prediction made by a well-fitted model are clear indicator of animal's diseases and can be used to prevent and detect udder diseases such as mastitis.

Keywords: lactation curve, Wood's model, cattle, mammary gland, milk production, environmental influence

The annual population growth entails an increase in the demand for dairy products. The dairy industry is showing impressive results in increasing the productivity of cattle. Directed selection taking into account genetic and breeding data, improved feed quality and housing conditions, effective management contributed to an increase in milk yield by more than 20%. According to FAO estimates [1], from 2008 to 2021, world milk production increased from 694.0 to 914.3 million tons per year [2].

Studies show that highly productive cows spend most of the nutrients received precisely on the synthesis of milk components. According to data, on average, about 31% of metabolic energy was spent on this in 1944, 65% in 2016. The current world record holding Holstein cow, My Gold, uses 84% of her metabolic energy to produce milk [3]. However, such an increase in productivity entails metabolic stress, which affects the quality of products and animal health, including reproductive function. Currently, selection for increasing milk production continues. According to some authors, the resulting metabolic problems indicate that every day in the process of selection we are approaching the limit of the adaptive capabilities of the animal [4]. As a result, means of timely monitoring of animal health and productivity are of particular importance. One of these tools is the modeling of lactation curves, which are a graphical representation of the dynamics of milk production of cattle and other domesticated animal species over the lactation period. The lactation curve is a graph, the abscissa of which marks the time since calving, the ordinate shows one of the productivity parameters: milk yield, fat and protein composition, and the ratio of milk components [5]. Thus, the value of the ratio of fat and protein in milk can serve as an indicator of the ability of the animal to adapt to the period of feeding, as well as an indicator of the rate of recovery of reproduction efficiency [6]. After calving, during a period of negative energy balance, high fat:protein ratios have been associated with reduced dry matter intake and increased fat mobilization [7]. The fat and protein content has an inverse curve with respect to milk yield, which is probably due to the effect of dilution [8].

In female mammals, milk production during lactation is usually characterized by two phases, which correspond to the change in the milk requirement of the offspring [9]. In cows, the phase of increasing milk production continues from 5-6 days from birth to the peak of productivity (2-3 months), which reflects the increase in the calf's need for milk, the phase of decreasing secretion from the peak to the start of the dry period (approximately day 305 of lactation) is associated with an expansion in the offspring's diet and, consequently, a decrease in the importance of milk as the sole source of nutrients [10].

Physiologically, the evolution of milk production, and thus the shape of the lactation curve, can be explained by the number and activity of milk-secreting cells [11]. The increase in milk yield from the beginning to the peak of lactation is explained by the increasing secretory activity of mammary epithelial cells (MECs), while their proliferation remains relatively stable throughout the lactation period [12]. The decrease in milk production between the 8th and 23rd weeks of lactation is due to a decrease in the MEC population due to an increase in the rate of apoptosis, and, at a later stage, also to a decrease in the secretory activity of cells. During the involution phase, the rate of apoptosis significantly exceeds the rate of proliferation [13], and thus the number of mammary epithelial cells is mainly modulated by the rate of apoptosis [14].

Breast development and milk synthesis are tightly controlled by the endocrine system, various growth factors, and other genetic and epigenetic factors [15, 16]. In addition, environmental factors such as nutrition, climate, calving season, photoperiod and circadian rhythms, heat stress, milking system and type of housing play an important role in the realization of genetic potential [17]. Animal age and health are also important in predicting expected production [11]. All of these factors cause changes in milk composition and milk yield and therefore should be taken into account when modeling the lactation curve [18].

The lactation curve can be described using mathematical models, which makes it possible to predict lactation activity. These models can predict a range of key milk parameters based on cow management parameters and data from previous lactations [8].

We present a brief review of mathematical methods for modeling lactation curves, described in domestic and foreign special literature. One of the most popular methods (Wood's method, P.D.P. Wood, 1967) as applied to the classical classification of lactation curves given by A.S. Emelyanov [19]. Curve models are considered both for milk yield and for other key parameters, such as the percentage of fat and protein, as well as the yield of fat and protein.

Predicting the evolution of milk yield is an important step in making managerial and breeding decisions on herd management and is widely used for diagnostic purposes [20]. Based on the analysis of the simulated functions, the relationship between their mathematical characteristics and parameters describing the state of health of an individual is traced. Thus, lower values of derivatives in the vicinity of the maximum and the presence of a single extremum characterize an individual as healthier, with stable fertility, and more efficient use of cheaper feed [21, 22]. Therefore, milk composition data can be used to adjust diets [23] and to detect diseases before clinical signs appear, helping to reduce treatment costs and improve disease prognosis [24, 25].

For dairy production, cows with an even type of lactation are considered the most valuable [26]. It is more economically beneficial when a cow produces a moderate amount of milk throughout the entire lactation period than when she quickly reaches the peak of productivity, after which milk yield drops sharply. The stability of lactation depends on genetic factors and thus may vary between breeds, as well as depending on physiological conditions (eg pregnancy) and external influences [27, 28]. The economic feasibility of genomic selection for traits of milk production to achieve the desired curve has been demonstrated in a number of works [29-31].

Physiological bases of the lactation cycle of cows. Reproduction of offspring and providing it with milk are two interrelated processes. It is known that during pregnancy, cows develop mammary tissue, which continues to grow until the number of mammary cells reaches a maximum. Shortly after birth, there is a decrease in the number of cells due to apoptosis (programmed death) of secretory cells. This decrease is usually observed before the end of the lactation period. Milk in a cow begins to be secreted during or immediately before calving. The entire lactation cycle can be divided into two periods: a rise period (calving to peak og milk production) and a decline period (from peak to dry period) [32]. An increase in milk yield at the beginning of lactation is directly related to the rate of cell differentiation, and a decrease in milk yield at the end of the lactation period is directly related to the apoptosis of these cells. Thus, it is quite logical to combine three processes into one model: differentiation of secretory cells, their apoptosis, and the rate of milk secretion per cell.

In cattle, the lactation period averages 10 months (305 days) and includes several phases. The first phase covers up to 70-100 days from calving, i.e., from calving to reaching the peak of productivity. The second phase lasts from the peak of lactation to the middle of lactation (up to 150-200 days from calving), the third phase from the middle to the end of lactation (up to 305-320 days from calving), and the fourth phase is the dry period (45-60 days from launch) [33].

Preparation for a new reproductive cycle (service period) can last 65-80 days. This period is considered optimal for preparing for insemination. The duration of pregnancy in cattle is 285 days (Fig. 1).

In dairy cattle, pregnancy, as a rule, occurs against the background of lactation. A significant decrease in milk secretion is recorded between day 100 and day 200 of pregnancy and does not have a pronounced dependence on the timing from the start of lactation [34]. By studying the relationship of these two states at the molecular level, J.V. Nшrgaard et al. [35] concluded that hormones produced by the fetoplacental system reduce the activity of mammary gland cell proliferation during lactation and do not affect apoptosis.

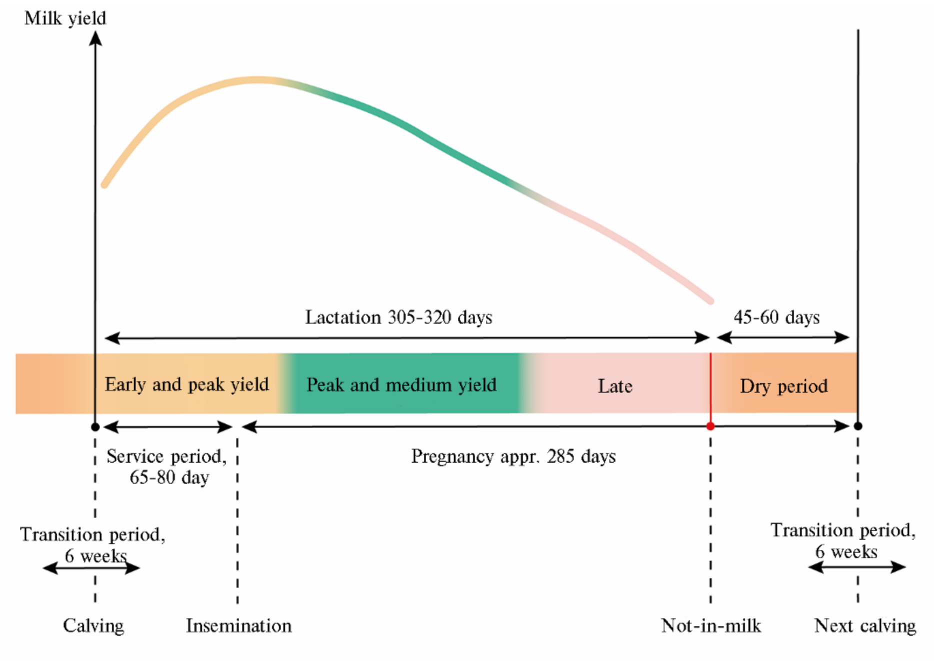

Fig. 1. The relationship between lactation and reproduction cycles in highly productive cows.

The shape of the lactation curve demonstrates the calf's need for milk: increasing milk secretion up to the peak of lactation reflects an increased demand for milk as the only source of nutrition, while a phase of declining milk production indicates an expansion of the diet and, as a result, a decrease in the proportion of milk consumed [9].

Approaches to the construction of models of lactation activity. Mathematical modeling of lactation curves makes it possible to predict milk yield depending on the time elapsed since the birth of a calf. Models can accept additional parameters such as lactation number, breed, feed-related parameters, etc. [36]. The lactation curve most often has a Λ-shape, rapidly increasing for several weeks, after which it passes into a decreasing phase with a much smaller derivative. With daily measurements of milk yield, there is usually a beating of the milk yield around the trend [19]. The highest productivity occurs between 4 and 8 weeks after calving. Over the long history of research, models of various types have been proposed - linear, exponential, polynomial, and many others [21].

The first attempts to describe the results of lactation were made as early as the 1920s, and since then the complexity and accuracy of the descriptions has only increased [37]. The models differ in the degree of dependence on the parameters of the medium and time (linear, exponential, polynomial), the number of these parameters, and the methods of describing the main characteristics of the curves (extremum points, values at the extremum points, the degree of decrease in the descending phase, etc.). In most cases, lactation curves are based on the amount of milk yield during the entire lactation period for a cow, with the idea of predicting subsequent ones. To increase the accuracy and stability of the results of the model of lactation activity, it is possible to take into account the change in the parameters of keeping animals over time [38].

Simple mathematical models predict the lactation activity of a cow at the beginning of lactation based on a fixed amount of data from the previous lactation. There are also studies that propose a model for predicting the entire curve at once by building deep learning structures based on all historical data about a cow. Such models make it possible to find at first glance implicit patterns. For example, in the work of A. Liseune et al. [39] showed that such a scheme can exceed the standard models in accuracy during the first 26 days of lactation. It can be used to detect deviations in milk yield from the norm, which reduces the time for detection of diseases. These forecasts are also useful when planning a farm budget.

Mathematical models of lactation curves. The lactation curve for milk is the function

$$y = f(t), \quad (1)$$

where t is the time since the birth of the calf, days; y is the amount of milk produced during the t-th day, kg. Perhaps the most popular model for describing lactation curves is Wood's empirical model (P.D.P. Wood, 1967), where milk yield, percentage of fat and protein, fat and protein yields by weight act as milk characteristics [18, 21, 40]. In general, the model looks like this:

$$y_t = at^b e^{ct}, \quad (2)$$

where y_t is the milk quality parameter on day t; e is the Euler number, the parameters b, c determine the slopes of the curve before and after the extremum (the function in the standard form has one maximum), the parameter a is the coefficient associated with the absolute values. The maximum productivity is determined at the point

$$t_{max} = \frac{b}{c}, \quad (3])$$

that is, the time to reach the peak of productivity does not depend on the parameter a. For a standard lactation curve, parameter b takes positive values, and parameter c takes negative values. Variations in b and c give four different configurations of lactation curves: standard iso-form for $b > 0$, $c < 0$; increasing isoform for $b > 0$, $c > 0$; decreasing isoform for $b < 0$, $c < 0$; reverse isoform for $b < 0$, $c > 0$.

The reliability of the model is assessed using the coefficient of determination. The coefficient of determination $R^2{}_{(adj)}$ shows what proportion of the variance of the resulting feature is explained by independent variables. The standard milk yield curve showed the highest average level of accuracy, for 64.7% of the points $R^2{}_{(adj)} > 0.75$. The use of the same form to describe the percentage of milk fat turned out to be the least accurate, only for 18.7% of the points $R^2{}_{(adj)} > 0.75$. These facts indicate that the same configuration of coefficients cannot be used to describe all milk parameters. Milk yield, protein yield and fat yield are well modeled by the standard form, while fat and protein percentages are more accurately described by the inverse form.

A number of studies have considered other characteristics of milk. For example, the ratio of the percentage of fat content of milk to the percentage of protein in milk (Fat Protein Ratio, FPR) [41]. The assumption is checked that this parameter plays a key role in predicting the overall productivity of cows. A variety of models have been built, e.g., Wilmink (J.B.M. Wilmink, 1987), Ali-Schaeffer (T.E. Ali and L.R. Schaeffer, 1987), Guo (Guo) and Salvador (Salvador), approximations using Legendre polynomials. The Bayesian information criterion and Akaike information criterion were used to assess the accuracy of the models, and in some cases, the correlation between the theoretically expected and actual values of the FPR parameter [41] was considered for this. The highest accuracy was shown by the function proposed by T.E. Ali and L.R. Schaeffer [42] in both random and fixed modifications. The study showed that FPR correlates with the energy status of animals, especially at the initial stage of lactation. According to the totality of studies, all considered models for constructing lactation curves gave almost identical predictions. The main factor in the decrease in accuracy was the reduction in the volume of input data on the dependence of daily milk yield on time. Models based on empirical approximation (Wood, Wilmink and Ali-Schaeffer models) turned out to be the least resistant to increasing intervals between measurements. Of the earlier works, it is worth noting the study conducted in 1953 by A.S. Emelyanov [19], where a detailed study of lactation curves was carried out with a high frequency of measurements throughout the entire lactation period and a differential mathematical model was proposed.

Application of Wood's model to different types of lactation curves. M*odeling lactation curves of milk yield.* The constructed lactation curve reflects the individual characteristics of the cow, such as the state of health, the tendency to milk, and the stability of the volume of milk produced throughout the cycle. To demonstrate, let us take a closer look at the demonstrative study of A.S. Emelyanov, mentioned above [19, 43]. For curves according to milk yield, he proposed the division of all individuals into groups according to the type of lactation activity (that is, according to the type of lactation curves that differ in height and stability): high stable, two-top, high unstable, low stable. It should be noted that these types were identified among individuals of different breeds under the same conditions of detention.

All these curves are quite accurately described by A.S. Emelyanov using the formula

$$y = \frac{A}{(t-1)} B(t-1) + 100, \tag{4}$$

where y is the percentage of increase in milk yield on the next day vs the previous one, t is the time from the birth of the calf, A is the percentage of lactation acceleration, that is, by what percentage does the milk yield increase in the first two periods of lactation compared to the first period, and B is the degree of decrease in the percentage growth. This formula is inherently differential when passing to the limit to infinitely small measurement intervals for the coefficients A and B. However, integrating this equation to obtain a lactation curve is laborious, so constructive models, such as the Wood model above, have become more common.

When selecting breeding pairs, preference is given to cows whose curves show the greatest resistance. Lifetime milk yield and the number of possible lactations are usually higher.

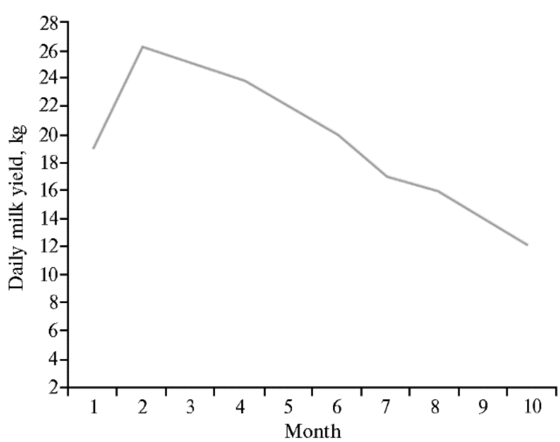

Fig. 2. Milk yield curve for cows with high productivity and lactation stability. Adapted from the work of A.S. Emelyanov [19]

I. High stable type. A group of individuals of this type is characterized by a low rate of decline in milk yield by the end of the lactation period. Lactation stably persists for all 300-305 days. Changes in feeding have little effect on milk output, animals are able to maintain an intensive metabolism for a long time, they have stable cardiovascular and nervous systems. As a rule, the integral milk yield of such cows is one of the best in the herd. Such individuals are highly desirable for selection (Fig. 2) [43].

These curves are described with good accuracy by the standard form of the Wood model discussed above. To evaluate according to the lactation curve, Wood proposed a stability coefficient expressed by the formula

$$p = -(b + 1)\ln(c), \qquad (5]$$

where b and c are the coefficients introduced in (2). The first type is characterized by high values of the stability parameter $p > 2.2$ [21].

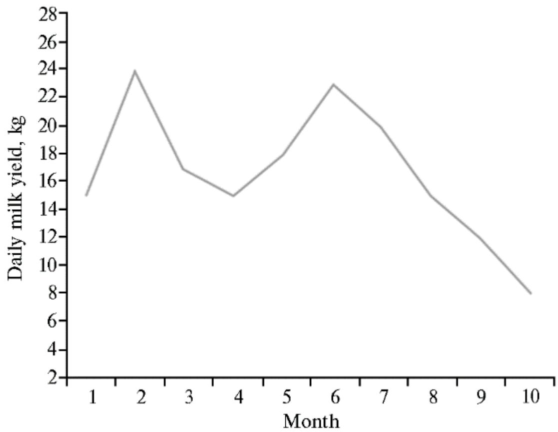

Fig. 3. Two-peak lactation curve. Adapted from the work of A.S. Emelyanov [19].

II. Double top type. In this group (Fig. 3), the milk yield has several significant periods of rise and fall. From the point of view of lactation activity, animals are similar to type 1 cows, but in general they have poorer health, which does not allow them to maintain a constant level of metabolism, as a result, alternation of periods of rest and intensive milk production is observed on the lactation curve. Fluctuations in lactation in this case are not related to the quality of feeding, since the conditions of detention are the same. Full 300-day lactation is considered acceptable, integral milk yields are slightly lower than in cows with the 1st type of lactation. It is believed that these animals can be involved in selection.

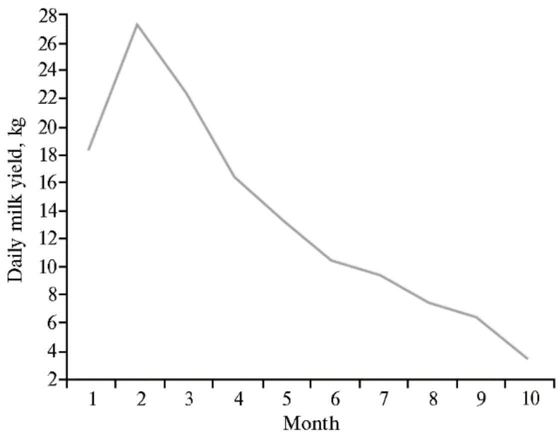

Рис. 4. Milk yield curve in cows with high productivity and unstable lactation. Adapted from the work of A.S. Emelyanov [19].

With the help of most standard mathematical models, modeling such curves is impossible. In such cases, the lactation curve can be described by polynomial series, taking into account a larger range of parameters [45, 46].

III. High unstable type. In the first months of lactation, these cows have high milk yields, but from the 5-6th month they quickly fall. The preferred lactation period is 250 days, while the integral milk yield is almost equal to that of cows of the 1st type. The cardiovascular system of such animals cannot cope with the long-term stress of metabolism. Suitable for selection in the second turn, also have a limited period of fertilization (Fig.

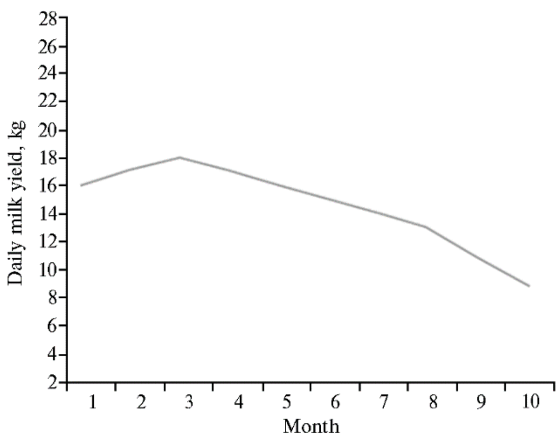

Рис. 5. Milk yield curve for cows with low productivity and stable lactation. Adapted from the work of A.S. Emelyanov [19].

4) [43]. Such curves are also well estimated using the Wood model, but have a significantly lower stability coefficient $p < 1.6$.

IV. Low resistant type. Almost the entire period of lactation, the milk yield curve reflects consistently low rates. Individuals are highly resistant, have a low integral milk yield, and are stable (Fig. 5) [43]. Animals of this type are mostly low-milk, have a weak metabolism, deficiencies in the structure of the mammary gland, problems with the cardiovascular system and digestion. If this type of lactation activity is detected in individuals of highly productive breeds, their use in breeding work is not recommended. However, one should not forget that this type is often found in representatives of native breeds and is the norm in the selection of animals for further breeding. Lactation curves of this type can be described by the Wood model with a stability coefficient $p \approx 2$.

Modeling lactation curves for milk components. I. Construction of lactation curves for fat and protein. As noted above, Wood's model is also used to describe fat percentage and protein content. It is noteworthy that the stability coefficient is calculated using the same formula. The curves describing the content of fat in milk do not have sharp drops, however, there is usually a local minimum at the time point of maximum milk yield. During the first 5 weeks (colostrum) of lactation, milk tends to have the highest fat content and highest protein content. Fat percentage is influenced by the same set of factors as milk yield, the curves for milk yield and for fat content have extremes at the same points, which means they are directly correlated [47)]. After the first 2 weeks of lactation, the short-term hormonal changes caused by the birth of a calf stabilize, and the volume of milk ceases to vary greatly over time.

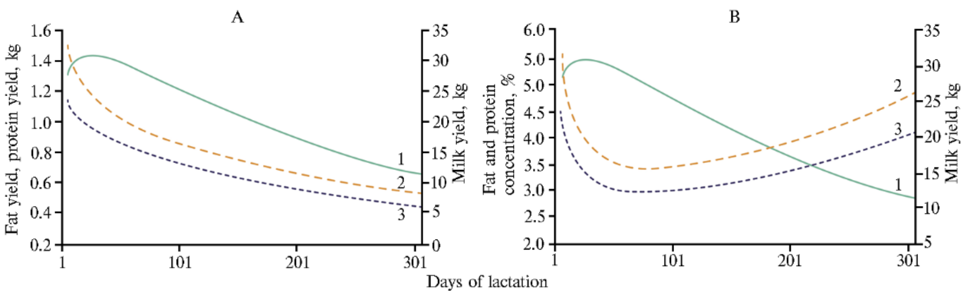

Рис. 6. Schematic representation of Wood's models for indicators of fat (2) and protein (3) in relation to milk yield (1) on the same coordinate plane: A — yield of protein and fat, B — percentage of protein and fat content. The data of milk productivity of individuals of the Holstein breed of cows were used. Adapted from A.M. Silvestre et al. [18].

As can be seen from the graphs (Fig. 6, A, B), these same processes almost do not affect the main components of milk - protein and fat, therefore, at the beginning of lactation (the first day), their abnormally high percentage in milk is possible. The yield of protein and fat in kilograms decreases in proportion to milk yield after passing the maximum point, which is associated with a general decrease in metabolic rate [48]. However, the drop in milk yield is always faster, so milk by the end of lactation becomes somewhat fatter and more saturated with protein [5, 18, 48].

Lactation curves as a tool for timely diagnosis of the physiological state of animals. Parameter "fat:protein ratio". As is known, the FPR coefficient has a high heritability and correlates with the energy state of the animal.

It has been reported that this indicator can be used for early detection of udder diseases. Also, FPR can be used to assess the general condition of an individual in order to make decisions about its further maintenance. For example, an important characteristic is the energy balance (EB), which allows you to adjust the diet and more accurately select feed. Correlations have been found between FPR and EB, which provide data on the deficiency or excess of certain dietary components on the farm during lactation (Fig. 7) [41].

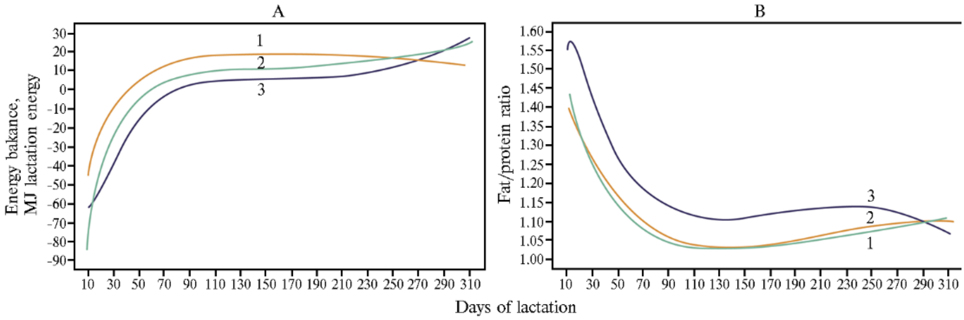

Fig. 7. Negative correlations of energy balance (EB, NEL — lactation net energy, A) **and fat:protein ratio** (FPR, B) **in the 1st** (1)**, 2nd** (2) **and 3rd or subsequent** (3) **lactations.** The data of milk productivity of individuals of the German Holstein breed of cows were used. Adapted from N. Buttchereit et al. [41].

Prediction of diseases by deviations of lactation curves from predicted values. The models built can be used to prevent and detect udder diseases such as mastitis. For example, you can build a model for individual parts of the udder, comparing deviations from which you can see the effects of the disease. Based on the milk yield for each quarter of the udder, a special improved Wood model is built. Based on the curves of these models and the actual readings of milk yield for parts of the udder, a graph of their difference (QL) is built. Figure 8 shows the curves for clinical mastitis in the case of acute QL_CM1 and more mild disease QL_CM2 compared with the healthy part of the udder QL_NI1 and QL_NI2, respectively. It can be seen that for QL_CM1 and QL_NI1 there is a common peak in the decline in productivity, and after several milkings it becomes possible to find out which particular quarter of the udder is infected. For QL_CM2 and QL_NI2, the productivity of the affected quarter is gradually decreasing. Notably, in this case, the healthy part of the udder compensated for the loss of milk (probably due to redistribution of nutrients) (see Fig. 8) [49].

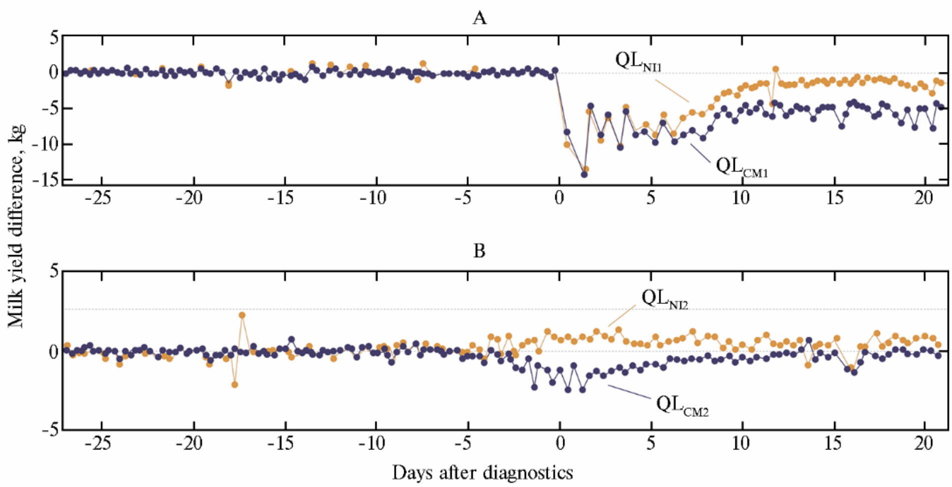

Fig. 8. The difference between expected and observed milk yields (QL) **in case of clinical mastitis for the diseased and healthy part of the udder of cows in the case of acute** (A) **and moderately severe** (B) **course of the disease.** Adapted from I. Adriaens et al. [49].

Modeling lactation curves to assess breeding value and take into account the influence of environmental factors. Improvement of models of lactation curves continues. In the studies of A.B. Abdelkrim et al. [38] used a sophisticated modeling approach to refine milk loss as a function of various factors affecting the animals. The approach uses a superposition of perturbation signature plots and the previously mentioned Wood's function. It is assumed that there is a certain reference curve that depends solely on genetic traits, on which perturbations caused by the imperfection of the habitat are superimposed (Fig. 9). The effects of a wide variety of parameters were taken into account, from lactation number to seasonality. This approach allows not only to calculate the influence of environmental factors on the integral milk yield with high accuracy, but also to assess the genetic potential of animals for further selection [38].

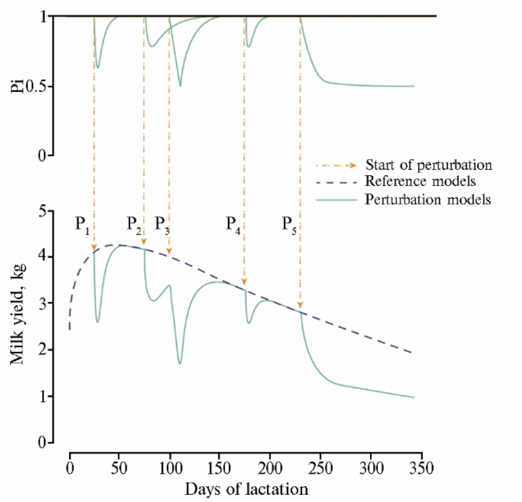

Fig . 9. Translation of the superposition of perturbation functions (P1-P5, top) **onto the milk yield curve** (bottom) **in the Wood model for cows by lactation.** The individual dynamics of disturbances is expressed as the proportion of the undisturbed lactation curve (P1-P5). The graph of milk yield shows the unperturbed and perturbed dynamics of milk yield. The data on the milk productivity of goats of the Alpine and Saanen breeds were used. Adapted from A.B. Abdelkrim et al. [50].

Genomic selection is another important way of using these lactation curves. To do this, animals with different types of lactation curves must be genotyped for the maximum set of markers associated with milk production and milk quality in order to identify correlations between the haplotype and the type of lactation curve. In the future, the selection of suitable animals can be carried out immediately after birth or at the stage of selection of pairs during breeding. This approach will significantly reduce the cost of growing and keeping animals that are unpromising for milk production. Animals whose lactation activity is characterized by lower peaks and a more persistent lactation curve experience fewer health and reproductive problems and can efficiently use cheaper feed [22]. Predicting the evolution of milk yield can be widely used for diagnostic purposes, being an important tool in choosing a management strategy and breeding policy for herd management [20].

So, forecasting the evolution of milk yield is widely used by farms for making managerial and breeding decisions. For dairy production, cows with an even type of lactation are considered the most valuable. Modeling of lactation curves is one of the most effective methods for predicting various parameters of milk based on a fixed amount of data at the beginning of lactation following lactation with measured indicators. Accounting for hereditary and non-hereditary factors affecting lactation activity is important to obtain a more accurate prognosis. In addition, the reliability of the model should be assessed based on its stability when modeling specific parameters. Some components of milk, as well as their ratios, can act as very accurate markers of the physiological state of animals. Thus, the modeling of lactation curves is an important tool for timely monitoring of the health status of animals and their productivity. Identification of diseases before the appearance of clinical signs helps to reduce the cost of treatment and improve the prognosis of the course of the disease. The main difficulty of regular monitoring of lactation activity lies in the difficulty of making accurate measurements and their subsequent analysis, the cost of these procedures, as well as the availability of technical capabilities. Recently, deep learning algorithms have begun to be used to model lactation curves, which can surpass standard models in accuracy (for example, in predicting productivity in the first day of lactation). When training, such models take into account the statistics of milk yield for previous lactations, health parameters (in an implicit form), including fertility, and use these data when modeling the entire curve at once. It is advisable to use these forecasts when planning the budget of the economy.

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