Review article

The use of thermal imaging measurements in dairy cow herds

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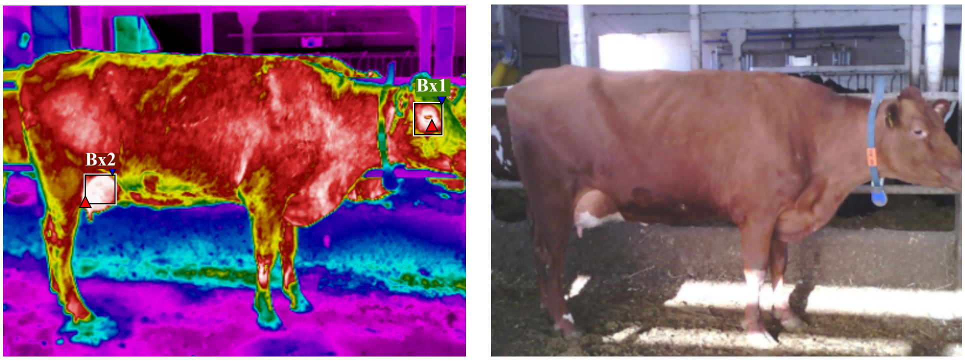
Infrared thermography (IRT) is a technique for contactless and remote evaluation of the temperature distribution on the surface of an animal's body. The surface temperature values obtained in IRT depend on the quantitative impact of the conditions of the surrounding environment and the thermoregulatory response of the animal. Besides the blood perfusion volume, the skin temperature depends on the metabolic rate of tissues, the type and colour of the hair coat, and the thickness of the adipose tissue. In a healthy organism, the temperature distribution between individual parts of the body shows a high degree of symmetry. Analysis of the surface temperature distribution of a given area of the body of an animal which is in homeostasis with the external environment provides a great deal of valuable information. By comparing the same parts of the body, we can easily identify hot spots, and the additional knowledge gained during more extensive veterinary diagnostics increases the chance of establishing the cause of this condition. The reliability of IRT depends on the technical parameters of the cameras, environmental conditions, the operator's experience, the animal's individual characteristics, and the testing methodology. As many factors can affect the surface temperature distribution of an animal's body, and thus the result of the thermographic measurement, the effect of any stimuli interfering with the measurements should be minimized during thermal imaging. Additionally, in order to reduce the risk of misinterpretation of the image, normalization protocols for imaging parameters, i.e. standards ensuring reliable results, should be applied. The main limitation in the implementation of these standards in thermography of livestock animals is that it is not possible to compare thermograms made under different environmental conditions. Research has been

carried out to assess the suitability of thermal imaging cameras in diagnosing inflammatory changes in the skin of cattle. The technique was found to have great potential in predicting local inflammation (hoof, udder or skin disease). Normalization protocols must be developed for imaging parameters, i.e. standards that will ensure reliable results in a variety of environmental conditions.

KEYWORDS: thermal imaging / dairy cattle / diagnostics / local inflammation

Infrared imaging is a technique enabling non-contact and remote evaluation of the temperature distribution on the surface of a body (photo 1). In veterinary medicine and animal sciences, it is used for both diagnostic and scientific purposes [14, 23]. The method enables visualization of infrared radiation, and hence the acquisition of information on physiological and pathological processes in animals [3, 7, 24, 40]. Thermal imaging cameras are devices designed to detect, process and record the intensity of infrared radiation [14].



Measurements		
Bx1	Max	35.7 °C
	Min	17.1 °C
	Average	28.7 °C
Bx2	Max	36.2 °C
	Min	21.6 °C
	Average	32.2 °C

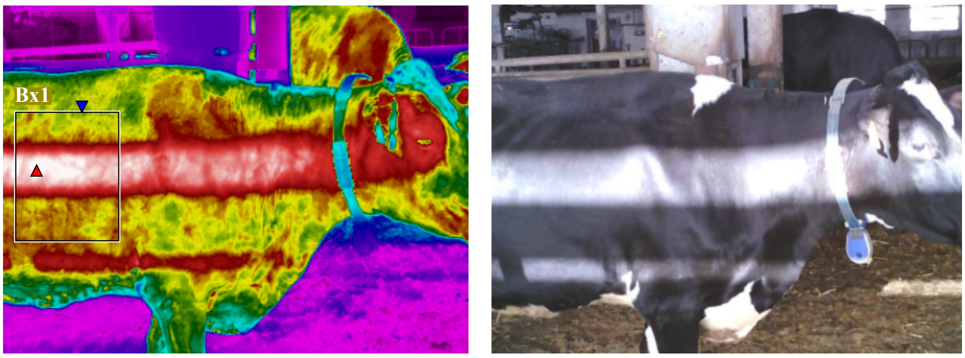
Phot. 1. Thermogram of the side of a cow's body, showing the distribution of surface temperatures seen in thermographic imaging, with 'thermal windows' on the skin indicated (our own work)

In nature, infrared radiation is emitted by all objects with a temperature higher than absolute zero (0 K, or –273.15°C). The infrared band is the entire electromagnetic spectrum between visible light and microwave light, in wavelengths from 0.7 µm to 1000 µm.

A large part of this spectrum, however, is not useful in thermal imaging cameras. Many wavelengths are blocked by atmospheric conditions prevailing on Earth and gases in the atmosphere. Therefore the ‘atmospheric windows’ defining the bands that can be used on Earth are significant. Four basic bands are distinguished: near-infrared (NIR) – 0.8-1.1 µm, short-wave infrared (SWIR) – 0.9-2.5 µm, medium-wave infrared (MWIR) – 3-5 µm, and long-wave infrared (LWIR) – 7-14 µm.

Thermal imaging cameras register infrared radiation emitted by the tested object on the detector. The infrared radiation for individual pixels is converted on the detector to the appropriate value of electrical resistance. Levels of resistance from the detector array are then digitized, saved and presented on the camera display in the form of a colour palette (thermogram), where a given colour corresponds to points with the same temperature [14, 19].

The development of modern detectors with high resolution and thermal sensitivity, as well as the development of digital image conversion software and systems, has recently contributed to an increase in the popularity of this technique as a diagnostic method for assessing specific diseases in farm animals. Mass production of thermal imaging cameras has resulted in a significant drop in their prices and made them popular in various areas of life. Thermography is currently used to study injuries and inflammation in the musculoskeletal system [1, 14], to detect udder inflammation [10, 30] and inflammation of the respiratory



Measurements		
Bx1	Max	42.6 °C
	Min	26.7 °C
	Average	32.8 °C

Phot. 2. Photograph and thermogram of the side of a cow’s body. The thermogram shows the effect of sunlight on the variation in surface temperatures seen in thermal imaging (our own work)

tract in cattle [34], to diagnose infectious diseases (e.g. foot-and-mouth disease) [6, 31], to study the oestrus cycle and gestation, and to monitor animal welfare and stress levels [15].

Infrared thermography (IRT) of animals involves measurement of the temperature on the surface of the body. In the case of warm-blooded animals, the temperature values obtained in IRT depend on the quantitative impact of ambient conditions and the animal's thermoregulatory response [8, 37]. In addition to the volume of blood perfusion, skin temperature depends on the intensity of tissue metabolism, the type and colour of the hair coat, and the thickness of adipose tissue [11, 12, 20].

An important effector of thermoregulation is the circulatory system. The loss of heat into the environment through radiation, convection and conduction depends mainly on the skin blood flow and arterial blood temperature [12].

The total radiation energy emitted or absorbed by an animal's body depends on the emissivity of the skin of a given species. The emissivity factor is necessary to determine the temperature on the surface of the body. It should be noted that bodies with surface temperatures higher than absolute zero emit energy at all wavelengths of the electromagnetic spectrum. The largest amount of infrared radiation (IR) energy is emitted in the wavelength range from 7 to 14 μm (LWIR). Therefore, the camera used for research was one that allowed an image to be recorded in exactly the same band. In animals, 40-60% of heat loss occurs as a result of thermal radiation and falls within the emission factor range of 0.97-0.98 [29].

Physiological processes in the tissues of warm-blooded animals affect their temperature. A causative factor affecting the temperature differences in tissues is blood perfusion [18]. In a healthy body, there is a high degree of symmetry in the temperature distribution between individual parts of the body. Analysis of the surface temperature distribution of an area on the bodies of animals that are in homeostasis with the external environment provides a great deal of valuable information. By comparing the same parts of the body, hot spots can be easily identified, and the additional knowledge gained during broader veterinary diagnostics increases the chances of establishing the cause of this condition [5]. Fluctuations in temperature distribution on the surface of the body result not only from the skin blood flow volume, but also from the rate of tissue metabolism, hair coat density, and fat thickness [11]. A significant factor that additionally affects the surface temperature is the microclimate.

During thermographic measurements it is important that the temperature and relative humidity where the test is being performed should be kept as constant as possible. It is also recommended that the airflow should be limited in the area where the measurements are made. Increased air circulation can cause uneven temperature distribution [24]. In a thermally unstable environment, small but significant differences in the interpretation of the thermogram may increase the percentage of false positive or false negative results, which may result in an incorrect diagnosis of the animal's health status.

The accuracy of thermal imaging is also influenced by light intensity (photo 2). The most reliable measurement results are obtained in poorly lit rooms. When the animal's body is exposed to solar radiation, some of the visible radiation may be absorbed and re-emitted in the form of heat or infrared radiation, creating difficulties in interpretation of the image [7].

Each animal should be acclimated to the ambient conditions before the examination. Acclimatization should last at least a few minutes, and if there is a substantial temperature difference between the room where the test is carried out and the place the animal has arrived from, the adaptation time should be extended [2, 3]. This has been confirmed in research by Schaefer et al. [35], evaluating the effectiveness of thermography as a prognostic method in enzootic bronchopneumonia of calves (BRDC – Bovine Respiratory Disease Complex). Church et al. [7] draw attention to the need to ensure stable atmospheric conditions during thermography, as even a slight fluctuation in temperature (<0.8°C) on the body surface of an animal can lead to an increase in incorrect diagnoses.

When recording thermographic images, it is recommended that the animal should be in a fixed position and at a fixed distance from the camera. Moreover, the distance between the camera and the animal should not be less than 1.0-1.2 m [10]. The area of the body being photographed should be perpendicular to the optical axis of the camera lens. Incorrect camera positioning may cause the phenomenon of parallax. Changing the angle of the camera lens or the area of the body being examined may result in an incorrect temperature reading (usually lowering its value), which in turn reduces the accuracy of the measurement. For this reason, it is recommended that thermal imaging temperature measurements in field conditions should be made in the most automated manner possible [2, 3, 10, 32]. An example of the use of such systems is measuring stations installed at

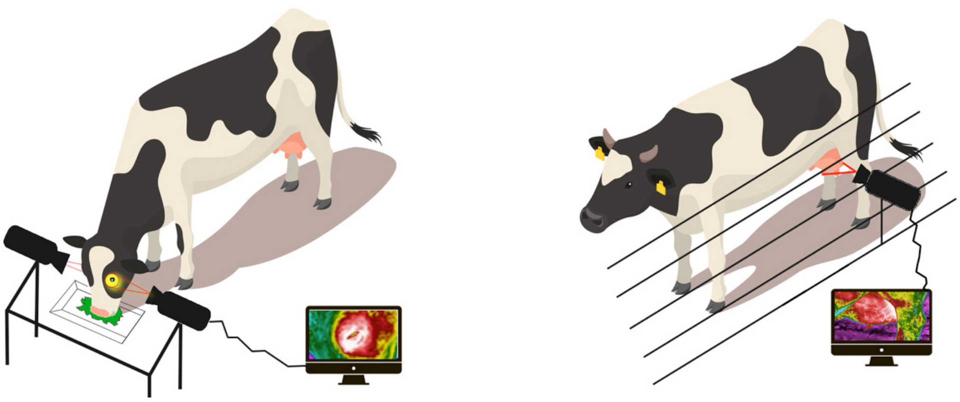


Fig. Examples of the use of automatic thermal imaging systems for assessing temperature differences in specific regions of a cow’s body

Measurements	
Sp1	36.0 °C
Sp2	29.4 °C
Sp3	22.8 °C
Sp4	10.4 °C

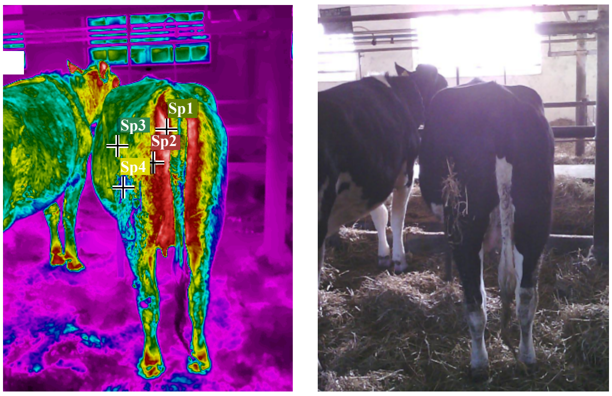
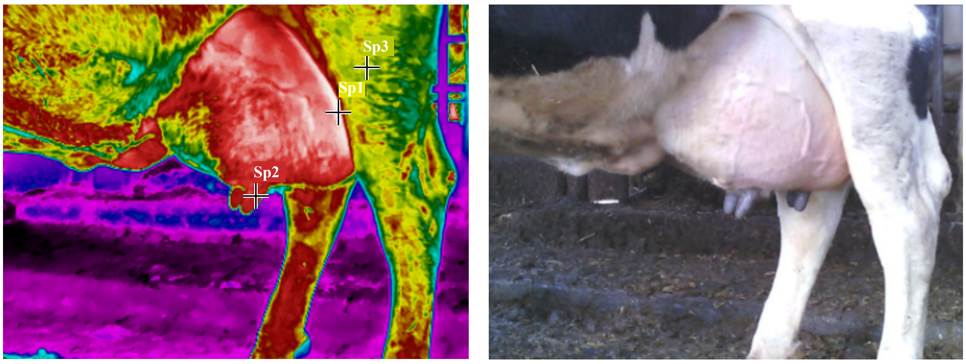


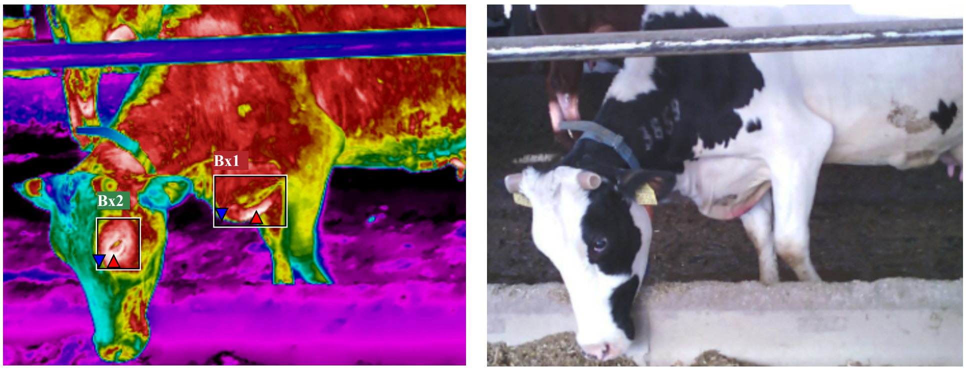
Fig. 3. Thermal profile of the rump, udder and hind limbs from the caudal side – animal on the right, and the right surface of a cow's body – animal on the left (our own work)

the site of cows' automatic feed or water supply in order to read the infrared radiation from the skin and canthi of the eyes. Another example is the installation of a system of cameras and measuring devices from the Swedish company Agricam in the passage



Measurements	
Sp1	36.8°C
Sp2	31.8 °C
Sp3	28.8 °C

Phot. 4. Photograph and thermogram of the lateral surface of the udder from the left side – front left and rear left quarters (our own work)



Measurements		
Bx1	Max	35.3 °C
	Min	6.6 °C
	Average	25.4 °C
Bx2	Max	35.5 °C
	Min	17.7 °C
	Average	29.1 °C

Phot. 5. Photograph and thermogram of the lateral surface of the skin of the head and torso of a cow from the left, with the area indicated where the temperature was higher in relation to the surrounding tissues (our own work)

Measurements		
Bx1	Max	35.7 °C
	Min	6.6 °C
	Average	23.4 °C
Sp1		26.8 °C

Phot. 6. Photograph and thermogram of the lateral surface of the skin around the hock and metatarsus seen from the right, with the area indicated where the temperature was highest in relation to the surrounding tissues (our own work)

leading to the milking parlour, in order to assess potential inflammatory changes in the udder [16].

According to a study by Stewart et al. [39], in IRT imaging the value of the temperature distribution from around the medial canthus is correlated with the internal temperature of the body. In the thermographic nomenclature, this area is described as a thermal window of the body. This is one of the places on the thermographic body map which are minimally subject to thermoregulation [29, 39].

The use of thermal imaging to measure the temperature of the eye itself and its vicinity is fast, relatively easy and less invasive than alternative methods of measuring body temperature, such as rectal thermometry, thermal microchips or intraruminal boli, used to register physiological parameters in ruminants [10].

The reliability of thermal imaging is determined by a number of factors, which depend on the technical parameters of the camera, environmental conditions, the operator's experience, individual characteristics of the animal, and the methodology of the examination. Because many factors can affect the surface temperature distribution of the body of animals, and thus the result of the thermographic measurement, the influence of any stimuli interfering with the measurements should be minimized during thermal imaging [3, 40]. At this stage, it is crucial to choose the proper equipment and correctly adjust the calibration parameters of the camera to the conditions of the site of the reading, i.e. the air temperature and relative humidity, the distance between the camera and the tested object, and the emissivity of the surface to be examined [14, 17].

Standardization plays a very important role in thermal imaging measurements. Uniform methodology makes it possible to compare results and interpret them correctly. There are currently several basic types of standards used in the field of human temperature measurement. Some of these have to do with the technical aspects of thermography, such as specification of the devices and measuring systems used. There are also several standards devoted to methods of testing and calibrating thermal imaging equipment, e.g. the use of specific statistical models (parabolic regression or ROC – receiver operating characteristic curve) and specific algorithms, in order to create a standard for correct assessment of fever in humans [26, 37]. Failure to comply with a specific diagnostic protocol often leads to errors in measurement and interpretation [3].

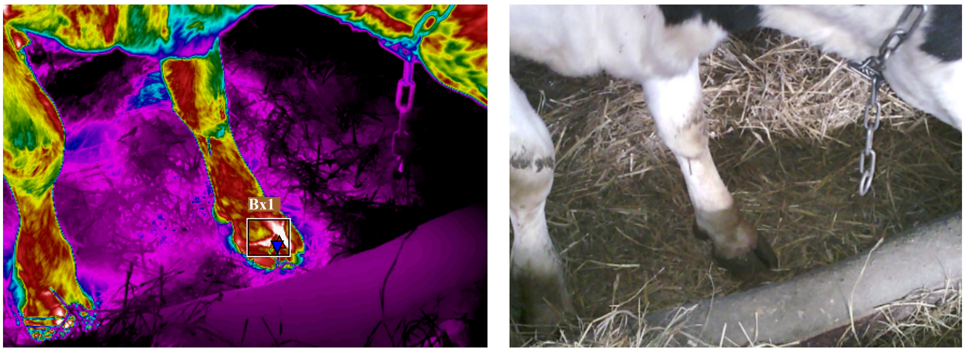
In veterinary medicine and related sciences, there is still a great need for scientific research to standardize information in tests using IRT cameras. The main limitation in implementing standards for thermography of animals is that it is not possible to compare thermograms carried out under different environmental conditions [38]. To minimize the risk of misinterpreting the image, protocols for normalization of imaging parameters, i.e. standards making it possible to obtain reliable test results, should be developed in the near future. The difficulty of standardization lies in the fact that numerous environmental and physiological factors influence the test results [37, 38]. Compliance with specific recommendations while performing tests may help to objectivize thermographic analysis and significantly reduce the number of incorrect diagnoses [38]. Standardization measures should be complemented with the organization of training and workshops on animal thermography, aimed at improving operators' competence in implementing precisely established imaging procedures, in a manner consistent with the assumptions of a given standard [28, 37].

Currently, the most common standard of digital medical information exchange in the field of imaging diagnostics is DICOM (Digital Imaging and Communications in Medicine). The DICOM standard was created to popularize digital data exchange and to facilitate the creation and expansion of diagnostic image archiving systems and the exchange of medical information with other IT systems used in human and veterinary medicine. The development of this undertaking with respect to veterinary diagnostic imaging techniques will make it possible to compare thermographic measurements carried out using different devices and by different operators, taking into account various factors that may interfere with the measurement results [36, 37].

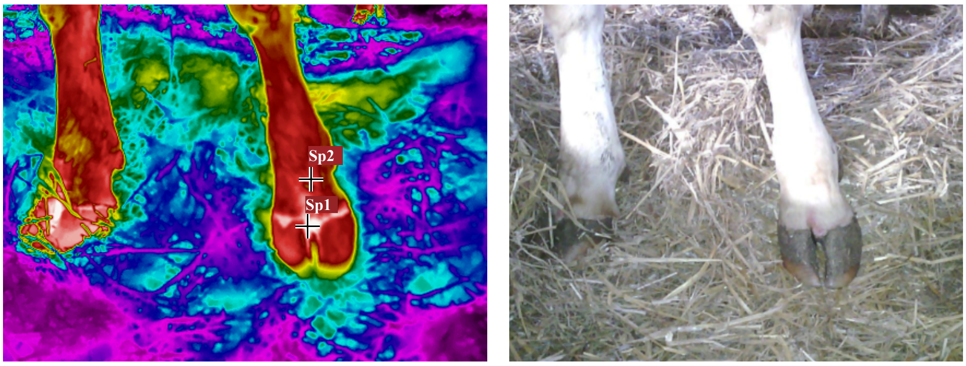
We have conducted research to assess the suitability of a thermal imaging camera in the diagnosis of inflammatory changes in the skin of dairy cows. The study was conducted using a FLIR T540 thermal imaging camera with an uncooled microbolometer in VOx (vanadium oxide) technology, with an effective resolution of 464 x 348 px (161,472 pixels). The microbolometer allows us to record the image in the LWIR window with a frequency of 30 frames/s. The temperature range of the camera is from –20°C to 120°C (–4°F to 248°F). The temperature sensitivity of the camera is <30 mK at 30°C, which means that the camera can be used to visualize temperature differences of 0.03°C. In addition, the camera is equipped with a visible light sensor with a resolution of 5 MPx. This means that images in the infrared band and the visible band can be recorded simultaneously. This is especially useful in subsequent processing of the images.

Photo 3 shows the thermal profile of the right body surface of a cow (animal on the left) and the rump, udder and hind legs from the caudal side (animal on the right). The image indicates differences in the surface temperature of different individual areas of the body. The ambient temperature during detection was 5°C and the relative humidity was 80%. The camera was calibrated to the ambient temperature and humidity during scanning. An emissivity value of 0.95 was set in the camera before scanning. The highest temperature, 36.0°C (Sp1 – white), was observed around the anus and vulva and the rear wall of the udder. These anatomical structures are called thermal windows, i.e. areas of the skin surface that are well perfused by the blood and where the temperature on the surface of the skin is highly correlated with the internal temperature of the body. A lower temperature, 29.4°C (Sp2 – red), was noted on the posterior medial surface of the thighs (*regio femoralis caudalis et medialis*) and distal segments of the hind limbs, in the vicinity of the *regio digitorum pedis*.

As a result of the cool stream of air from the left side, in the right lateral thigh area (*regio femoralis lateralis sinistra*) a skin surface temperature of 10.4°C (Sp4 – blue) was obtained in the thermogram. The IR temperature in the area of the left haunch (*regio glutea sinistra*) was 22.8°C (Sp3 – green) and as in the case of the skin of the left thigh, the ambient temperature had a greater influence on the result.



Measurements		
Bx1	Max	36.7 °C
	Min	8.0 °C
	Average	27.6 °C



Measurements	
Sp1	36.9 °C
Sp2	29.2 °C

Phot. 7. Thermal profile of the front limbs of a cow with a clearly visible hyperthermal area on the skin near the toes (our own work)

The ambient temperature at which the IRT is carried out has a significant effect on the temperature read from the body surface [9]. According to Martello et al. [22], the skin temperature of animals often shows values lower than the internal body temperature. The difference can range from 2°C to 7°C (on average 5°C). These changes also depend on the species, sex, site on the skin surface where the test is performed, and environmental conditions [4, 22].

Photo 4 shows a photo and a thermogram of the lateral surface of a healthy udder from the left (front left quadrant – FLQ and rear left quadrant – RLQ). The photo was taken from a distance of 1 m. The highest temperature, 36.8°C (Sp1 – white), was recorded in the rear left quadrant. The temperature at the base of the teat was lower, 31.8°C (Sp2 – red).

Udder inflammation has been the main cause of economic losses in dairy farms for many years. Although various methods have been developed to combat this disease, early diagnostics remains the most important issue. Thermography is increasingly used to diagnose sub-clinical inflammation of the mammary gland. Modern cameras are sufficiently sensitive to detect abnormal heat patterns even within a small area located on one of the udder quarters [33]. Owing to thermographic monitoring and appropriate calculations (predictive modelling), mastitis can be effectively detected at an early stage of the disease [4, 27, 33].

Infrared thermography (IRT) also makes it possible to diagnose skin injuries, such as abrasions, inflammation, abscesses, etc., by presenting differences in the gradient of colours on the surface of the area tested. In photograph 5, there are two clearly visible white areas on the skin, where the highest temperatures were recorded: near the eye (Bx2) and in the presternal region – *regio presternalis* (Bx1). In the clinical examination of the skin in the presternal region, symptoms characteristic of inflammation were noted – redness, slight swelling and pain, which confirmed the initial diagnosis based on thermal imaging.

Photo 6 shows the thermal profile of the lateral surface of the skin around the tarsal joint and metatarsus seen from the right, with the area marked where the temperature was highest in relation to the surrounding tissues. In areas of skin with the highest emission of infrared radiation, clinical examination confirmed local inflammation of the skin due to trauma.

Thermographic imaging is a practical tool for detecting temperature symmetry and asymmetry on the examined skin surface. Estimation of subtle temperature changes in a given area in thermographic imaging can be an important indicator in early diagnosis of lameness in cattle [1]. The accuracy of thermographic examination in the detection of hoof disorders is in the range of 0.81-0.86% for sensitivity and 0.56-0.83% for specificity [1, 21].

Evaluation of the thermal imaging of the cow's forelegs revealed marked differences in the temperature distribution in different areas of the skin (photo 7). The highest temperature, 36.7°C, was noted in the toe area (*regiones digitorum manus*), in the interdigital space (Bx1 – white). A significantly lower temperature, 27.6°C (Bx1 – red), was observed on the surface of the skin around the claw horn and metacarpus (*regio metacarpi*), as well as the medial side of the skin of the antebrachium (*regio antebrachii*). The clinical examination found lameness as well as swelling and redness of the skin. In this case, the data obtained from the camera together with the veterinary examination are sufficient for a full diagnosis – interdigital dermatitis.

IRT can therefore be a useful additional tool for early diagnosis of lameness at an early stage of the inflammatory process in the hooves. Systematic detection of this type of disease, especially during early lactation, will be of great importance for maintaining milk production in the herd.

Disorders of the limbs, especially the hooves, are a frequent cause of culling of cows. They are a health problem associated not only with pain, but also with reduced milk production and reproductive results and with metabolic disorders, which in turn lead to significant economic losses [25]. One of the reasons for this is that pathological changes are diagnosed too late. Field diagnostics of limb diseases, in addition to specialized clinical tests, currently includes the use of radiography, ultrasonography, arthroscopy and joint aspiration (arthrocentesis) [25]. One of the modern methods enabling rapid detection of diseases of the motor system is thermography [13].

In summary, recent years have seen a significant increase in interest in the use of thermal imaging in veterinary diagnostics. Owing to the possibility of fast, non-invasive and automated temperature measurement on the surface of an animal's body, this technique shows great potential in predicting local inflammation (diseases of the hooves, udder and skin). This technique is also helpful in assessing animal welfare. However, there is still a need for further research in order to standardize measurement data in thermal imaging. Protocols for normalization of imaging parameters must be developed – standards making it possible to obtain reliable test results in a variety of environmental conditions.

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