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THE USE OF INFRARED THERMOGRAPHY TO
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CORONARY BAND OF DAIRY COWS AS A TOOL FOR
LAMENESS DETECTION

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By

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ABSTRACT

THE USE OF INFRARED THERMOGRAPHY TO DETERMINE SURFACE TEMPERATURES OF THE CORONARY BAND REGION OF DAIRY COWS AS A TOOL FOR LAMENESS DETECTION

By

Beth Munsell

Lameness is a major concern in the dairy industry because of its implications on animal welfare and economics. Currently, locomotion scoring is the most common method to detect lameness. However, this method is subjective, causing variability in detected rates of lameness. The objective was to expand our knowledge of the use of infrared thermography (IRT) in dairy cattle and to assess its usefulness as an on-farm tool for lameness detection. We hypothesize that IRT may be able to detect inflammation in the coronary bad region that is associated with lameness earlier than locomotion scoring. In Study 1, the rear limbs of 10 sound Holstein cows were imaged at different times of the day and from different views of the hoof. In Study 2, 15 lame and 15 sound cows were selected based on locomotion score and their rear limbs were imaged for 5 days prior to and 5 days following hoof trimming. Results from both Study 1 and Study 2 indicate that for cows without hoof lesions, there is no significant difference in surface temperature between the left and right rear limbs. Also, in Study 2, results showed a significant difference in temperature between the left and right rear limb when only one of these limbs was affected by hoof lesions. These results indicate that IRT may be a useful tool to assess lameness in dairy cattle.

I dedicate this achievement to my family, who have always encouraged me to be the best, but who have loved and supported me regardless.

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KEYS TO SYMBOLS OR ABBREVIATIONS

ΔT - Temperature difference

μm - Micrometer

λ - Wavelength

BIC - Bayes

BRD - Bovine respiratory disease

BVD - Bovine viral diarrhea

c_1 - Constant of the value 3.743×10^8 W $\cdot$ μm/m^2

c_2 - Constant of the value 1.4387×10^4 μm $\cdot$ K

cm - Centimeter

d - Day

DFD - Dark firm and dry

DIM - Days in milk

ε - Emissivity

exp - Exponent

E_λ - Emissive power

$E_{\lambda,b}$ - Emissive power of a blackbody

h - Hour

IRT - Infrared thermography

K - Degrees Kelvin

LRL - Left front lateral claw

LS - Locomotion score

LRL - Left rear lateral claws

LRLM - Left rear lateral and medial claws

LRM - Left rear medial claws

m - Meter

MBST - Mean body surface temperature

MST - Maximum surface temperature

PSE - Pale soft and exudative

SARA - Sub acute ruminal acidosis

SEM - Standard error of the mean

RFL - Right front lateral claw

RRL - Right rear lateral claw

RRLM - Right rear lateral and medial claws

RRM - Right rear medial claw

T - Temperature

CHAPTER ONE

Introduction

Lameness is a multi-factorial disease associated with an abnormal gait caused by a cow's attempt to alleviate pain (Scott, 1989; Kelton et al., 1998; Galindo and Broom, 2000). Lameness is also a major animal welfare concern (Hemsworth et al., 1995). Based on results from trained observers, Kopcha et al. (2003) reported that 52% of a sample of Michigan dairy cows were mild to severely lame. Lameness rates across the US and the UK have been reported between 5% and 68.9% (Eddy and Scott, 1980; Wells et al., 1993; Hedges, 2001; Cook, 2003). Greenough and Weaver (1997) estimated that each case of lameness costs the producer between $300 and $400 for various reasons that will be discussed further in Chapter 2.

The early detection of lameness and the lesions that cause lameness in cattle is important to facilitate the relief of suffering (Whay, 2002). Currently, locomotion scoring is the most common method used to quantify lameness. However, scoring systems are subjective resulting in variability of the perceived incidence of lameness. Using a technology-based approach to quantify lameness will decrease this variability (Tasch and Rajkondawar, 2004) and may facilitate lameness detection earlier than locomotion scoring. To date, force plates (Tasch and Rajkondawar, 2004) and pressure plates (Scott, 1988; van der Tol et al., 2002, 2003; Almeida et al., in press) have been used to detect lameness. Other methods to detect lameness should be investigated. Researchers recently have begun to investigate the use of infrared thermography (IRT) to detect lameness in cattle (Schmidt et al., 2003; Whay et al., 2004; Haley et al., 2005;

Nikkah et al., 2005). Previous studies have provided evidence that IRT may be a useful tool for lameness detection in dairy cattle. However, these studies have provided limited results and conclusions on lameness detection on-farm. In addition, none of these studies have reported baseline data of sound animals.

The main objective of the research reported herein was to expand our knowledge of the use of IRT in dairy cattle and to assess the usefulness of IRT as an on-farm tool for lameness detection. To answer this question we performed two studies. In the first study (Chapter 3), 10 sound, lactating Holstein cows were imaged at multiple times over a 2-d period to give us an understanding of the normal thermal characteristics of healthy animals. In the second experiment (Chapter 4), 15 sound and 15 lame cows were imaged in order to determine the ability of IRT to detect lameness. We hypothesize that by focusing on the coronary band region, IRT will be able to detect inflammation associated with lameness in the distal limb(s) in dairy cattle. We anticipate that this technology may be used to identify lameness at an earlier stage than by currently used methods and protocols.

CHAPTER TWO

Review of Literature

Section 1: Review of Dairy Cattle Lameness Literature

1.1 Definition and Incidence of Lameness

There are multiple definitions for lameness in cattle. Kelton et al. (1998) defined clinical lameness in cattle as an episode of abnormal gait attributable to either the foot or leg, regardless of etiology or duration. Lameness also has been defined as the abnormal gait caused by painful lesions of the limbs or back as the cow attempts to alleviate or avoid pain in the affected area (Scott, 1989) by reducing propulsion, reducing her speed of walking, arching her back and lowering her head (Almeida et al., in press). The definition of clinical lameness in cattle is variable and these imprecise definitions may cause misclassifications of lameness (Green et al., 2002).

Lameness is a major animal health and welfare concern within the dairy industry that also has significant economic effects (Nordlund et al., 2004). The term welfare refers to the state of an individual as regards to its attempts to cope with its environment (Broom, 1991). On a dairy farm, different factors can affect cow welfare and the practical use of the term welfare applies to the comfort of the cow in the environment and husbandry that is provided by the farmer. This includes housing, nutrition and the manner in which farm workers treat the animals. Lameness may be affected by all of these factors and therefore can serve as a means to measure the overall welfare of a dairy herd (Hemsworth et al., 1995).

In a survey of a sample of Michigan dairy farms, Kopcha et al. (2003) reported that 52% of 13,144 cows (about 4% of the total adult population in MI) were at least mildly lame and 42% were moderately or severely lame as scored by trained observers. Cook and Nordlund (2003) reported lameness rates ranging from 7.9 to 51.9% in Wisconsin dairy herds with mean lameness of 24.8% in the winter and 21.8% in the spring/summer. Wells et al. (1993) reported slightly lower lameness incidence rates of 13.7 % in the summer and 16.7 % in the spring in Minnesota dairy herds. Overall, Cook and Nordlund (2003) reported that 23% of US dairy cows are lame at any given time. Estimates of lameness incidence in the UK have been reported between 5% (Eddy and Scott, 1980) and 68.9% (Hedges et al., 2001). The lack of a standard definition of clinical lameness in cattle discussed earlier may partially explain the high variability in the reported incidence of clinical lameness (Green et al., 2002).

1.2 Impacts of Lameness

According to Greenough and Weaver (1997) the average cost associated with each case of lameness is between \$300 and \$400. These losses may result from more than one source. The most significant costs of lameness come not from the treatment of the problem itself, but from the aftereffects of the incident such as decreased milk production (Warnick et al., 2001; Green et al., 2002), longer calving intervals, reproductive disorders (Hernandez et al., 2005; Sprecher et al., 1997), premature culling, and reduced carcass weight at culling (Enting et al., 1997).

Warnick et al. (2001) found that lame cows had reduced milk production following treatment of the lameness. This particularly was evident in multi-parous cows and cows with more severe cases of lameness. Reproductive disorders associated with lameness are another key concern to dairy producers. Hernandez et al. (2005) found that cows classified as lame were 3.5 times more likely to have delayed ovarian cyclicity, which can have detrimental effects on a cow's reproductive cycle. Cows with more severe cases of lameness are predicted to have a longer period of time from calving to first service and pregnancy, spend more time in the breeding herd and require more services to become pregnant (Sprecher et al., 1997). These reproductive disorders likely contribute to the decline in total lactation milk production because longer calving intervals result in lower milk production in later lactation (Oltenacu et al., 1981).

Other losses due to lameness may include premature culling and decreased carcass weight of cull cows (Enting et al., 1997). Sprecher et al. (1997) reported that lame cows are 8.4 times more likely to be culled from the herd. When cows must be culled from the herd, economic losses result from missing income from the milk and offspring that were not produced. Lame cows are also likely to have a decreased carcass weight which will result in lower returns to the farmer when the animal is sent to slaughter (Enting et al., 1997).

1.3 Causes of Lameness

In dairy cattle, lameness most readily occurs due to diseases of the foot (Clarkson et al., 1996; Warnick et al., 2001). Shearer and Van Amstel (2000) reported that 90% or more of lameness is associated with the foot and most of these cases occur in the rear feet, particularly in the lateral claw. Lameness is ultimately a result of the cow's genetics or environment (Fatehi et al., 2003), however, the numerous factors associated with both of these parameters makes identifying the specific cause of lameness problematic for producers.

Both direct and indirect consequences of feet and leg problems can be reduced by genetic selection (Fatehi et al., 2003). van der Waaij et al. (2005) reported that there is evidence that susceptibility to a number of claw disorders is heritable. Boelling and Pollott (1998) also reported correlations between genetic parameters and lameness, but concluded that changes in body conformation and locomotion over the years need to be taken into consideration for genetic selection. Fatehi et al. (2003) also reported that the effects of different environments and management practices had a more pronounced effect on lameness than genetic parameters.

Environmental factors that affect lameness include management procedures as well as housing systems and conditions. Proper feeding management and nutrition plans are imperative for maintaining the health and vitality of a dairy herd. Both subacute ruminal acidosis (SARA) and acute acidosis appear to be associated with laminitis (Nocek, 1997; Stone, 2004; Vermunt, 2000). Rumen acidosis in cattle is caused by large increases in the amount of lactic acid in the rumen, attributable to high carbohydrate, low fiber diets (Nocek, 1997) as well as meal size and frequency (Owens et al., 1998). The link between acidosis and laminitis appears to be associated with the release of vasoactive substances during the decline in rumen pH, which ultimately destroy the microvasculature of the corium and lead to lesions of the hoof (Nocek, 1997).

The cow's housing environment effects both the spread of infectious diseases associated with lameness, as well as the physical integrity of the hoof. When assessing the housing environment of a dairy cow, a variety of factors need to be considered, such as the type of housing system, bedding, flooring, the cleanliness of the environment, and the stocking density. The type of housing system can have a significant impact on lameness (Cook and Nordlund, 2003). Housing systems include free-stalls, tie-stalls, group housing on straw packs or compost, and pasture based systems or a combination of any of these systems. Free-stall housing is the most common system implemented on large scale dairy farms in the US. Cook and Nordlund (2003) found significantly lower incidence of lameness in herds using sand bedding in free-stalls when compared to other types of stall surfaces, including rubber mats and rubber crumb filled mattresses. Design of free-stalls also may have an effect on lameness. Gaworski et al. (2003) reported that cows with access to larger stalls spent 70% more time standing with all four feet in their stalls than those housed in smaller stalls. This increased time standing in the stall is thought to be favorable as it decreases the amount of time the cows spend standing on concrete which is a contributing factor to hoof injuries (Gaworski et al., 2003).

Rubber flooring provides an alternative flooring surface to the commonly used concrete. In a study looking at time budgeting of cows housed in barns with rubber flooring in front of the feed bunk, Fregonesi et al. (2004) concluded that cows find rubber flooring more comfortable to stand on than concrete. Wilkes (2005) found that cows housed in a free-stall facility with rubber mat in front of the feed bunk had lower lameness scores than cows housed in pens with concrete floors. However, Vokey et al. (2001) concluded that the use of rubber flooring had no effect on reducing the number of claw lesions or clinical lameness.

It also is important that cows are provided with a clean and well-maintained environment. Cook and Nordlund (2003) reported that cattle housed in wet conditions with manure contamination are more likely to contract infectious foot diseases such as interdigital necrobacillosis (foot rot), heel horn erosion and digital dermatitis (heel warts). Keeping a clean environment also helps to reduce the risk of physical injuries to the hoof by keeping floors clear of stones or other items which may cause bruising or puncture the sole.

Stocking density is another factor to consider when assessing at the environment of dairy cattle. Overstocking will lead to more manure production which could contribute to the spread of infectious foot diseases (Cook and Nordlund, 2003). Also, Cook et al. (2004) reported that overstocking could limit access to feed, which may cause cows to eat larger, less frequent meals which could lead to ruminal acidosis. Overstocking also has been shown to reduce laying times which is believed to be linked with lameness (Friend et al., 1977; Gaworski et al., 2003).

1.4 Lameness Detection Methods

Traditionally, the herdsperson has detected lameness in cattle through observation of the cow's behavior. However, the subjectivity of this approach led researchers to devise more objective methods of detection through lameness scoring systems. Manson and Leaver (1988) published a lameness scoring system using a 9-point scale with scores 1 through 5 pertaining to animals that are not clinically lame. While this system has the advantage of stressing the importance of detecting lameness early, the large point spread makes the system complicated to learn and implement (Nordlund et al., 2004). Simpler, more accessible systems using 4 and 5-point scales were developed by Wells et al. (1993), Sprecher et al. (1997), Vokey et al. (2001) and Nordlund et al. (2004). The system devised by Wells et al. (1993) uses a scale range from 0 to 4 while the Nordlund et al. (2004) and Vokey et al. (2001) systems use a range from 1 to 4 with a score of 4 indicating a severely lame animal in all of these systems. Sprecher et al. (1997) proposed a 1 to 5 point scoring system based upon both gait and posture that has become a widely used system in dairy research and herd management.

The variety of lameness scoring systems allows researchers to choose a system to suit them best. However, because there is no set standard for locomotion scoring, perception of lameness is variable. As reported earlier, trained observers determined that 52% of dairy cows in a sample of Michigan herds are at least mildly lame, while results of a survey in the same study indicated Michigan dairy producers perceived the incidence of lameness to be an average rate of 4.5% (Kopcha et al., 2003). This perceived low incidence of lameness also was found in a recent survey conducted by Edgecomb et al. (2006), which indicated that 53% of Michigan dairy producers perceived lameness incidence rates to be less than 10% in their herds. These differences between perceived and actual incidence of lameness may be accounted for by the subjectivity of locomotion scoring, which often results in high inter-observer variability (Engel et al., 2003).

The use of a technology-based approach to lameness detection will help the dairy industry to assess the realistic level of lameness prevalence on-farm (Tasch and Rajkondawar, 2004). Changes in ground reaction force measured using force plates were used as indicators of lameness in horses (Clayton et al., 2000) and cattle (Scott, 1989; Tasch and Rajkondawar, 2004). Tasch and Rajkondawar (2004) recently developed a mechanical approach to lameness detection which analyzes the ground force reaction of each limb to assess how a cow is distributing her weight to determine if a cow is lame.

This technology is now commercially marketed by Bou-Matic as the StepMetrix system. This automatic system may prove to be a valuable and more standardized alternative to existing scoring systems which are based on observation alone (Tasch and Rajkondawar, 2004).

Other studies have used pressure plate technology to assess weight distributions within each claw (Scott, 1988; van der Tol et al., 2002, 2003; Almeida et al., in press). Scott (1988) measured the pressure distribution of a cow while walking and found that the hoof wall carried the most pressure. This finding was contradicted by van der Tol et al. (2002) who found that the maximum pressure was exerted almost always in the sole of the claws. van der Tol et al. (2003) also found that pressure is not distributed evenly between claws in both the fore and hind limbs, with more pressure was being exerted on the medial claw in the fore limbs and on the lateral in the hind limbs. Almeida et al. (in press) used similar pressure plate technology to detect lameness in heifers with hairy heel warts. In this study, peak vertical force was measured as Holstein heifers walked across a pressure plate after assessment of locomotion based on the Sprecher et al. (1997) system. The researchers concluded that gait abnormalities that were undetectable in locomotion scoring were evident using a pressure plate. This research indicates the potential of using a pressure plate to enhance lameness detection in cattle (Almeida et al., in press).

Lesions associated with lameness also may be assessed through tactile inspection of the hoof by checking for soft soles or inflammation. However, hoof inspections are typically carried out only after cows are showing obvious signs of lameness or during routine hoof trimmings. By using IRT to assess surface temperatures of limbs, it may be possible to identify inflammation at an early stage. Infrared thermography has previously been used in several animal studies and because IRT is the main focus of the current research, an in-depth review of this technology is presented in the next section.

Section 2: The Use of Infrared Thermography as a Diagnostic Tool for Livestock

2.1 Introduction

A growing number of animal science studies use infrared thermography (IRT) to assess the distributions of surface temperatures in livestock. Variations in surface temperature of mammals often indicate the presence of an underlying pathology (Cena and Clark, 1973; Barnes, 1968), although surface temperatures also are influenced by the environment. Early instruments used to detect surface temperature included mercury thermometers and thermocouples; however, these methods require surface contact, which may alter the temperature of the surface itself (Barnes, 1968; Stoll, 1964). IRT provides a non-invasive, non-tactile method for determining surface temperature by measuring the infrared radiation emitted by the object and converting it into a pictorial representation of the surface temperature (Barnes, 1968).

Early ventures into the use of IRT in livestock applications yielded variable results. A major limitation of these early studies was the need for subjects to remain still for periods of up to 6 min while the scan was completed (Delahanty and Georgi, 1965). Advances in technology have reduced the time needed for the scan to fractions of a second, making thermography more feasible for use with live animals. Nonetheless, it is important to recognize that IRT is limited to measuring only the surface temperature of the skin or hair coat. Thus, IRT may only be useful in situations where this surface temperature provides an accurate model for the condition of the underlying tissue.

IRT has been used to explore diagnostic issues, ranging from identification of pain and inflammation to the confirmation of pregnancy, in several studies involving horses, cattle, and swine (Table 1). These studies used IRT to investigate variations in surface temperature as signs of unease, to diagnose ailments and to assess treatment methods.

Table 1. Examples of previous studies that have used infrared thermography with livestock.

Subject	References
Horses	
Surface Temperature	Smith, 1964; Delahanty and Georgi, 1965; Palmer, 1981
Pain	von Scwienitz, 1999
Inflammatory Process	Purohit and McCoy, 1980
Lameness	Purohit and McCoy, 1980; Denoix, 1994; Turner, 2001; Eddy et al., 2001; Head, 2001
Drug Effects	Van Hoogmoed and Snyder, 2002; Deumer et al., 1991; Harkins et al., 1996; Holmes et al., 2003
Exercise Effects	Marlin et al., 1998
Cattle	
Surface Temperature	Berry et al., 2003
Infection	Lepper et al., 1974; Merkal et al., 1977; Spire et al., 1999; Schaefer et al., 2004; Schaefer et al., 2005
Branding	Schwartzkopf-Genswein and Stookey, 1997
Reproduction	Purohit et al., 1985; Gábor et al.; 1998, Jones et al., 2005a ; Jones et al., 2005b
Lameness	Cockroft et al., 2000; Momcilovic et al., 2000; Schmidt et al., 2003; Whay et al., 2004; Haley et al., 2005; Nikkah et al., 2005
Stress	Stewart et al., 2005
Environmental Effects	Knizkova et al., 2002
Swine	
Infection	Loughmiller et al., 2001
Environmental Effects	Loughmiller et al., 2001
Meat Quality	Gariepy et al., 1989

The objectives of this review are to: 1) describe the science and technology underlying IRT, 2) discuss results of previous studies, and 3) explore future possibilities for the diagnostic use of IRT with livestock.

2.2 Technical Overview and Considerations

Thermal radiation encompasses the portion of the electromagnetic spectrum ranging in wavelength, λ, from approximately 0.1 to 100 μm. This includes the visible part of the spectrum ($0.35 \leq \lambda \leq 0.75$ μm) and the infrared region ($0.75 \leq \lambda \leq 100$ μm) (Incropera and DeWitt, 2002). Infrared thermography cameras operate similarly to standard digital cameras, except that they capture images by assessing wavelengths from the infrared portion of the electromagnetic spectrum, usually from 3 to 14 μm, depending on equipment. Typical IRT systems are termed mid-wave (3 to 7 μm) or long-wave (8 to 14 μm), the difference being based on the detector material of the infrared camera used (Kastberger and Stachl, 2003). Mid-wave cameras tend to have greater temperature sensitivity, but require internal mechanisms to cool the detector.

The physical basis for IRT relies on the concept that all matter emits electromagnetic radiation at power that is a function of the temperature of the matter. This power is called the emissive power, E_λ, and for a perfect emitter (i.e., a blackbody emitter) is described by Planck's distribution

$$E_{\lambda,b} = \frac{c_1}{\lambda^5\left[\exp\left(c_2/\lambda T\right)-1\right]}, \qquad (1)$$

where $E_{\lambda,b}$ is the emissive power of a blackbody, T is the temperature of the matter, and c_1 and c_2 are constants with values of 3.743×10^8 W $\cdot$ μm/m^{2}and 1.4387×10^4 μm $\cdot$ K, respectively. The spectral emissive power calculated using Equation 1 at 300 K (27 °C or 81 °F) is illustrated as a function of wavelength in Figure 1. Each pixel of an IRT detector measures the power emitted from a portion of a surface and within the range of wavelengths corresponding to the sensitivity of the detector (e.g., 3 to 7 μm for a mid-wave camera). Software then calculates the corresponding temperature viewed by each pixel.

Real materials emit less power than is predicted by Equation 1. The ratio of the emissive power of real matter (i.e., an animal), E_λ, to that of a blackbody emitter, $E_{\lambda,b}$, is the emissivity, ε,which is defined as:

$$\varepsilon = {}^{E_\lambda}\!\big/_{E_{\lambda,b}} \tag{2}$$

Emissivity has a value between 0 and 1. Most electrically non-conducting materials have values of 0.8 or greater, with human skin having $\varepsilon = 0.95$ at 300 K (Incropera and DeWitt, 2002). Figure 1 illustrates the estimated emissive power of a bovine surface with $\varepsilon = 0.96$ compared to that of a blackbody emitter at the same temperature.

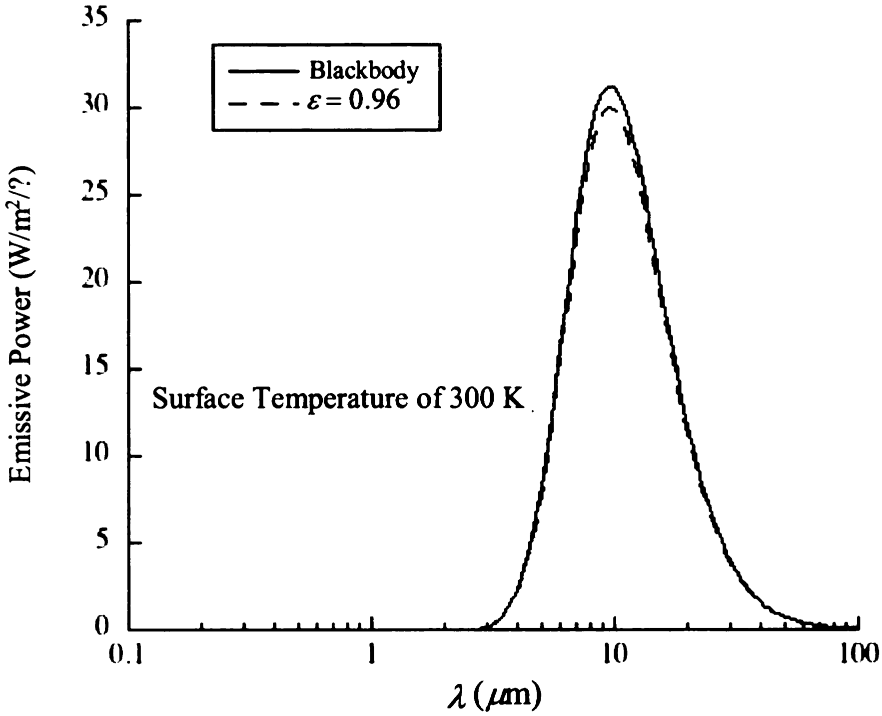


Figure 1. Emissive power for a surface at 300 K (27 °C, approximately the surface temperature of a cow) for a blackbody emitter and a surface with an emissivity of 0.96 (the estimated emissivity of a bovine surface).

In addition to being emitted from a surface, infrared radiation may be absorbed, reflected, or transmitted in a manner similar to light at other wavelengths. (Eddy et al., 2001; Purohit and McCoy, 1980). Because of these four properties, the infrared radiation leaving a surface may be affected by environmental conditions. For example, water vapor is transparent to the visible spectrum, but readily absorbs infrared radiation at some wavelengths. Also, dust particles suspended in air may absorb, reflect, or emit radiation. For practical applications of IRT, care must be taken to limit dust and humidity in the atmosphere of the collection environment. Substantial amounts of either could alter the signal from the animal to the detector, which would result in erroneous temperature readings. Similarly, reflective surfaces and extraneous sources of substantial infrared radiation, such as sunlight and radiant heat sources, must be avoided to reduce measurement errors. Ideally, IRT measurements should be collected in a closed room that is free of drafts, changing temperatures, and external light sources (Barnes, 1968). Turner (1991) also has suggested that a draft-free and low-light area with an ambient temperature less than 30 °C should be used when collecting thermal images of horses. Even recent changes in environmental conditions may produce anomalous results. Cena and Clark (1973) measured the temperature of zebras that had been standing in the sun and found that the black stripes of the animal displayed maximum temperatures of 39 °C, which were 9 °C warmer than the white stripes of the same animal. Similar differences between light and dark surface areas also were measured in giraffes and penguins exposed to sunlight.

In addition to the collection environment, the state of the surface itself plays an important role in the accuracy of temperature measurements. For example, hair can block infrared radiation, so that the image of an animal reveals the temperature of the surface of the hair, rather than the temperature of the skin. Because hair is a thermal insulator, its surface temperature may be substantially different than that of the underlying skin. Turner (2001) suggests, however, that an accurate thermal image can be produced as long as the hair is short and uniform in length. Any differences in hair length should be taken into consideration when analyzing data. We do not anticipate hair length to be a contributing factor when assessing the coronary band region in cattle as hair in this area is generally short (< 2 cm) and uniform in length. Nevertheless, the most accurate measurement of the skin surface temperature requires imaging the skin directly.

2.3 Livestock Production Applications

2.3.1 Lameness

Lameness is associated with injury of the distal limb and may be caused by an array of factors (Galindo et al., 2000). Many of the pathologies that cause lameness also create inflammatory responses. IRT was used to study lameness and these inflammatory responses in both cattle and horses. Smith (1964) and Delahanty and Georgi (1965) studied both lame and sound horses using early IRT technology, which required the horse to stand still for up to 6 min. Both studies found that IRT made it possible to detect differences in temperature between lame and sound legs when the animal was properly restrained. Delahanty and Georgi (1965) concluded that there were possible applications for IRT in veterinary medicine and speculated that with advances in technology, these possibilities would increase.

Several years later, Purohit and McCoy (1980) used IRT to examine the inflammatory process by studying three groups of equids: clinically normal horses, those with some sort of inflammatory disease, and normal ponies that were treated with an inflammatory agent in the distal limb. Clinically normal horses of various ages and breeds were imaged following 30 min of exercise to determine the normal thermal pattern of a horse. When examining these normal horses, Purohit and McCoy (1980) found that the coronary band was the warmest area in thermograms taken from the frontal view of both the thoracic and pelvic limbs. In thermograms taken from the palmar and plantar views, the warmest area was between the bulbs of the heel. Eddy et al. (2001) concured with this finding and reported that the coronary band and laminar corium just proximal to the hoof were the warmest regions of the distal limb. The second group in the study by Purohit and McCoy (1980) consisted of nine horses, each expressing different clinical cases involving acute or chronic inflammatory conditions of the distal limb. One horse with laminitis showed no signs of excessive temperature when examined clinically, however, the thermograms showed a distinct change to the normal temperature pattern of the hoof, thus indicating laminitis. Twenty-four h after the thermograms were taken, laminitis was evident in clinical examinations. In the third group of sound ponies, the researchers investigated the effects of anti-inflammatory drugs on surface temperature. Thirteen Shetland ponies were injected with 1.25 ml of 1.9% iodine solution to create an inflammatory response. The ponies were then split into four groups. Three of these groups received different anti-inflammatory treatments (topical benzydamine HCL ointment; IV injections of benzydamine HCL twice a day; IV injections of phenylbutazone and a Poltis leg wrap), while the remaining group served as an untreated control for the inflammatory agent. A decrease in inflammation was evident in thermal images taken of all three groups treated with anti-inflammatory agents while continued inflammation in the untreated inflammatory control group was evident in thermal images for 4 to 8 d after the cessation of all clinical signs. The authors concluded that IRT could aid detecting sites of early inflammation.

Turner (2001) reported that in cases of laminitis, IRT images of horses show a change in the thermal pattern of the hoof wall. The coronary band of a horse is generally 1 to 2 °C warmer than the rest of the hoof. In cases of laminitis, however, the hoof begins to approach the temperature of the coronary band due to inflammation of the laminar structures within the hoof. Thermography detects inflammation associated with laminitis well before lameness is evident through traditional detection methods, allowing preventive therapies to be applied before the laminitis becomes irreversible. Turner (2001) suggested that inflammation in the area of the coronary band, however, may be hard to detect as this area is the warmest area of the leg and therefore comparisons between all four hooves (from front to front, rear to rear and rear to front) should be made. A difference of more than 1 °C between any two of the four hooves was suggested to be significant with need for further examination.

Studies using IRT also have been conducted in cattle to assess hoof and limb health. Whay et al. (2004) used IRT to verify lame limbs in cattle. They imaged the lateral aspects of each limb of 50 dairy cows. In addition, each cow was locomotion scored following imaging. The results showed that the temperature in the lame limbs was increased and that the difference in temperature between the lame and sound limb extended beyond the horn capsule into the proximal region of the limb. Schmidt et al. (2003) also suggested that IRT may be useful for diagnosing lameness in cattle. They found an association between lameness score and variations in claw temperature in cases where pathologies of the claw were found. Another recent study used IRT to assess temperatures of the coronary band of dairy cows in two stages of lactation: early to mid-lactation, ≤ 200 d in milk (DIM), or in late lactation, > 200 DIM (Nikkah et al., 2005). The temperature difference, ΔT, between the coronary band and a control area just above the coronary band was analyzed. Temperatures of the coronary band were found to be higher in cows ≤ 200 DIM than in the late lactation cows. Increased temperatures of the coronary band and ΔT corresponded with an increased incidence of sole ulcers, but not to incidences of underrun heels in the early to mid-lactation group. Nikkah et al. (2005) concluded that measurement of hoof temperatures in early lactation cows may be useful for monitoring hoof health.

Momcilovic et al. (2000) attempted to induce acidosis by feeding a higher energy diet in an effort to cause laminitis in dairy calves and then used a digital infrared scanner to measure the surface temperature of the hoof. This device measures only the surface temperature of a small area rather than the entire distal limb as is possible with IRT. Temperature readings were taken eight times during the 48-h period after feeding the acidosis-inducing diet. Overall, hoof temperatures varied significantly, but were generally lower in the high energy group. Hooves inspected 3 mo after the acidosis experiment indicated hoof damage may have begun during administration of the high energy diet. In this case, the infrared scanning may have been done too soon to show any signs of inflammation.

2.3.2 Reproduction

Infrared thermography also was used in reproductive studies of cattle. Purohit et al. (1985) established the thermographic patterns of the scrotum of 15 normal bulls and 10 bulls with scrotal or testicular disease. Thermograms of the normal bulls showed a symmetrical and constant thermal pattern of the scrotum with a temperature difference of 4 to 6 °C between the base and the apex of the scrotum. In bulls where one testicle was inflamed, differences in scrotal surface temperature were evident between the two sides. Furthermore, in bulls with inflammation of both testicles, there was an overall increase in surface temperature. The authors concluded that when semen cannot easily be collected for quality evaluation, IRT may be a useful tool for evaluating testicular damage. Lunstra and Coulter (1997) employed IRT to investigate the relationship between scrotal infrared temperature patterns and natural-mating fertility in beef bulls. Temperature patterns were recorded on 73 yearling bulls using IRT. For each thermogram, the average scrotal temperature, temperature at the base and apex of the scrotum, scrotal temperature gradient and thermal class (normal, questionable or abnormal scrotal surface temperature as determined by a subjective interpretation of each bull's scrotal surface temperature) were recorded. Half of the 73 bulls showed a normal thermal pattern whereas 20 (27%) had a questionable thermal pattern and 16 (22%) had an abnormal pattern. The 16 bulls showing an abnormal pattern also had lower percentages of sperm exhibiting normal head and tail morphology, and higher percentages of sperm with proximal droplets than bulls exhibiting normal or marginal thermal patterns. Furthermore, the impregnation rate was lower for bulls with abnormal thermal patterns compared to those with normal or marginal patterns. The data from this study indicate that bulls with abnormal thermal patterns of the scrotum, as determined by IRT, had a reduced ability to maintain an effective thermal gradient from top to bottom of the scrotum and had reduced fertilization rates when used for natural mating. The conclusions of both studies support the hypothesis that IRT can be useful when evaluating the reproductive soundness of bulls.

In reproductive studies of females, IRT has not been as effective as a diagnostic tool. Jones et al. (2005a) used IRT to assess the pregnancy status of Holstein heifers. Both the left and right sides (from shoulder to flank) of pregnant heifers were imaged and the right side images were more accurate predictors of pregnancy than the left side images. However, researchers concluded that the ability to discriminate between pregnant and non-pregnant heifers is questionable and greatly affected by ambient temperature. In another study, Jones et al. (2005b) investigated the ability of IRT to detect differences in vulva surface temperature of cows in estrus versus those not in estrus. When comparing vulva surface temperatures of cows in estrus and in early diestrus at an ambient temperature of 21.4 °C, the researchers found no difference in minimum temperatures and standard deviations, whereas the maximum temperature of the vulva of a cow in estrus was higher than that of a cow in diestrus. No differences in temperature were found between cows in late diestrus and the second estrus period. At an ambient temperature of 12.1 °C no temperature differences were found between groups of cows in estrus and cows in diestrus. It was unclear whether this magnitude of temperature change is physiologically relevant for the detection of estrus. Furthermore, ambient temperature greatly influenced the ability to discriminate between estrus and diestrus.

2.3.3 Infection and Pain

Schaefer et al. (2004) used IRT to detect the progression of infection with bovine viral diarrhea (BVD) in 15 calves. Ten of the calves were inoculated with Type 2 BVD and housed separately from healthy control calves. The animals were not restrained at the time of imaging and the technician took images from dorsal, lateral, distal, and selected facial views. Blood samples and rectal temperatures also were collected to help determine the progress of the infection. All inoculated animals responded to the infection and the results showed significant changes in temperature at approximately 4 to 5 days post inoculation during the 10-d collection period for many of the areas imaged. Images taken of the orbital area were notable especially in the BVD-inoculated calves as they were the most consistent and most sensitive to increases in temperature and were also the earliest images to display temperature differences during the 10-d trial. Increases in orbital temperature were significant as early as d 1, allowing early detection of infection. In the control animals, there were some differences from day to day in the orbital temperature, but these changes were sporadic and inconsistent. Clinical symptoms occurred later than changes in the IRT images and were not evident in the inoculated animals until 8 to 9 d post inoculation, reaching a peak at d 11. This study proved to be a breakthrough in the possibilities of IRT as a means to detect infection earlier than through observation of clinical signs, making earlier treatment possible. Schaefer et al. (2005) also used IRT images of the orbital area for early detection of bovine respiratory disease (BRD), a costly heath affliction in the cattle industry. Of the 13 weaned calves used in the experiment, 11 were exposed in a herd known to be infected with BRD and two were used as controls. Thermal data were collected through an automatic system which took IRT images of the orbital area and these data were then analyzed to determine which calves were showing an inflammatory response. The results from this study showed that IRT may assist in the earlier detection of BRD. Stewart et al. (2005) have suggested, however, that orbital temperatures in cattle may be affected by stress, which could be a confounding factor for the previous studies.

Schwartzkopf-Genswein and Stookey (1997) used IRT to assess inflammation associated with both hot-iron and freeze branding in cattle. Currently, these are two of the most common methods used to make permanent marks on cattle, even though temperature associated injuries are linked with pain (Provost, 1992). Thirty beef heifers were used in this study, with 15 heifers in the freeze branding group and 15 heifers in the hot-iron branding group. Two patches were shaved on the right thigh of each heifer the day prior to the start of the experiment. The patch located on the upper part of the thigh was the treatment site while the lower patch was designated as the control site. Infrared images of the branding sites were collected starting at 5 min prior to branding and continued at various intervals until 7 d post branding. The results of this study indicate that while both the hot-iron and freeze branding methods caused an inflammatory response, hot-iron branding caused a longer lasting response, thus suggesting that hot-iron branding may cause more intense and prolonged pain than freeze branding.

Another study of cattle by Spire et al. (1999) used IRT to detect inflammation associated with contaminated growth-promoting ear implants. Growth promotants commonly are used in the beef industry to improve average daily gain of feeder steers and heifers. If the implants are administered improperly, partial or complete interference with absorption may occur. Thirty-two crossbred beef steers were used as the experimental group with 16 steers implanted with a clean needle after scrubbing the ear. The remaining 16 steers were implanted after the ear and implantation needle had been contaminated with a mixture of fecal material and water. In each animal, the non-implanted ear was used as an internal control. Thermal images were collected on d 0, 2, 4, 7, 14 and 21. Significant differences were evident between the temperature of the ears with contaminated implants and control ears. Spire et al. (1999) concluded that the use of IRT is a non-invasive diagnostic tool that may be useful in feedlots to identify cattle with ear abscesses caused by contaminated growth-promoting implants.

2.3.4 Animal Environment and Stress

Infrared thermography is not only useful for identifying inflammation associated with disease, but also is useful for evaluating animal environments and habitats. Knizkova et al. (2002) used IRT to assess the thermal comfort of dairy cattle based on body surface temperature. They considered both barn air temperature and velocity, and the effects these had on dairy cow comfort. The results showed no changes in body surface temperature when barn air temperature dropped by 3.1 °C, while still within the cow's thermoneutral zone. Conversely, when barn air temperature dropped by 6.5 °C from 22.7 to 16.2 °C, changes in body surface temperature were evident. Moreover, significant changes in air velocity within the thermal neutral zone also caused changes in body surface temperature. The results of this study not only indicate the importance of ambient temperature on cow comfort, but also the importance of maintaining constant temperature and air velocity in any environment used for thermal data collection.

The relationship between mean body surface temperature (MBST) and ambient temperature was analyzed in clinically normal pigs and pigs inoculated with *Actinobacillus pleuropneumoniae,* a bacteria that causes the respiratory disease porcine pleuropneumonia (Loughmiller et al., 2001). First, Loughmiller et al. used four castrated male pigs housed in a controlled temperature environment to determine the relationship of ambient temperatures to MBST in normal pigs. Ambient temperatures were adjusted to 10, 13, 16, 18, 21, 24, 27, 29 and 32 °C and each temperature was maintained for a period of 60 minutes. The left side of each pig was then imaged 30 min after each temperature had been reached. The results of this part of the study showed a positive linear relationship between MBST and ambient temperature with a 0.4 ºC increase in mean body surface temperature with every 1 ºC increase in ambient temperature. In a second part of the study, 24 pigs were divided into inoculated and non-inoculated groups. In this part of the study, the researchers concluded that a treatment by time interaction was evident as a result of increased combined MBST and rectal temperature in febrile pigs inoculated with *Actinobacillus pleuropneumoniae* as compared to the non-inoculated ($P < 0.001$) and inoculated non-febrile pigs from 4.25 to 18 h after inoculation. The results of this study indicate that the use of IRT in imaging broad areas (≥ 10 cm) in pigs can detect accurately changes in the MBST temperature in pigs and may serve as a useful, non-invasive tool in identifying febrile pigs.

Animal stress is a concern not only from an animal welfare standpoint, but it also has a significant impact on the meat packing industry. In the pork processing industry, IRT can be a useful tool to predict meat quality. Dark, firm and dry meat (DFD) and pale, soft and exudative meat (PSE) are important quality issues in the pork industry and both result from stressful situations. DFD is caused by long-term stress prior to slaughter while PSE is caused by high levels of acute stress immediately prior to slaughter. Gariepy et al. (1989) obtained IRT images of hogs immediately prior to electrical stunning to determine the skin temperature of the animals before slaughter. All images were taken from the dorsal view to include the entire hog. After arbitrary partitioning of IRT data, some form of decreased meat quality was found in 71% of hogs exhibiting skin temperatures higher than 32.2 °C. Handling, behavior, and genetics of the animals prior to the study may have affected meat quality, but these data were not included in this study. These results illustrate that IRT may be a useful tool for detecting pigs with the potential to yield lower quality meat.

2.4 Future Possibilities of IRT Use for Livestock

New opportunities for research and production applications come with technological advances and reduced costs of IRT. Newer, more sensitive thermographic cameras help researchers to distinguish minute temperature differences, and the decreasing cost of cameras will make this technology more affordable. Thermography already is being used as a diagnostic tool by some veterinarians and has the possibility of becoming an on-farm tool to help herd managers identify illness in animals. Future research on lameness in dairy cattle could lead to on-farm scanning systems that could detect lameness earlier than through the use of locomotion scoring. In the horse industry, IRT may become available to barn managers to regularly scan animals for signs of injury. Automatic IRT systems in feedlots may be able to identify sick animals before they spread disease to the larger group of cattle. Meat packing plants could use IRT to scan for sick or stressed animals upon their arrival. While the possibilities for IRT use in livestock applications seem numerous, more research is needed to set standards and protocols for collection and interpretation of data from different animal species. Additionally, it will be important for researchers and industry alike to consider that IRT does not provide a cure for these various maladies, but only serves as a tool to help veterinarians and managers detect these illnesses and therefore IRT also may be used to supplement research and practice directed towards diagnosing and curing illnesses.

Subsequent chapters will illustrate the use of previous research to assess the possibility of using IRT as an on-farm tool to detect lameness in dairy cattle.

CHAPTER THREE

Use of Infrared Thermography to Determine Surface Temperatures of the Coronary Band Region of Sound Dairy Cows

Abstract

Infrared thermography (IRT) creates a pictorial representation of the surface temperature of an object. It has potential as a method to detect inflammation associated with lameness. In this study, IRT was used to assess surface temperature near and at the coronary band of the hind limbs of non-lame dairy cows. Ten visibly sound 2-yr-old Holsteins less than 150 DIM were clinically examined for soundness. IRT images were obtained six times per day (before and after each of two milkings and again 3 h after milking) for two consecutive days to determine differences in surface temperature among cows, at different image views, different measurement times, and between hind limbs of the same cow. Three different image views of the coronary band were analyzed for both hind limbs: dorsal, lateral and plantar aspects. Images were analyzed using ThermaCAM Reporter 7.0 (FLIR Systems, Inc., Boston, MA). Average and maximum temperatures were determined for an area approximately 2 cm above and below the coronary band. Maximum temperatures were correlated with average temperatures ($r = 0.826$, $P < 0.01$) and were used for all subsequent statistical analyses. A mixed model procedure was used for statistical analysis with cow and the interaction of cow by side (left or right) as random effects and time, view and side as fixed effects. Image view was a significant factor ($P < 0.05$) with average maximum temperatures of 33.5, 31.9, and 31.5 °C for

dorsal, lateral and plantar views, respectively. Time of IRT measurement affected temperatures ($P < 0.05$) with average maximum temperatures ranging from 30.5 to 33.0 °C for the six measurement times. There was also no interaction of side by view and no difference in temperature between left and right limbs in the plantar view. These results suggest that IRT data should be collected using a standardized protocol with a consistent image view and time of day. Also, differences in temperature measured by IRT between left and right limbs may be useful for detecting inflammation associated with lameness in one limb.

1. Introduction

Infrared thermography (IRT) measures the radiant energy emitted by an object and provides a non-invasive means of determining surface temperature (Barnes, 1968; Head, 2001). In mammals, variations in surface temperature often indicate the presence of some underlying pathology (Cena and Clark, 1973; Barnes, 1968). Thus far, IRT has been used to detect inflammation associated with lameness in horses (Purohit and McCoy, 1980; Denoix, 1994; Turner, 2001; Eddy et al., 2001) differences in surface temperature of limbs in cattle (Cockroft et al., 2000; Momcilovic et al., 2000; Schmidt et al., 2003; Whay et al., 2004; Haley et al., 2005, Nikkah et al., 2005), presence of infection in cattle (Lepper et al., 1974; Merkal et al., 1977; Spire et al., 1999; Schaefer et al., 2004; Schaefer et al., 2005), and to assess inflammation associated with branding of cattle (Schwartzkopf-Genswein and Stookey, 1997).

Lameness in dairy cows has been shown to decrease milk production (Warnick et al., 2001) and increase the incidence of reproductive disorders (Hernandez et al., 2005, Sprecher et al., 1997) which have a direct impact on the productivity and economic output of the herd. Lameness is also a major animal welfare concern for dairy cattle (Hemsworth et al., 1995) as it is associated with pain (Whay et al., 1998). Currently, locomotion scoring is a common method used in research to detect lameness and numerous scoring systems have been proposed (Manson and Leaver, 1988; Nordlund et al., 2004; Wells et al., 1993; and Vokey et al., 2001). Locomotion scoring quantifies lameness by using a numerical scale to assign a score to a cow based on posture and gait symmetry. A commonly used locomotion scoring system is the 5 point scale described by Sprecher et al. (1997) which uses both gait and posture to determine lameness.

Locomotion scoring is helpful in determining the overall lameness prevalence of a herd, however, scoring systems are subjective and perception of lameness is variable. Results of a recent survey in Michigan reported that 53% of a sub sample of dairy herd owners perceived lameness rates to be <10% in their herd (Edgecomb et al., 2006). These results were similar to those found by Kopcha et al., (2003) who reported that a sample of Michigan dairy producers perceived lameness to be at an average rate of 4.5% in their herds. However, trained observers determined that in a sub sample of Michigan dairy cows (approximately 4% of the total adult population) 52% showed mild to severe lameness, suggesting that producers may not perceive the full extent of lameness in their herds (Kopcha et al., 2003). In addition to low rates of detection by untrained observers, the subjectivity of locomotion scoring often results in high inter-observer variability (Engel et al., 2003).

Researchers currently are working to determine more objective methods to help the dairy industry assess the true prevalence of lameness on-farm (Tasch and

Rajkondawar, 2004). Recent studies have shown evidence that the use of force plates (Tasch and Rajkondawar, 2004) and pressure plates (Almeida et al., in press) may be useful to aid in the early detection of lameness. IRT is another technology being used in research to assess lameness. Whay et al. (2004) reported a difference in temperature between lame and sound limbs while Schmidt et al. (2003) found an association between lameness score and claw temperature in animals where pathologies of the claw were found. Further, Nikkah et al. (2005) assessed coronary band temperatures of cows in different stages of lactation and determined that monitoring hoof temperature in early lactation may be useful in detecting lameness.

While previous research with IRT has expanded our understanding of the potential to use IRT to detect lameness, there has been no report of baseline data from sound dairy cows. The objectives of this study were to examine the coronary band region of sound Holstein cattle in order to determine the normal surface temperature pattern, particularly in the coronary band region; to determine the least variable view for collecting IRT images of the rear limb; and, to determine within day variation in the surface temperature of the distal limb.

2. Materials and Methods

2.1 Animals

This study was conducted in May, 2005 at the Michigan State University Dairy Cattle Teaching and Research Center in East Lansing. The experimental protocol was reviewed and approved by the All University Committee on Animal Use and Care. Ten visibly sound 2-yr-old Holsteins, less than 150 d into their first lactation, were selected for study. Each cow had a locomotion score of 1 based on the Sprecher et al. (1997) system (Table 1). On the day prior to the onset of the study, all four hooves of each cow were examined for any signs of lesions by a qualified veterinarian. During the exam, cows were restrained in a hoof trimming chute and each foot was lifted and checked for soft soles and obvious signs of inflammation of the hoof and joints. Hoofs were not trimmed. Herd health records also were examined and cows with signs of poor health were excluded.

Table 1. Locomotion scoring system as described by Sprecher et al., (1997).

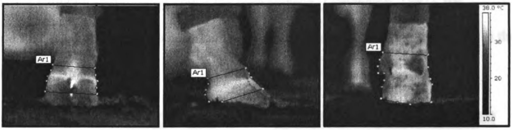
Lameness score	Clinical Disposition	Assessment Criteria
1	Normal	The cow stands and walks with a level-back posture. Her gait is normal.
2	Mildly Lame	The cow stands with a level-back posture but develops an arched back posture while walking. Her gait remains normal.
3	Moderately Lame	An arched-back posture is evident both while standing and walking. Her gait is affected and is best described as short-striding with one or more limbs
4	Lame	An arched-back posture is always evident and gait is best described as one deliberate step at a time. The cow favors one or more limbs
5	Severely Lame	The cow additionally demonstrates an inability or extreme reluctance to bear weight on one or more of her limbs or feet.

2.2 Housing and Management

Cows were housed in a 70-cow tie-stall barn with stall dimensions of 1.82 m x 1.32 m. Stalls were bedded with rubber crumb filled mattresses lightly covered with lye and sawdust. Manure was removed from stalls every day during the two milking times, with fresh sawdust being added to each stall at this time and fresh lye added to stalls once a day with the sawdust. The barn had a ventilation system with air inlets and fans controlled by thermostats. The diet consisted of a totally mixed ration (TMR) balanced to meet NRC (1989) requirements for lactating cows; it was fed daily at 0900 h. Cows were milked twice daily at 0200 h and 1400 h in a double-7 herringbone parlor. All cows were in the same milking group and were released daily into a concrete floored, outdoor exercise pen for 1 h prior to the 1400 h milking period.

2.3 IRT Data Collection

IRT images were collected for two consecutive days, six times a day with collection times at 0130, 0430, 0800, 1130, 1445 and 1900 h. The 0130 and 1130 h collection times were pre-milking, 0430 and 1445 h were post-milking, and 0800 and 1900 h were 3 h post-milking. All IRT data collection occurred while cows were standing in their tie-stalls. Images were taken in a random, order for the pre-milking and 3 h post-milking collections. For the post-milking collection period, cows were imaged based on the order that they came from the milking parlor. Images of both rear limbs were taken from three different views, dorsal, lateral and plantar, from a distance of approximately 1 m (Figure 1) measured by a string attached to the camera, which was held up to the area being imaged. Images of the fore udder also were taken from as distance of 1 m as a possible control measure.



A B C

Figure 1. Infrared images of the dorsal (A), lateral (B), and plantar (C) image views with area of interest around the coronary band region.

Prior to imaging, all cows were made to stand and any manure was removed from the stall. The rear distal limbs and fore udders were then brushed lightly to remove any wood shavings or manure. Images were taken at least 10 s after brushing.

Images were taken using a FLIR P-65 infrared camera (FLIR Systems Inc., New Billerica, MA). The sensitivity of the camera is 50 mK at 30 °C with a spectral range of 7.5 to 13 μm and the accuracy of the camera is ± 2 °C. After all data were collected, IRT images were analyzed using ThermaCAM Reporter 7.0 (FLIR Systems, Inc., New Billerica, MA) and were corrected for average ambient temperature during each collection time and distance within the software. In each udder image, average and maximum temperatures were reported from within a pre-set rectangle encompassing an area of approximately 14 cm^2 of the fore udder above the front teat on each side. In each hoof image, the average and maximum temperatures were determined from within an area approximately 2 cm above and 2 cm below the coronary band (Figure 2). We assumed that the horn capsule likely serves as more of a natural insulator to the internal temperature of the hoof than the skin of the coronary band and therefore may not accurately express any inflammation within the horn. As the coronary band is a highly vascularized area located directly above the horn capsule (Greenough, 1997), we assumed that any inflammation occurring within the horn capsule will be expressed in the coronary band.

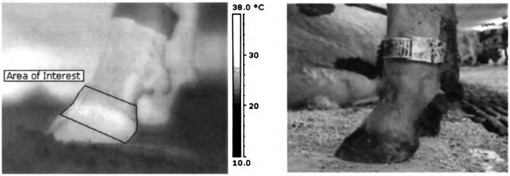


Figure 2. On the left, an infrared image of a non-lame limb of a Holstein cow. On the right, a digital image of the same limb.

2.4 Additional Temperature Measurements

Ambient air temperature was recorded every 10 min during each collection time over the 2-d period with a thermometer (WS-9014 U Wireless 433 MHz Temperature Station, La Crosse Technology) suspended from the ceiling at a height of 2 m in the center of the area in the barn where data were collected. Ambient temperatures within the barn ranged from 11.4 to 20.9 °C during the collection times. Rectal temperatures were taken immediately following IRT imaging of each cow using a digital probe type thermometer (GLA M525/550, GLA Agricultural Electronics, San Luis Obispo, CA).

2.5 Statistical Analysis

Data were analyzed using a mixed model procedure (PROC MIXED, SAS version 9.1.3). Side (left or right limb), view of the limb, and day were modeled as fixed effects and cow was modeled as a random effect. To account for variability between the two sides, cow by side interaction was modeled as a random effect. In addition, repeated measures across time were accounted for by modeling time as a random effect with each cow as a subject. The residual variation was partitioned as follows to examine the variability due to view. A log-linear variance model was adopted with view and time as effects contributing to dispersion effects.

$$\sigma^2_{(\mathrm{VIEW,\,TIME})} = \sigma^2_{(\mathrm{error})} \exp\{\delta_{(i)} * \mathrm{VIEW}_{(i)} + \delta_{(j)} * \mathrm{Time}_{(j)}\}$$

Residual and influence diagnostics (Schabenberger, 2004) were performed and we determined that no single cow had a significant effect on the conclusions of this analysis.

3. Results

Among the fixed effects, view was highly significant ($P < 0.001$) and side was marginally significant ($P = 0.058$). The significance of side changed based on whether or not side by cow was included in the model indicating that there is some effect of the variability due to side on the response. As a general trend, the left side had a slightly higher maximum temperature than the right side. There was no significant interaction of side and view, however, when analyzed individually, there was a difference ($P = 0.026$) in temperature between left and right limbs in the dorsal view, a trend for a temperature difference ($P = 0.072$) in the lateral view and no difference ($P = 0.242$) in the plantar view (Table 2). There was a subject-specific trend of the variability of maximum surface temperature across time within each cow. The Wald test for the coefficients for view in the log-linear model for the residual variation was significant indicating heterogeneity of variances among views (Figure 3). Furthermore, the Wald test for coefficients of time was also significant, indicating that there was an effect of time on the variability associated with view. Therefore, view may need to be controlled for when assessing temperature. The tests were not significant for times 0130 and 1900 h suggesting that in this study, there was no effect of time on the variance heterogeneity of view at these collection periods.

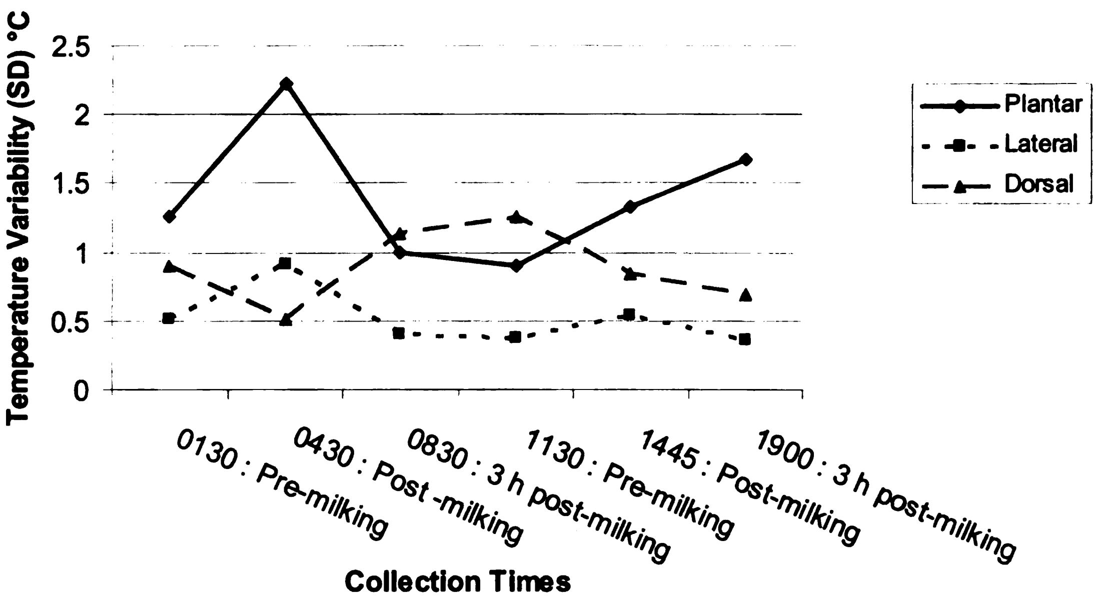


Figure 2. The variance of the three views (plantar, dorsal, and lateral) over time.

Table 2. Maximum surface temperatures (MST) °C and P values for the left and right limbs at each image view.

View	MST Left	MST Right	P value	MST Both[b]
Dorsal	33.7	33.4	0.026	33.5
Lateral	32.0	31.8	0.072	31.9
Plantar	31.6	31.4	0.242	31.5
Overall[a]	32.4	32.2	0.055	32.3

[a] MST for left and right pooled across dorsal, lateral and plantar were different at P = 0.058.

[b] MST for dorsal, lateral, and plantar pooled across left and right were different (P < 0.001)

4. Discussion

The results from this study showed that there is variability in surface temperature amongst sound cows. This variability may be in part due to natural circadian rhythms such as those previously reported in core (Lefcourt et al., 1989), vaginal (Wrenn et al., 1961; Araki et al., 1984, 1987) and rectal temperatures (Lefcourt et al., 1999). Variability amongst cows may also be associated with environmental effects such as ambient temperature and exercise. Berry et al. (2003) reported that mechanical brushing caused a momentary cooling of udder surface temperature (< 10 s) due to removal of the warm air layer trapped in the hair, however, surface temperature rapidly returned to normal. We waited > 10 s after brushing before imaging cattle and therefore would not anticipate any variability due to brushing. There were also differences in variability of temperatures in each view over time. A noticeable rise in variability can be seen following the first post-milking collection time, particularly in the plantar view. This rise in variability may be due to water splash or other foreign material on the limb coupled with the lower ambient temperatures found in the morning as moisture on the limb will cause evaporative cooling (Knizkova et al., 1996). Overall, the lateral view showed the least variability across time and therefore provides the most reliable source of IRT surface temperature data of the distal limb. However, if a cow has a lesion on the medial claw, inflammation may not be evident in IRT images taken from the lateral view. Therefore, it also may be important to assess images of the dorsal view to investigate for lesions in both claws.

In addition, we found no effect of day in this study, however, data were only collected over a 2-d period. Measurement time within each day was a significant factor. Our results indicated that the 0130 and 1900 h collection periods showed no effect of time in this study. The variability due to time is likely affected by management practices and uncontrollable environmental factors that will vary on different farms. This variability also may be accounted for by the natural circadian rhythms of cattle as mentioned previously. Therefore, even considering the lower variability encountered in our study, we cannot conclude that 0130 and 1900 h are the best times to collect IRT data in other farms. Nonetheless, we did see a noticeable rise in variability in the post milking collection times, particularly in the plantar view, and we do suggest this is not the most ideal time to collect IRT data.

Images were taken only on the rear hooves because these were most accessible. In addition, Shearer and van Amstel (2000) reported that 90% of all lameness occurs in the rear limbs. Our results revealed no interaction of side and view, thus suggesting no difference in MST of the coronary band region between the left and right rear limbs at each image view. However, upon further analysis we found a difference ($P = 0.026$)

between temperatures of the left and right limbs in the dorsal view, a trend towards difference ($P = 0.072$) in temperature between limbs in the lateral view, and no difference ($P = 0.242$) between limbs in the plantar view. As there was no interaction of side by view we may be able to account for these limited differences we observed between limbs by applying a correction factor to account for the left limb generally being warmer than the right limb. Overall, these results indicate that a cow may serve as a self control when comparing images of the same view between limbs.

5. Conclusions

In conclusion, we determined that IRT images taken from the lateral view had the least variability. Also, we found no interaction of side by view indicating no difference in surface temperature between coronary band temperatures of the left and right limbs of the same cow. These results suggest that a cow may serve as its own control to compare images between left and right limbs at each image view. Therefore, we may be able to identify inflammation associated with lameness when comparison between limbs reveals a difference in surface temperature within cow.

CHAPTER FOUR

Using Infrared Thermography of the Coronary Band to Detect Hoof Lesions in Dairy Cows

Abstract

Infrared thermography (IRT) creates a pictorial representation of the surface temperature of an object. It has potential to detect inflammation associated with lameness. In the dairy industry, lameness is a costly problem. Currently few methods are available for early lameness detection. In this study, IRT was used to assess the surface temperature of the coronary band region of the hind limbs of sound and lame dairy cows. On day 1 of the 11-day collection period, 30 multiparous Holstein cows less than 40 DIM were selected based on their locomotion score: 15 sound (score = 1) cows and 15 moderately lame (score = 3) cows. IRT images of the dorsal, lateral and plantar aspects of both distal limbs were collected once daily after the second of 3 milkings for 11 consecutive days. Using the IRT images, average and maximum temperatures were identified from within an area approximately 2 cm above to 2 cm below the coronary band. Maximum temperatures were correlated with average temperatures ($r = 0.88$, $P < 0.01$) and were used in all statistical analyses. On d 6, claws of all cows were trimmed to identify lesions. Sixteen cows had 1 or more lesions; 7 of which had been selected as sound and 9 of which had been selected as lame on d 1. Data were analyzed using a mixed model procedure with view, limb, lesion, pre and post trimming as fixed effects. Cow was a random effect. Variability due to cow, view, and limb were modeled using appropriate

covariance structures. Cows with lesions had a higher maximum temperature of the coronary band in the dorsal view than cows without lesions over the 5 days prior to trimming. There was no significant difference in maximum temperature between lesion and non-lesion cows over the 5 days post trimming. These results suggest that IRT may be useful to distinguish cows that have claw lesions.

1. Introduction

Lameness is a major concern for the dairy industry due to its impact on profitability and animal welfare (Greenough et al., 1997, Hemsworth et al., 1995). Lameness in dairy cattle decreases milk production (Warnick et al., 2001) and increases the incidence of reproductive disorders (Hernandez et al., 2005, Sprecher et al., 1997) which have a direct impact on the productivity of the herd. Lameness most frequently occurs soon after calving (Offer et al., 2000; Leonard et al., 1996) and is caused by a multitude of factors (Galindo and Broom, 2000). In dairy cattle, lameness is most often a result of diseases of the foot (Clarkson et al., 1996; Warnick et al., 2001) which are associated commonly with laminitis (Nocek, 1997). Laminitis appears to be associated with the release of vasoactive substances during the decline in ruminal pH that occurs during acidosis, which ultimately destroys the microvasculature of the corium leading to sole hemorrhaging and the formation of claw lesions (Nocek, 1997). Lesions often mature in a predictable manner with an initial increase in vascular supply and tissue permeability during acute inflammation (Trent and Redic-Kill, 1997).

Locomotion scoring is a common method used to detect and quantify lameness by using a numerical system assigned to a cow based on posture and gait symmetry. Several locomotion scoring systems have been proposed (Manson and Leaver, 1988; Wells et al., 1993; Sprecher et al., 1997; Vokey et al., 2001; Nordlund et al., 2004). While locomotion scoring is helpful in determining the overall hoof health of a herd, the systems are subjective (Engel et al., 2002). Researchers are currently working to develop more objective methods to assess lameness using more advanced technologies including force plates (Tasch and Rajkondawar, 2004), pressure plates (Scott, 1988; van der Tol et al., 2002, 2003, 2004; Almeida et al., in press) and IRT (Whay et al., 2004; Schmidt et al., 2003; Nikkah et al., 2005).

Infrared thermography non-invasively measures the radiant energy emitted by an object to determine its surface temperature (Barnes, 1968; Head, 2001). It has been used to assess inflammatory conditions in livestock in several studies (Purohit and McCoy, 1980; Spire et al., 1999; Loughmiller et al., 2001; Turner, 2001). Previously, IRT was used to detect differences between lame and sound limbs in cows (Whay et al., 2004) and to determine associations between lameness score and claw temperatures where pathologies of the claw were present (Schmidt et al., 2003). Nikkah et al. (2005) found that early lactation cows have a higher coronary band temperature which corresponded to a more frequent occurrence of sole hemorrhaging in this group. Together these studies indicate that IRT may be a useful tool for lameness detection in cattle. However, none of these previous studies have reported baseline data of sound cattle and results of surface temperature data in lame cattle are limited.

Therefore, the objective of this study was to determine the ability of IRT to detect lameness in dairy cows by comparing surface temperatures of the coronary band region between lame and sound cows and cows with and without claw lesions.

2. Materials and Methods

2.1 Animals

This study was conducted in September 2005 on a large commercial dairy farm in central Michigan. The experimental protocol was reviewed and approved by the All University Committee on Animal Use and Care. Thirty second and third lactation cows less than 40 DIM were selected based on their locomotion score on d 1 of this 11-d study. Fifteen sound (locomotion score = 1) and 15 lame (locomotion score = 3) cows, were selected based on the Sprecher et al. (1997) locomotion scoring system (Table 1). All cows were locomotion scored daily by one of four different observers. Three of the observers scored the cows on only one day each, while the remainder of the scoring was completed by one person. Each observer watched a training video and completed at least one session of on farm scoring with a trained observer before collecting data. Videos of locomotion also were collected daily for each cow and a subset of videos were reviewed by a veterinarian to confirm locomotion scores. The hooves of all cows were trimmed on d 6 and lesions were recorded and treated at this time. Health records also were monitored throughout the study.

Table 1. Locomotion scoring system as described by Sprecher et al., 1997.

Lameness score	Clinical Disposition	Assessment Criteria
1	Normal	The cow stands and walks with a level-back posture. Her gait is normal.
2	Mildly Lame	The cow stands with a level-back posture but develops an arched back posture while walking. Her gait remains normal.
3	Moderately Lame	An arched-back posture is evident both while standing and walking. Her gait is affected and is best described as short-striding with one or more limbs
4	Lame	An arched-back posture is always evident and gait is best described as one deliberate step at a time. The cow favors one or more limbs
5	Severely Lame	The cow additionally demonstrates an inability or extreme reluctance to bear weight on one or more of her limbs/feet.

2.2 Housing and Management

Cows were housed in a four-row free-stall facility with a center drive through feeding lane, natural ventilation with side curtains, and an open peak. Free-stalls were 1.2 m wide by 2.2 m long and were bedded with sand, which was replenished weekly. All flooring surfaces in the barn were concrete except for the holding area behind the milking parlor, which was a rubber mat surface. Concrete alleys were cleaned during each milking time. All cows used in this study were kept in a pen of 175 cows with a 97% stocking rate. Cows were fed a totally mixed ration, consisting of 52% grain mix, 23% corn silage, 21% haylage, and 4% dry hay on an as-fed basis, twice a day. Cows were milked three times a day at 0700, 1700, and 2300 h and all IRT images were collected following the 1700 h milking.

2.3 Hoof Trimming

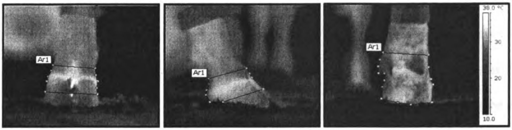
All cows had all four hooves trimmed on d 6 of the 11-d collection period. Hoof trimming was performed by a trained hoof trimmer who regularly trims hooves on the farm where this study was conducted. During trimming, lesions were assessed by the hoof trimmer and were recorded by both the hoof trimmer and the researcher. Photographs of the lesions also were taken at this time. In claws where lesions were identified, therapeutic hoof trimming was performed according to standard farm procedures; the damaged portion of the claw was removed and when severe lesions were discovered, wooden blocks were attached to the sound claw to relieve pressure on the damaged claw. All cows remained in the study after hoof trimming regardless of lesions and treatments.

2.4 IRT Data Collection

Infrared images were collected once a day for 11 consecutive d. Image collection began at 1700 h following the second of three milkings and concluded at approximately 2100 h daily. Cows were sorted automatically from their milking group upon exiting the parlor and their hind limbs imaged based on the order that they exited the parlor. All cows had full access to water and hay after exiting the parlor and before imaging commenced.

For IRT imaging, cows were restrained in a headlock chute used for veterinary procedures on the farm. Images were taken from the dorsal, lateral, and plantar views of both rear distal limbs as well as the both sides of the fore udder above the front teat. The rear limbs and the udder were not cleaned of any foreign material for IRT imaging. All images were taken from a distance of 1 m measured by a string attached to the camera which was held up to the area being imaged.

Images were taken using a FLIR P-65 infrared camera (FLIR Systems Inc., New Billerica, MA). The sensitivity of the camera is 50 mK at 30 °C with a spectral range of 7.5 to 13 μm and the accuracy of the camera is ± 2 °C. IRT images were analyzed using ThermaCAM Reporter 7.0 (FLIR Systems, Inc., New Billerica, MA) and were corrected for average ambient temperature during each collection time and distance within the software. In each udder image, average and maximum temperatures (MST) were reported from within a pre-set rectangle within ThermaCAM Reporter 7.0 encompassing an area approximately 14 cm^2 of the fore udder above the front teat on each side. In each hoof image, the average and MST were determined from within an area approximately 2 cm above and 2 cm below the coronary band (Figure 1). Average and MST from within the specified area of the coronary band and the fore udder were correlated highly ($r = 0.879$, $P < 0.001$) and MST was used for statistical analysis.



A B C

Figure 1. Infrared images of the dorsal (A), lateral (B), and plantar (C) image views with area of interest around the coronary band region.

2.5 Additional Temperature Measurements

Barn temperature and relative humidity were measured using a HOBO® H8 Data Logger (Onset Computer Corp., Bourne, MA) affixed to the headlock chute used for data collection at a height of approximately 2 m. Temperature and humidity were recorded every 5 min and the daily ambient temperature and relative humidity was determined by averaging data from within the collection time period. Ambient temperatures within the collection area ranged from 21.4 to 29.2 °C with relative humidity ranging from 37.1 to 67.0 % during this study. Rectal temperatures were collected during IRT imaging using a digital probe thermometer (GLA M525/550, GLA Agricultural Electronics, San Luis Obispo, CA).

2.6 Statistical Analysis

A mixed model procedure (PROC MIXED, SAS ver 9.1.3) was used for data analysis. Pre and post-trimming data were analyzed separately because of differences in the data sets. Image angle, side (left or right side), cows with or without lesions and the occurrence of lesions in only one rear hoof were treated as fixed effects. The number of lesions was also tested as a covariate. To test for the effect of lesion on MST, cows were classified as lesion or non-lesion based on the presence or absence of a lesion in any claw. In addition, repeated measures on individual cows across days were modeled as subject-specific random effect profiles. Based on the Bayes Information Criterion (BIC) value for model fit, in conjunction with the residual analysis, day was fit as a covariate in the pre-trimming analysis and as a factor in the post-trimming analysis. The residual variation was modeled as a log-linear variance model with view and day as the only significant factors. For all analyses, observations with MST < 29 °C were deleted as these data were highly influential and were treated as outliers. Most of these observations were from one cow on the first day of data collection. Significance was set at $P < 0.05$ and a significant trend was considered to be $0.05 < P < 0.1$.

3. Results

Of the 15 cows selected as sound (locomotion score = 1 on d 1 of the study), eight cows had no hoof lesions, five cows had one limb affected by hoof lesions (two of these cows had lesion in both claws), one cow had two limbs affected by hoof lesions, and one cow had three limbs affected by hoof lesions as determined by the hoof trimmer on d 6 (Table 2). Of the 15 cows selected as lame (locomotion score 3 on d 1 of the study), six cows had no lesions, seven cows had one limb affected by hoof lesions (one cow had lesions in both claws), and two cows had two limbs affected by hoof lesions (Table 2). After conducting a Spearman's correlation analysis, lesion number was not correlated with daily locomotion scores in both the pre-trimming ($r = 0.0574$, $P = 0.3254$) and post-trimming (r = 0.0869, P = 0.1332) data sets. The occurrence of lesions also was not correlated with daily locomotion scores in both the pre-trimming (r = 0.0843, P = 0.1478) and post-trimming (r = - 0.0809, P = 0.1621) data sets.

Table 2. The cows selected as sound based on locomotion score (LS), the number of limbs affected by lesions, and the limb and claw where the lesions were discovered (RRL = right rear lateral; RRM = right rear medial; RRLM = right rear lateral and medial; LRL = left rear lateral; LRM = left rear medial; LRLM = left rear lateral and medial; RFL = right front lateral; LFL = left front lateral).

Selected Sound Cows				Selected Lame Cows			
Cow	Day 1 LS	Number of limbs with lesions	Lesion locations	Cow	Day 1 LS	Number of limbs with lesions	Lesion locations
1	1	0	--	16	3	0	--
2	1	0	--	17	3	0	--
3	1	0	--	18	3	0	--
4	1	0	--	19	3	0	--
5	1	0	--	20	3	0	--
6	1	0	--	21	3	0	--
7	1	0	--	22	3	1	RRM*
8	1	0	--	23	3	1	RFL
9	1	1	RRL*	24	3	1	LFL
10	1	1	LRL*	25	3	1	LRM*
11	1	1	RRLM*	26	3	1	RRL*
12	1	1	LRL*	27	3	1	RRM*
13	1	1	LRLM*	28	3	1	LRLM*
14	1	2	LRL RRL	29	3	2	LFL RFL
15	1	3	LFL RFL RRM	30	3	2	RFL LRL

* Indicates cows with one hind limb affected by lesions used in subsequent analysis.

3.1 Pre-Trimming IRT Data Analysis

Data were analyzed with lesion as a factor to check for differences between lesion and non-lesion cows. MST data for both rear limbs of all non-lesion cows and all lesion cows, regardless of the location or number of lesions were pooled for this analysis. There was no difference in MST of the coronary band between lesion and non-lesion cows in the dorsal ($P = 0.28$) and lateral ($P = 0.14$) views but there was a significant trend in the plantar ($P = 0.06$) view. While the values are not significant there is a trend that the cows with lesions have a somewhat higher MST across all views (Figure 2).

To set a standard within cows, we compared MST in both limbs of cows that were not affected by any hoof lesions. There were no differences in MST between left and right rear limbs among cows with no lesions ($P = 0.8085$) of the dorsal (34.7 °C; $P = 0.4958$), lateral (33.8 °C; $P = 0.4183$), and plantar (34.1 °C; $P = 0.6005$) views.

We also assessed differences in temperature between the lesion and non-lesion limb in cows with lesions in only one rear limb (Table 3). In the dorsal view, when lesions were found in the left limb, there was a trend for the right limb to have a lower MST ($P = 0.0526$) and when lesions were found in the right limb the left limb had a lower MST ($P < 0.05$). In the lateral view, when lesions were found in the left limb there was a trend for the right limb to have a lower MST ($P = 0.056$) and when lesions were found in the right limb there was a trend for the left limb to have a lower MST ($P = 0.0669$). In the plantar view, when lesions were found in the left limb there was no difference in MST ($P = 0.1384$) and when lesions were found in the right limb there was a trend for the left limb to have a lower MST ($P = 0.0663$).

Table 3. Maximum surface temperature (MST) values, standard error of the mean (SEM) and P values based on the least squares means for left and right limbs from dorsal, lateral and plantar views in cows with only one hind limb affected by lesions over the 5-d pre-trimming.

View	Lesion Location	MST Left °C	SEM	MST Right °C	SEM	P value[1]
Dorsal	Left	35.4	0.359	34.7	0.368	0.053
	Right	33.1	0.294	33.8	0.293	0.016
Lateral	Left	34.4	0.357	33.8	0.362	0.056
	Right	32.3	0.292	32.8	0.291	0.067
Plantar	Left	35.2	0.403	34.6	0.415	0.138
	Right	32.7	0.329	33.3	0.329	0.066

[1] Values based on n = 5 cows with lesions in the left limb and n = 5 cows with lesions in the right limb over the 5 d pre-trimming.

Lesion also was tested as a covariate to check for trends associated with the number of lesions among cows. MST of the coronary band increased as the number of lesions on all hooves (both front and rear) increased ($P < 0.05$). Furthermore, there was a significant interaction of lesion number by side ($P < 0.01$) indicating that the increase in MST depends on the side in which the lesions are occurring.

3.2 Post-Trimming Data Analysis

In general, there was more variability in the post-trimming data than the pre-trimming data. When testing lesion as a factor, no difference in MST between non-lesion cows and lesion cows in the post-trimming analysis was detected. Among non-lesion cows, there was no difference of MST between limbs in images of the plantar ($P = 0.5656$) view. However, there was a difference in MST between sides in images of the lateral view ($P < 0.05$) and a trend for a difference in MST in the dorsal ($P = 0.0622$) view. Additionally, there was no effect of number of lesions on MST ($P = 0.9561$) in the post-trimming analysis.

For cows with only one rear limb affected by lesions, there was an effect of lesion location by side interaction post-trimming ($P < 0.005$). Pair-wise comparison of the LS means showed that lesions located in the left hoof caused no difference in maximum temperature of the coronary band when compared to the right. In contrast, lesions located in the right hoof caused the right coronary band to have a higher maximum temperature than the left (Table 4). In the post trimming analysis, we found no significant trends associated with lesion when tested as a covariate.

Table 4. Maximum surface temperature (MST) values and P values based on the least squares means for left and right limbs from dorsal, lateral and plantar views in cows with only one hind limb affected by lesions over the 5-d post-trimming.

View	Lesion Location	MST Left °C	SEM	MST Right °C	SEM	P value[2]
Dorsal	Left	35.4	0.415	35.0	0.402	0.314
	Right	33.6	0.332	35.0	0.332	$P < 0.001$
Lateral	Left	34.4	0.431	34.1	0.417	0.625
	Right	32.8	0.347	34.0	0.344	0.002
Plantar	Left	34.8	0.446	34.3	0.432	0.271
	Right	33.0	0.359	34.1	0.356	0.010

[2] Values based on n = 5 animals with lesions in the left limb and n = 5 cows with lesions in the right limb over the 5 d post-trimming.

4. Discussion

Cows were selected for this study based on their locomotion score at d 1, with the assumption that at least some of the cows would have claw lesions upon inspection at hoof trimming on d 5. After inspection at hoof trimming, we found no correlation between the number of lesions and daily locomotion score. This finding is consistent with previous research with no correlation between hoof lesions and lameness after collecting data on 3,444 cattle on 77 Swedish dairy farms (Manske et al., 2002). A downfall of the current study was that locomotion scoring was not collected using the most ideal protocol, with only one person recording locomotion per day. In addition, we had four different observers perform the scoring and although all were trained, some observers had more experience than others. While the occurrence of claw lesions was recorded in this study, scoring of lesion type and severity was not performed. This information perhaps would have allowed us to test for temperature differences associated with different types and severity of lesions, which could have complemented the study by Schmidt et al. (2003), who reported in an abstract that IRT may be useful for assessing claw abnormalities.

In this study, MST was derived from an area surrounding the coronary band, the highly vascularized area located just proximal to the hoof wall (Greenough, 1997). During preliminary analysis of data, we determined that differences existed between pre-trimming and post-trimming data and therefore we carried out independent data analyses. These differences may be due to the invasiveness of hoof trimming and further studies should investigate the effects of hoof trimming on surface temperature values of the distal limb. In the pre-trimming data analysis, we found no significant difference in MST between cows with lesions and cows without lesions, although there was a trend for cows with lesions, regardless of lesion location, to have a higher MST in all three image views. In the post-trimming analysis, we also found no differences between limbs of non-lesion cows in images taken from the plantar view. However, there was a difference in MST from the lateral view and a trend in the dorsal view. In a similar study, Haley et al. (2005) also found no difference between lame and sound cows based on locomotion score. Together, these results indicate that the cow should serve as its own control for surface temperature determination.

Previous research has determined differences in surface temperatures between lame and sound limbs (Whay et al., 2004). Therefore, in the pre-trimming analysis of cows with a lesion in only one hind limb, we expected to find differences in MST between lesion and non-lesion limbs. However, significance of results depended on the location of the lesion and the image view. In the plantar view, we found a trend for difference in temperature between limbs when lesions were found in the right limb; however, there was no difference in MST when lesions were found in the left limb. In the lateral view, we found a trend for difference in MST between limbs when lesions occurred in both the left and right limbs. Differences in the MST of the dorsal view were found when lesions occurred in the right limb and a trend for differences in MST when the lesions occurred in the left limb. In Chapter 3, we concluded that images of the lateral view showed the least variation in sound cows and should be used for IRT data collection. In the current research, differences may be evident in the dorsal view but not the lateral view because of the occurrence of lesions in the medial claw as well as the lateral claw. Differences in significance when lesions occurred on left and right limbs may be associated with the severity of the lesions. In contrast, our post-trimming data analysis did not show differences in MST of the coronary band between lesion and non-lesion limbs. This may be due to the invasiveness of hoof trimming or the effects of treatment methods (i.e., wooden blocks).

When testing lesion as a covariate in the pre-trimming analysis, we determined that as the number of limbs (including both front and rear) affected by lesions increased, there was a trend for the MST of the coronary band to increase. As with other measures, these results were not repeated in the post-trimming analysis where there was no effect of the number of limbs affected by lesions on the MST.

5. Conclusion

In conclusion, we found that in non-lesion cows before hoof trimming there was no significant difference between MST of the left and right limbs in each image view, which corresponds with results from Chapter 3. Furthermore, in cows with only one rear limb affected by one or two hoof lesions (three cows had lesions in both claws of one hind limb), a difference in MST was evident in images taken from the dorsal view indicating that we may be able to use IRT images of the dorsal view to detect lesions. The results of this study suggest that IRT may be a useful tool in detecting inflammation associated with hoof lesions when comparing MST between limbs of the same cow. This technology merits further research to determine differences in surface temperatures between limbs affected by different hoof lesions and sound limbs.

CHAPTER FIVE

Discussion and Future Research Directions

5.1 Discussion

Lameness may be caused by an array of factors (Galindo et al., 2000). This disease, which is often perceived by farmers at level lower than the actual occurrence (Kopcha et al., 2003; Edgecomb et al., 2006), has a major impact on economics (Nordlund et al., 2004) and animal welfare (Hemsworth et al., 1995; Whay et al., 1998). More than 90% of lameness cases involve the foot (Shearer and VanAmstel, 2000) and many of these pathologies also create an inflammatory response. Infrared thermography (IRT) provides a non-invasive method to measure the surface temperature (e.g. Barnes, 1968; Head, 2001). It has been well documented that IRT is a useful tool to detect lameness in horses (Denoix, 1994; Turner, 2001; Eddy et al., 2001). Some studies also have been successful in detecting lameness in cattle using IRT (Cockroft et al., 2000; Schmidt et al., 2003; Whay et al., 2004; Nikkah et al., 2005) while others have failed (Momcilovic et al., 2000; Haley et al., 2005).

We concur with Whay (2002) who reported that the early detection of lameness in dairy cattle is pivotal to all subsequent action to relieve suffering. Also, Clarkson et al. (1996) reported evidence that early detection and subsequent treatment of lameness resulted in a reduction in the duration and cases of lameness. Therefore, the main objective of this project was to assess the usefulness of using IRT, on-farm, to detect lameness in dairy cattle. We hypothesize that this technology may be used to detect lameness at an earlier stage than the existing protocols. To answer this question we performed two studies. In the first study (Chapter 3), 10 sound, lactating Holstein cows were imaged at multiple times over a 2 d period to give us an understanding of the normal thermal characteristics in limbs of healthy animals. In the second experiment (Chapter 4) 15 sound (locomotion score = 1) and 15 lame (locomotion score = 3) cows were imaged in order to determine the ability of IRT to detect lameness.

In Study 1 we determined that sound cows have no significant interaction between side and view and that there was no difference in temperature between the left and right limbs in the plantar view, a trend towards difference in the lateral view, and a difference in temperature between limbs in the dorsal view. As there was no significant interaction, these results indicate that a correction factor may be used to account for slight differences between limbs. We also found a general trend that the left limb has a slightly higher maximum surface temperature (MST). These differences may be due to a variety of factors including which side the cow generally lays on, which limb was exposed to the most moisture and possible interference from extraneous sources of radiation (i.e., windows). In Study 2, we found that cows without lesions show no significant difference in temperature between left and right hind limbs at each image view, which concurs with the findings in the plantar view for Study 1, but differs from our findings in the dorsal and lateral views . We also found differences of MST between lame and sound limbs in images taken of the dorsal view and a trend for differences in images taken from the lateral view in cows with only one rear limb affected by a hoof lesion, indicating that a cow may serve as a self control measure of inflammation as suggested in Study 1.

In Study 2, we also determined that there was no correlation between locomotion score and the occurrence of lesions indicating that lesions do not always cause lameness which concurs with previous research (Manske et al., 2002). However, the locomotion scoring protocol used in Study 2 (i.e., different observers, one observer per day) was not ideal for a decisive locomotion scoring study. Also, although we recorded the occurrence and type of lesion, severity and specific lesion etiologies were not recorded at the time of hoof trimming.

It was interesting to see that when assessing the MST values of the two studies, we observed noticeable differences in the MST of non-lesion cows between the two facilities. MST values in Study 2 were approximately 1 °C higher in the dorsal view, 2 °C higher in the lateral view, and 3 °C higher in the plantar view. These differences may be due to a number of factors including ambient temperature, the amount of foreign material on the hoof, the amount of exercise the animals had before imaging, and the overall hoof health of the animals. To reiterate, the animals used in Study 1 were housed in a tie-stall facility at the MSU Teaching and Research Center and hooves of these animals were generally cleaner and dryer than those of the cows used in Study 2, which were housed in a large free-stall facility on a commercial dairy. Also, data for Study 1 was collected in May and ambient temperatures were lower than those during the data collection for Study 2, which took place in early September.

Overall, the results from these studies in conjunction with previous research indicate that IRT has the possibility to detect lameness earlier than through conventional methods such as locomotion scoring. Results from both studies (Chapters 3 and 4) indicate that a cow may be able to serve as a self control when one hind limb is sound, which is important because of the numerous opportunities for variability in IRT data between cows and at different facilities. This technology presents a more objective measure to detect temperature changes in the hoof which may be useful to detect lameness early and ultimately increase productivity and decrease suffering in dairy cattle.

5.2 Future Research Directions

The use of IRT to measure surface temperature as an indicator of inflammation, provides a unique and innovative way to assess lameness in cattle and further studies should be performed to continue to explore the possibilities and limitations of this technology. Longitudinal studies which follow cows throughout lactation and the dry period should be encouraged. Purohit and McCoy (1980) reported that thermograms of a horse with laminitis showed an increase in surface temperature 24 h before clinical signs were evident. It is likely that in cattle we may find similar increases in surface temperature before clinical signs of lameness are evident. Future studies also will help to further understand differences in temperature throughout a cow's lactation. Nikkah et al. (2005) reported a higher surface temperature in early lactation cows than in late lactation cows. By following cows throughout multiple lactations, we may be able to better understand why these temperature differences occur as well as exactly when they occur. In addition, collecting data at different intervals throughout these studies will help us to understand how often cows need to be imaged in order to detect lameness earlier than through conventional methods.

Further research is also needed to help us better understand the normal thermal patterns of dairy cows, not just the temperature values, as the patterns of temperature may tell us more than just the temperature values. Turner (2001) reported that in a horse with laminitis, the temperature of the hoof will begin to approach the temperature of the coronary band. In cattle, it is likely that we could see similar changes in the thermal patterns of the coronary band and the hoof. In addition, further studies need to be conducted which include data from the front hooves. In the present study, we chose to assess only the rear limbs because most lesions occur in the hind limbs (Shearer and VanAmstel, 2000) and at both facilities used, the rear limbs were more accessible for imaging. It will be interesting to see if the results found in this study would be consistent in the front limbs and to see if front limbs also may serve as controls for rear limbs.

Moreover, large scale studies conducted on multiple commercial dairies in different environmental conditions will help us better understand the amount of variability due to cows, facilities, and environment. While we expect to see differences in surface temperature due to a variety of factors including ambient temperatures and circadian rhythms, we need to determine a range of normal temperatures for sound cows in specific environmental conditions.

Further studies investigating the use of IRT to detect lameness may provide researchers with an objective method to detect inflammation in the limbs of dairy cattle. In summary, future studies should investigate the use of IRT to detect lameness early and ultimately increase productivity and welfare of the animals.

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