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Research Article

Biophysical Properties of Hoof Horn and Their Connection with Some Biological Parameters of Cows in the Conditions of Industrial Technology

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ABSTRACT

Limp is one of the most common problems of modern dairy cattle breeding. It leads to a decrease in the productivity of cows, their reproductive ability, lack of calves and forced culling.
In more than 90 % of cases, limp is caused by hoof injuries due to the poor quality of horny tissue.
The article presents the results of studies of the strength of hoof horn of cows as an indicator of the hoofs resistance to adverse factors of the industrial technology. The hardness of the hoof horn and its elastic properties (Young's modulus and internal friction) were studied using own methods, as well as the influence of various factors on them: animal breed, age, sex, productivity level, phase of the physiological cycle.
As a result of investigations, it has been established that the strength of the hoof horn depends on the optimal ratio of its hardness and elasticity. A harder hoof horn to a certain threshold has a higher elasticity. Such a threshold for Kholmogorskaya cows is 90 T_{III} and that for the black-and-white cows is 87 T_{III}.
The study of the relationship between the hardness of the cows' hoof horn and its other biophysical parameters showed that the hardness of the hoof horn can be used as a generalized indicator of its quality.

Keywords: cows, hoofhorn, limbs, hardness, elasticity, strength.

INTRODUCTION

With intensive animal husbandry technology, animals are kept in an environment with excessive moisture, increased density of accommodation, in conditions of hypodynamia, in rooms whose design does not fully meet the biological needs of the body, which leads to an increase in the number of cases of problems with limbs accompanied by limp (Clarkson, M.J. et al., 1996; Algers, V. et al., 2009; Samolovov, A.A., 2018).

The limp of dairy cows causes significant economic damage to modern dairy farms and adversely affects the welfare of animals, reduces the reproductive function of cows, milk production and increases culling rates (Oberbauer, A.M., 2013; Short communication: Genetic character of digital cushion thickness, 2014; Vander Spek, D. et al, 2015; Frondelius, L. et al, 2015).

Over 90 % of limp cases are caused by hoof injuries. The nomenclature of the most common diseases of hooves is about the same in both Russian and foreign literature. The most common pathologies are digital and interdigital dermatitis (Mortellaro disease), laminitis and laminitis-related lesions (hoof sole ulcer, ulcers and abscess of the white line, hemorrhage of the sole and the white line, double sole and crack of the white line), erosion of the horn of the pulp, interdigital phlegmon (Analysis of foot health records from 17 confinement dairies, 2013; Vander Spek, D. et al., 2013; Schöpke, K. et al., 2013; Becker, J. et al., 2014; Simonov, I.Yu. et al., 2018).

Cattle disposal due to hooves pathology is one of the most important issues of cattle breeding, both in Russia and abroad (Tunikov, G.M. et al., 2018).

In Western European countries, culling of dairy cows due to problems with hooves increased from 6.8 % in 1990 to 15.8 % in 2006. In Germany, more than half of milk cows have diseases of hooves, which leads to significant economic losses (Melnik, N.V., 2009).

In England, injuries to the distal portion of cattle limbs are recorded in 30-60 % of the total number of diseases (Boosman, R., 2006; Nuss, K., 2006).

The losses caused by these diseases consist of forced culling of animals, reduction of milk yield, reproductive functions, and the lack of calves (Raber, M., 2000; Lomander, H. et al., 2013). In the absence of treatment or its unsatisfactory organization, up to 70 % of sick animals are prematurely rejected for slaughter.

Thus, it can be said that industrial methods of cattle breeding impose higher demands on the functional ability of joints and hooves.

The prolonged deforming effect of a concrete surface or rubber floor creates an improper pressure on the sole dermis. This serves as one of the causes of various diseases of hooves, united under the general term “the destruction of the hoof horn”, which further leads to the development of laminitis (Baird, L.G., Mulling, C.K., 2009; Sagliyan, A. et al., 2010; Haufe, H.C. et al., 2014).

What is the reason for the weakness of the hoof horn and why some animals are resistant to adverse environmental factors, while others are simply not suitable for the industrial technology? The lack of consensus on this issue is a significant reason for conducting such investigations.

In connection with the above relevance of the problem, the purpose of these investigations was to study the biophysical properties of the hoof horn of cows comprehensively in conditions of intensive milk production technology. The following tasks were set for this:

- to study the degree of incidence of diseases of the cattle hooves in conditions of dairy complexes, depending on the age;
- to determine the biophysical parameters of the hoof horn of cows, depending on the breed, age, physiological state and the level of milk production;
- to determine the relationship between biophysical parameters of the cows' hoof horn.

MATERIALS AND METHODS

To fulfill the program of investigations, a series of scientific and business experiments were carried out on black-and-white and Kholmogorskaya breed cows on the basis of farms in Ryazan region.

The growth of animals was monitored by weighing and measuring at different age periods, and milk recording - according to meter readings during milking. The physiological state of the animals was taken into account according to the documents of the primary zootechnical record, as well as by rectal examination. The exterior of hooves was studied according to the method of G.M. Tunikov (1986) by taking measurements with the help of a tape and a caliper.

The moisture of hoof samples and their moisture-absorbing capacity for 24 hours were established according to generally accepted methods. The intensity of growth and erasure of the hoof horn was studied by the method of V.V. Kalinikhin (1990) by control scarifications to the dorsal wall of the hooves with subsequent measurement of the change in their position relative to the rim edge and the toe edge of the hoof sole after 30 days. Chemical analysis of feed, the hoof horn and the blood biochemical analysis were carried out according to generally accepted methods in the chemical-analytical laboratory of the testing center of VGNIIZh RAAS, Russia.

New investigation methods have been proposed that allow a more informative assessment of the biophysical properties of the hoof horn:

- a method of determining the hardness of the hoof horn (Tunikov, G.M., Kuschev, I.E., Bystrova, I.Yu., 1993);
- a technique for measuring the elastic properties (Young's modulus, internal friction and velocity of longitudinal waves) by the method of resonant piezoelectric generation (Tunikov, G.M., Kleimenov, E.V., Mayorova, Zh.S., Bystrova, I.Yu.).

The digital material obtained during the experiments, as well as the original statistical data are processed by the method of variation statistics, described using modern computer technology and the reliability of the parameters was estimated by Student.

The previously used methods for determining the hoof horn hardness involved the use of presses for metals (Rockwell, Brinell, etc.), which distort the true characteristics of hoof horn samples. Therefore, a technique involving the use of TIR 2033 device has been proposed.

The hoof horn hardness was measured at points of the hoof toe with the same pigmentation closer to the dorsal edge. According to our data, the correlation coefficient between the hardness of the hoof horn of the thoracic and pelvic limbs is 0.52-0.55, therefore the results of the experiments reflect the hoof horn hardness of only the front hooves, since they are the most accessible ones for investigations.

The advantage of the method of determining the hoof horn hardness using TIR 2033 device over other methods is as follows:

- the device is mass produced by the factory;
- the device is easy and practical to handle;
- the technique does not require any special training and is available to all zoo and vet specialists;
- the method is completely painless for animals;
- the device makes possible to measure samples and their cutting at farms quickly, without any prior preparation;
- it is possible to measure the horn hardness in those places of the hooves, where it is impossible to take samples. Measurement of the elastic properties (Young's modulus and internal friction) was carried out by the method of resonant piezoelectric generation.

The essence of this method, originally proposed by S.L. Quimby (1925), and then J. Zacharias (1933), is that the piezoelectric converter is attached to the sample in the form of a cylindrical or rectangular rod and the resulting system is tuned into resonance.

When measuring the frequency and quality of the system, taking into account the influence of the converter, one can determine the property of the sample.

This method is widespread due to the relative simplicity of the necessary equipment, as well as due to the fact that commonly used quartz converters have ideal mechanical properties and very small energy losses of the ultrasonic wave. The use of piezoelectric generation can significantly improve the accuracy of measurements when determining the elastic modulus and internal friction. To create elastic resonant oscillations in the ultrasonic range, a quartz X monocrystal of a rectangular cut with a cross section of 4 x 4 mm and a length of 40 mm was used.

The resonant frequency corresponding to the voltage maximum was 67 356 Hz. The resonance curve of this quartz in the frequency range from 66 kHz to 68 kHz is presented in Table 1 and Figure 1.

The calculation was carried out according to the following formula:

$$Q^{-1} \approx \frac{2 \cdot \left(f_m - f_x\right)}{f_m}, (1)$$

Where f_x is the frequency corresponding to the minimum of the resonance curve, Hz;

f_m is the frequency corresponding to the maximum of the resonance curve, Hz, giving a quality factor for quartz equal to 410.7, that corresponds to internal friction of 0.0024.

Table 1 - Resonance curve of quartz

U,V	0.34	0.65	1.20	2.20	1.59	0.35	0.03	0.14	0.25
F, H	66813	67285	67330	67356	67365	67384	67447	67497	67861

$f_m f_x$

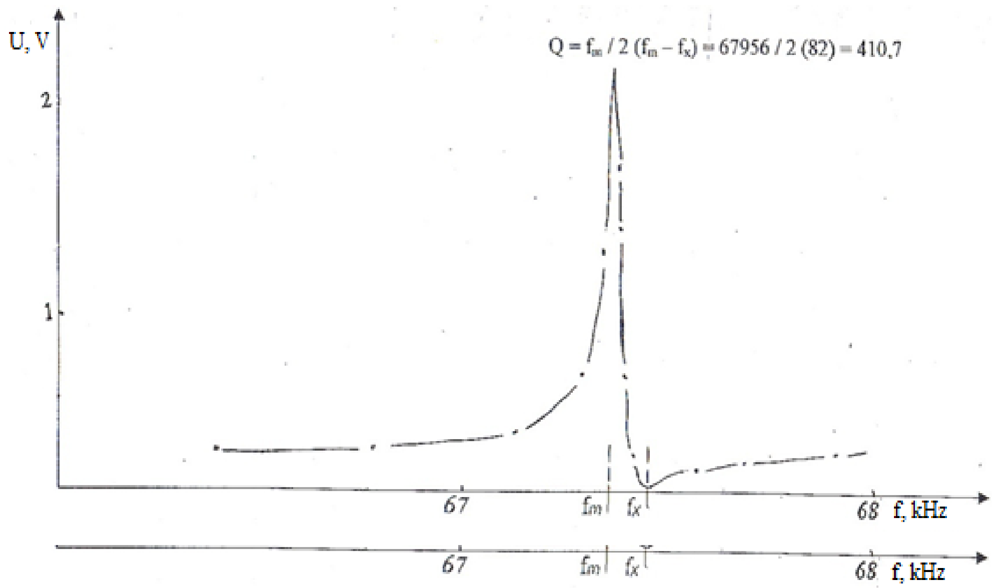

Figure 1 - Resonance curve in the stretched scale of section A

The objects of the study were samples of hoof horn of a rectangular shape with a size of 4.5 x 4.5 mm and a length of 30 ... 40 mm. A sample was glued to the quartz and the compound was polymerized by heating.

To ensure that the amount of internal friction is not significantly affected by the deformation at the junction due to the difference in linear expansion of the quartz and the sample, the sample and quartz were chosen with close natural frequencies, so that the node of oscillations was obtained at bonding point.

The following instruments were used in the laboratory setup (Figure 2): harmonic oscillator (GZ-112), frequency meter (ChZ-38), millivoltmeter in the range from 10 mV to 3 V (VZ-25) and quartz converter of X-cut 40 mm long. Alternating voltage is applied to the "converter-sample" system from a sinusoidal signal generator. With the coincidence of the oscillator frequency and the natural frequency of the “converter-sample” system, the latter begins to resonate.

The main parameters of the resonance curve are determined using a frequency meter and millivoltmeter.

Based on these parameters, the elastic modulus is determined using the appropriate formulas.

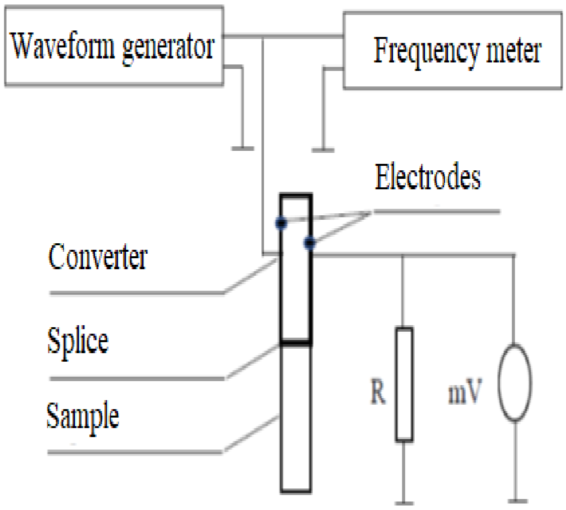

Figure 2 - Diagram of the laboratory setup for ultrasonic measurements by the method of piezoelectric generation

RESULTS AND DISCUSSION

It was established in the course of investigations that diseases of the hooves in cattle appeared at the age of more than 7 months and became widespread during DIM. So up to 6 months of age, no animals with sick hooves were found. At the age of 7-12 months, from 2.0 to 4 % of animals had sick hooves and in 13-18 months the number of sick animals was 6.0 %. For heifers, this figure increased to 17.0 %, and in the group of first-calf heifers, this indicator reached the 30.0 % mark.

Hoof horn defects begin to be registered at 13-18 months of age. With advancing age, the percentage of animals with hoof diseases is steadily increasing; this is especially sharp from the age of 18 months.

The number of heifers, first-calf heifers, and cows with defects of the hoof horn is higher than the population with hoof diseases. That is, if the zoo-hygienic and technological standards are observed, hoof horn defects do not always cause subsequent lesions of the hooves.

The growth of hooves begins to be registered in heifers (8.7 %), and it is already widespread in first-calf heifers and cows (35.1 % and 49.7 %, respectively). The dynamics of growth in the number of animals with overgrown hooves is identical to the dynamics of growth in the number of animals with hoof diseases, and the dynamics of hoof injuries is similar to the dynamics of the number of animals with defects of the hoof horn. Consequently, the hoof horn growth can be considered the cause of the hoof disease. The damage to the hoof horn is the result of its poor quality.

It is believed that increasing with age, the live weight has some negative effect on the hoof horn. The intensity of hooves growth in length and height at different age periods is similar, which contributes to their proper formation. The growth of hooves in width reaches its maximum in the period of the highest intensity of the live weight growth, which allows to reduce the load per unit surface area of the hooves. The load index on the hooves of animals decreases with age from 9.46 kg / cm^2at 9 months of age, to 3.13 kg / cm^2 in full-grown cows, which indicates that an increase in body weight cannot be the cause of hooves damage.

The hoof, as a "supporting structure", must have high resilience to loads, that is, strength, composed of a number of physical-mechanical characteristics and, first of all, of hardness and elasticity.

The hof horn hardness is of breed nature and depends on factors such as age, live weight, the milk yield and the physiological state of the animal.

Among the studied breeds, cows of Kholmogorskaya breed had a harder hoof horn - 92.67 ± 1.79T_{III}, that is 9.59T_{III}more, than the analogs of the black-and-white breed had (Table 2).

With advancing age, the hoof horn hardness of cows increases, reaching a maximum value for Kholmogorskaya cows at 8-9 years old (95.5 T_{III}) and for black-and-white cows at 5 years old (89.0 T_{III}). In later life periods, the hoof horn hardness decreases. Black-and -white cows had higher intensity of the hoof horn hardness reduction and by the age of eleven, the hardness was 83.5 T_{III}, and the Kholmogorskaya breed cows had 91.6T_{III}.

It is noted that the hoof horn hardness depends on the sex of the animal. So, in bulls throughout the entire observation period, it was significantly higher than that of the same breed heifers, on average by 3.8T_{III}.

The higher the milk yield is, the lower the hoof horn hardness is. The hoof horn hardness decreased from 98.31 ± 2.32 T_{III} to 84.06 ± 2.42 T_{III} in cows of Kholmogorskaya breed, when the milk yield changed from 3,800 kg to 5,100 kg. In black-and-white cows, the hoof horn hardness decreased from 94.22 ±1.13 $T_{III}$to 78.41 ± 3.33T_{III}, when the milk yield changed from 4,000 kg to 6,200 kg.

Figure 3 shows the dependence of the hoof horn hardness of cows on the phase of the physiological cycle. During the dry period, the hoof horn hardness increased from 86.41 T_{III} to 96.24 T_{III} in cows of Kholmogorskaya breed and from 77.13 T_{III} to 85.78 T_{III} in black-and-white cows. By the end of lactation, the hoof horn hardness gradually decreased to a minimum: in Kholmogorskaya cows to 76.67 T_{III} and in black-and-white cows to 66.03T_{III}.

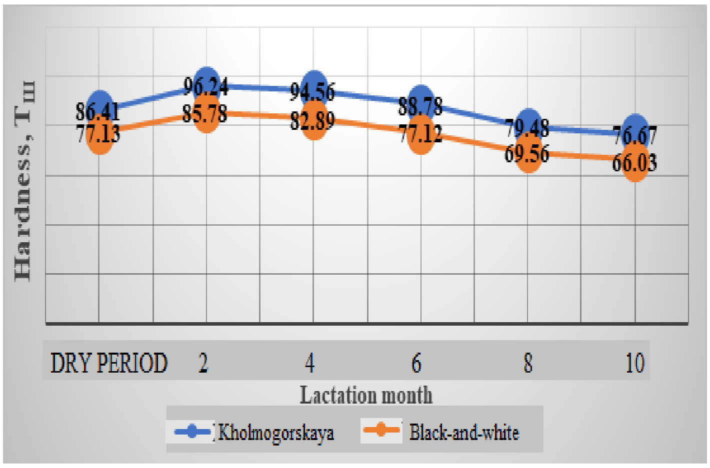

Figure 3 - Dependence of the hoof horn hardness on the lactation phase

To assess the degree of elasticity of the hoof horn, the Young's modulus (E), the elastic modulus when longitudinal vibrations, and the magnitude of internal friction (Q^{-1}) were measured.

Cows of Kholmogorskaya breed possessed a more elastic hoof horn (the Young's modulus was 2.240 ± 0.060 · 10^{10}N / m^2), than cows of black-and-white breed (the Young's modulus was 1.687 ± 0.050 · 10^{10}N / m^2).At the same time, the internal friction index of the hoof horn was significantly lower - 0.015 ± 0.001, versus 0.134 ± 0.002, which indicated a higher quality of horny tissue (Table 2). With an increase in the hoof horn hardness, the Young's modulus increases. But it has been noted that black-and-white cows with hoof horn hardness of 87.0 T_{III} and the Young's modulus of 3.5 · 10^{10}N / m^2had some decline in the increase degree of the Young's modulus in a case of an increase of hoof horn hardness. Cows of Kholmogorskaya had a less decrease in elasticity (the Yong's modulus growth), than black-and-white cows, when an increase in the hoof horn hardness.

Table 2 - Physical-mechanical characteristics of the cows' hoof horn

Parameters	Black-and-white breed, n = 50	Kholmogorskaya breed, n = 50
Hardness, T_{III}	83.08 ± 2.25	92.67 ± 1.79*
Young's modulus, 10^{10}·H/ m^2	1.687 ± 0.050	2.240 ± 0.060**
Internal friction, Q^{-1}	0.134 ± 0.002	0.015 ± 0.001**
Moisture, %	7.89 ± 0.45	8.80 ± 0.38
Moisture capacity, %	21.16 ± 2.53	18.99 ± 2.22
Waterabsorption, %	3.31 ± 0.30	1.66 ± 0.34**
Growthrate,cm / day	0.080 ± 0.001	0.050 ± 0.001**
Erasing rate,	0.034 ± 0.006	0.027 ± 0.006

*P ≥ 0.95 **P ≥ 0.999

Thus, a hard hoof horn is more elastic, but there is a non-linear relationship between elasticity and hardness, that is, there is a hardness threshold at which elasticity begins to decrease. Such a threshold for Kholmogorskaya cows is 90 T_{III} and that for black-and-white cows is 87T_{III}.

The change in the elastic properties of the hoof horn is associated with age-related changes in its hardness, therefore, as cows change the hardness of the horn with age, its elasticity and the amount of internal friction change according to the established pattern.

The elastic properties of the hoof horn of cows of different breeds change differently during lactation (Figure 4).

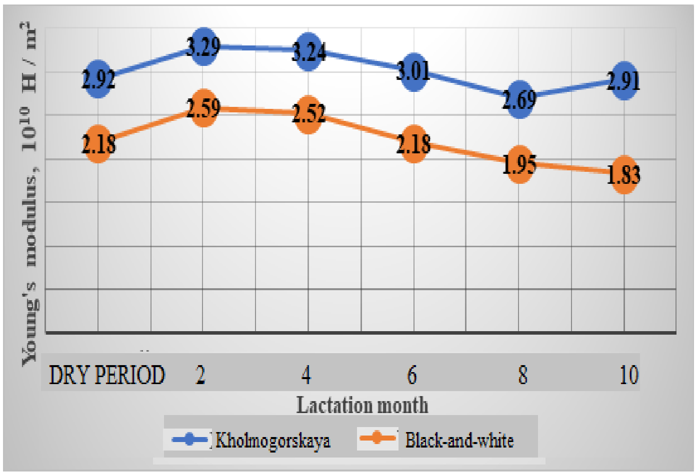

Figure 4 - The dependence of the Young's modulus of the hoof horn on the lactation phase

The maximum elasticity index of 2.60 ± 0.19 · 10^{10}N/ m^2in black-and-white cows corresponds to the end of the dry period and then it decreases to calving (1.83 ± 0.05 · 10^{10}N / m^2. Cows of Kholmogorskaya breed had the peak of the elasticity index at the end of the service period and the third month of lactation (3.37 ± 0.21 · 10^{10}N / m^2), as well as the peak of hardness, which is explained by the genotype determined longer DIM. The magnitude of the internal friction of the hoof horn has changed with the same pattern.

Maceration of the hoof horn reduces its hardness and promotes the penetration of pathogenic microflora into the underlying tissues. Therefore, knowledge of the moisture-absorbing properties of the hoof horn is necessary to prevent limb diseases. Samples of hoof horn were tested for moisture, moisture capacity and water absorption.

The cows of Kholmogorskaya breed had higher moisture in the samples and amounted to 8.80 ± 0.32 %, against 7.89 ± 0.45 % in black-and-white cows.

In spite of the fact that the primary moisture of hoof horn samples of cows of Kholmogorskaya breed was higher, than that of the black-and-white breed, the capacity of the horn of Kholmogorskaya cows was lower and amounted to 18.99 ± 2.22 %, against 21.6 ± 2.53 % for black-and-white cows.

The moisture of the hoof horn of first-calf cows of Kholmogorskaya breed was 0.36 % higher (11.69 ± 0.28 %), than their herdmates of the black-and-white breed had (11.33 ± 0.15 %). On the contrary, moisture capacity was lower - 30.49 ± 0.90 % and 31.35 ± 0.66 %, respectively. The water absorption of the hoof horn of first-calf cows of Kholmogorskaya breed was 1.66 ± 0.34 % and that of their herdmates of the black-and-white breed was 3.31 ± 0.30%.

The average for breeds water absorption of full-grown cows was 3.15 ± 0.27 %, while that of Kholmogorskaya breed cows it was 1.65 % lower, than that of the first-calf black-and-white breed (1.66 ± 0.34 and 3.31 ± 0.30 %, respectively). This indicates that the hoof horn of Kholmogorskaya breed cows gives back absorbed water better, that is, it possesses higher quality characteristics.

The negative correlation established between hardness and moisture capacity and the positive correlation between hardness and water absorption of the hoof horn suggests that the harder horn absorbs less moisture from the external environment, but also retains it inside better.

Assuming that hardness is the main and generalizing parameter of the hoof horn quality, a relationship between its hardness and the intensity of growth and abrasion has been established.

The cows of Kholmogorskaya breed had the growth rate of the hoof horn equal to 0.050 ± 0.001 cm / a day, which was 0.030 cm / a day lower, than that of the black-and-white cows (0.080 ± 0.001 cm / a day).Their hooves were also less intensively abraded - 0.027 ± 0.006 cm / a day, while the hoof horn abrasion of black-and-white cows was 0.034 ± 0.006 cm / a day. At the same time, parameters of the hoof horn growth and abrasion are in inverse linear dependence on its hardness. The growth rate of the hoof horn in full-grown Kholmogorskaya cows was also lower (46.0 %), than in black-and-white cows (57.7 %).

The same pattern was observed in first-calf cows, and the growth rate of the hoof horn of both breeds (0.157 ± 0.006 and 0.167 ± 0.007 cm / a day) significantly exceeded this parameter in full-grown cows (0.050 ± 0.001 and 0.080 ± 0.001 cm / a day), which was associated with intensive growth processes, both of the whole organism of first-calf cows, and of its individual components, including the hoof horn. The intensity of the hoof horn abrasion in full-grown cows was also lower - 0.027 ± 0.006 cm / a day and 0.034 ± 0.006 cm / a day, respectively, by breed.

The fist-calf heifers had a higher growth rate of the lateral hoof horn (0.177 ± 0.009 cm / a day), than the growth of the medial one (0.153 ± 0.006 cm / a day). The abrasion rate, was 0.109 ± 0.010 and 0.084 ± 0.008 cm / a day, respectively ($P \geq 0.95$).

The growth rate of the lateral hooves is 6.7 % lower than that of the medial ones, while the heritability of the growth rate of the hoof horn is 0.4-0.5. Consequently, a harder hoof horn, has a lower intensity of growth and abrasion.

CONCLUSIONS

Thus, hoof diseases in cattle occur over the age of 7 months, with age the percentage of animals with hoof diseases is increasing, especially from 18 months of age.

Damage to the hoof horn is the result of its poor quality. The hardness of the hoof horn is of pedigree nature and depends on factors such as age, live weight, milk yield and the physiological state of the animal.

Of the species studied, the hoof horn of Kholmogorskaya breed cows is harder - 92.67 ± 1.79 T_{III}, for analogues of the black-and-white breed the hardness of the horn is 83.08 ± 2.25T_{III}.It increases with the age of the cows, reaching the maximum value in Kholmogorskaya breed at 8-9 years and in the black-and-white breed - at 5 years. In later life periods, the hardness of the hoof horn decreases.

The hardness of the hoof horn with a high or medium degree is correlatively related to all the studied physical properties, therefore, it can be used as a generalized indicator of the hoof horn quality.

Up to a certain threshold a harder hoof horn, has higher elasticity, grows less intensively, and also has a lower abrasion intensity. With higher hardness, the hoof horn has higher moisture and less moisture capacity.

For normal functioning of the musculoskeletal system, the hoof horn must have an optimal ratio of hardness and elasticity. Cows with high yield had a less qualitative hoof horn (hard and inelastic), which performs its protective function poorly, is prone to overgrowth and is more often injured. In this regard, highly productive cows are more susceptible to the occurrence of inflammatory processes of chronic and acute nature in the area of the distal limbs and require special attention from the zootechnical and veterinary services.

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