Acta Veterinaria-Beograd 2023, 73 (3), 289-316
UDK: 636.1.09:616-073.65
DOI: 10.2478/acve-2023-0023

Review article

THERMOGRAPHIC EXAMINATION OF THE HORSE

Peter KRULJC*

University of Ljubljana, Veterinary Faculty, Gerbičeva 60, Ljubljana, Slovenia

(Received 12 June, Accepted 01 Septemeber 2023)

Thermography is a noninvasive diagnostic imaging technique that detects regions of the body surface with increased (or decreased) temperature by measuring infrared radiation. It reveals physiological and pathophysiological changes primarily related to blood flow and metabolic rate in the examined body regions, as well as altered heat production. These include physical stress, various physical injuries, medical conditions, and environmental factors. In equine medicine, thermography can be used for early detection of tissue temperature changes, allowing intervention at an early stage of a medical deterioration. Thermographic examination can be used to detect tissue abnormalities in all regions of the body. It is particularly useful for the detection of musculoskeletal disorders. Inflammatory processes are present in many diseases and injuries, which can be successfully detected with thermography. Thermography makes it possible to monitor the success of treatment. Often, thermographically visible disease changes are detected before clinical signs or other imaging techniques become visible in the animal. In physical therapy, it helps locate regions of the body in need of treatment and plays an important role in detecting illegal procedures (such as local analgesics) to improve competitive performance in horses.

Thermography serves as a complementary diagnostic tool. However, in practice, it has some limitations. The method is not specific and cannot determine the etiology of pathological changes. Therefore, it is usually used together with other diagnostic methods (such as X-ray, ultrasound, computed tomography and magnetic resonance imaging) and can not replace them.

Keywords: disease, Lipizzan horses, thermography, skin temperature, sport horses

INTRODUCTION

The electromagnetic spectrum consists of the shortest (gamma) rays, X-rays, visible and infrared light to the longest radio waves. The wavelength of infrared radiation is invisible to humans and is perceived as heat. Infrared radiation is emitted by all objects as electromagnetic waves of different wavelengths (0.7 to 1000 μm). Energy emitted in the infrared wavelength range can be detected by thermographic cameras that reveal temperature differences between the animal's body surface and its environment, the latter producing images based on the amount of heat generated and

*Corresponding author: e-mail: peter.kruljc@vf.uni-lj.si

not reflected. In correlation with the body surface temperature (BST), a color image is then displayed with the corresponding temperature values. This method measures BST without physical contact with the animal under study [1-4]. The most important factor affecting the peak emitted wavelength is the ambient temperature. The higher it is, the higher the BST, resulting in a shorter wavelength of radiation. At lower ambient temperatures, low BST is reflected in the emission of long wavelength radiation, while short wavelength radiation is characteristic of high BST. Because of the range of ambient temperature that can usually be detected, long-wavelength thermal imagers are suitable for use with animals [4,5].

The most important characteristic of warm-blooded animals is their nearly constant body temperature. To avoid overheating during work, the excess heat generated mainly in the active muscles during their work must be removed from the body. The main mechanisms for heat transfer from the organism to the environment are conduction, convection and radiation. A significant part of the excess heat in horses is removed by evaporation of sweat [1,4,6]. Conversely, in a cold environment, thermogenesis is activated and maintains a stable body temperature.

The body surface of an animal loses heat by emitting infrared radiation and absorbs heat by absorbing infrared radiation emitted or reflected from external sources such as direct or indirect solar radiation, other animals, or objects that emit heat. This phenomenon affects the recorded BST and may be the main reason for erroneous BST measurements. Therefore, the ability of the body to simultaneously absorb and reflect infrared radiation must be taken into account when thermographically examining animals [1,4,7].

Heat exchange between the body surface and the environment through infrared radiation is essential for the animal's heat balance [8], which occurs between the temperature of the animal's surface and its environment. The amount of energy emitted from the body surface in the form of infrared radiation is influenced by physiological processes in the animal's body and by environmental factors that affect blood circulation under the skin. Measurement of infrared radiation is therefore important for monitoring physiological changes in animals manifested by changes in heat production, such as workload, injury, disease, and environmental factors [4,5,9-12].

THERMOGRAPHY AS A DIAGNOSTIC METHOD

The body constantly produces heat, which is emitted from the skin to the environment by radiation, convection, conduction, and evaporation [13]. Skin temperature is on average 5 °C lower than core body temperature (37 °C) and is the result of regional blood flow and tissue metabolism [14]. It is usually constant, but its changes are caused by changes in local tissue perfusion. Veins are usually warmer than arteries because they drain blood from metabolically active regions. Those that lie directly under the skin also warm it more. Blood drawn from tissues or organs with high metabolic rates is also warmer than that from other normal tissues.

Thermography is a non-invasive, non-contact imaging technique that detects and displays surface temperature emanating from the body surface in the form of infrared radiation. A rise in temperature is a common result of changes in various factors, particularly blood flow, and the resulting altered heat patterns indicate sites of inflammation [6].

Thermography relies on the fact that BST is elevated, one of the most important signs of inflammation. Therefore, an increase in BST may indicate inflammation of structures near the thermal recording site. As mentioned earlier, temperature in individual body parts is a product of cellular metabolism and local blood flow. An increase in this temperature is usually the result of an increase in these factors, blood flow being the most important. In some disease processes, blood flow to affected tissues is decreased, which is also reflected in a decrease in BST [15].

A medical thermogram is an image of the surface temperature of the skin. The noninvasive evaluation and measurement of inflammatory changes makes thermography an ideal imaging tool and aid in the diagnosis of various equine diseases [11]. At the same time, it provides an element of physiological imaging that allows the graphical representation of inflammation, monitoring of its progression and/or resolution, and early detection of inflammatory responses [15]. Blood circulation and relative blood flow determine the thermal pattern that forms the basis for thermogram interpretation. The normal thermal pattern of any region can be predicted based on its vascularity and superficial body contours. This is also true for the skin, which covers the muscles and also heats up during muscle activity [13].

THERMOGRAPHIC CAMERA AND THERMOGRAM

A thermographic camera detects and measures infrared radiation. Its use in veterinary diagnostics has expanded, especially in equids. Cameras with sufficiently high spatial and thermal sensitivity, which is less than 0.05 °C, can simultaneously capture infrared images and classical photographs of the same object. Since this type of imaging allows only basic evaluation of thermographic images (thermograms), the interpretation requires special software that allows accurate analysis of the images [2,3,7,11,16] (Fig. 1).

A thermogram is created by converting infrared signals into the color palette of visible light. Different shades of the color palette correspond to specific temperatures. This creates a map of the temperature distribution in the regions under study. Usually, thermograms show the warmest regions in white or red, regions with an intermediate temperature in yellow and green and the coldest regions in blue and black [7]. After visual inspection, thermograms can be processed with software that extracts useful temperature data from the image, such as point, average, maximum, and minimum temperature values within the different regions examined [17]. At the same time, it is very sensitive to external temperature changes indicating inflammation, vascular or neurological disorders, and physiological changes in environmental conditions [6,18].

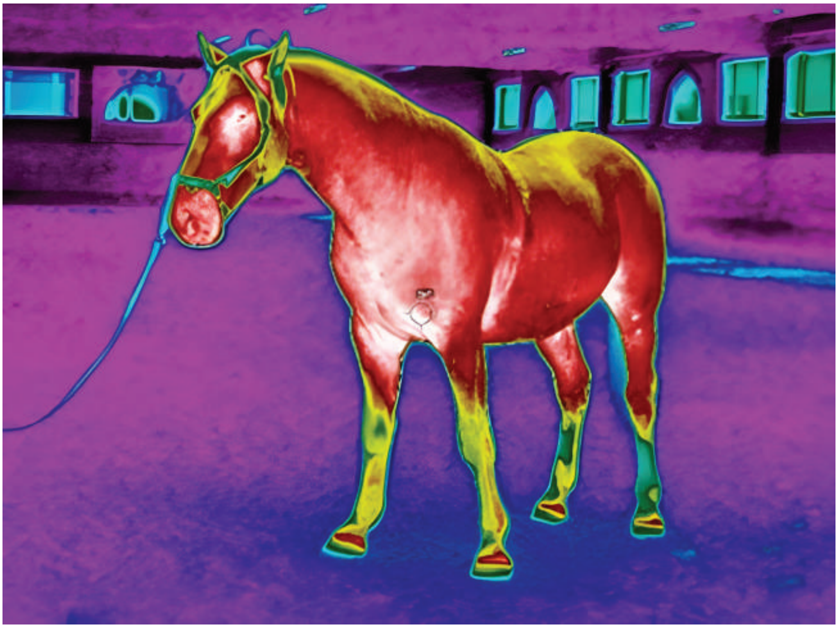

Figure 1. Thermogram of a Lipizzan horse with different thermal patterns in the different body regions (warmest regions in white (31.9°C-33.7°C) or red (26.2°C-30.7°C) with an intermediate temperature in yellow (21°C-21.6°C) and green (14.9°C-20.3°C), and the coldest regions in blue (12.1°C-12.3°C) and black color.

THERMOGRAPHIC EXAMINATION OF THE HORSE

For a thermographic examination and the production of a thermogram, the horse must be completely calm, the temperature of the environment must be suitable, the influence of external energy radiation and the influence of various artifacts must be avoided [19]. It is always necessary to systematically take multiple images [20] from at least two directions, approximately 90 ° apart, so that hot spots are also captured. All limbs are imaged from all four sides in the same manner [13]. The thermographic examination takes place at rest or before exercise. This avoids changes in body temperature and increases blood flow to the muscles. In special cases, if the purpose of the examination requires it, the examination can be performed after training. Thermographic examination takes place in a room, at a constant temperature and with an appropriately prepared horse. Because room temperature has a significant effect on the distribution of body temperature, large temperature differences can cause asymmetry [9,10,21]. The most suitable room temperature is in the range of 20 °C. It can be higher, but it must not induce sweating in the horse, which does not occur below 30 °C, because below this value radiation and convection are responsible for heat loss. Too cold environment may cause vasoconstriction of distal parts of legs (Fig. 2) and appearance of color changes on thermograms.

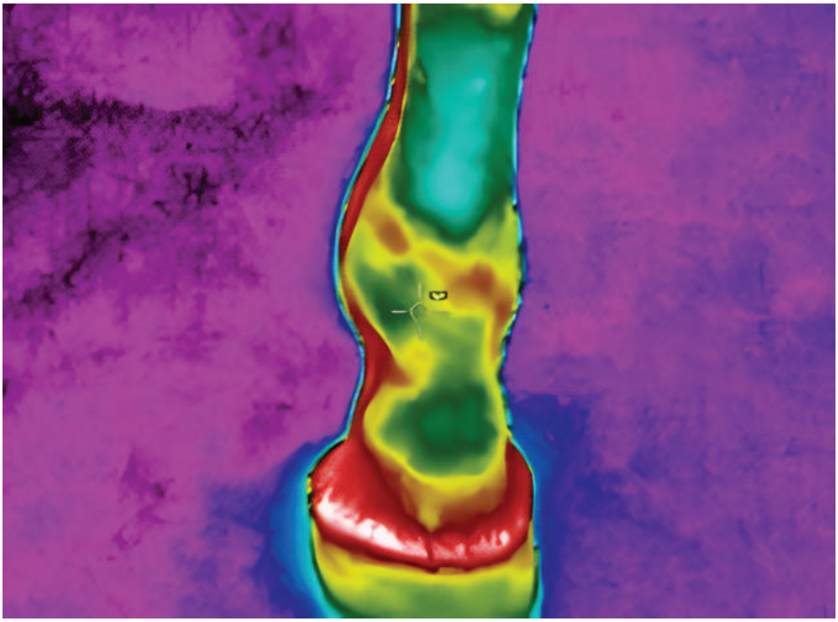

Figure 2. Thermogram of the distal limb of a Lipizzaner horse with regional vasoconstriction (green color)

In such cases, it is necessary to perform a short exercise with the horse (e.g., lunging) that establishes appropriate vasodilation. A steady flow of air should surround the recording region to avoid errors in the thermograms due to subsequent cooling. Also, the horse should not be in traction [6,13].

A higher room temperature (up to 25 °C) may cause disturbances in the differentiation of BST and mask local inflammation on the body. A room temperature of 18 °C to 20 °C may lead to increased and uneven distribution of blood flow in the distal parts of the limbs due to vasodilatation. If the room temperature is too low (below 15 °C), vasoconstriction may occur [22] causing a general decrease in blood flow and a decrease in BST at a temperature below 12 °C, which is particularly noticeable in the distal parts of the limbs [10,23]. BST in the distal parts of the limbs is unstable at low ambient temperatures, probably due to periodic vasodilation [22]. Asymmetry of distal limb BST may be normal and not necessarily pathological at low ambient temperatures. Some studies show that this difference, without the horse showing signs of inflammation or lameness, can exceed 5.5°C. However, subclinical inflammation cannot be ruled out. In practice, thermographic examination is nowadays also performed at a stable temperature between 12 °C and 25 °C, despite the ideal room temperature of 20 °C [7].

Before thermographic examination, the horse must be accustomed to the room in which the imaging will take place. 10 to 15 minutes is also sufficient if the horse moves from a warmer to a cooler room, or longer (more than 2 hours) if it comes from an extremely cold or hot place [6]. Thermal patterns do not change during acclimation, but the horse requires 39 to 60 minutes to stabilize absolute BST [21]. The most important factor affecting this time is the difference in temperature between the environment in which the horse lived before imaging and the environment in which imaging will take place. A period of 1 hour is usually sufficient to stabilize this temperature, with long-haired horses taking longer than clipped or short-haired horses [10].

It is very important that the horse should rest during the thermographic examination. It is ensured by restraining the animal in a box or with the help of a trained handler [11]. Because the examination is performed in real time, the animal usually does not require sedation. Sedatives, even in combination with analgesics [24] (Fig. 3), can affect the peripheral circulation and cardiovascular system and cause altered thermal patterns on the thermogram [11].

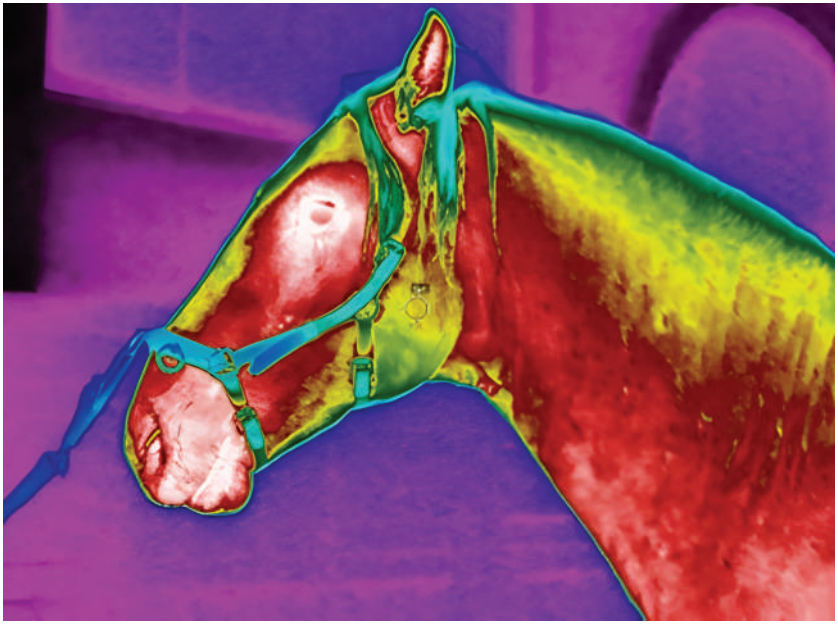

Figure 3. Thermogram of a calm Lipizzan horse showing thermal patterns of the head and neck region during a thermographic examination (warmest regions in white or red, regions with an intermediate temperature in yellow and green, and the coldest regions in blue and black)

To avoid false thermographic patterns on the thermograms, it is necessary to remove the applied bandages or riding gear from the horse's body at least 2 hours before the examination. Excessively long hair also blocks infrared radiation, so it must be short and even, as this may result in false hot spots on the thermogram. There must be no artifacts on the skin, such as various debris, scars, excessively long hair, applied ointments, bandages, blankets, and other equipment [13] and solar heat sources, lights, and heaters installed in the environment [23]. Drafts must be avoided, which can lower BTS, especially on the legs [25]. Infrared radiation can interfere with even a small amount of dust particles in the air, which reduce the quantity and quality of electromagnetic wave energy detected by the thermographic camera.

To reduce external radiation, thermographic imaging should be performed in a room protected from the sun [13], in the dark or in low light, in a well-ventilated room or in a shaded corridor with a clean and level floor. Due to external factors, the thermographic survey is not performed outside the room, as this may cause errors on the thermograms [26]. Thus, external and internal factors have a marked influence on BST [22]. Proper use of thermography and identification of heat patterns on the body surface require a controlled environment and consideration of the physiological state of the horse, which reduces diversity and eliminates errors in the interpretation of thermograms [15].

A thick winter coat can also lead to false thermal patterns on thermograms [27]. In clipped horses, the temperature distribution does not change, but the temperature of the entire body surface increases. The coat must have a suitable length and fit that allows normal heat conduction [28]. The horse's body surface must also be dry, as wet or damp hair lowers temperature. Limbs, hooves, and body must be cleaned. Horses should not receive systemic or topical medications prior to thermographic examination. Residual ointments must be removed from the skin at least one day before [6]. This also applies to head coverings and clothing (shields or bandages) that cause prolonged elevated temperatures in the distal parts of the limbs due to contact with these parts. Thick blankets and other coverings must be removed for at least 30 minutes before painting [23]. Because of the effect on BST, all elastic tissues under the blanket that are adhered to the body must also be removed the day before. Mane and horse hair must be braided and protected. BST is also affected by hair changes after injury, lacerations, scars, and other treatment sequelae, as well as skin tags caused by freezing and indirectly damaged regional cutaneous nerves.

The examined animal must not receive any physical therapy 24 hours before the thermographic examination. Therapy with warm (40 °C) or cold (4 °C) compresses on the distal parts of the limbs has a significant effect on BST. Cold therapy can produce a temperature difference of 2.5 °C between the treated and untreated limbs 2 hours after application [1]. Warm compresses are effective for 30 min. after removal and increase the temperature difference by 2.8 °C. This can be increased by 3.7 °C after 75 min. Even a 10-min application of therapeutic ultrasound to the flexor tendon increases the temperature of the treated leg for more than 1 hour. The same applies to acupuncture treatment. A thermographic examination must also be performed before a planned systemic treatment, as the administered drugs may affect the blood flow and alter the BST. Local shearing of a body part in preparation for an ultrasound examination can also affect the thermogram. The same applies to nerve blocks, neurectomy, skin injuries, scars, administered irritant drugs, or surgically treated regions [7,16].

DISTRIBUTION OF BODY SURFACE TEMPERATURE

A normal thermographic pattern can be mapped to correspond to equine veining [6] with a high degree of symmetry between the left and right sides of the body [10]. The usually high degree of symmetry between adjacent body parts in a healthy horse contributes significantly to the diagnosis of a pathologic condition attributable to various inflammatory diseases on either side. Such thermal asymmetry may indicate such disorders. They are indicated by temperature variations between comparable body parts greater than 1 °C [29,30].

BST directly reflects blood flow and metabolism in the tissues. Thermographic BST patterns correspond to both surface veining and contours of the equine body [1,6]. Understanding the normal changes in thermal patterns is key to interpreting a thermogram. Changes in BST are also influenced by various internal factors, such as anatomical structures, density and volume of subcutaneous and muscle tissue, and characteristics of the hair coat. At the same time, the effects of the environment (season), the type of training, and the degree of adaptation of the animal to the workload must also be considered [1,6,7,31]. The shape of the horse's body surface is irregular. Some parts are convex, others are almost flat or concave. As a result, infrared radiation energy is emitted unevenly over the body surface [32]. Concave parts of the body (e.g., around the neck) and protected parts (elbow joint) are subject to little environmental influence and therefore have higher BST values under normal conditions. Lower BST values are found on more convex regions (e.g., croup) that are exposed to more direct environmental influences. Body regions with higher metabolic activity (shoulders and croup) have higher surface temperatures. Local blood flow also plays an important role and influences BST changes [3,7,12,31,33,34]. The BST of the regions perfused by veins is usually higher than that of the arteries, which is due to the superficial location of the vessels (e.g., jugular veins). The skin covering or adjacent to major veins (e.g., cephalic vein and great saphenous vein) is usually warmer than the skin covering the regions of the less vascularized distal parts of the limbs (e.g., metacarpus/metatarsus) and is therefore cooler. The warmest region of the distal parts of the legs is the coronary and laminar corium, which lies proximally over the hoof wall and adjacent to the arterio-venous plexus [1,6] (Fig. 4).

The warmest regions on the forelimbs are located along the major blood vessels, i.e., palmar and digital arteries and palmar veins from the lateral and medial sides [9]. Similarly, the warmest sites on the hindlimbs are located along the plantar and digital arteries and plantar veins from the lateral and medial sides [35].

The subcutaneous tissue, which often contains a larger amount of adipose tissue, absorbs heat from the underlying vessels and internal organs. Therefore, the distribution and amount of subcutaneous tissue can also affect the distribution of BST.

Skeletal muscle also has a significant influence on BST. Body parts with extensive skeletal musculature and abundant blood supply (in the neck, upper forelimb, and hindlimb regions) have higher BST than regions with less muscle (in the forearm and gaskin regions) or regions without muscle (distal forelimb, anterior carpal joint to hoof) [7]. Changes in BST may also be the result of activity of active subcutaneous muscles and associated changes in the blood flow [36].

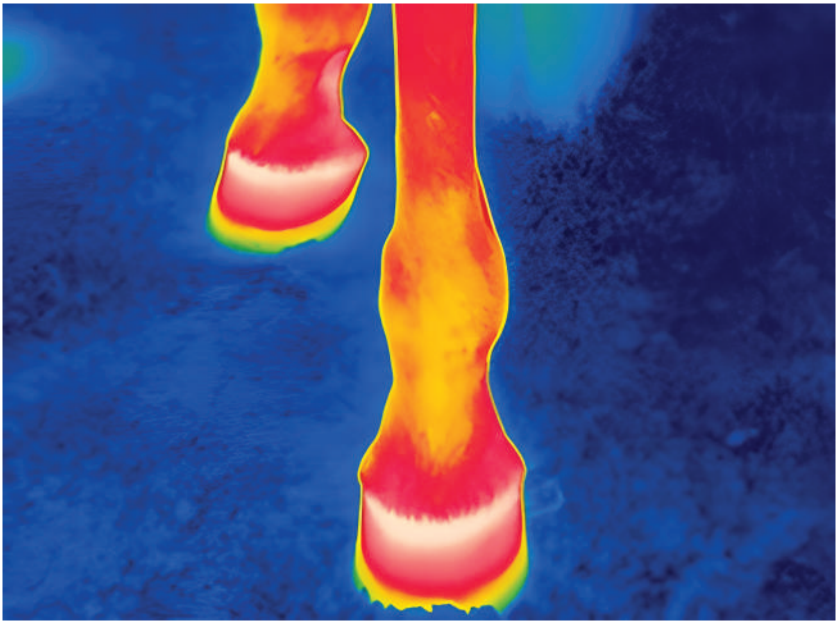

Figure 4. Thermogram of the left forelimb with normal thermal pattern of the Lipizzan horse (the warmest coronary band)

Hair is an important factor affecting BST. In a low temperature environment (winter season) it becomes longer and denser. Dense hair strongly absorbs infrared radiation radiated from the skin surface [37]. An effective insulation against excessive heat loss is the air trapped in the fur, which is a poor conductor of heat with low heat capacity. Therefore, coat density, length, and fit significantly affect the distribution of BST [32,38]. Regions of the body with thinner, less dense, or shorter hair (around the head and flanks) have higher BST than regions with thicker, denser, or longer hair, such as around the croup and pasterns. BST is affected by horse clipping during the fall and winter months, with higher temperatures on the clipped parts of the body than on unclipped parts, which affects thermomorale. Because of efficient heat exchange through radiation, conduction, and convection, sweating is prevented, reducing the risk of hypothermia in a cold environment [28]. Clipped horses also dissipate heat more easily during work because sweat evaporates quickly from the bare skin, thus preventing overheating. This may also explain the unchanged rectal temperature and lower respiratory rate [39]. Depending on the length of the coat, the distribution of BST also differs between summer and winter. In summer, hot spots are clearly visible on the thermogram over the region of thickened superficial blood vessels, which increase blood flow and heat exchange between the body and the environment, contributing to cooling. Another adaptation to a cold environment is vasoconstriction, which reduces blood flow in superficial blood vessels. This leads to a smaller difference between the BST and the ambient temperature, which also leads to a corresponding reduction in heat loss [1,3,7,12,31].

CHANGE OF BODY SURFACE TEMPERATURE DURING WORK

In the resting phase of the horse, the distribution pattern of BST depends on the individual animal, although it is influenced by many environmental factors. BST measured by thermography is usually bilaterally symmetrical [12,31,33,34]. For an individual horse, the temperature during the resting period can vary between 19 °C and 32 °C. The highest BST (27 °C to 32 °C) was found on the head, neck, shoulder, upper arm, forearm, and flank and the lowest (24 °C to 26 °C) on the distal parts of the limbs. Similar values were also reported by other authors [34,40]. They measured the highest temperature range (25 °C to 28 °C) on the head, middle part of the neck, chest, and flanks (middle part of the neck, chest, and flanks) and the lowest temperatures (19 °C to 23 °C) on the distal parts of the limbs. Similar values and distributions of BST were also found in studies of Lipizzan horses [5,31,41,42] where they ranged from 26.5 °C to 30.4 °C in May and from 22.7 °C to 28.7 °C in October. The residual BST during rest was significantly lower in October than in May, and the differences between the temperatures of different regions were significant in both months, indicating a different blood supply in different regions of the skin and different contributions of these regions to the thermoregulatory function of the horse. In addition, higher ambient temperatures were measured in May than in October, indicating the influence of ambient temperatures on the BST of Lipizzaner horses, reducing the efficiency of convection [31]. These differences in temperature ranges between studies highlight the impact and importance of varying ambient temperatures [7].

The basal metabolic activity of the horse generates a stable amount of heat at rest. During muscular activity, the heat emitted increases proportionally to the work activity. During work, almost 75% of the energy consumed by the locomotor system is dissipated as heat. To maintain body temperature within the physiological range of 37 °C to 40 °C, the horse employs thermoregulatory mechanisms, including convection and evaporation [3]. After competition, the maximum temperature of body regions of show jumpers was measured between 25.2 °C and 34.2 °C, with the greatest increase in the chest, elbow, forearm, and gaskin, indicating a significant role of these regions in body heat dissipation during extreme workload [34]. Similar responses of BST to workload have also been observed in Thoroughbred horses at trot [33] and in Lipizzan horses after performing lunging work [12,31,42,43] (Figs. 5-7).

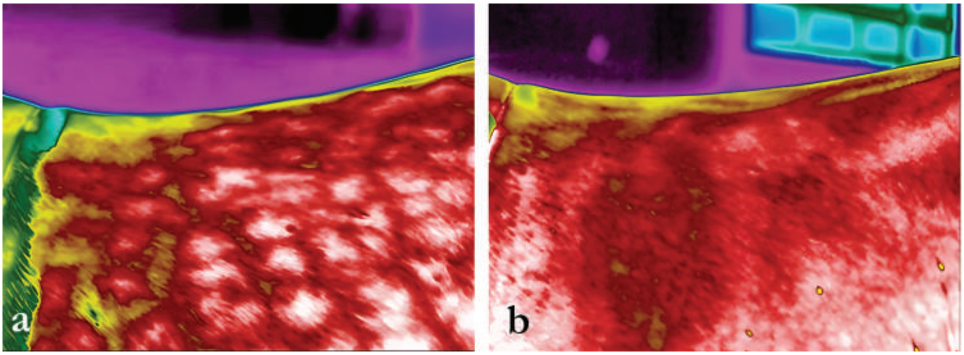

Figure 5. Body skin temperatures of the back body region (left side) of Lipizzan horse (with hot spots in white color) before **(A)** and immediately after the exercise test **(B)**

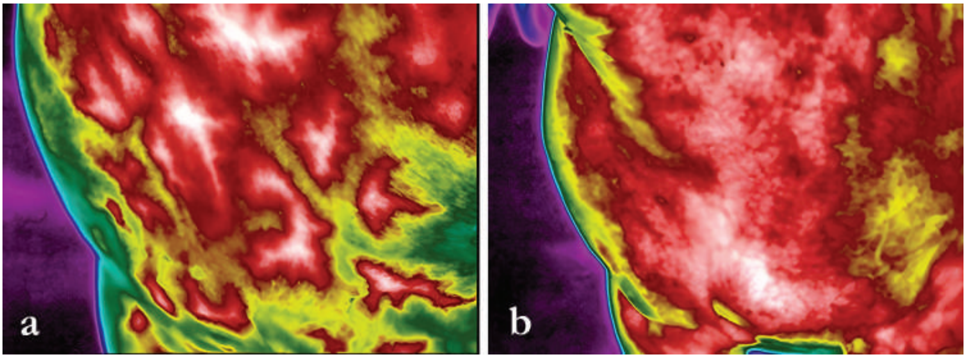

Figure 6. Body skin temperatures of the chest body region of Lipizzan horse (with hoot spots in white color) before **(A)** and immediately after exercise test **(B)**

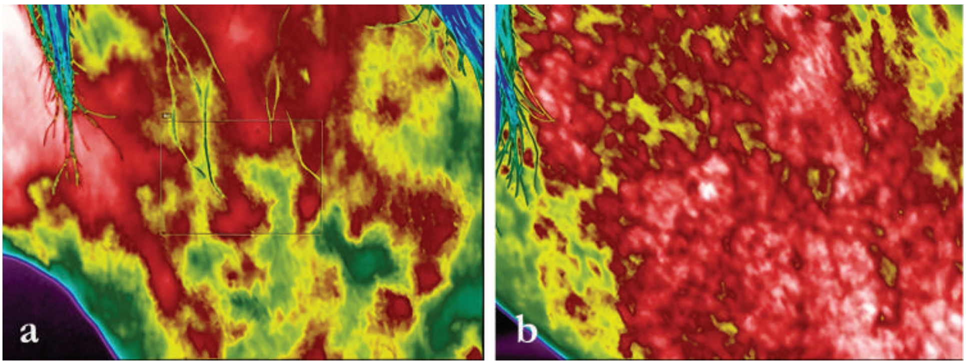

Figure 7. Body skin temperatures of the neck body region (left side) of Lipizzan horse before **(A)** and immediately after the exercise test **(B)**

THERMOGRAPHY AS AN INSTRUMENT OF CLINICAL EXAMINATION

Today, thermography is an important diagnostic tool in equine medicine, as a tool for better physical examination of animals, for regular routine examinations, and it also concerns important regions of health of sport horses [11]. Thermography with an infrared camera records the distribution of BST on the horse [17]. Thus, thermographic examination contributes significantly to an accurate clinical examination and identifies temperature differences in regions suspicious for temperature, with further diagnosis supplemented by other diagnostic metods (radiography, ultrasound, etc.) [1,7].

In clinical examination, thermography is 10 times more sensitive in determining temperature differences than the human hand in palpating the examined site [11,44]. In this way, temperature asymmetries can be detected, which the veterinarian uses to diagnose the actual cause and significance of the temperature differences. A thermographic camera can detect a temperature difference of less than 1 °C between two anatomically symmetrical regions. In addition to the inflamed region, it can also detect regions of decreased temperature, which also has important diagnostic significance. Routine weekly thermographic examinations of the horse during exercise can reveal thermographic changes in the body and are perceptible 2 weeks before the appearance of visible clinical changes. In this way, thermography identifies subclinical disorders, allowing adjustment of training and preventing the occurrence and development of major injuries [11]. Another important professional application of thermography is the assessment of well-being and acute stress in sport horses [45,46] and the evaluation of performance during work, training and competition in particular environmental conditions [4,11,33,47,48].

DIAGNOSIS OF INJURIES AND DISEASES

In recent decades, thermography, which is undergoing significant technical development, is most commonly used in equine medicine in the diagnosis, prognosis, and evaluation of various limb injuries, including hoof abscesses, laminitis, tendonitis, inflammation of the fetlock joints, and inflammation of the carpal and tarsal joints. It makes an important contribution to the diagnosis of abnormalities and early signs of musculoskeletal diseases [11,49,50,51]. In monitoring the efficacy of certain drugs, recovery from neurological diseases, diagnosis of back and limb diseases [7,16]. In addition to diagnosing diseases, it makes an important contribution to evaluating the effects of various topical treatments (e.g., cold, biomagnets, and ultrasound) on skin temperature [11].

In competition horses, thermography can also be used to detect unauthorized interventions in equine competitions, particularly the administration of certain drugs, topical and subcutaneous irritants [52], irritants under bandages, and injured regions infiltrated with potent analgesics [1]. The latter are thought to cause a change in the thermal pattern and an increase in BST, which the thermographic camera could detect two days after administration [53], but this ability is disputed by some authors in their study [54]. Digital palmar nervectomy can also result in different thermal patterns, with damaged nerves causing a decrease in BST [55]. Although the method helps to detect illicit doping procedures in competition, it has its limitations due to the lack of specificity, as the increased temperature in a body part may be the result of exercise performed immediately before the examination, and undetected subclinical injuries may lead to an inflammatory pattern similar to that caused by an illicit substance. Therefore, thermography can serve as a screening method to detect abnormal thermal patterns resulting from such actions. Despite its good features and advantages, thermography is not a sufficiently specific method and cannot distinguish between an inflammatory response as a result of the illicit procedure itself or as a result of other injuries [56]. Noninvasive methods of monitoring internal temperature using thermography have also been developed to meet the needs of sport horses based on measuring the surface temperature of the horse's eye rims (Fig.8) [45, 57]. In the study, it was found that thermography is a suitable practical tool in equine competitions for preliminary measurement of eye temperature, because it is the only way to select those animals with eye temperature above the threshold values, which are then referred for further veterinary examination [57].

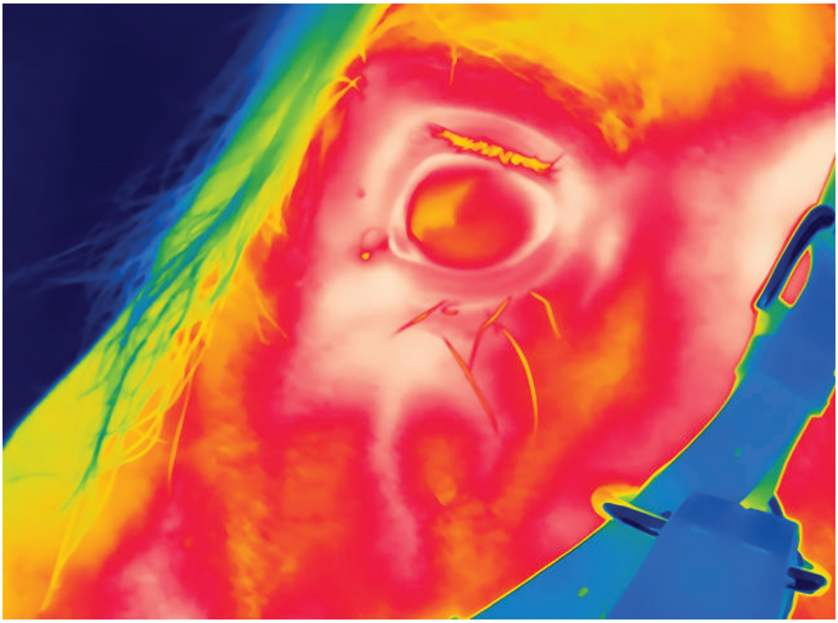

Figure 8. Thermogram of the eye rim region of the Lipizzan horse

In another study, the authors noted that eye temperature and heart rate may have a similar physiological basis. The lower the eye temperature before and after work, the better the horse's outcome. Horses with an acute increase in eye temperature and/or heart rate are under greater stress and therefore more prone to errors that occur during competition [58]. Unfortunately, this method has not been shown to be reliable in another region, such as determining uveitis, because the slightly elevated measured temperature of the diseased eye is usually not different from the temperature of the healthy eye [59]. Thus, several studies have been published in the field of ophthalmology that addressed the problem from different angles, either to determine temperature, inflammation, or as an indicator of physiological stress, but there is currently insufficient evidence to link eye temperature to other accepted measures of core equine temperature [60]. In one of the studies, they examined the highest ocular surface temperature values as an indicator of physical fitness in riding horses and concluded that the increase in ocular surface temperature is likely due to physiological changes and workload, as shown by the correlation between the highest ocular surface temperature and creatine cinase (CK). This finding implies that peak ocular surface temperature is a possible indicator of physical fitness in sport horses [61], but Jansson [62] stated in their study that the main factors affecting ocular rim temperature are endogenous (gender and breed), environmental factors, and differences between seasons. The size and age of the horse do not play a role. There is no linear relationship between maximum ocular rim temperature and rectal temperature at rest, and ocular temperature may not be an appropriate indicator for evaluating the animal's body temperature.

THERMOGRAPHY OF SPORTS INJURIES

Intensive training of horses is associated with high physical stress on the musculoskeletal system and frequent injuries, which are associated with increased blood flow and increased BST. These changes can be detected by thermography and used to diagnose and monitor treatment of musculoskeletal injuries, diseases, and work overloads [1,7]. During the treatment of injuries, thermography can assess the progress and resolution of the inflammatory process as well as the effectiveness of anti-inflammatory therapy [63]. Sports injuries occur most frequently in the limbs, back, and joints. Treatment of such injuries requires administration of drugs (anti-inflammatory drugs, analgesics) or even surgical treatment [52]. Thermography has also been successful in assessing tissue damage and superficial bone damage, complementing other ultrasound and radiographic examinations [16,50,64].

THERMOGRAPHY OF THE SKIN

Inflamed and damaged tissue always has altered blood flow [13]. One of the most important signs of inflammation is heat, which is the result of increased blood flow in the inflamed region. A thermographic change is a hot spot resulting from local inflammation that is visible on the skin immediately over the injury [63,65]. Damaged and diseased tissue results in decreased blood flow due to swelling, vascular thrombosis, and tissue infarction) [28,66]. The region of such lesions has decreased temperature and is usually surrounded by increased thermal emissivity (radiation) due to blood bypass (Fig. 9).

Thermography can successfully monitor the treatment of bandaged wounds and injuries that occur primarily on the distal limbs, as well as injuries caused by bandages applied for too long and the resulting formation of deep skin wounds. Because of these capabilities, it can help determine the optimal time for changing bandages and avoid complications that can lead to irreversible consequences for the health and life of the injured animal [67]. One of the studies on skin wounds confirmed that the temperature of wounds increases from the time of injury to one week after injury, regardless of the location of the injury. The temperature of wounds on extremities is lower during healing than wounds on other parts of the body. In addition, the temperature of bandaged wounds on the extremities covered with granulation tissue is significantly lower than that of uncovered wounds without granulation tissue. This is also true for the temperature of uncovered skin wounds with granulation tissue, which is lower than the temperature of wounds without granulation tissue [68].

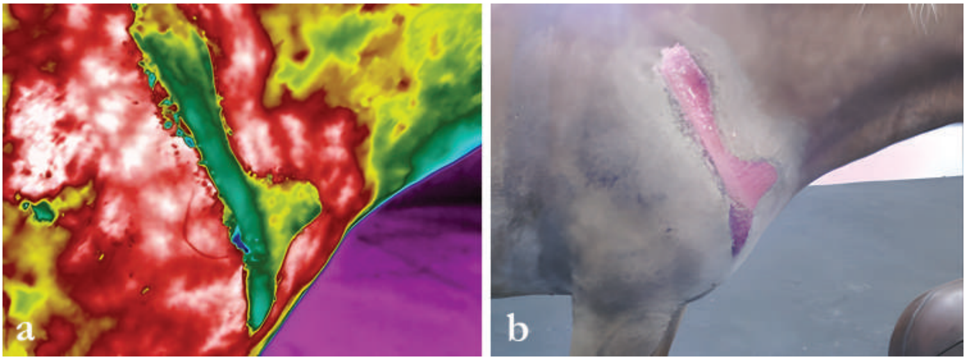

Figure 9. Thermogram of the extensive skin lesion (right prescapularis region) with decreased heat (green spot) and surrounded by increased termal radiation (white and red spots) **(A)** and photo of the same lesion **(B)**

THERMOGRAPHY OF THE EXTREMITIES

Thermography is also an effective method in the diagnosis of leg diseases and fresh and old limb injuries, where clinical examination and radiological imaging could not provide the required diagnostic results. With this method it is often not possible to make a definitive diagnosis of diseases, but it helps to determine the location of the disease and the degree of inflammation, which contributes significantly to the choice of the right treatment method [11]. The most common diseases and injuries of the limbs detected and defined by thermography are laminitis, podotrochlosis, hoof abscesses [6,9,69,70] tendinopathies, inflammation of the stifle joint, inflammation of the carpal and tarsal joints, and bucked shins (stress fracture) in show horses [71].

Hoof thermography can also be used to assess asymmetry of the load on the limb. After trotting on hard ground, increased hoof temperature can show which side of the horse is carrying more weight and medio-lateral hoof imbalance can be further confirmed by radiography [72].

The coronary band of the hoof is the warmest part of the limb, making its inflammation difficult to detect [9]. During examination, all hooves must be compared from the front and back, and a temperature difference of more than 1 °C indicates which of the hooves is affected. If all hooves are affected, it is important to compare the temperature between the soles of all hooves and detect a temperature difference greater than 1 °C.

The changed thermal pattern of the hoof wall is critical to the diagnosis of laminitis. In the early period of laminitis, the temperature of the coronary band is elevated compared to the distal part of the hoof and sole [6]. During this period, the coronary band is usually 1 °C to 2 °C warmer than the rest of the hoof. When the temperature of the hoof wall begins to approach that of the coronary band, it is a sign of its inflammation. Due to the stress and pain associated with laminitis, horses often shift their weight to the adjacent sound leg, overloading it, which can lead to lameness and a persistent increase in limb temperature [4,11]. In such a case, thermography confirms inflammation of the adjacent limb long before the onset of lameness, allowing therapy to be initiated early enough before chronic laminitis develops [4]. Hood [73] found decreased hoof wall temperature in the prodromal period of laminitis in their study, which calls into question the evaluation of hoof wall temperature as a more reliable indicator of laminitis than coronary band. Rosenmeier [74] believe that coronary band temperature fluctuates throughout the day, which may limit the accuracy of detecting early laminitis.

Thermography plays a special role in patients who experience pain due to podotrochlosis. It can provide information about the inflammatory process affecting blood supply to the limb [28]. Podotrochlosis is not manifested by superficial inflammation. Thermal patterns appear normal or cooler due to vasoconstriction of the hoof vessels, particularly in the heel [75]. The objective is to determine the decreased blood flow in the caudal portion of the hoof and the thermal stress that develops as a result of the hoof imbalance. A thermographic examination of the affected leg before and after work is required to check the blood flow. In a healthy horse, the temperature usually increases by 0.5 °C after work, although it should be noted that in approximately 50% of diseased horses, blood flow does not increase after work because of the low blood flow to the caudal part of the hoof [28]. Temperature changes may also occur as a result of laminitis, sole abscesses, and other hoof problems [76]. This differs from other foci of inflammation in the hoof (e.g., abscesses, callus, or fractures), which manifest as foci of increased temperature at the site of injury. In such cases, workload exacerbates hot spots [11]. Despite the advantages offered by thermography, in the recent years magnetic resonance imaging (MRI) has come to the forefront in the diagnosis of podotrochlosis [75].

THERMOGRAPHY OF BONES AND JOINTS

Thermography usually measures the temperature of the skin or skin region and has less diagnostic significance in diseases of the long bones. Their temperature can be measured only on those directly covered by the skin [77]. This limitation is particularly important for bones covered by muscle. Thermography has been used most successfully in detecting fractures of the radius and tibia and in diseases of the metacarpal bone [78]. Damage to the metacarpal initially manifests as hot spots located centrally over the dorsal long bone, usually 1°C to 2°C warmer than the surrounding tissue. As the disease progresses, the hot spots are no longer located centrally, but laterally and medially. This region is 2 °C to 3 °C warmer than the surrounding tissue. Based on thermographic examination and sufficiently early diagnosis, further deterioration of such a condition can be prevented while allowing a timely treatment approach [69]. Accordingly, thermography is a less suitable method for detecting bone damage or chronic degenerative joint diseases, the cause of which is mainly poor blood circulation in this region [1].

BST is used in regular training in the joint regions of a healthy horse. It is higher in the joints of the upper limbs (shoulder, elbow, hip, stifle joint) and lower in the joints of the distal limbs (carpal and tarsal joints, fetlock joint of the forelimb and hindlimb). The temperature of healthy joints depends on several factors, including the ambient temperature, which correlates with the absolute temperature of the joint. The temperature gradient between all joints of the same leg also correlates with ambient temperature [71]. BST differences in the joint region before and after exercise are an important indicator of the thermoregulatory response to the workload performed. Temperature differences that occur during regular training, especially in young show horses, can provide important diagnostic information about possible joint injury [79]. Characteristic heat patterns also occur in arthritis and are most pronounced from the dorsal side in most inflamed joints [35,69].

A normal joint is usually cool compared to the surrounding tissue structures. In an inflamed joint, the thermal pattern takes the form of an oval region of increased temperature running centrally across the joint and extending horizontally from medial to lateral. The distal joints are an exception, where the inflammation appears in the form of a round heat pattern. The attachment site of the joint capsule is usually warmer, while the center of the joint is relatively cooler. This may also be the result of joint swelling or pressure on the joint due to decreased microcirculation. However, the temperature of the joint and the damage to the joint are not correlated. The temperature of the inflamed joint also depends on the chronicity of the process, which is lower in a prolonged chronic process, as well as the degree of involvement of the synovium, the extent of damage to the articular cartilage, and the presence of osteochondral fragments. The above factors influence the temperature of the inflamed joint and at the same time interact in a complex manner. In one study, it was found that thermal joint patterns change 2 weeks before the appearance of clinical signs of lameness as one of the indicators of inflammation. In such cases, thermography contributes significantly to the prevention of joint injury by the early identification of inflamed regions before the appearance of external clinical signs, and at the same time, the data obtained contribute to the selection of the appropriate level or method of training that will reduce the load on the inflamed regions and thus also prevent further damage to the joints [11,35,66].

THERMOGRAPHY OF TENDONS AND LIGAMENTS

The thermal patterns of normal flexor tendons are bilaterally symmetrical and consist of elliptical isothermal zones [65, 69]. The lowest temperature of the tendon is in the middle of the palmar side, and the peripheral regions near the carpus and pastern are about 1 °C warmer. An important capability of thermography is the detection of subclinical inflammation and pathological conditions in the distal parts of the limb. Soroko [51] found in their study that a temperature difference of 1.25 °C of the right or left distal part of the limbs can indicate subclinical inflammation of the tendons (superficial digital flexor and bucked shins in racehorses). These thresholds are based on the standards for thermographic measurements in veterinary medicine, taking into account the influence of external environmental factors on BST at this body surface [5,26,41,51]. In acute tendinitis, there is always a hot spot at the site of the lesion [69], which can be seen more than two weeks before swelling and pain appear on the tendon. This allows early detection of tendon lesions, which helps prevent further tendon damage [11]. In healing lesions, the heat pattern is more uniform but higher than in a healthy tendon [69]. During healing and scarring, the skin over the injured region may have a lower temperature while the rest of the tendon remains elevated. At the same time, the thermal changes do not correlate with the structural change of the tendon tissue, which can also be confirmed by ultrasound examination [65]. The reason for this is that the tendon undergoes neurovascularization (growth of new blood vessels), during which the thermal pattern dissipates and there is no longer a hot spot. Comparing the treated tendon and the healthy tendon, the damaged tendon has increased overall thermal radiation. Thermography can therefore be used to identify the affected regiona in time before the onset of clinical disorders, allowing timely and appropriate therapy.

Ligament damage is thermographically similar to tendon damage. There are hot spots in the middle of the damaged ligaments. The only exceptions are injuries to some suspensory ligaments on the metacarpus. A dorsal thermal image of the injured limb shows a circumscribed hot spot that is unusually located proximally over the cannon bone, although inflammation and pain would be expected on the palmar side of the limb.

Thermography should also effectively confirm the interdependence of temperature and ligamentous tenderness, which is especially true for the suspensory ligaments or the interosseous ligaments, where one can also palpate a tender spot on the ligament. Clinically, this is not reliable, but thermography can confirm the relationship between inflammation and ligament sensitivity. Bone fragments (splint) or metacarpal callus can cause suspensory desmitis. Thermography detects inflammation of the suspensory ligament as a result of impact of a bone fragment, which is also true for all other similar cases of ligament inflammation [11].

MUSCLE THERMOGRAPHY

An indicator of nonspecific muscle lesions is an increase in muscle enzymes in the serum. It is in muscle injury that thermography probably has the greatest clinical significance [52], as it can determine the region of muscle inflammation or muscle groups or warn of muscle atrophy before it becomes clinically apparent. The most common cause of muscle inflammation in sport horses is their overuse. Muscle inflammation is visible thermographically as a hot spot on the skin directly over the affected muscle. Swelling and edema of the affected muscle occurs, which can stop blood flow through the muscle, visible thermographically as a cold spot. For a correct diagnosis, it is necessary to thermographically examine the affected muscle and compare it with the paired muscle on the opposite left or right side. The differences between them show, on the one hand, muscle damage, which can be seen as hot or cold spots. [13,52].

Thermography can also detect inflamed regions that affect the horse's decreased athletic activity, determine the location of pain, and detect skeletal-muscular overloads [4], while also assessing changes in muscle blood flow following work performed [36].

Regular thermographic examinations can also detect subclinical diseases of the forelimbs, such as tendinopathies, bucked shins and tendon overloads, which can be supplemented by additional examinations using radiography and ultrasound [51]. In the rehabilitation of injured horses, thermography helps determine upper limb muscle tension, muscle inflammation, croup, and caudal myopathies and can determine regions that require more detailed clinical examination and the use of therapeutic ultrasound, massage, or other treatments [80], as well as verify the effectiveness of acupuncture treatment for neuromuscular disorders [27].

THERMOGRAPHY OF THE BACK

The normal thermal pattern of the back shows the warmest region along the midline from the withers to the tail, the back, the chest, between the hind legs, and along the ventral midline. The lumbar region is slightly cooler, but the region between the two tuber coxae (tuber coxae to tuber coxae) and the tuber sacrale is warm again, and then down to the middle of the croup [13,81]. The temperature along the midline of the spine may be 2 to 3 °C higher at rest at the thoracic and lumbar vertebrae laterally on both sides of the spine when considered [70], the gluteal region is slightly cooler, but the temperature may also vary between horses [9]. Any deviation from this pattern may be due to artifacts or pathologic processes. If the lesions occur along the midline of the thoracolumbar region, radiography is required to clarify such a condition, and if the lesion is off the midline, ultrasonography is necessary [81].

The warmest part of the spine is the thoracic spine [82]. The increased temperature of this part of the spine in a sport horse may be the result of intense work or an imbalance of the rider, an improperly filled saddle, or poor riding technique. Thus, the rider's imbalance, especially at the trot, can cause asymmetry or increased BST [7]. During a thermographic examination, the skin region of the thoracic, lumbar, and sacral vertebrae must be imaged so that the camera captures the regions from top to bottom and from the right or left side of the animal so that it covers all vertebrae. Lesions are usually located along their midline. Thermally altered regions directly indicate the location of the damage. Cold spots over the spine, unlike other regions, are not the result of chronic injury, but may indicate injury with large swellings that affect the function of the autonomic nervous system. The temperature around the nerve roots originating in the spine may be elevated, which may be due to irritation of the local sympathetic nerves. If the entire sympathetic trunk is affected, the entire side may have an elevated temperature [9,11].

The method is also useful in neuromuscular diseases of the thoracolumbar region, muscular and spinal inflammatory processes (spinous process inflammation of the thoracic vertebrae and subluxation of the third lumbar vertebra, kissing spines, distal ligament injuries, withers injuries, saddle seat problems) [7,69,81]. Such injuries are characterized by hot or cold spots. For example, an incomplete sacral dislocation results in a cold spot between the two tuber sacrales.

Damaged muscles of the thoracolumbar region do not have characteristic thermographic heat patterns. Hot or cold spots occur along the midline, and ultrasonography provides additional identification of the injuries. All withers injuries exhibit hot spots in the withers region [81]. The croup muscles show somewhat specific changes [52]. The most common pattern is a cold region located on the sacral tuberosity, probably due to lack of normal movement of the sacroiliac region. This may be the result of a pathologic condition or other causes that cause irregular movements in the pelvic region. Approximately half of the horses with this thermal pattern have pain in the sacroiliac region.

Thermographic changes in supraspinous ligament or dorsal sacroiliac ligament injuries (adult sacroiliac ligament injury) show irregular thoracolumbar thermal images. Characteristic changes may present as increased or decreased temperatures and an irregular thermogram of the back, and the diagnosis may be confirmed by ultrasonography (ultrasnography), which provides evidence of this lesion.

Thermography plays a special role in detecting injuries caused by an improper saddle fitting [83]. In determining the reciprocal connection between the saddle and the horse's back, not only is the expressed heat in the regions of contact between the saddle and the horse important, but also the physiological effects of the saddle on the horse's back. When examining this region, it is necessary to approach the horse to work (walk, trot, canter), then remove the saddle and thermographically examine the saddle panels. After removing the saddle, it is also necessary to examine the back and take a picture of the thermal symmetry on the left and right sides of the back. In most cases, the horse's midline is cooler than other structures under the saddle due to the temperature emanating from the saddle. Along the spine, there are important focal hot spots or hot or cold spots on regional back muscles. These defects in the heat pattern indicate interference from the saddle. The same examination must be repeated with the rider, defining the effect of the rider on the horse's back under the installed saddle [7,83].

Many injuries to the horse's spine are often not detected in time, which can also be the reason for a complicated radiographic examination that includes a demanding general anesthesia. For a simpler approach to this type of diagnosis, a transient thermographic examination, which can be performed on a standing animal, can be used to suspect a back injury, and the horse can then be referred for radiographic imaging under general anesthesia [11], which facilitates the diagnostic spine examination process. Fonseca [50] investigated the simultaneous use of thermography and ultrasound in the detection of back disease and found that all lesions detected by thermography in a given region matched those detected by ultrasound, but at the same time not all lesions detected by ultrasound were also detected by thermography, indicating the justification and purpose of the complementary use of the two aforementioned diagnostic methods.

MUTUAL COMPLEMENTATION OF DIAGNOSTIC IMAGING METHODS

Various modern methods of diagnostic imaging in equine medicine complement each other and together contribute to the establishment of an accurate diagnosis. None of them by itself can replace an accurate clinical examination, which is enriched and complemented by the imaging techniques used. However, each of these techniques also has its limitations. Thermography and scintigraphy are imaging techniques that provide information about injury or disease and the viability of tissues, but do not provide specific information about the nature of disorders in the body. This falls into the realm of anatomical imaging of tissue structures. Scintigraphy is used to detect hidden skeletal lesions radiographically [84], and temography complements it. Scintigraphy is intended for selective use in the examination and diagnosis of bone lesions, whereas thermography is intended for the evaluation of overlying soft tissues [7,11].

Radiography mainly shows tissue contrasts, especially bone lesions. Except for fractures, most radiographic changes on bones become visible after 10 to 14 days [69,77]. Many of these are often permanent, making it difficult to determine whether an alteration, especially a chronic one, is the cause of pain or lameness [9,13]. Thermography and ultrasound are also complementary. Thermography is used to determine the location of the damage, while ultrasound is used to assess the morphology of the damaged structure and the size and shape of the damage [85]. Therefore, the use of ultrasound is suitable for monitoring the treatment, while thermography assesses when the inflammatory process is/will be healed [7,11].

CONCLUSION AND FURTHER DIRECTIONS

Thermography is a diagnostic imaging technique recorded with a thermographic camera. The first cameras were manufactured in the 1940s and were initially intended for military and industrial use [86], and in the mid-20th century they began to be used in medical diagnostics [87]. One of the first published studies in the field of human medicine was a study on breast cancer [88], which was followed by many others in the following years [89]. In veterinary medicine, thermography was first used between the 1960s and the early 1970s and became an important diagnostic tool, especially for use in horses [13,63,90].

Since then, other studies have been published on the use of thermography in various regions of equine medicine, particularly in physiology, pathophysiology, clinical diagnosis, injury, treatment, and physiotherapy.

In veterinary medicine, thermography gradually became the primary and a complementary diagnostic tool, especially as an aid in the clinical examination of horses. It plays a special role in equine sports medicine, where it can monitor work and detect equine sports injuries. In addition to many advantages, thermography also has certain limitations in its practical application. The method is not specific and cannot determine the etiology of pathological changes. Therefore, it is often used together with other modern diagnostic methods (such as X-ray, ultrasound, computed tomography and magnetic resonance imaging) and not as a substitute for them.

In the future, thermography will remain an important diagnostic method that offers many opportunities for the development and progress of veterinary medicine, not only in the equine field but also in other animal species. The development of thermal imaging cameras with even better resolution and more advanced technology will make thermography even more useful for the diagnosis of animal diseases and their welfare.

Autor's contribution

Rewiev was entirely conceived and designed by the author, who obtained the necessary scientific and professional data, processed, analyzed and interpreted them. The attached images (thermograms) were taken by the author during his work.

Competing interests

The author declared no potential conflict of interest with respect to the research, authorship, and/or publication on this article.

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TERMOGRAFIJSKO ISPITIVANJE KONJA

Peter KRULJC

Termografija je neinvazivna dijagnostička tehnika snimanja koja detektuje delove površine tela sa povišenom (ili sniženom) temperaturom merenjem infracrvenog zračenja. Otkriva fiziološke i patofiziološke promene prvenstveno vezane za protok krvi i brzinu metabolizma u ispitivanim delovima tela, kao i izmenjenu proizvodnju toplote. To uključuje fizički stres, razne fizičke povrede, medicinska stanja i faktore životne sredine. U medicini konja, termografija može da se koristi za rano otkrivanje promena temperature tkiva, omogućavajući intervenciju u ranoj fazi medicinskog pogoršanja zdrastvenog stanja. Termografski pregled se može koristiti za otkrivanje abnormalnosti tkiva u svim delovima tela. Posebno je koristan za otkrivanje mišićno-skeletnih poremećaja. Inflamatorni procesi su prisutni kod mnogih bolesti i povreda koje se mogu

uspešno otkriti termografijom. Termografija omogućava praćenje toka lečenja. Često se termografski vidljive promene bolesti otkriju pre nego što klinički znaci ili druge tehnike snimanja postanu vidljive. U fizikalnoj terapiji, pomaže u lociranju regiona tela kojima je potreban tretman i igra važnu ulogu u otkrivanju nelegalnih procedura (kao što je aplikacija lokalnih analgetika) za poboljšanje takmičarskih performansi konja.

Termografija služi kao dopunska dijagnostička alatka. Međutim, u praksi to ima neka ograničenja. Metoda nije specifična i ne može utvrditi etiologiju patoloških promena. Zbog toga se obično koristi zajedno sa drugim dijagnostičkim metodama (kao što su rendgen, ultrazvuk, kompjuterska tomografija i magnetna rezonanca) i ne može ih zameniti.