Veterinary applications of infrared thermography

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Received January 2, 2015.
Accepted April 14, 2015.

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Abnormal body temperature is a major indicator of disease; infrared thermography (IRT) can assess changes in body surface temperature quickly and remotely. This technology can be applied to a myriad of diseases of various etiologies across a wide range of host species in veterinary medicine. It is used to monitor the physiologic status of individual animals, such as measuring feed efficiency or diagnosing pregnancy. Infrared thermography has applications in the assessment of animal welfare, and has been used to detect soring in horses and monitor stress responses. This review addresses the variety of uses for IRT in veterinary medicine, including disease detection, physiologic monitoring, welfare assessment, and potential future applications. (*Am J Vet Res* 2016;77:98–107)

Change in body temperature has been recognized as an important indicator of disease since approximately 400 BC, and quantitative measurement of body temperature has been a standard in medical practice since the thermometer was invented in the 17th century. Although IRT has been incorporated into many architectural and engineering professions, leading to industry-wide standardization, its uses in medicine are still being discovered. Given the various potential uses of IRT in the medical field, few standards for its use have been established. Perhaps the most promising application of IRT in individual animal medicine is the early identification of an increase in body temperature that is indicative of the development of a fever or local inflammation. Early identification of febrile patients by IRT is advantageous because those patients can then be isolated and treated, which should help control disease transmission within a susceptible population. During the outbreaks of severe acute respiratory syndrome and avian influenza in humans during the early 2000's, IRT was used to identify febrile individuals at airports and thereby prevented the transmission of disease by travel.[1] In veterinary medicine, IRT can be used to screen animals for abnormally increased body temperature, so pyrexic animals can be isolated, tested, and treated.

ABBREVIATIONS

BRDC	Bovine respiratory disease complex
BVDV	Bovine viral diarrhea virus
FMDV	Foot-and-mouth disease virus
HPAA	Hypothalamus-pituitary-adrenal axis
IRT	Infrared thermography

Conditions Affecting IRT

The most appealing or unique aspect of IRT for veterinary medicine is that it is a remote, noncontact, and noninvasive process for acquiring individual animal data. A number of factors influence the quality and usefulness of any thermogram, regardless of its intended use. Those factors can be allocated among 3 categories: the subject, environment, and acquisition and processing of the image. Variables in each of those categories can affect thermographic image interpretation, so identifying and controlling them are essential. Environmental factors that can affect a thermogram include ambient temperature and its stability, air movement such as wind or drafts, sunlight, rain, and other weather conditions. As Wirthgen et al[2] stated, "Under good conditions the expected uncertainty is in the range of the camera uncertainty and in many cases greater than the diagnostic temperature difference." In other words, the cutoff temperature used to differentiate sick from healthy animals is often confounded by uncertainty in the generation of the thermographic image. Wirthgen et al[2] identified potential uncertainties in thermogram generation and devised a series of algorithms to achieve the most accurate measurements from thermographic images. This holistic approach requires collaboration between veterinarians, who acquire the thermograms, and technically skilled professionals, who refine image processing. It is also important to develop and maintain a catalog of thermographic images of healthy animals under controlled conditions to account for normal variation of thermal patterns in each species evaluated.

Multiple studies[3–6] have been conducted to investigate how individual animal factors can affect IRT results among healthy animals. Temperature varies between abutting haired and nonhaired skin, which suggests that hair absorbs some radiated heat and blocks that energy from being detected by an infrared camera.[3] Results of that study[3] indicate that although the temperature differs between clipped and nonclipped areas of skin in dogs, the IRT readings are stable within each area.[3] Skin color can also affect IRT readings. In black and white cattle, black areas are generally warmer than adjacent white areas.[4] Similarly, in zebras, there is a temperature difference between black and white stripes.[5] Black stripes are warmer than white stripes during the day, presumably because the black stripes absorb a greater amount of solar energy; however, the black stripes are cooler than the white stripes during the night, which might be the result of differences in the emissivity, or efficiency with which a surface releases thermal energy, between the black and white stripes.[5] The eye is a common site for temperature measurement with IRT. Results of a study[6] that involved humans suggest that age may affect ocular temperatures determined by IRT, and it is possible that age may likewise affect the temperature at other body sites.

Environmental factors affect IRT readings,[7] and some of the most common environmental factors that affect IRT readings are moisture and debris on the subject. In veterinary medicine, IRT is frequently implemented for use as a screening tool in field settings where animals are rarely clean and dry. Water or dirt on the hair or skin of an animal affects its emissivity.[8] Wet ambient conditions limit the usefulness of IRT[9] and might affect IRT readings, although results of 1 study[10] indicate that changing the humidity from 0% to 100% has little effect on IRT readings when room temperature is held constant. However, that effect was validated at a distance of only 1 m; results may vary at other distances.[10]

Church et al[10] used fans to investigate the effect of wind on IRT readings obtained from the eyes of cattle. The IRT temperature reading decreased from baseline at wind speeds of 7 km/h and decreased even further at wind speeds of 12 km/h.[10] The investigators then fabricated a surrogate eye in which water was used as the temperature medium; the temperature of the water in the surrogate eye likewise decreased as the wind speed increased, which confirmed the effect observed in the in vivo model.[10] In another study,[11] investigators directed a fan onto the distal portion of the right forelimb of horses to determine the effect of wind speed on IRT temperature readings. The temperature of the right forelimb decreased with wind speeds as low as 1.8 km/h and continued to decrease as wind speed increased.[11] The temperature of the left forelimb, which was partially blocked from the fan by the right forelimb, also decreased as wind speed increased.[11]

Circadian, infradian, and ultradian rhythms affect body temperature and should be taken into consideration when IRT is planned or thermographic findings are interpreted.[12] Berry et al[13] reported that the udder temperature of dairy cows undergoes daily variation. Other investigators[14] reported that physiologic factors such as the plasma cortisol concentration in dairy cows also follow circadian and ultradian rhythms and may likewise affect body temperature. Still other investigators[15] suggest that IRT may be most useful at night because the technology is based on the identification of temperature differences and the temperature contrast between the subject and its environment will be greatest after the sun sets. Obviously, this suggestion would be most relevant for IRT performed on animals housed outdoors. Church et al[10] also observed that solar loading, or the increase in the temperature of an object caused by absorption of solar energy, appears to be dependent on hair color and has a dramatic effect on IRT temperature readings.

In animals, many physiologic factors have circadian and infradian rhythms. Although the effects of those factors on IRT have not been explicitly studied, it seems reasonable to assume that blood flow, and thus thermoregulation, will also undergo some type of cyclicity. Aside from those cyclic patterns, body temperature is generally maintained within a homeostatic range. Even though body temperature may vary significantly from day to day, it may not necessarily indicate a true change (ie, disease) in the physiologic state of an individual.

Internal factors that influence circulation and thermoregulation also affect IRT temperature readings. Results of a study[16] in which IRT was used to determine the effect of various sedation protocols on the superficial temperature regulation in dogs indicate that administration of medetomidine alone causes a decrease in peripheral skin temperatures. Conversely, the administration of MK-467, a site-specific α_2-adrenergic receptor antagonist, in addition to medetomidine causes an increase in peripheral skin temperatures.[16] Thus, recent administration of any drug that affects blood circulation should be considered during the interpretation of thermographic images.

Another important factor to consider during the interpretation of thermographic images is the position of the IRT camera in relation to the subject. In 1 study,[17] a 20° change in the camera angle or 0.5-m increase in the camera distance from the subject had no effect on the IRT temperature readings. Changes in camera angles < 30° relative to perpendicular are generally considered to not have an effect on thermographic image interpretation; however, Watmough et al[18] reported that changes in the camera angle relative to the subject can substantially affect detection of emissivity and the IRT-measured temperature. In the study by Church et al,[10] as the distance of the IRT camera from the surrogate eye was increased from 0.2 m to 2.0 m by 0.2-m increments, the effect of heat transmission through and absorption by the intervening atmosphere became more pronounced. Some IRT cameras have a setting to account for the distance between the camera and subject. Given the proper algorithm and inputs such as distance, humidity, and environmental temperature, the effect of the environment on IRT temperature readings can be controlled.

Infrared technology has improved dramatically during recent years. With the availability of advanced cameras and software, thermographic images are easier to acquire and interpret. Infrared cameras are mobile and compact, and many of the new models can wirelessly transmit images to a remote computer for immediate processing. Some camera models are also equipped with audible and visual alerts that can draw the user's attention to a specific region on the subject being evaluated, and further imaging and evaluation can be immediately performed to ensure that the most useful images are acquired to aid in accurate diagnosis.

Use of IRT to Detect Disease

Infrared thermography has the potential to be a useful screening method for detection of animals affected by any disease that induces pyrexia or localized inflammation. This represents a myriad of diseases with various etiologies across multiple species. Infrared thermography may be most useful for large groups of animals (eg, herds or flocks), in which obtaining the body temperature of each individual by conventional means is prohibitively time consuming, or for wildlife that cannot be easily restrained. Although it is difficult to determine a pathognomonic thermal profile for a disease in a species, rapid determination of the presence of pyrexia or inflammation can help identify individuals at high risk of becoming ill. Those individuals can then be isolated for additional diagnostic testing and treatment as necessary. The following paragraphs describe the use of IRT to detect various diseases and physiologic conditions.

BVDV

In calves experimentally inoculated with BVDV, IRT was able to identify body temperature changes consistent with disease as early as 1 day after inoculation.[19] In that study,[19] orbital temperature was the most reliable indication of disease progression; the orbital IRT temperature readings peaked in conjunction with abnormal clinical scores (ie, at the time that the clinical signs of disease were most severe). Use of IRT to measure the rate of change in temperature at a specific anatomic site resulted in detection of BVDV-infected calves before other diagnostic tests yielded positive results or clinical signs of disease were manifest.[19] Results of that study[19] suggest that IRT can be used as a screening tool for cattle herds and can identify BVDV-infected animals up to 1 week before onset of viral shedding. Infected animals can then be isolated from the rest of the herd prior to becoming infectious, which should minimize virus transmission within the herd and decrease the economic impact of the disease.

BRDC

Bovine respiratory disease complex is a common multifactorial disease, in which various viruses, bacteria, and physiologic and environmental factors contribute to the pathogenesis. As with many other diseases, successful treatment of BRDC is dependent on early disease recognition and appropriate intervention. Results of 2 studies[20,21] indicate that IRT of the eye is able to identify cattle with BRDC several days before manifestation of clinical signs of disease at a rate comparable to that of the more invasive methods (rectal temperature and serial blood tests) that are currently considered by the industry to be the gold standard for BRDC diagnosis. Additionally, in 1 study,[21] the use of IRT in conjunction with radiofrequency identification tags that were applied to each animal and sent a signal to a remote computer whenever the animal approached the water station in the pen further facilitated detection of cattle in the early stages of BRDC. Activation of the IRT camera whenever an animal voluntarily approaches the water station obviates the need for the capture and restraint of individual animals, which makes IRT more appealing, compared with other traditional testing methods such as rectal temperature monitoring or blood sampling. This system could potentially allow producers and veterinarians to isolate and treat cattle for BRDC during the early stages of the disease, which would increase the probability of treatment success and minimize transmission of the disease within the herd.

FMDV

Results of a study[22] that involved cattle experimentally inoculated with FMDV and their noninoculated pen mates indicate that IRT, in combination with other traditional rapid diagnostic tests, could be used to detect FMDV-infected cattle during an outbreak. Early identification of FMDV-infected cattle during an outbreak will facilitate control and hasten disease eradication and recovery. A pen-side screening tool such as IRT could be used for selective on-site testing of animals suspected of being infected with FMDV and would complement the current gold-standard FMDV testing protocol, which involves virus isolation with confirmation by PCR assay and is time-consuming and labor-intensive. Following the establishment of adequate standard operating protocols, IRT and pen-side diagnostic tests could be used for early detection of FMDV-infected animals, which would facilitate quarantine or even preemptive culling.

In 1 study,[22] IRT was used to monitor temperature increases associated with inflammation at the coronary band of FMDV-infected cattle as the disease progressed, and the results indicate that coronary band temperature increased in FMDV-infected cattle 24 to 48 hours before the appearance of vesicular lesions and was not affected by floor temperature. However, an abnormally increased coronary band temperature is not pathognomonic for FMDV infection and can be caused by other inflammatory processes. Experiments are currently being conducted in an attempt to identify a specific thermographic signature for animals infected with FMDV.

Results of a study[23] that involved mule deer (*Odocoileus hemionus*) experimentally infected with FMDV are consistent with those of the study[24] that involved cattle experimentally infected with FMDV in that mean body and eye temperature as determined by IRT peaked on the day that foot lesions first became evident. In pigs experimentally infected with FMDV, disease progression is positively correlated with temperature increases in the extremities as determined by IRT.[24] Collectively, the findings of those studies[22–24] suggest that implementation of IRT as a remote screening tool may reduce the amount of animal handling required to identify suspect FMDV-infected animals for further testing. However, those studies[22–24] were conducted in animal facilities with highly regulated conditions where confounding factors such as ambient temperature could be controlled. It is unknown whether IRT will be able to identify FMDV-infected animals in a field setting where confounding factors cannot be controlled as effectively as it did in a rigidly controlled laboratory setting.

In clinically normal cattle in a field setting, hoof temperature as determined by IRT varies substantially with ambient temperatures and various conditions.[25] In that study,[25] temperatures varied among the hooves of individual cattle, and there did not appear to be any systematic differences among cattle. However, evaluation of serial IRT images of individual hooves obtained during the same day revealed only small variations in temperature.[25] Although some of that variation could be accounted for by camera variability and how each image was acquired, the greatest influence on hoof temperature was ambient temperature, and the investigators generated equations to predict hoof temperature in healthy cattle as a function of ambient temperature.[25] The investigators of that study[25] also reported that eye temperature is a reliable indicator of body temperature and is not affected by ambient temperature. Even though the findings of that study[25] support the theory that a threshold temperature can be established to identify FMDV-infected cattle at specific ambient temperatures, the investigators concluded that relative rather than absolute temperatures have the most predictive ability for identification of diseased animals.

Results of the studies by Dunbar et al[23] and Gloster et al[25] suggest that maximum eye temperature as determined by IRT can be used to identify pyrexic animals because it is not affected by ambient temperature and may be indicative of the early stages of disease caused by FMDV or other pyrexia-inducing viruses. Also, an abnormally increased hoof temperature relative to other animals within a herd in combination with an abnormally increased eye temperature might be used as a threshold to identify diseased animals.[23,25] Evidence clearly suggests that IRT can be used as a rapid, remote, and noninvasive screening method to identify suspect FMDV-infected animals for further testing during an outbreak.

Bluetongue virus

In a study[26] of sheep experimentally infected with bluetongue virus, the sensitivity and specificity of IRT for detection of sheep with pyrexia were 85% and 97%, respectively. In that study,[26] eye temperature as determined by IRT was strongly correlated with rectal temperature, which further validated the use of IRT in sheep; however, as with other studies,[22–24] the investigators caution that those results were obtained in a controlled laboratory setting. Further evaluation of IRT in sheep in field settings is necessary.

Rabies virus

Rabies is a viral disease of substantial public health concern. In the United States, infected wildlife generally act as vectors for rabies virus, and rabies-infected animals that develop clinical signs of the disease almost invariably die. Infrared thermography has been used to detect raccoons that were in the infectious stage of rabies disease after being experimentally infected with the virus.[27] In that study,[27] the maximum nose temperature of experimentally infected raccoons with clinical signs of rabies was significantly higher than that of uninfected raccoons, which allowed the infectious raccoons to be visually identified in the IRT images. The investigators[27] theorized that the increase in nose temperature in rabies-infected raccoons is caused by an increase in the vascular permeability and blood flow to the nasal tissues subsequent to the release of chemical mediators such as histamine. Because animals in the early stages of rabies do not have the classic neurologic signs associated with the disease, IRT detection of abnormally increased nose temperatures might be used to identify potentially rabid animals so that they can be managed to reduce the risk of viral transmission. However, an abnormally increased nose temperature is not pathognomic for rabies infections, and diagnosis of rabies must be confirmed by standard laboratory techniques. Regardless, the findings of that study[27] suggest that other diseases such as canine distemper may cause similar thermal changes that can be identified by IRT.

Tuberculosis

Tuberculosis is a zoonotic bacterial disease that is transmitted by contact with infected animals or the consumption of unpasteurized milk or dairy products. Many countries impose strict regulations on the sale and transportation of animals with tuberculosis and the products produced from those animals to mitigate the risk of disease transmission. Traditional premovement testing of animals for tuberculosis requires a minimum of 72 hours to complete, which can be onerous for producers. The current tuberculosis testing protocol consists of an ID injection of a mycobacterium antigen and evaluation of the skin thickness at the injection site 72 hours later.[28] In tuberculosis-infected animals, a local inflammatory response caused by delayed-type hypersensitivity to the antigen causes an increase in the skin thickness at the injection site.

Infrared thermography might significantly shorten the time required to screen animals for tuberculosis. In cattle that were hypersensitized to either *Mycobacterium bovis* or *Mycobacterium avium* or not hypersensitized and then underwent the traditional tuberculosis testing protocol, IRT identified a temperature increase associated with swelling or inflammation at the mycobacterium injection site of all 10 hypersensitized cattle and correctly identified the sensitization group for 13 of 15 cattle.[28] Conversely, measurement of skin thickness correctly identified the sensitization group for only 12 of 15 cattle.[28] Moreover, when the temperature threshold was set at 37.5°C, the IRT identified reactors within 24 hours after injection of the mycobacterium antigen.[28] Those findings suggest that IRT may complement or possibly supplant traditional testing methods currently used to screen animals for tuberculosis.

Mastitis

Mastitis is the most costly disease for the US dairy industry and results in a estimated loss of $1.7 to 2.0 billion annually because of lost production and discarded milk.[29] Mastitis is generally caused by bacteria, and endotoxins produced by those bacteria can damage the mammary tissue and result in a decrease in milk production and occasionally systemic illness or death. As bacteria proliferate within the mammary tissues, the blood vessels in the udder dilate to facilitate blood flow and the delivery of WBCs to the site of infection. Cows with mastitis frequently develop pyrexia and hyporexia. The inflammatory response in the udder often causes localized hyperthermia, hyperemia, and swelling.

Infrared thermography can be used to detect a localized increase in the temperature of the udder skin during the early stages of mastitis. Berry et al[13] reported that udder temperature as determined by IRT could be predicted with a high degree of accuracy on the basis of the previous day's udder temperature and various environmental variables. The residual values for that model ranged between 0.22° to 0.46°C, a variation that was well below the expected change in udder temperature subsequent to infection; therefore, the investigators concluded that the model could be used to assess the risk of mastitis.[13] An udder temperature change outside of that range (0.22°C to 0.46°C) may provide early indication of mastitis or some other problem.

In a study by Hovinen et al,[30] mastitis was induced in each of 6 cows by the intramammary injection of 10 µg of *Escherichia coli* lipopolysaccharide into the left forequarter; the right forequarter was used as the control. Infrared thermography was then used to monitor temperature changes in the udder skin.[30] Results indicate that the IRT temperature readings in both the experimentally infected and control quarters of the udder increased over time and coincided with an increase in rectal temperature,[30] which was indicative of a systemic response to the lipopolysaccharide. Although that finding did not support the hypothesis that IRT would be able to detect mastitis in a specific quarter, it did suggest that IRT can be useful for detecting clinical mastitis as early as 4 hours after infection.[30]

Results of 2 other studies[31,32] indicate that there is a strong positive correlation between mammary skin temperature as determined by IRT and the severity of mastitis as determined by the California mastitis test. Compared with the California mastitis test, IRT is quicker, less invasive, and at least as capable of detecting thermal changes indicative of subclinical mastitis.

Accurate early diagnosis of mastitis in individual animals is important for the development of appropriate intervention and treatment measures. Those measures can reduce economic losses associated with mastitis and potentially improve general animal health and welfare. However, the use of IRT for early diagnosis of mastitis is not without its challenges. Current limitations that affect the use of IRT for detection of mastitis include wet conditions and debris on the udder and individual animal factors such as physiological state, production, exercise level, body posture, and time of feeding and milking relative to initiation of IRT. Also, the initial acquisition and implementation of an IRT system for a dairy herd is quite costly. Additional investigation is needed to validate the findings of previous studies[13,30–32] and account for various individual animal and environmental factors before IRT becomes standard in the dairy industry. However, preliminary findings[31,32] suggest that IRT can be useful for identification of cows with subclinical and clinical mastitis.

Detection of additional diseases

The most direct use for IRT is monitoring individual animals for pyrexia or localized inflammation, which may be indicative of a serious or otherwise undetectable disease. Infrared thermography is a sensitive method for detection of ponies with pyrexia[33] and may be useful for identifying cats that are in pain.[34] It has also been used to aid in the detection of keratoconjunctivitis sicca in dogs, and although IRT alone is not sufficient to diagnose that disease, it may become a popular ancillary method for the diagnoses of ocular surface disorders.[35] In beef cattle, IRT has been used to detect infections in the ear pinna associated with contaminated growth-promoting implants[9] and establish the normal thermal signature for the distal limbs, the deviation from which has been used to diagnose skin lesions.[36] It has also been used to distinguish between cattle with and without hoof lesions.[37] However, substantial variation among farms has prevented the establishment of a normal thermal signature for cattle hooves[37] and may suggest that IRT standards will need to be established for each individual farm, which may limit or slow adoption of IRT.

The remote nature of IRT provides park rangers and other wildlife technicians the ability to monitor animals at a distance in their natural habitat for temperature changes that may affect their health and welfare. Investigators of a study[38] in which long-distance

IRT was compared with optical telediagnosis, the gold standard for diagnosis of sarcoptic mange in Spanish ibex (*Capra pyrenaica*), reported that IRT is of limited use at distances > 100 m and concluded that a better, more sensitive screening method than IRT is necessary for long-distance screening of animals for mange, especially when disease prevalence is low. In Yellowstone National Park, sarcoptic mange is a serious problem for wolves, which were reintroduced into the park in 1995 and 1996. Infrared thermography has been used to detect hair loss and inflammation associated with mange in those wolves, and once detected, the affected individuals or packs are treated accordingly.[39]

Laminitis

Over the past 20 years, IRT has been used as a complement to ultrasonography and scintigraphy for the diagnosis of thermal changes caused by inflammation associated with lameness, signs of back pain, Horner syndrome, osteoarthritis, tendonitis, fractures, and navicular disease in horses.[40] Infrared thermography is used fairly routinely for detection of lameness in horses, either alone or frequently in conjunction with traditional lameness evaluations that involve regional nerve blocks and joint flexion, and is commonly used during prepurchase or performance evaluations.[41] Infrared thermography results are compared between both forelimbs or hind limbs, and areas with substantial differences in IRT readings are identified as areas of interest for further diagnostic testing such as ultrasonography, radiography, or muscle biopsy.[41] Abnormally decreased IRT readings are considered as equally important as abnormally increased IRT readings because they are often associated with areas with low blood flow, which may result from fibrotic scar tissue or chronic or recurring injuries.[41] Infrared thermography can also be used to detect abnormalities in the proximal aspect of limbs, which are usually difficult to examine by other methods.[41]

Results of a study[42] that involved Thoroughbred racehorses suggest that IRT frequently detects abnormally increased skin temperatures in injured areas as early as 2 weeks before manifestation of clinical signs despite recent application of bandages and liniments or corticosteroid administration. In that study,[42] certain muscle groups were associated with a high frequency of false-positive IRT results, and factors that confounded IRT readings included age of the horse, its recent work history, and the type of surface on which it worked.

Infrared thermography has also been used to detect lameness in cattle, especially dairy cattle.[43–45] In 1 study,[43] hoof temperature as determined by IRT was abnormally increased in the affected feet of cows with sole hemorrhages during the early and middle portions of the lactation cycle. When a lesion is present in a bovine foot, the coronary band temperature in that foot increases significantly after it is trimmed,[44] and < 10% of the expected variance in maximum coronary band temperature is attributed to ambient temperature changes and no significant difference can be detected by IRT before and during lifting of the foot for trimming.[44,45] Unfortunately, IRT was unable to differentiate between different types of bovine foot lesions and should not be used as a diagnostic test for a specific lesion or disease.[44,45] Collectively, the results of those studies[40,42–45] suggest that IRT can be used to detect temperature changes associated with laminitis and other lesions in the hooves of horses and cattle; however, it cannot differentiate between lesions and its cost may limit its application in field settings.

Branding and dehorning

Infrared thermography can be used to detect inflammation caused by external physical stresses such as branding and dehorning. In a study[46] in which inflammation associated with hot-iron and freeze branding in cattle was assessed, IRT was used to measure the extent and duration of the inflammatory response; results indicate that tissue damage persists until a new collagen matrix is formed and the blood supply is reestablished at the branding site. In another study,[47] IRT and other methods were used to assess the extent of pain and the efficacy of pain-reducing treatment in dairy calves following dehorning with a hot iron; results indicate IRT can be used to both identify and monitor the progression of inflammatory responses.

Tissue perfusion

Although IRT is commonly used to detect abnormally increased surface temperatures, it can also detect abnormally decreased surface temperatures, and the results of multiple studies[48–54] indicate that IRT can be used to effectively identify poorly perfused or compromised tissues. In a dog with malignant mammary carcinoma, evaluation of IRT images revealed an abnormally decreased infrared radiation pattern unilaterally that was associated with unilateral thrombosis of the femoral artery.[48] Thrombolytic treatment with streptokinase was initiated, and the dog was serially monitored with IRT.[48] Following treatment, the affected limb developed a fairly normal infrared signature that was comparable to that of the contralateral limb.[48] Vertebral and spinal cord injuries can result in altered blood flow, and IRT has been used to detect altered blood flow in dogs with thoracolumbar vertebral disk disease[49] and spinal compression.[50] Intestinal tissue viability in rats,[51] dogs,[52,53] and pigs[54] before, during, and after experimental induction of ischemia has been evaluated with IRT, and results suggest that IRT can be used intraoperatively to identify compromised intestinal tissue that should be removed to promote successful healing.

Use of IRT to Detect Nondiseased States

Although detection of disease is an exciting use for IRT, it is far from the only one. Infrared thermography can be used to help improve livestock operations through monitoring of feed efficiency and determining whether animals are pregnant. Pregnancy determination by IRT is also useful for rare or particularly dangerous animals such as those maintained in zoological collections. Infrared thermography can be used to gather evidence to help enforce animal welfare regulations and monitor animal stress regardless of whether it is associated with pathology.

Pregnancy and reproduction

The use of IRT for pregnancy detection has been investigated in various species with varying degrees of success. Infrared thermographic images were obtained from both the left and right flanks of pregnant and nonpregnant mares, and evaluation of those images revealed that pregnant mares had a substantial temperature differential between the flanks.[55] The reason for that temperature differential was believed to be caused by the implantation of the fetus in either the right or left uterine horn, which increases the local metabolic requirements and leads to an increase in blood flow and temperature, which is detected by IRT.[55] Infrared thermography has been used to detect pregnancy in giraffes,[a] zebras,[56] and black rhinoceros[56] and differentiate between pregnancy and pseudopregnancy in giant pandas.[57] Conversely, results of studies involving dogs[57] and cattle[58] indicate that IRT is not useful for pregnancy detection. This is likely the result of physiologic characteristics unique to those species. Bitches tend to have litters of puppies, and there is no evidence that fetuses implant more frequently on one side or the other; consequently, the flank temperature does not vary substantially between sides. Cows have a large, physiologically active rumen that takes up most of the left flank and likely obscures any pregnancy-induced temperature changes. Giraffes are also ruminants, but their rumen is small, compared with that of other ruminants[59]; therefore, it is less likely to confound or obscure pregnancy-induced changes in flank temperature. In general, it appears that IRT is useful for detection of pregnancy only in uniparous species and a small subset of ruminants.

Reproductive efficiency is vital to the livestock industry and is frequently one of its more challenging aspects. Infrared thermography has been used to detect the climax of the estrous cycle of cows and identify the optimal time for breeding.[4] In sheep, IRT was used to measure perivulvar temperature of ewes following implementation of an estrous synchronization protocol to distinguish ewes that were in estrus from those in anestrus.[60] In mares, IRT was used to monitor estrus and identify ovulation.[60] In pigs, the maximum and mean temperature of the perivulvar area of gilts during estrus as determined by IRT were significantly higher than those for gilts not in estrus, and that temperature difference was exacerbated during periods of cold ambient temperatures.[61] Investigators of that study[61] also found a correlation between vulvar temperature and ambient temperature; however, changes in vulvar temperatures did not coincide with changes in rectal temperatures.

Welfare

Because hyperthermia is widely regarded as a stress response, IRT can be used to monitor how animals are treated. Although the use of IRT for welfare assessment has been evaluated in healthy dogs such as working dogs,[62] racing Greyhounds,[63] and household pets,[3] most of the studies in this area have focused on horses. Professional horse organizations such as the Tennessee Walking Horse Breeders' and Exhibitors' Association, American Endurance Riders Conference, and Fédération Equestre Internationale (the international organization that governs equine athletics) have strict regulations regarding the types of treatments that horses can and cannot receive prior to or during competitions. Injections of local anesthetics to alleviate lameness or the application of caustic chemicals to the distal aspect of limbs (soring) to exaggerate a horse's gait can give competitors an unfair advantage but, more importantly, can negatively affect horse welfare. Infrared thermography can detect evidence of those treatments, sometimes long after the treatment was administered, and help regulatory officials identify violations and enforce sanctions.

The HPAA controls the physiologic mechanisms responsible for moderating the stress response.[64] Cortisol, one of the products of the HPAA, can be readily measured in saliva, and cortisol concentration in saliva is strongly correlated with the cortisol concentration in blood, which makes it a useful biomarker.[64] In horses, eye temperature as determined by IRT is significantly and positively correlated with both salivary and plasma cortisol concentrations,[65] and results of another study[66] indicate that both salivary cortisol concentration and eye temperature are significantly greater in horses immediately after competition, compared with those immediately before the competition. Conversely, investigators of a study[67] that involved cattle found no association between IRT findings and HPAA activity. In sheep, eye temperature as determined by IRT decreases in response to stress, likely because stress causes sympathetic systemic vasoconstriction, which diverts blood flow away from the lacrimal caruncula, the area of the eye with maximum temperature.[68] Thus, IRT can accurately measure a stress response in some species; however, substantial differences in the temperature response to stress exist among species.

During dressage, nose bands are commonly used to prevent a horse from exhibiting signs of resistance to the rider such as opening its mouth or fighting the bit. In 1 study,[69] excessively tight nose bands resulted in an increase in eye temperature and a decrease in the surrounding skin temperature, possibly indicating a stress response and compromised circulation, respectively. Because each horse, rider, and nose band combination is unique, IRT has become a standard noninvasive method for monitoring the welfare of dressage horses.

To evaluate the effect of intrasynovial injections on IRT readings in horses, investigators of another study[70] injected bupivacaine into the metacarpophalangeal (fetlock) and middle carpal joints of 1 forelimb and saline (0.9% NaCl) solution into the fetlock and middle carpal joints of the contralateral limb. Although IRT could not distinguish between joints injected with bupivacaine and saline solution, it did detect an increase in the skin temperature of those joints within 15 minutes after injection that persisted for at least 24 hours.[70] In another study,[71] various injection and surgery sites in horses were evaluated with IRT. Infrared thermography was able to detect a temperature increase at the injection site for 2 days after injection of an analgesic into the muscles of the lumbar region and the suspensory ligament or injection of a neurolytic into the tibial nerve. Local analgesia of the palmar digital nerve resulted in an increase in skin temperature that persisted for 1 to 5 days depending on the analgesic used, and palmar digital neurectomy resulted in variable, but detectable, changes in skin temperature.[71] Even though IRT cannot distinguish a temperature change associated with an injury from that associated with injection of a local anesthetic or minor surgical procedure, it is a valuable tool for monitoring and enforcing welfare-specific regulations because it can identify horses with injuries that might become worse if the horse is allowed to compete as well as horses that have been injected with some type of agent to mask an injury.

Infrared thermography has been used for years as the main method for detection of soring, a practice in which trainers or handlers use chemical or physical means to purposefully injure specific parts of a horse's leg to exaggerate its gait for competition purposes. In 1975, Nelson and Osheim[72] described a thermographic pattern specific for inflammation and scarring associated with soring in horses.

Infrared thermography is commonly used for saddle fitting because it can identify issues associated with poor saddle fit that might be inapparent otherwise. In a study[73] in which IRT was used to assess jumping horses before and after a training session, evaluation of thermographic results identified several issues associated with saddle fit. Of the 129 horses evaluated, 72 (55.8%) had asymmetric thoracolumbar heat patterns and 51 (39.5%) had a heat point compatible with a pressure area from the saddle when at rest.[73] The investigators also detected asymmetry issues associated with the saddle, evidence of hot spots cranial to the saddle, and contact along the central canal, yet despite the multiple problems identified, only 2 of the 129 (1.6%) horses resisted being saddled.[73]

Production

In production livestock, welfare is often intertwined with production, and IRT is used to detect diseases as well as assess treatment and handling of animals. Results of IRT revealed that various milking machine teat cup liners and overmilking were associated with an increase in the udder temperature of dairy cows that was suggestive of injury.[74] The investigators of that study[74] also reported that proper premilking handling of cows has a significant effect on IRT results. Results of another study[36] indicate that proper milking technique is associated with no detectable change in udder temperature.

Infrared thermography is used for the assessment of meat quality before and after slaughter. It can detect cattle likely to produce dark, firm, dry beef[75] and pigs that produce pale, soft, exudative pork.[76] It is also used to screen hams to determine their suitability for dry-curing.[77] Evaluation of IRT images obtained from pigs just prior to slaughter revealed the IRT findings were correlated with meat quality for some muscle groups[78]; however, more research is necessary to better characterize how meat quality affects IRT.

Feed conversion efficiency is an important parameter in livestock production; typically, there is a positive correlation between the amount of weight produced per unit of feed and economic return. In a study[79] in which IRT findings were correlated with heat and methane production in cattle, foot temperature was positively correlated with heat production and flank temperature. The temperature of the left flank was greater than the right flank (most likely because the rumen is located on the left side) and was positively correlated with methane production during the immediate postprandial period.[79] Residual food intake is another measure of efficiency; the lower it is, the better an individual animal is at converting feed into meat.[80] Results of study by Montanholi et al[80] indicate that IRT can be used to identify beef cattle with low residual feed intake, which may allow producers to increase feed efficiency for their operations and potentially improve the genetics of their herds. Results of another study[81] suggest that IRT measurements are a better indicator of the residual feed intake of an individual animal than is either feeding behavior or glucocorticoid concentration.

Automated, remote IRT is useful for serial monitoring of feed intake over time. Feed consumption provides the energy necessary for homeostatic maintenance and thermoregulation. When a cow becomes hyporexic, its skin temperature decreases initially and then may stabilize and follow normal circadian rhythms, albeit at lower temperatures than those in its healthy cohorts.[b] Consequently, IRT can be used to distinguish between healthy and sick cattle, which allows each group to be appropriately managed for maximum efficiency.

Conclusion

Infrared thermography is a rapid, remote method for assessing surface temperature that has many diagnostic and screening applications in veterinary medicine. In general, interpretation of IRT findings is intuitive, and although mastery of the technique is difficult, the technology is easily approached and integrated into existing knowledge. Those characteristics allow IRT to complement, or sometimes supplant, existing methods for diagnosing disease, evaluating welfare, or assessing other conditions or characteristics. Infrared thermography technology is constantly improving, thereby increasing the sensitivity of the detectors and allowing for further definition and refinement of its existing uses. Consequently, IRT is likely to be increasingly recognized and used as a valuable tool for the promotion of animal welfare and protection of public health.

Acknowledgments

Supported in part by CRIS project 1940-32000-057-00D (USDA Agricultural Research Service) and an interagency agreement with the Science and Technology Directorate of the US Department of Homeland Security (award No. HSHQPM-13-X-00131). Steven Rekant and Mark Lyons were recipients of Plum Island Animal Disease Center Research Participation Program fellowships, administered by the Oak Ridge Institute for Science and Education through an interagency agreement with the US Department of Energy.

The authors declare that there were no conflicts of interest.

The content of this article is solely the responsibility of the authors and does not necessarily represent the official views of the USDA or any other federal entity.

The authors thank Andre-Denis Wright and Christina Kim for technical support.

Footnotes

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