Infrared thermography on animal livestock

Termografia infravermelha na pecuária animal

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ABSTRACT

Infrared thermography has become increasingly promising in veterinary medicine, for being a non-invasive method for detecting body thermal variation. The objective of this review was to elucidate some applications of infrared thermography and its importance on animal livestock. This tool can substitute conventional techniques for diagnosing diseases, inflammation and fever. The body temperature is an important indicator to diagnostics and to understanding physiological aspects due to the close relation between abnormal temperatures and inflammatory processes. Also, it can help monitor reproductive performance and identify more efficient animals, among other purposes. The measurement of infrared temperature allows identifying sick animals, before the appearance of clinical symptoms, making treatment and isolation faster and more accurate, enhancing the profitability and sustainability of the system. However, this tool has some limitations, such as the animal species and environmental factors. Thus, further studies are needed for the application of the thermographic on animal livestock.

Keywords: Thermographic image; infrared radiation; surface temperature; disease diagnosis; body temperature.

RESUMO

A termografia infravermelha tem se tornado cada vez mais promissora na medicina veterinária, por ser um método não invasivo para detectar a variação térmica corporal. O objetivo desta revisão foi elucidar algumas aplicações da termografia infravermelha e sua importância na pecuária. Essa ferramenta pode substituir as técnicas convencionais de diagnóstico de doenças, inflamação e febre. A temperatura corporal é um importante indicador para diagnóstico e compreensão de aspectos fisiológicos devido à estreita relação entre temperaturas anormais e processos inflamatórios. Além disso, pode ajudar a monitorar o desempenho reprodutivo e identificar animais mais eficientes, entre outras finalidades. A medição da temperatura infravermelha permite identificar os animais doentes, antes do aparecimento dos sintomas clínicos, tornando o tratamento e o isolamento mais rápidos e precisos, potencializando a rentabilidade e sustentabilidade do sistema. No entanto, a termografia infravermelha apresenta algumas limitações, como a espécie animal e fatores ambientais. Sendo assim, futuros estudos são necessários para a aplicação da termografia na produção animal.

Palavras-chave: Imagem termográfica; radiação infravermelha; temperatura superficial; diagnóstico de doença; temperatura corporal.

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INTRODUÇÃO

Infrared light was discovered by the German astronomer, naturalized English, Sir William Herschel in the year 1800 after carrying out several experiments, which led to the discovery of thermal radiation, later called infrared light or infrared radiation (Ricca, 2013). Infrared thermography (IRT) is a non-invasive tool that allows the remote measurement of the surface temperature of an animal (Castells et al., 2019), emitted as thermal radiation (Sathiyabarathi et al., 2016; Lowe et al., 2019).

The principle of IRT is that every object with a temperature above absolute zero emits thermal radiation to the environment, in all wave lengths of the infrared spectrum (Poikalainen et al., 2012). The radiation is captured and recorded by a thermal imaging camera that creates a color thermal image, and each color corresponds to a specific temperature (Redaelli and Caglio, 2013). The thermographic image presents a color scale that varies from cold (green and blue) to hot (yellow, orange, red and white) (Castells et al., 2019). Currently, there are several thermal camera models used in animal studies, Table 1. IRT can identify metabolic changes through of the temperature variations in body surface, due to the blood flow variations and tissue metabolic rate (Eddy et al., 2001; Berry et al., al., 2003; Martins et al., 2013; Ludwing et al., 2013).

The IRT can be applied in all animal classes and species, however, anatomical, morphological, metabolic, and physiological differences must be considered (Mitchell, 2013). The use of IRT in large animals and large herds has become a useful tool in the preventive diagnosis of several metabolic changes, due to its ability to detect heat variations on the body surface caused by inflammatory processes (Ludwig, 2013). Moreover, IRT makes it easier to monitor herd health because it does not require direct contact with animals (McManus et al., 2016). Also, it allows the adaptation of ethical and sustainable management methods that can be applied in farms, monitoring the herds without stress for the animals. Therefore, IRT can improve the productivity and profitability of different production systems (Neethirajan et al., 2017).

Diseases and heat stress are limiting factors that compromise the productivity of herds and the supply of animal protein to human food, resulting in economic losses. Disease detection is often expensive and time-consuming (Neethirajan et al., 2017), demanding skilled labor. Body temperature is an important indicator for diagnosing diseases and understanding physiological parameters in animals (Poikalainen et al., 2012; Nääs et al., 2014). Each region of the animal body has a different temperature due to

physiological variations, which can help the clinical assessment of these areas (Deak et al., 2019).

The application of IRT in livestock production has been studied for several species such as beef cattle (Montanholi et al., 2009; LokeshBobu et al., 2018; Lowe et al., 2019; Vicentini et al., 2020), dairy cows (Chacur et al., 2016; Daltro et al., 2017; Schaefer et al., 2018; Sathiyabarathi et al., 2018; Tangorra et al., 2019; Deak et al., 2019), laying hen (Loyau et al., 2016), buffaloes (Barros et al., 2016; Sevegnani et al., 2016; Ahirwar et al., 2017; Ahirwar et al., 2018; Chacur et al., 2018), dairy sheep (Martins et al., 2013; Castro-Costa et al., 2014; Cannas et al., 2018; Byrne et al., 2019; Castells et al., 2019; Sutherland et al., 2020; Pulido-Rodríguez et al., 2021), dairy goats (Silva et al., 2014; Façanha et al., 2018), Broiler chickens (Nascimento et a., 2014; Candido et al., 2020), turkey (Moe et al., 2018) and pigs (Justino et al., 2014; Boileau et al., 2019), Table 2.

Therefore, the objective of this review is to present some applications of infrared thermography and its importance for animal production. We searched for papers in high-impact scientific journals that addressed the use of IRT in diseases diagnosis, inflammatory processes, reproductive monitoring, semen quality, animal efficiency, animals' adaptation, aid to selection, heat stress, and animal welfare.

The search for papers was carried out with the internet search tool in databases: Science Direct (https://www.sciencedirect.com), PubMed Central (http://www. ncbi.nlm.nih.gov/pubmed); Scielo (http://www.scielo.org) and CAPES (https://www.capes.gov.br), using the keywords: infrared thermography, disease diagnosis, dairy farming, livestock.

Table 1 - Thermal camera models used in farm animals

Model	Infrared resolution (pixels)	Thermal accuracy	Animal	Source
FLUKE Ti25	640 x 480	+/-2.0°C	Dairy cattle	Berry et al., 2003
Therma Cam P26 IRI 4010	-	-	Dairy cattle	Colak et al., 2008
FLEX Cam S	-	+/-2.0°C	Dairy cattle	Polat et al., 2010
FLIR System série-i	-	-	Dairy sheep	Martins et al., 2012
FLUKE TiS	640 x 480	+/-0.1°C	Cattle	Poikalainen et al., 2012
FLUKE Ti25	640 x 480	+/-2.0°C	Dairy cows	Assoad et al., 2014
FLIR 760 IR	640 x 480	+/-2.0°C	Dairy cattle	Metzener et al., 2014
FLIR T620	-	-	Dairy cows	Talukder et al., 2014
FLUKE Ti50FT IR flexcam	320 x 240	-	Goats	Alejandro et al., 2014
FLIR A320	-	-	Piglets	Cook et al., 2014
IRI 400	-	+/-0.15°C	Dairy ewes	Castro-Costa et al., 2014
FLUKE Ti20TM	-	-	Cattle	Salles et al., 2016
Therma Cam Pro 2.10	-	+/-2.0°C	laying hens	Loyau et al., 2016
FLIR T300	320 x 240	+/-2.0°C	Cattle	Cortivo et al., 2016
FLIR System T300	320 x 240	+/-2.0°C	Dairy cattle	Daltro et al., 2017
FLUKE Ti200	200 x 150	+/-2.0°C	Goats	Façanha et al., 2018
FLIR i5	-	-	Dairy cattle	Sathiyabarathi et al., 2018
FLIR Thermovision E40	-	-	Buffalo	Ruediger et al., 2018
FLIR T450SC	320 x 240	+/-0.1°C	Beef cattle	Schaefer et al., 2018
Therma GEAR-G120 EX	320 x 240	+/-2.0°C	Dairy cows	Zaninelli et al., 2018
FLIR T450SC	320 x 240	+/-2.0°C	Dairy cows	Perez Marques et al., 2019
Therma GEAR-G120 EX	320 x 240	+/-2.0°C	Dairy cattle	Tangorra et al., 2019
Therma CAMB60	2048 x 1536	+/-2.0°C	Broiler chickens	Candido et al., 2020
Therma Cam S60	640 x 480	-	Sheep	Sutherland et al., 2020
Testo 875-2i	640 x 480	+/-2.0°C	Sheep	Pulido-Rodríguez et al., 2021

Table 2 - Applications of the IRT in different goals on livestock animals

Study objective	Animal species	Animal region	Focus distance	Source
Food efficiency	Cattle	Eye, ribs, leg	1.5 m	Montanholi et al., 2009
Mastitis	Sheep	Udder	1.5 m	Martins et al., 2012
Mastitis	Sheep	Udder	0.5 m	Castro-Costa et al., 2014
Digital dermatitis	Cattle	Hoof	0.5 m	Alsaaod et al., 2014
Parasite count	Cattle	Scrotum, flank, forehead and face	1.0 m	Cortivo et al., 2016
Mastitis	Cattle	Udder	1.5 m	Digiovani et al., 2016
Estrus detection	Goats	Vulva	1.0 m	Façanha et al., 2018
Estru	Buffalo	Eye, vulva and snout	1.0 m	Ruediger et al., 2018
Animal selection	Cattle	Eye, face and digital region	2.0 m	Schaefer et al., 2018
Sêmen quality	Buffalo	Testicles	1.0 m	Yadav et a., 2019
Changes of the teats after mechanical milking	Cattle	Teats	0.5 m	Tangorra et al., 2019
Autonomic nervous response	Sheep	Eye	1.0 m	Sutherland et al., 2020
Thermoregulation	Sheep	Ocular, dorsal, ventral, shoulder, rump, forelegs, hind legs and ribs	1.0 m	Pulido-Rodríguez et al., 2021

USE OF INFRARED THERMOGRAPHY IN FARM ANIMALS

The first record of IRT in veterinary medicine was in 1963 in horses. Observing the promising results of IRT in the diagnosis of diseases in humans, the researcher Smith Wendell sought to know the possible applications of IRT in detecting the thermal variation of horses with injured hocks and with calcium deposits in the limbs (Smith, 1964). Over the years, IRT has been widely used in livestock production to register the surface temperature variations in the animals, emitted as infrared radiation, (Sathiyabarathi et al., 2016; McManus et al., 2016; Loyau et al., 2016, Castells et al., 2019). According to Chacur et al. (2018), the IRT is an easy technique to be applied,

allowing to perform diagnostic imaging on different body regions, without stress to the animals during the measurements.

Castells et al. (2019) related that, as well as ultrasonography, radiography and computed tomography, the infrared thermography is non-invasive tool useful to diagnose diseases. Furthermore, it is a useful tool that helps to understand the interactions between organisms and animal production systems (Eddy et al., 2001; Berry et al., 2003; Ludwig et al., 2013), and there are several applications in livestock production, Table 2.

Bovine

The detection of diseases using IRT can be used in a population of individuals where monitoring can be continuous or repeated, i.e. temperature detection can be performed in a group of animals or among individuals in the group. Lowe et al. (2019) evaluated the association between body thermography and neonatal diarrhea in calves and identified significant changes in the flank and shoulder surface temperatures before the onset of clinical symptoms of the disease. According to these authors, the decrease of temperature of these regions may be due to reduced food intake and metabolic activity caused by disease. Schaefer et al. (2012) evaluating the alterations of the body temperature in calves, reported a relation between the increase of body and eye temperatures and respiratory disease.

Mastitis is an inflammation of the mammary gland caused by several microorganisms, resulting in big economic losses to milk production due to alterations of physical, chemical and bacteriological characteristics of milk (Radostits et al., 2009). The onset of mastitis presents an inflammatory response associated with a rise in temperature in the affected region of the udder (Berry et al., 2003). Research showed that the IRT can identify thermal variations in the mammary gland surface due to increased blood flow in the affected region, Figure 1 (Eddy et al., 2001; Berry et al., 2003; Martins et al., 2013).

Figure 1 - Thermographic images of bovine mammary glandule. Caudal region (A) and left side lateral region (B)
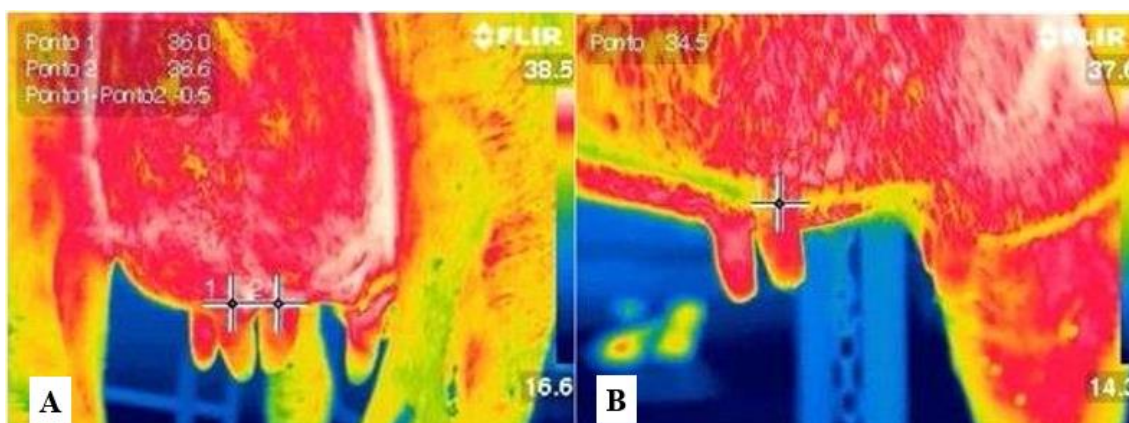

Source: Digiovani et al. (2016, p. 687)

In study, Zaninelli et al. (2018) found a significant and positive correlation between the udder skin surface temperature (USST) and somatic cell count (SCC) in dairy cows, recording an increase of approximately 1.6°C in affected mammary quarters, concluding that the IRT is a useful tool for early detection of mastitis. Similar result was found by Sathiyabarthi et al. (2018), which recorded the increase of 1.51°C in the USST in dairy cows with subclinical mastitis, when compared to USST in healthy cows, concluding that the IRT was effective in detecting animals with subclinical mastitis. In another study, Golzarian et al. (2017) observed difference for USST (0.44°C) between healthy and sick cows, showing that the IRT was able to detect slight differences in USST, being extremely useful in the diagnosis of mastitis. Therefore, the IRT can be a valuable tool that simplifies the method of control and detection of mastitis, reducing the diagnostic costs, reducing laboratory tests, contributing to the adaptation and promotion of ethical and sustainable techniques on dairy production.

Digital dermatitis is a serious disease that affects farm animals, causing economic losses and prejudice in animal welfare. According to LokeshBabu et al. (2018), the detection of early lameness is essential for animal welfare and reduction of economic losses. Harris-Bridge et al. (2018) evaluating the mean temperature as probable indicators of dermatitis in dairy cows, showed significant difference in temperature between lame and healthy hooves. Alsaaod et al. (2014) showed that the surface temperature of crown and hoof in dairy cows with digital dermatitis was 2.56°C and 2.49°C, respectively, higher than temperature of crown and hoof in healthy cows.

The standard method of counting parasites on cows and bulls requires a lot of time, work and attention to obtain an accurate result (Fraga et al., 2003; Fraga et al., 2005). A study using IRT, Cortivo et al. (2016) compared the standard method of counting tick and horn flies in cattle raised on pasture with an automatic counting program combined with infrared images. The authors reported that the IRT was efficient and accurate when compared to visual counting. According to those authors, these parasites have a lower temperature than the animals, being easily captured by thermal images (Figure 2).

Figure - 2. Thermographic images of ticks on the scrotum. Color scale (A) and gray scale (B)
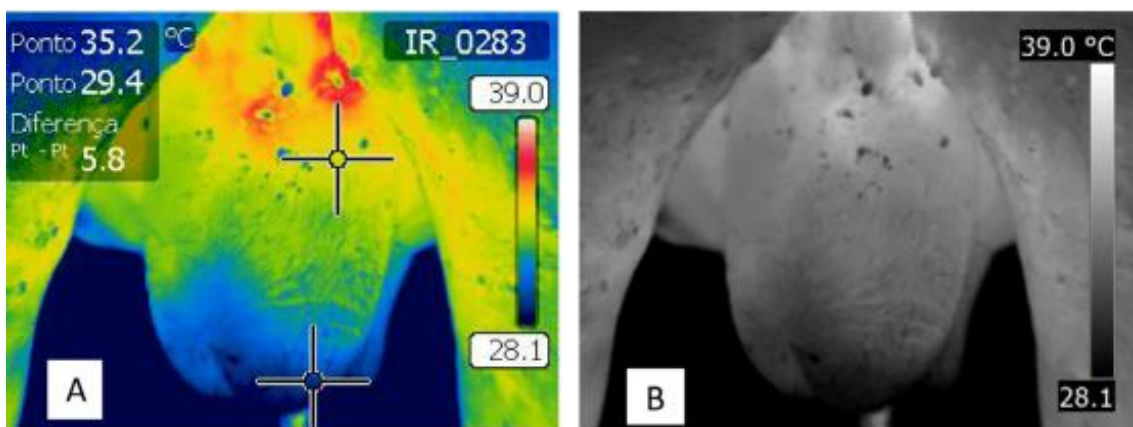
Source: Cortivo et al. (2016, p. 415)

Research have evaluated the ability of the IRT to identify heat stress in cattle and the best anatomical region that would indicate this situation. Mammals can maintain a constant body temperature in several environmental conditions, however when body temperature is above normal, these organisms do not function properly (Hansen, 2013). Daltro et al. (2017) showed that the IRT allowed to show that purebred Holstein cows are less heat tolerant when compared to crossbred Holstein cows, and that the mammary gland would be the ideal anatomical region to find heat stressed animals.

Cardoso et al. (2015) recorded differences on the body surface temperature between several Zebu breeds (Gir, Girolanda, Nellore, Indubrasil and Sindhi). The study showed that the temperatures were significantly influenced by environmental factors. Moreover, the morphometry, coat and skin color traits affected the skin surface temperature, rectal temperature, physiological parameters, and thermal regulation. The study also reported that the Gir breed was the least adapted to the climatic conditions, while the Girolanda and Sindhi breeds were the best adapted. The eyes were significantly

more affected by the environmental effects and therefore could be used to identify animals under heat stress.

The traditional techniques of estrus detection may have some limitations in herds, directly compromising the reproductive efficiency and longevity of animals (Perez Marques et al., 2019). IRT has been applied as a tool to facilitate estrus or ovulation detection. In a study, Vicentini et al. (2020), showed that IRT is a tool to detect temperature variation during the proestrus and estrus phases in heifers, and that the regions around the vulva exhibited the highest temperature. Perez Marques et al. (2019) identified increase of the infrared temperature of 0.5°C and 1.20°C into 48 and 24 hours, respectively, before ovulation in various regions of the body during the estrus in cows, concluding that the IRT can be useful in identifying of pregnancy dairy cows, in estrus, cyclic or non-cyclic. Talukder et al. (2014) also reported an increase of 1.50ºC in the vulva surface temperature of cows 24 hours before the start of ovulation and a regression to normal 48 hours after ovulation, and that the IRT was able to identify 83% of the cows in estrus. According to Ruediger et al. (2018), the ability to detect estrus or ovulation can be due to the increase of tissue vascularization and blood flow of the vulva surface in females in estrus. Therefore, IRT has enormous potential for monitoring animal reproduction, aiming to improve herd fertility rates.

Management techniques prone to influence animal behavior, such as fear and pain, are among many factors that compromise animal welfare and livestock profitability. Therefore, the ability to measure fear in non-invasive ways is essential to assess animal behavior and welfare, to identify and correct actions that cause discomfort (Cannas et al. 2018). According to Sammer et al. (2019), the application of new tools able to identify management practices that cause fear and pain in cattle is necessary. Stewart et al. (2008) evaluating the ability of IRT to detect stressed cattle after management practices, registered that the eye temperature quickly reduced after handling, and this may be associated to the level of fear or pain of animals, suggesting that the IRT can be used to assess the degree of stress caused by different management practices at commercial livestock farms.

One of those techniques that can cause discomfort and fear in beef cattle is weighing. In most farms, the monitoring of weight gain is done by weighing the animals on scales, which requires restraining, causing discomfort and stress. However, research has evaluated the capacity of the IRT to assist and facilitate the handling of cattle

weighing. Stajnko et al. (2008) found positive correlations between infrared body temperatures and live weight in beef cattle, and that IRT can be used to estimate body weight quickly and without the need to contain the animals. According to Sammer et al. (2019), the application of these modern technologies that aim to adapt management systems is essential to maintain the productivity of the animal industry.

Animal feeding contributes about 70% of production costs, and animals with low feed efficiency can increase these costs. The ability of animals to use energy and convert it into products is called "feed efficiency". According to Leão et al. (2018), animals with high feed efficiency have lower residual food intake (negative intake), while animals with low feed efficiency have higher residual food intake (positive intake). Schaefer et al. (2018) reported that this information is fundamental to increase the productivity and sustainability of livestock production systems. However, Berry et al. (2014) revealed that these measurements have high operational cost in a large population of animals. Conventional methods, such as calorimetry and feed intake, cost approximately US $300.00/animal (Schaefer et al., 2018). So, researchers have shown that the IRT can be an alternative to assess the association between body surface temperature and physiological processes related to feed efficiency, especially on commercial farms (Montanholi et al., 2008). Leão et al. (2018) identified that the eye infrared temperatures were significantly higher (0.5°C) in calves with high feed efficiency, i.e., lower dry matter intake (-0.14 kg/day), when compared to calves with low feed efficiency, i.e., high dry matter intake (0.13 kg/day), suggesting that the IRT is a tool capable of identifying calves with better feed efficiency.

Montanholi et al. (2009) recorded moderate correlations between infrared temperature of eyes, cheeks, paws and residual food intake, dry matter intake and the weight gain in adult beef cattle, indicating that their infrared temperature can be useful to facilitate the assessment of feed efficiency in adult beef cattle. Schaefer et al. (2018) registered an increase of 0.37°C in cheek infrared temperature in dairy cows with positive residual food intake (1.93 kg/day), when compared to the animals with negative residual food intake (-1.76 kg/day). The authors concluded that the IRT is a quick and non-invasive method to measure the metabolic efficiency in dairy cattle due to the positive correlation (0.39) between residual food intake and cheek temperature.

Buffalo

In recent years the IRT has been applied to different goals in buffalo production, such as evaluation of thermal stress, body temperature, thermoregulation, and semen quality, among others. Body infrared temperature can be used as an indicator of thermal stress on a determined environment (Salles et al. 2016). IRT can detect the body temperature without the use of a rectal thermometer (Candido et al., 2020), without direct contact with the animal (McManus et al., 2016).

Barros et al. (2016) evaluating the variations of body IRT in buffalo bulls, estimated a correlation of 0.58 between maximum rectal temperature and maximum eye temperature, concluding that the IRT may be useful to detect the variations in buffalo bulls. According to Chacur (2017), high correlation between eye IRT and rectal temperature may be an alternative to make the measurement of temperature of buffaloes easier, reducing animal stress.

Sevegnoni et al. (2016) evaluated the thermoregulation response of dairy buffaloes by body mapping IRT in pre-milking and post-milking. They reported that the dairy buffaloes are sensitive to environmental variations and that after milking, the animals activate body thermoregulation mechanisms with greater intensity, suggesting that the skin surface temperature measured by IRT can be a better indicator of thermal comfort than the respiratory rate. According to Mitchell (2013), when an animal is under heat stress, the thermoregulation will involve physiological homeostatic mechanisms that will increase heat transfer from the core to the body periphery. This occurs due to the change in blood flow from the core to the skin surface and/or increased respiratory rate, at body periphery vasodilation occurs, in the skin, regulating the release of heat into the environment.

Chacur et al. (2018) analyzed the variations of udder surface temperature in different periods of mammary development in buffaloes. IRT detected little variations in udder surface temperature, thus reflecting the physiological changes expected for each phase. Ruediger et al. (2018) reported that the vulva IRT showed the physiological changes associated with the variation of progesterone concentration during the reproductive cycle of female buffaloes (Figure 3). According to authors, the strong correlation between the vulva surface temperature and progesterone plasmatic concentration can indicate pregnancy in female buffaloes.

Figure - 3. thermographyc images of the vulva in buffalo
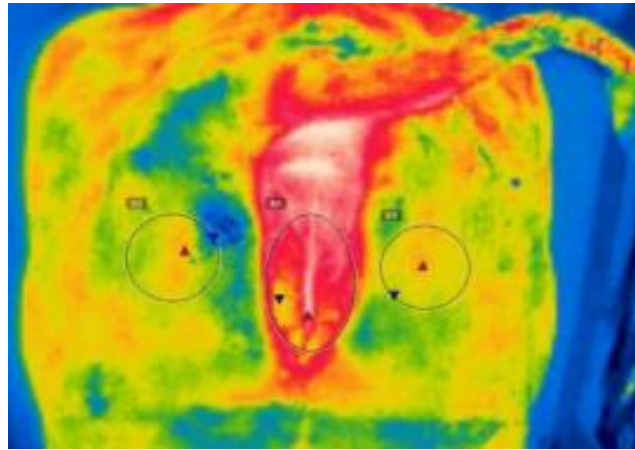
Source: Ruediger et al. (2018, p. 156)

Biological and cellular functions are affected by elevated temperatures, such as embryonic death and reduced sperm quality, affecting animal reproduction. According to Hansen (2009), the rise in body temperature can compromise the function of germ cells, embryonic development and other cells involved in reproduction. Reproductive efficiency of the herd depends on the sperm quality used in reproduction. Therefore, semen quality assessment requires specific laboratory equipment and methods. Thus, researchers have used IRT as a method to assess semen quality through testicles surface IRT. Yadav et al. (2019), reported that scrotal surface IRT in buffalo bulls was positively correlated with sperm mass motility (0.29) and sperm concentration (0.20), and negatively correlated with sperm abnormality (-0.17). Animals with higher scrotal temperature gradient ($\geq$ 6.5°C) had better semen quality than those with an inferior gradient ($\leq$ 4.0°C and 4.1 - 6.4°C). According to these results, the greater the temperature gradient, the better the sperm quality, and that IRT can be used as a tool to assess the reproductive performance of buffalo bulls.

Ahirwar et al. (2018) showed that the higher the air temperature and humidity index, the higher the superficial testicle IRT of buffalo bulls, and consequently, the higher the abnormal sperm rate, concluding that the scrotal IRT was enough to identify the environmental variables affecting semen quality. According to Chacur (2017), that is due to positive correlation between scrotal temperature and semen quality, satisfactorily indicating the semen quality. Nonetheless, semen quality in buffalo bulls can be associated with the testicle coverage thickness, which can compromise the testicle heat loss. According to Yadav et al. (2019), buffalo bulls with little testicle coverage thickness

have a lower percentage of abnormal sperm than buffalo bulls with greater testicle coverage, and this may be due to greater amount of scrotal heat loss and greater thermoregulatory capacity of buffalo bulls with smaller testicle coverage.

Ovine and caprine

The choosing of animals more adapted to climatic change is a decisive factor to obtain good productive and reproductive rates. The maintenance of body temperature reflects the thermoregulation ability of animals. Hansen (2009), reported that during heat stress the animals regulate body temperature, reducing food intake, which decreases metabolic heat production, maintaining ideal body temperature. According to Montanholi et al. (2009), the metabolic heat produced is distributed to the body through the blood, however, when animals are exposed to high ambient temperature, peripheral vasodilation occurs, increasing blood flow to the skin to dissipate internal heat to the environment.

Pulido-Rodríguez et al. (2021), studying the thermoregulatory response of Santa Inês, Dorper × Santa Inês and White Dorper × Santa Inês sheep, found a positive correlation between rectal temperature and ocular infrared temperature (0.71), and that all breeds have similar thermal tolerances, concluding that IRT is a tool capable of detecting changes in body temperature and that it can be used to identify animals that are more tolerant to heat stress situations. In another study, evaluating the heat tolerance of different sheep breeds, Cruz Júnior et al. (2015) showed that Santa Inês was more tolerant to tropical conditions than the other breeds. So, this breed was considered the most suitable breed in this environmental condition, concluding that the IRT can be a useful tool to identify sheep breeds more adapted to the tropics.

McManus et al. (2015) showed that lambs less efficient in thermoregulation had higher IRT and lower carcass weight. These authors concluded that the lighter carcasses could be associated with reduced food intake, compromising the productivity of animals. Silva et al. (2014), evaluating the adaptation of Parda Alpina and Anglo-Nubiana dairy goats to dry weather, reported that the neck, rump, thigh, and flank IRT presented differences between breeds. The highest infrared temperatures and respiratory rates were recorded in the Parda Alpina breed, therefore, being considered less adapted to dry weather.

In a study about the use of IRT to register a physiological reaction through the change in eye temperature as response to stress and fear during handling, Cannas et al.

(2018) suggested that IRT combined with behavioral data can identify the stress and make inference about negative emotions in sheep. IRT allows the monitoring of herd health without direct contact with animals. The use of IR as an image diagnostic method has been tested for some respiratory diseases, such as enzootic sheep nasal adenocarcinoma. This disease is characterized as a tumor in the upper airways, causing pressure around the nasal bone, leading to deformation of the bone or of the entire skull in more severe cases. The IRT image of the nostril of a healthy animal had blue and green colors (Figure 4A), while in sick animals, IRT images showed red and white in the injured region of the nose. This is because in healthy animals, the air that travels through the nostril cools the area, while in sick animals, the air does not penetrate normally, causing the injured area to heat up, displaying color red or white, Figure 4B (Castells et al., 2019).

Figure - 4. Image infrared of a healthy animal with normal refrigeration of the nostril (A). Image infrared of a sick animal with a enzootic sheep nasal adenocarcinoma (B).
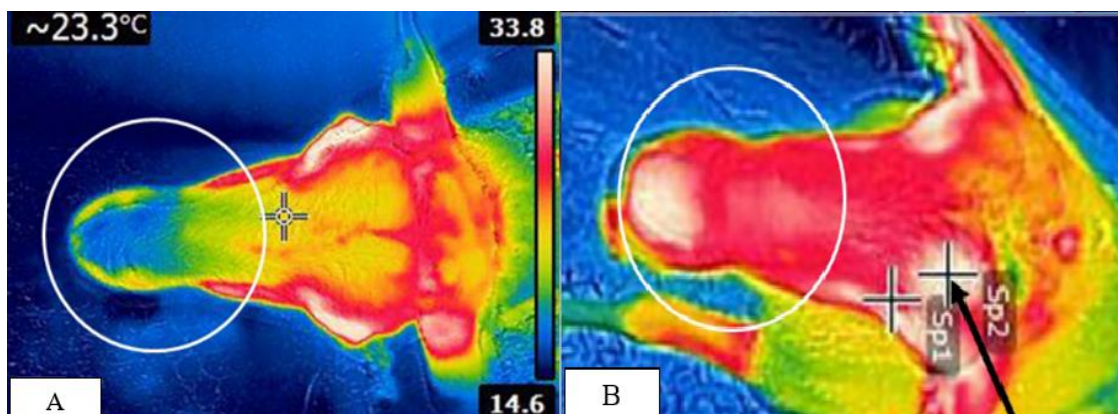
Source: Castells et al. (2019, p. 113), figure adapted

Laminitis is one of the main diseases that affect sheep, especially in places with high humidity and rainy areas. However, monitoring and diagnosing this disease in the field is very laborious and difficult to carry out, especially in large herds, where it is necessary to visually examine each hoof with of the sheep (Byrne et al., 2019). Byrne et al. (2019) assessing the use of IRT to detect lameness in sheep, found a temperature difference of 8.5°C between healthy and infected hooves, and that the IRT showed sensitivity of 77% and specificity of 78%, indicating that it has the potential to detect infection in sheep hooves.

Another disease of great economic importance in the production of dairy sheep and goats is mastitis. Mastitis is a serious health problem for dairy sheep and IRT has

been a tool for mastitis detection in sheep and goat. Castro-Costa et al. (2014) detected variations in udder surface temperature of ewes associated with the inflammatory process caused by mastitis. Martins et al. (2013) reported that IRT is a promising technique to detect subclinical mastitis in ewes. According to these authors, this may be due to, in the acute process, during subclinical mastitis, the affected region produces a higher temperature, while in clinical mastitis, the temperature is lower.

The IRT has been reported as a useful tool for identifying the variation in surface temperature of the vulva in estrus goats. Façanha et al. (2018) identified an increase in temperature in the vulva region by infrared thermography (Figure 5B and Figure 5C). According to these authors, the accuracy and agility of IRT, when combined with visual detection of estrus and estrogen hormone levels in Canindé goats, is a faster and more accurate option for estrus detection by breeders. However, more studies are needed.

Figure - 5. Photography (A) and thermographic image of vulvar and perivulvar regions of Canindé goats in pro-estrous (B) and estrous (C) identified by external signs and hormonal measurements
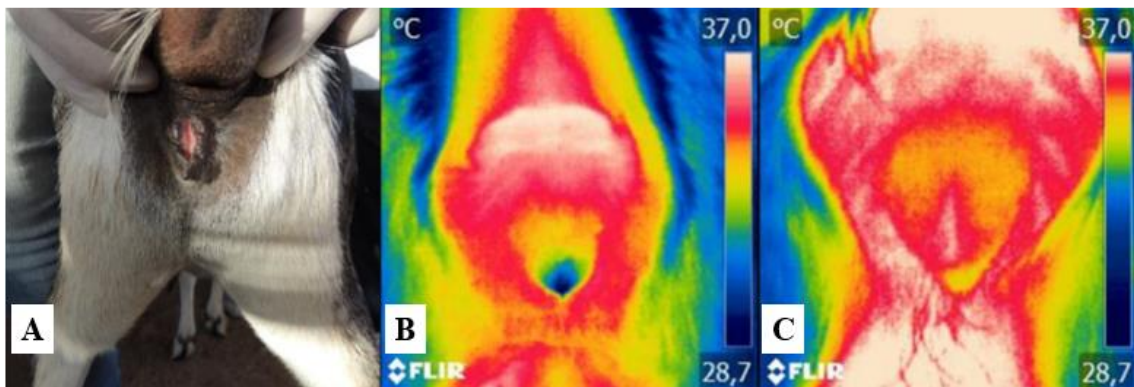

Source: Façanha et al. (2018, p. 51)

Swine

The monitoring and controlling of ambient temperature, and the maintaining optimal thermal conditions are the main difficulties for pig production. Some researchers have shown that the IRT can facilitate the measurement of body temperature in swine due to the association between body IRT and rectal temperature. In a recent study, Schmitt and Driscoll (2021) evaluating the IRT as an alternative to measure temperature of piglets after birth, registered a stronger correlation between rectal temperature and ear base IRT. According to authors, piglets with lower birth weight had less IRT and higher risk of

hypothermia, confirming that IRT could be used to investigate the risk of hypothermia in piglets.

Justino et al. (2014) evaluated the heat loss and variables related to the thermal comfort of lactating sows submitted to an evaporative cooling system during the summer. The results indicated that the evaporative cooling system significantly reduced the skin surface temperature in 0.47°C when compared to sows in natural ventilation, and increased heat losses by convection and evaporation, resulting in lower skin surface temperature. In another study, Cook et al. (2015) reported that IRT can be used to detect febrile responses and behavioral changes after vaccination against Parvovirus in weaned piglets. They affirmed that 3 h after getting the vaccine, the animals showed higher body surface temperatures and grouping behavior, when compared to unvaccinated animals (Figure 6A and Figure 6B). The IRT is a tool for obtaining precise measurement of cardiorespiratory signals in swine (Pereira et al., 2019). Boileau et al. (2019) showed that the dorsal plane is the best anatomical region for thermographic studies in pigs when compared to the eye or ear. The IRT can be used to obtain measures and responses associated with stress situations, and welfare on farm pigs.

Figure - 6. Spatial distribution of pigs after (A) and before (B) vaccination against parvovirus. In (A) observing the behavior of watering between the animals after 3 h from receiving the vaccine.
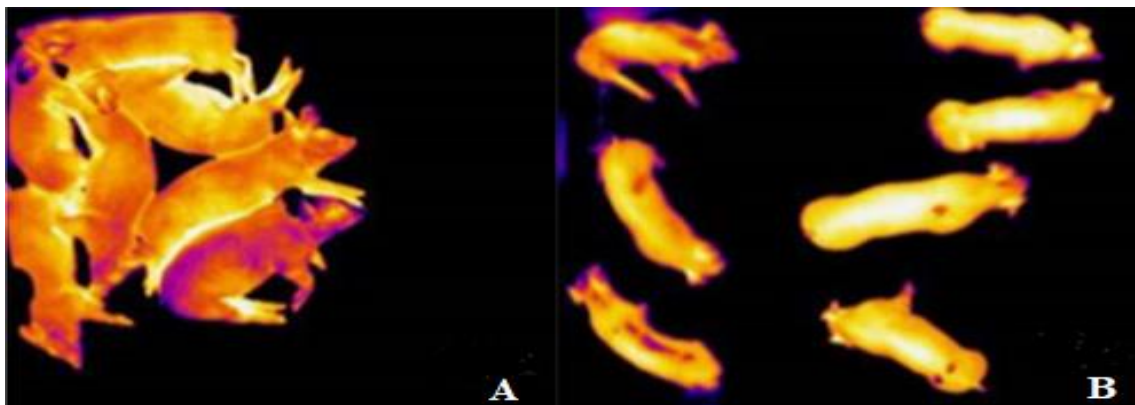
Source: Cook et al. (2014, p. 341), figure adapted

Bird

In poultry production, body temperature is obtained by the rectal thermometer. This method is invasive and causes stress in the animals (McManus et al., 2016). So, studies have tested IRT as an alternative to measure the body temperature in birds.

Candido et al. (2020) reported a strong correlation between cloacal temperature and body IRT in broiler chickens. The study also recorded 95% accuracy of IRT, suggesting that this technology can be a useful tool to obtain the body temperature in broiler chickens.

In another study, Nascimento et al. (2014) found a high positive correlation between the IRT of poultry facilities and body IRT of broilers chickens. The authors highlighted the importance of the materials of choice, pointing out that they must have low thermal conductivity to reduce heat transfer from the external environment to facilities and to the chickens.

Thermal stress has a negative impact on poultry production. Therefore, in addition to the correct management and suitable poultry facilities, the choice of animals should consider the climatic conditions and the animal's thermoregulation ability (Justino et al., 2014). According to Malcom et al. (2013), body surface temperature can provide information about the degree of thermal stress of animals. In production poultry, Loyau et al. (2016) reported that the body surface temperature of laying hens is an indicator to be used as a selection criterion for climate adaptation in chickens. Furthermore, the authors showed that the IRT is easy to be standardized and automated on farms, providing an accurate temperature reading in large numbers of animals.

Alves et al. (2012) reported that laying hens in cold stress expended about four times more energy to keep homeothermy due to the decrease in the ability of birds to consume food. According to Young (1981), the decrease in food intake can be due to the behavioral changes in the animals, such as grouping between laying hens to reduce the loss of body heat. Furthermore, the reduction of egg production may be associated with the deviation of energy to keep the homeothermy, reducing the efficiency of food conversion. Ferreira et al. (2011) evaluating the behavior of body IRT in broilers and diets with different energy levels, showed that broilers fed with diet rich in energy lost less metabolic heat than broilers fed a lower energy diet, and that the IRT was efficient to detect variations in metabolic heat production these animals.

Pododermatitis is a disease of economic importance in poultry which affects the locomotion of the birds, compromising the productivity, carcass quality and egg production. The IRT has been used as a tool to identify pododermatitis in birds. In commercial farms, poultry feet contain soil, feed and other dirt, which compromise the skin emissivity. Moe et al. (2018) evaluating thermal variations by IRT in turkey paws, reported that the maximum foot pad temperature was more accurate in detecting thermal

variations and, therefore, could be a good anatomical region used in future thermographic studies of detection of pododermatitis in turkeys. Jacob et al. (2016) revealed that chickens with pododermatitis have a 5.0°C lower surface temperature on the skin of their feet than healthy chickens (Fig. 7.A and Fig. 7.B). According to the authors, the decrease in the surface temperature of the feet of sick birds may be associated with vasoconstriction caused by skin necrosis. The study concluded that the IRT of the feet can replace visual inspection in the identification of clinical and subclinical lesions in broiler chickens. According to Harris-Bridge et al. (2018) the development of an automated system to detect pododermatitis in commercial birds is essential, reducing the need for visual inspections during animal locomotion.

Figure - 7. Thermography imagens of broilers with pododermatitis (A). Birds without footpad lesions presented feet with uniform surface temperature and bird with pododermatitis (B). Birds with pododermatitis presented points on the footpad with low surface temperature indicating tissue necrosis
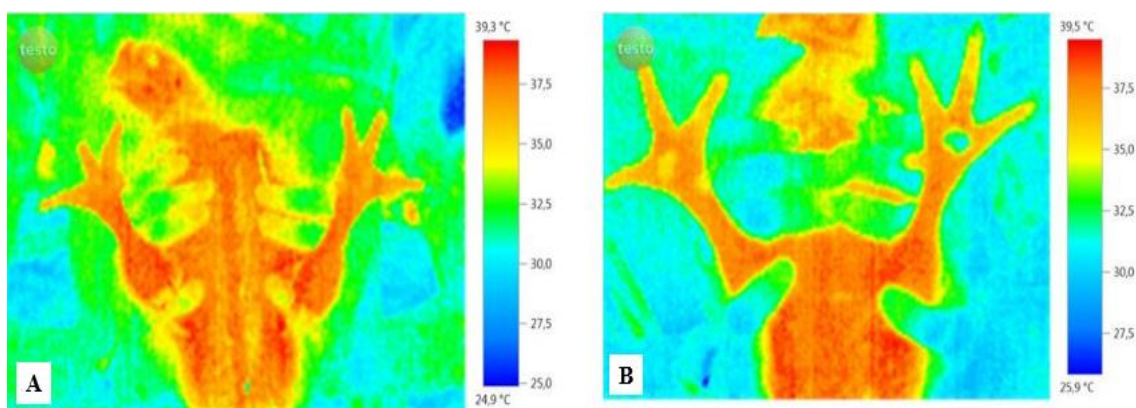
Source: Jacob et al. (2016, p. 257)

Limitations of the IRT in livestock animals

Even if infrared thermography has some limitations, it can be used in thermographic study of animals to increase the precision of temperature measurement. Researchers have shown that several factors can affect the reliability of IRT, such as camera configuration (Knížková et al., 2007); camera cleaning (Glavas et al., 2018); feeding period (Montanholi et al., 2008); Day period (Castro-Costa et al., 2014); Pelage and plumage (Malcolm, 2013; Pulido-Rodrígues et al., 2021); body color (Ludwing et al., 2013; Chacur et al., 2014); solar radiation on the study surface (Ludwing et al., 2013; Chacur et al., 2014); season (Chacur et al., 2016; Ahirwar et al., 2017); breed (Cruz Júnior

et al., 2015); milking period (Yang et al., 2018); air temperature and humidity (Chacur et al., 2016; Schaefer et al., 2018); animal stress (Pulido-Rodrígues et al., 2021) and reproductive stage (Deak et al., 2019). According to Polat et al. (2010), the identification and control of these factors is necessary when using IRT.

The elaboration of specific protocols for each animal species and anatomical region allows to reduce errors and increase the accuracy of IRT in future studies (Moe et al. 2018). Studies have shown that other sources of variation, such as anatomical region, analysis methods, feeding time, camera focus and angle, milking and physical activities of animals before of the measurements should also be considered in thermographic studies (Knížková et al., 2007; Talukder et al., 2014; Moe et al., 2018).

In addition, other factors such as animal handling, non-standardized environment and animal physiology should be taken into account before thermographic analysis (Ricarte et al., 2014). Furthermore, it is necessary to understand the principles related to thermal variations and surface heat exchanges, to know how these thermal distributions can be influenced by the relationship of physiological and metabolic processes with pathologies and adaptive factors.

Perspectives of IRT in livestock animals

Currently, thermal imagers are developed with innovative technology, increasingly affordable acquisition cost and considerable durability (Ricarte et al., 2014). Besides, the new devices have greater precision, around ±1.0°C (Nääs et al., 2014), and the thermal images are saved and processed easily, quickly, and can be applied as a routine procedure complementary to clinical examinations in animals (Chacur et al., 2016).

Infrared thermography is a promising method for several goals in livestock production. Due to its non-invasive nature and safe procedures (Castells et al., 2019) IRT provides a way to obtain data in different anatomical regions, without stress (Chacur et al., 2016). The high correlations between normal thermal variations and abnormal thermal variations from inflammatory processes and other clinical data, show that the IRT still has a lot to contribute for livestock production. The technological development of the IRT method should be explored to facilitate the monitoring and controlling of body temperature changes of animals.

CONCLUSIONS

Infrared thermography has been used for several purposes in animal production as it's a non-invasive, accurate and quick tool for detecting changes related to metabolic, physiological, and inflammatory processes in animals. Despite being more used in cattle, IRT can be applied in several animal species and with different purposes, to substitute the conventional methods of diagnosing diseases, inflammatory processes, reproductive stage, semen quality, selection aid, adaptive traits and heat stress. In addition, IRT can quickly identify disease, preventing the spread of contagious maladies to the herd.

This review aims to clarify some difficulties, advantages, and the various possibilities of IRT use in livestock production. However, more studies are needed to improve the thermographic apparatus and software, and to obtain standardized detection models with sensitivity to diagnose physiological and biological changes in the several animal species.

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