University of Alberta

Relationship of Radiated Heat Loss Measured by Infrared Thermography to Residual Feed Intake in Beef Heifers

by

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Dedication

This thesis is dedicated to my wife, Denise; and children, Serafia and Jacob.

Abstract

Infrared thermography (IRT) has shown utility in predicting residual feed intake (RFI) differences in mature cows, growing bulls and finishing steers. It was hypothesized that efficient heifers would exhibit decreased radiated heat loss. RFI_{fat} determined on sixty-one crossbred beef heifers over a 113 day post-weaning feed trial ranged from -1.55 to 2.19 kg d^{-1} (sd= 0.78). Heifers were classified into low, medium, or high RFI_{fat} groups (±0.5 sd of RFI_{fat} µ). Pooled average radiated temperature estimates from multiple IRT images collected on head and ribcage sites over four dates were determined. Low and medium RFI_{fat} heifers had similar cheek-mean temperatures of 19.88ºC and 20.40ºC but were lower than high RFI_{fat} heifers (21.29ºC; $P<0.0001$). Of the sites examined, cheek-mean temperatures were correlated ($r=0.46$; $P<0.001$) to RFI_{fat} while ribcage sites were not. Measurement of radiated heat loss by IRT from the cheek warrants further study to predict growth efficiency in heifers.

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CHAPTER 1

Introduction and Literature Review

1.1 Early Concepts

Through a combination of observation, curiosity, realization, and even serendipity, countless people have added to our understanding of animal production and efficiency. The modern study of feed efficiency has its roots in the formalization of the Laws of Thermodynamics in the 1840s by Clausius and Thomson (Lord Kelvin) and also Hess's Law (Brody 1964). These concepts of energy transformation applied to living organisms were essential to the development of energy difference calculations used today. Pioneers in the field of bioenergetics such as Priestley, Scheele, Lavoisier, and Crawford were able to expand the generalization about life being primarily a combustion process (Johnson et al. 2003). Knowledge about the relationships between gas exchange, heat production, and causes of animal energy expenditures progressed with the use of live animal subjects in calorimetry experiments. The development of direct calorimetry to measure heat loss and of indirect calorimetry to measure heat production contributed greatly to the evolution of nutrition as a science. The use of calorimetry in a wide variety of species of various sizes led to agreement on how to estimate basal metabolic rate, sometimes referred to as the "Brody-Kleiber unit". The general equation of $ME = RE + HP$ (metabolizable energy required is the sum of retained energy plus heat production) and concepts like thermal homeostasis, thermal neutral zone, and calorigenic effects of feed contributed to the development of the metabolizable and net energy-based system by Armsby, Kellner, and others (Kleiber 1961). Equally important were experiments utilizing the comparative slaughter technique to expand on the requirements for retained energy (Lawes and Gilbert 1861) This lead to the proposal of separating the net energy requirements for maintenance and gain (Lofgreen and Garrett 1968) and forms the basis to the net energy system used today. Additional adjustments to energy requirements based on the need to continually cope with environmental stressors were also necessary. The use of calorimetry chambers with modifiable temperature and wind speed conditions allowed study of the physiological adaption to environmental factors. For example, the University of Alberta's Laird McElroy Environmental and Metabolic Center is equipped with these capabilities and has been used to study metabolic and endocrine responses to factors such as cold exposure and feed restriction (Webster 1971; Christopherson et al. 1977; Kennedy et al. 1981; Young et al. 1989; Kennedy et al. 2005). The principles of the current recommendations for feeding beef cattle (NRC 1996) continue to be grounded on many of these earlier efforts in the concepts of animal energetics.

Traditionally, animal performance was measured in terms of outputs, depending on what was most applicable to the particular phase of a production system. For example, measurements of post weaning growth rate of calves, milk yield from lactating cows, and carcass composition of finished steers. Each of these can be affected by the dam, environment, and management but also by the animal's genetic makeup. Extensive literature reviews of the research were used to determine estimates of the genetic and phenotypic parameters of performance traits in beef cattle (Preston and Willis 1974; Mohiuddin 1993). Growth patterns of the major tissues of muscle, fat, and bone in cattle (Berg and Butterfield 1976) and sheep (Butterfield 1988) have also been intensively studied using dissection programmes with emphasis on the influences of mature size, sex, and breed.

1.1.1 Feed conversion ratio

In most scientific literature, measures of animal production efficiency refers to the ratio of feed to an output (such as weight gain, milk yield, lean tissue) in one defined aspect of the production system over a set period of time. For growing and finishing cattle, the feed to gain or feed conversion ratio (FCR) has long been used as the standard for expressing gross efficiency. Just a few examples include studies on the Line 1 Herefords in Montana (Knapp and Nordskog 1946; MacNeil 2009), studies on various production systems and genotypes of cattle in Denmark (Andersen 1978), and studies with the Germ Plasm Evaluation Program in Nebraska (Smith et al. 1976).

As the phenotypic and genetic correlations of gross efficiency (FCR) with aspects of production became well documented, the importance of determining individual feed intake was largely dismissed. For some time, it was believed selection for production would automatically produce a correlated improvement in gross efficiency (Archer et al. 1999). This was demonstrated by Mrode et al. (1990) showing that the direct response in improving gross efficiency was higher when selection was based on lean growth rather than by selecting for gross efficiency itself (Mrode et al. 1990).

However, massive reviews of the literature published between 1940 and 1991 of genetic parameter estimates for beef production traits contradicted these views. FCR is negatively correlated with measures of growth and mature size, mature cow weight is highly heritable and positively correlated with growth rates at younger ages (Koots et al. 1994a;

Koots et al. 1994b). Suggesting animals with high genetic potential for growth rate and assumed to have a lower FCR also have an increased genetic potential for mature size, and presumably, higher maintenance requirements (Crews 2005). Likewise, selection based on improving FCR tended to increase mature cow weight and any improvement in feed efficiency in growing calves was lost by the increased feed requirements of the cows (Archer et al. 1999). The relevance of this unintended selection for increased cow size becomes important when it is considered that the energy required just for maintenance functions is estimated to require 70-75% of the total annual energy requirements of a beef cow (Ferrell and Jenkins 1985). Another study suggests the cow herd requires 65-75% of the total energy required for beef production and that 50% of the total energy required for beef production is used for cow maintenance (Montano-Bermudez et al. 1990).

Another limitation in the use of FCR is the difficulty in accurately determining the input side of the ratio as obtaining individual feed intake is both time-consuming and costly (Basarab et al. 2007). Many studies were limited to measuring feed intake as a pen average, losing the measure of individual feed intake variation. The variation in feed intake between pens, admittedly a less powerful test of differences in efficiency, was the only one suitable to this type of data (Smith et al. 1976).

A final problem with selection based on FCR deals with the issue of it being a ratio of two traits, gain and intake, each with their own mean and variance and somewhat independent of each other. Unpredictable responses to selection tend to occur because a disproportionate amount of selection pressure is placed on the component of the ratio with the higher genetic variance (Gunsett 1984; Crews 2005). Ratios become complex problems because of multiple levels of confounding, depending on the situation, and make it almost impossible to define the actual efficiency (Johnson et al. 2003).

1.1.2 Alternative measures of efficiency

For these reasons, genetic progress in the improvement of feed efficiency in cattle has remained largely ineffective especially as the maintenance requirements of cattle appears to have been largely unchanged for the last 100 years (Johnson et al. 2003).

An alternative to calculating growth efficiency normally based on a time-constant basis was studied by Salmon et al. (1990) using mice selected for increased body weight. FCR in growing animals was suggested to be largely a function of maturity patterns. Therefore, using a weight-constant basis or a maturity-constant basis would remove the effects of maturity patterns or scale from the growth efficiency measurement (Salmon et al. 1990). While this concept has merit, the increased amount of data required generally makes this impractical for beef cattle (Archer et al. 1999).

The relative rate of gain ratio (growth rate/metabolic mass) proposed by Kleiber (1936) identifies animals with a high efficiency of growth relative to body size. An increase in KR implies that more growth is obtained without an increase in maintenance energy requirement (Kleiber 1936). The Kleiber ratio (KR) has been suggested as an effective indirect predictor of FCE in feedlot conditions where individual feed intake cannot be determined (Bergh et al. 1992). However, the correlated response data showed that despite having advantages over ADG as an indirect selection criterion for efficiency, an improvement in KR would still increase feed intake slightly (Bergh et al. 1992). A more recent study by Nkrumah et al. (2004) comparing different measures of energetic efficiency found that KR might not detect obvious differences in energetic efficiency between animals. As well, the phenotypic relationship of KR with animal performance and efficiency may not be any different from the reported relationships with FCR (Nkrumah et al. 2004). Finally, KR was found to not account for differences in the fat and protein contents of gain, ultimately resulting in selection for large frame animals, without necessarily changing growth efficiency (Tedeschi et al. 2006).

Two other approaches for measuring feed efficiency reviewed by Archer et al. (1999) are the calculation of maintenance efficiency and the calculation of partial efficiency of growth. While both are important in determining the efficiency of beef production systems, inherent difficulties and the large resources required limit their use to small numbers of animals. Maintenance efficiency is the ratio of body weight to feed intake at body weight stasis. However, it is difficult to hold animals to a constant live weight for a long enough period to get a true measure of the maintenance requirement. The requirement for weight stasis also hinders testing on growing animals (Archer et al. 1999). Partial efficiency of growth is the ratio of weight gain to feed after expected maintenance requirements are subtracted. But once again the difficulty in accurately determining the maintenance requirements limits its effectiveness (Archer et al. 1999). The use of calorimetry chambers or hoods to measure the energy balance is preferred but is limited to low numbers of animals. An alternative of estimating maintenance requirements utilizes feeding tables but does assume a constant (Archer et al. 1999). The constant in this case was FHP= 77 $BW^{0.75}$, the Brody-Kleiber unit for fasting heat production, the accuracy and relevance being widely challenged as reviewed by Johnson et al. (2003). For example, Ferrell and Jenkins (1985) suggested sufficient data was available to reject the assumption of a maintenance requirement constant, varying only with body weight or metabolic body size, and that the variation in animal energy expenditures may be attributable to variation in the metabolism of visceral organs (Ferrell and Jenkins 1985). In a later study on limit-fed versus ad libitum feeding of steers, Ferrell and Jenkins (1998) demonstrated that the relationship between energy gain and metabolizable energy intake was not linear above maintenance. The incremental increase in rate of gain decreases as intake increases and therefore maximum efficiency of growth may occur at less than maximum intakes (Ferrell and Jenkins 1998).

1.2 Residual feed intake concept

All of these limitations pointed to the need for an alternative measure of efficiency that could account for the individual variation in animal energy expenditures. In a review of studies on different species, such as mice, poultry, and pigs, it was known that individual animals of the same body weight can require differing amounts of feed for the same level of production (Herd and Arthur 2009). Koch et al. (1963) recognized that differences in both weight maintained and weight gain affect feed requirements. The individual feed intake of 1324 bull and heifer calves from experimental breeding herds located in Nebraska and Oklahoma in the 1950’s was collected and different methods of calculating feed efficiency in growing cattle was tested. One of the indices utilized the concept that feed intake could be adjusted by regression for body weight and for body weight gain. This effectively partitioned feed intake into the portion expected for the given level of production and a residual portion which became the measurement of efficiency. This deviation from the expected value is attributed to differences in efficiency of feed use and calves with low or negative values of adjusted feed consumption would be more efficient than those with high or positive values. As the study only involved the increases in body weight, it was acknowledged that more studies involving carcass composition were needed to determine feed efficiency measures for the composition of gain. Yet, the concluding comments appear to take a step backwards by suggesting that in light of the difficulties in determining individual feed intake that selecting for higher gain rates should be as effective and lead to both increased feed efficiency and increased feed consumption (Koch et al. 1963). Despite demonstrating this novel concept of basing efficiency on residuals, most research continued using FCR as the basis of feed efficiency or else concentrated on growth rate only. For example, Dickerson (1978) made recommendations in relation to animal efficiency, to first choose a mature body size best adapted to the environmental, breeding system, and market factors, and second, focus primarily on improving the genetically variable performance traits like reproductive rate, relative growth rate, and body composition. Brelin and Brannang (1982) summarized the data from four studies, including Koch et al. (1963), arguing that the strong genetic correlations between growth rate and FCR supports the consideration that selection for growth rate would automatically lead to an improvement in feed efficiency. While their results supported this reasoning, they conceded that feed efficiency measured as a ratio between feed consumption and growth is a very doubtful trait. Selection for growth rate might not necessarily mean an improvement in the ‘true feed efficiency’, which was suggested to be the efficiency of nutrient absorption, the rate of basal metabolism and the energy efficiency of the process of growth (Brelin and Brannang 1982).

1.2.1 Advances in individual feed intake measurement

Starting in the 1970's, several automated systems were developed for feeding individual animals in groups including the Calan Individual Feeding System (Broadbent et al. 1970) and the Pinpointer system (Gonyou and Stricklin 1981), each of which incorporated an individual identification tag (transponder) to either unlock a gate for access to feed or dispense a measured amount of feed to consume. The common problem with these systems was the frequency of electronic failures requiring careful monitoring to correct problems promptly (Cole 1994). Feeding data was limited to relatively low numbers of animals per feeding stall. There was also a difficulty in training animals to use the system; in fact, extra animals were required as replacements for those that were not trainable. It took until the 1990's for the technology to reliably identify animals and measure individual feed intake to advance to a point where it became affordable and practical to do so on large enough numbers of cattle.

1.2.2 RFI research in Australia

In 1993, Australian researchers started to use the concept of RFI, often also referred to as net feed intake, to search for biological predictors of feed efficiency following the development of an automated feeding and electronic identification system as described by Herd (1992). Arthur et al. (2004) gave an overview of ongoing research and development projects started at the Agricultural Research Centre in Trangie, NSW, and continuing at the Cooperative Research Centre for Cattle and Beef Quality with the Beef CRC I and Beef CRC II projects (Arthur et al. 2004). The main focus has been on the phenotypic and genetic variation in feed intake and efficiency and relationships with production traits in bulls, heifers, cows, and calves. Based on RFI, high and low feed efficiency selection lines were also established and the responses to selection monitored over 2 generations (Arthur et al. 2004). The details of the project design has been reported by Arthur et al. (1996) and numerous publications and reviews have been written (Arthur et al. 1997; Arthur et al. 2001; Richardson et al. 2001; Johnston 2002) on the results from this work. Considerable variation in net feed intake of individual animals has been reported and appears to have moderate heritability. At the same time, the phenotypic correlations indicated that net feed intake was unrelated to growth, and eye muscle area, while fat depth was reduced slightly in high efficiency animals. Selection for net feed intake was unlikely to have any undesirable responses in production traits of growing animals (Arthur et al. 1997).

1.2.3 RFI research in Canada

One of the initial studies to use the residual feed intake concept in Canada was on the records collected from 1981 to 1987 of station tested beef bulls by Liu et al. (2000). The Pinpointer system had been utilized to record the feed intake of individual bulls. RFI was then calculated in two ways. The first method determined the dry matter intake requirement from NRC prediction equations. The second method was a phenotypic regression approach using actual test data with an analysis of covariance. Dry matter intake was modelled to adjust for climatic and management conditions, and maintenance and production requirements. This method of modelling the actual data was found to be more appropriate than using the NRC prediction equations. The range in RFI calculated by this method between the least and most efficient bulls was 583.13 kg over the 140 day trial period and was sufficient to suggest substantial variation in feed efficiency among the bulls (Liu et al. 2000).

Investigations using RFI as a measure of feed efficiency have expanded greatly in Canada with the development and refinement of the Growsafe® system (McAllister et al. 2000; Basarab et al. 2002; Basarab et al. 2003; Nkrumah et al. 2004; Wang et al. 2006), and the Insentec monitoring system (Chapinal et al. 2007; Mader et al. 2009) to measure individual feed intake. Likewise, a great deal of the recent efficiency research done worldwide has been based on the use of RFI concept (Jensen et al. 1992; Fox et al. 2004; Bingham et al. 2009; Crowley et al. 2010; Cruz et al. 2010; Kelly et al. 2010).

1.2.4 Calculation of RFI

Regardless of how the individual feed intake is determined, the calculation of RFI by phenotypic regression follows a set procedure as described by Basarab et al. (2003). It is crucial that the animals remain healthy and fed ad libitum on the same ration throughout the feeding trial. The intention is that the animals are growing linearly during the length of the trial, confirming that there are no nutritional limitations or morbidity issues. Each animal's growth curve is determined by linear regression of weight on time and requires the collection of body weights at the start, at several intermediate points, and at the end of the feeding trial. Initial weight, mid-point metabolic weight (MMW), final weight, and average daily gain (ADG) are calculated from the regression coefficients from each animal's growth curve. The total as-fed feed intake during the feeding period is determined for each animal, and divided by the number of days on trial to give an average standardized daily feed intake (SFI). In order to calculate the expected feed intake (EFI), the variables of ADG and MMW are used to model the daily SFI. The model fitted can generally be summarized as: $Y_i = ß_0 + ß_1ADG_i + ß_2MMW_i + e_i$, where Y_i = daily SFI for animal i, $ß_0$ = regression intercept, $ß_1$ = partial regression coefficient of SFI on average daily gain, $ß_2$ = partial regression coefficient of SFI on mid-point metabolic weight, and e_i = residual error in SFI of animal i. This model results in an equation used to calculate expected feed intake (EFI) for each animal. Residual feed intake (RFI) for each animal is then calculated as the deviation of SFI from EFI (RFI = SFI – EFI). Animals with low or negative RFI values are more efficient than those with high or positive RFI values (Basarab et al. 2003).

1.2.5 Advantages of the RFI concept

The calculation of residual feed intake in this manner has the advantage that it is by definition phenotypically independent from the production traits used to calculate expected feed intake. In practice, measures of RFI have shown no phenotypic or genetic correlations with body weight or growth rate, as expected. Unlike selection based on FCE, there will be no tendency to select animals of increased body size. Importantly, the advantage of RFI is that expected feed intake can be adjusted not only for body weight and weight gain, but for any other production trait or energy use identified. For example, some studies have shown that RFI has weak positive correlations with measures of fatness suggesting that low RFI animals are leaner (Arthur et al. 1997; Herd and Bishop 2000; Richardson et al. 2001). If selection for efficiency by RFI results in leaner animals, this may have negative consequences on reproductive fitness in breeding heifers, and on carcass marbling in feeder animals. The concern is that the original method of calculating

RFI, using body weight and weight gain only, is lowly related to the composition of gain. Fortunately, variations in individual body composition can be tested for inclusion in the regression model as an additional energy use. By including live ultrasound measurements of body composition such as backfat thickness in the regression model, generally a small amount of additional variation in the expected feed intake can be accounted for. This approach has been used by several researchers (Basarab et al. 2003; Basarab et al. 2007; Mader et al. 2009; Kelly et al. 2010) to calculate a fat-adjusted RFI value, with the intention of reducing adverse effects on carcass characteristics in feeder cattle and fat deposition in breeding females. This same approach can be used to adjust the calculation of RFI to allow for adjustments to requirements of feed intake in different segments of a production system. For example, while tissue growth may be the main concern in young, growing cattle, maintenance of body condition for reproduction and lactation may be the concern in the mature cow herd (Crews 2005; Basarab et al. 2007).

1.2.6 Implications for the breeding herd

Initially the RFI concept was used in determining the efficiency of young animals in growing and finishing operations. However, a large proportion of the feed used in a beef production system is consumed by the cow breeding herd and the feed efficiency of this class of cattle is an important consideration. There have been limited studies testing if the variation in efficiency in young animals is associated with variations in efficiency when the animals are older and in the cow breeding herd. One of the initial studies in this area investigated determining the amount of forage intake in a pasture-based production system. The amount of forage intake by grazing beef cows that had been classified as being low RFI or high RFI based on their post-weaning test was conducted by Herd et al. (1998). An intraruminal controlled-release device of C32 and C36 alkane was used to indirectly measure feed intake on pasture over a short period of time. Although low RFI cows were heavier, they consumed no more feed than high RFI cows. There was a 15% advantage in efficiency of the low RFI cows, expressed as a ratio of calf weight to cow feed intake but this was not statistically significant. The inabilities of the alkane technology to account for individual diet selection of each cow, along with other limitations of the method, added to the error in measurement of intake. Although the results were mostly inconclusive, it still demonstrated a phenotypic association between post-weaning RFI and efficiency on pasture (Herd et al. 1998).

The added difficulty of measuring feed intake on pasture has led some investigators to explore other indicators of mature cow efficiency. Archer et al (2002) examined the relationship of feed intake and RFI in mature beef cows to the same measurements taken post-weaning. The 751 mature cows used were originally tested for post-weaning RFI in the Trangie project as heifers. In this case, the methods to measure either feed intake on pasture or at maintenance feeding levels were not available for such large numbers. Instead the cows were tested on the same ad libitum pelleted ration as the post-weaning test protocol. Therefore weight gains and feed intakes were much higher than normally expected in pasture-based systems. The results indicated that while RFI has only a moderate phenotypic correlation between the trait measured in the young animal and that measured as an adult, the genetic relationship was high. It was suggested that selection of replacement cattle based on post-weaning RFI should result in reduced cow feed intake with a slight increase in cow weight, thus improving the efficiency of the cow herd. But most notably, there were indications of strong genetic relationships between feed intake and efficiency measured post-weaning and the same traits in the breeding herd (Archer et al. 2002).

Basarab et al. (2007) confirmed this by measuring the relationships between progeny RFI and dam productivity traits. Cow body weights over 10 production cycles were similar at weaning, pre-calving and pre-breeding for dams that produced low, medium and high RFI progeny. A portion of the cows were also measured for RFI during the second trimester of pregnancy on a maintenance style diet. Efficient RFI progeny and dams consumed less feed, had improved FCE, and spent less time in feeding activity than inefficient cows and calves. Cows that produced efficient progeny produced the same weight of calf weaned per cow exposed to breeding compared to cows producing inefficient progeny. Also, the cows that produced efficient calves were fatter, had fewer twins and had less calf death loss. However, these cows did calve 5-6 days later than cows that produced inefficient or high RFI progeny. This suggests the need to monitor reproductive fitness in low RFI replacement heifers and breeding bulls. A relationship of cow RFI and their progeny RFI in the same year of production was found but the correlation coefficient value was low suggesting that cow RFI might well be a different trait than post-weaning RFI (Basarab et al. 2007).

Meyer et al. (2008) measured the difference in grazed forage intake between grouped beef cows of known RFI classification in two separate trials. Grazing enclosures, weekly rising plate meter readings, and forage harvests were used to indirectly measure average forage intake of each group. No differences in changes in body weight and body condition score were detected between the low and high RFI groups for either trial. The low RFI cow groups had a 21% and 11% lower dry matter intake than high RFI cow groups in each trial but these results were not statistically significant. The results were deemed to be inconclusive as the current methodology and small animal numbers may have limited the ability to detect differences (Meyer et al. 2008).

The difficulties in determining individual feed intake on pasture is another daunting challenge limiting more study on whether the RFI differences in young growing cattle continue in mature cows. In the meantime, the focus has been on generating more young animals with known RFI classification and on determining the sources in variation in RFI.

1.2.7 Sources of variation in RFI

Several reviews attempting to outline the contribution of various processes contributing to the variation in RFI have been published (Herd et al. 2004; Swanson and Miller 2008; Herd and Arthur 2009). Herd et al. (2004) suggested that there are likely 5 major processes contributing to the variation in RFI. These include variations in the intake of feed, digestion of feed (and the associated energy costs), metabolism (anabolism and catabolism associated with and including variation in body composition), activity, and thermoregulation (Herd et al. 2004). The suggested percentage contribution of variation of each of these five processes to RFI were: 9% for heat increment of feeding (HIF); 14% for digestion; 5% for body composition (energy retention); and 5% for activity. The remainder of 67% was suggested to be variations in other processes including protein turnover, ion pumping, and proton leakage (Herd et al. 2004). Despite mentioning thermoregulation as a major process, there was no suggested estimate of the contribution of variations in thermoregulation.

A single generation of divergent selection for residual feed intake was used to further quantify the contribution of the many physiological mechanisms contributing to variation in residual feed intake (Richardson and Herd 2004). The contribution of 10% for differences in digestion, 5% for body composition, and 2% for feeding patterns is estimated towards the variation in RFI. The heat increment of feeding contributes 9% and activity contributes 10%. Indirect measures of protein turnover indicated that protein turnover, tissue metabolism and stress response contributed at least 37% to the variation in RFI. The remaining 27% was suggested to be due to the variation in other processes not yet measured, such as ion transport (Richardson and Herd 2004) while the contribution of thermoregulation was once again not explored.

Additional factors are being studied which impact RFI variation such as methane production (Nkrumah et al. 2006), GIT kinetics such as the site of starch digestion (Channon et al. 2004), combinations of genetic markers (Sherman et al. 2008) and protein synthesis efficiencies (Lobley 2003). Of particular interest to the current study is the issue of thermoregulation and specifically heat loss in the infrared spectrum.

1.3 Infrared Thermography

The measurement of heat radiation, either lost or gained, was made possible by the accidental discovery of the infrared portion of the electromagnetic spectrum. The infrared spectrum was first discovered by Sir William Herschel in 1800, while repeating Newton's prism experiment of passing sunlight through a glass prism. His initial intention was to find an optical filter material to reduce the brightness of the sun's image during solar observations. In testing the heating effect of the various colors of the visible spectrum, the maximum temperature point was found in the dark region well beyond the red end of the spectrum. He referred to this phenomenon as 'dark heat' and it eventually became known as 'infrared' (FLIR Systems AB 2003). Later, the work of theoretical physicists such as James Clerk Maxwell recognized that electricity, magnetism, and light (including radiant heat) were all related as part of a unified model of electromagnetism (Maxwell 1865). Today, it is recognized that radiated heat loss is a form of energy transfer governed by the laws of thermodynamics. In general, energy is transferred by photon particles travelling at the speed of light in a wave like pattern. This transfer of energy, known as electromagnetic radiation, can be described by three related physical properties; wavelength, frequency, and photon energy. Wavelengths can be as long as thousands of kilometres or down to a fraction of the size of an atom. The frequency of the wave is inversely proportional to the wavelength; a shorter wavelength therefore has a higher frequency. Lastly, photon energy is directly proportional to the wave frequency in that photons with the highest energy correspond to the shortest wavelengths. The range of all possible wavelengths of electromagnetic radiation is known as the electromagnetic spectrum. The spectrum is divided arbitrarily into a number of wavelength regions called spectral bands ranging from radio at the longest wavelengths to gamma at the shortest. Spectral bands have been categorized by the methods used to produce and detect the radiation but are all fundamentally governed by the same laws. The infrared spectral band occurs at a longer wavelength than visible light, beginning at the limit of visual perception of deep red colours and increasing in wavelength until merging with the microwave radio band. The wavelengths of the infrared spectrum range from 0.7 to 1000 µm and are inversely proportional to the absolute temperature (Kelvin) of the subject (FLIR Systems AB 2003). Infrared radiation is emitted by all objects as a function of their temperature because of the internal movement of molecules. The vibration and rotation of atoms and molecules represents charge displacement and results in electromagnetic radiation of photon particles which can be reflected, refracted, absorbed and emitted (FLIR Systems AB 2003). The measurement of the surface temperature of objects from the intensity of infrared energy has been made possible because of the statements and laws equating emission and absorption in heated objects proposed by several physicists. Kirchhoff's law stated that a body capable of absorbing all radiation at any wavelength is equally capable in the emission of radiation and is defined as a blackbody (FLIR Systems AB 2003). Planck's formula determined the maximum rate of energy flow by radiation from a blackbody as a function of surface temperatures and was used to graphically construct a family of curves. These Planck curves showed the typical radiation of a blackbody at different temperatures and showed that the radiation maximum moves towards shorter wavelengths as the temperature increases according to the Wien's displacement law (Dereniak and Boreman 1996). Subsequently, the Stefan-Boltzmann law determined the radiant emittance of a blackbody is proportional to the fourth power of its absolute temperature (FLIR Systems AB 2003). But an additional consideration is the radiating qualities of the surface. A blackbody is a theoretical perfect emitter and will absorb, at any wavelength, all incidental radiation that impinges on it. That is, a perfect emitter of radiation is also a perfect absorber of radiation at the same wavelength (Speakman and Ward 1998). However, real objects can also reflect and transmit a fraction of the incidental radiant energy from their surface and therefore are not perfect emitters. Biological materials are opaque in the visual spectrum and therefore will not transmit radiation so reflectivity becomes the remaining important factor. Such an object is then referred to as a graybody and a dimensionless correcting factor called emissivity is required. This emissivity value (ε) ranges from zero to unity and is inversely proportional to the degree of reflectivity. In fact, the absorptivity of radiation at any wavelength is equal to the emissivity of the material at the same wavelength (Speakman and Ward 1998). As a result, when at the same temperature, the total emissive power of a graybody is the same as a blackbody but reduced by a proportion of the emissivity (FLIR Systems AB 2003). The Stefan-Boltzmann's formula then becomes: $W= \varepsilon\sigma T^4$ and shows that the measurement of temperature can be determined from the radiation signal (Dereniak and Boreman 1996) and is generally called infrared thermography (Speakman and Ward 1998).

1.3.1 Infrared thermographic imaging systems

The development of an imaging system to detect and measure infrared radiation emitted from objects is rooted in the inspiration of many inventors. For example, the production of the first thermograph is credited to Sir John Herschel (son of William Hershel, discoverer of the infrared) in 1840. He found a way to focus the heat pattern of an object onto a plate with a thin film of oil. The differential evaporation and the interference effects of the oil film reflecting light created a thermal image which could be reproduced on paper (FLIR Systems AB 2003). It is difficult to fully appreciate the vast number of advances in the fields of physics, mathematics and engineering that have made the development of thermal systems possible. A major motivation to develop infrared thermographic devices was the obvious military advantages to detect personnel, artillery, aircraft and ships. Control of the development of infrared imaging systems by the military was substantial and guarded in secrecy up until the middle of the 1950's. Since then, adequate thermal imaging devices were increasingly made available for civilian science and industry development (FLIR Systems AB 2003).

The key component of a thermal system is the infrared detector. The earliest and simplest detectors were thermometers, followed by the thermocouple and thermopile and later by the development of the bolometer. All these are generally known as thermal detectors in that they produce a form of a signal as their own temperature changes. In the case of the bolometer, by focusing infrared radiation on a junction between two different types of conductors, a voltage or resistance related to a temperature difference is produced (Lloyd 1975). The technology took a huge leap forward with the development of photon detectors. A photon detector is a semiconductor that produces an electrical signal proportional to the photon flux impinging on it. Photon detector systems are faster, more sensitive and stable compared to thermal detectors. However, the detector's own radiant temperature interferes with the signal. The use of liquid nitrogen or cooling engines was required to bring the detector to cryogenic temperatures in order for maximum performance. For this reason, photon detector systems are generally more expensive, complex and fragile (Orlove 1994).

While radiation could be detected by infrared detectors and measured; thermal images or thermographs were still difficult to produce. A major step forward in thermal imaging came with the processing and amplification of analog electrical signals for display to a monitor. Electronics and measurement formulas were also needed to calibrate an image and assign a temperature to a displayable gray or color level representing thermal information. Mechanical scanning systems using a series of movable reflecting mirrors were developed to physically move the field of view of a single detector so an image of the infrared energy sensed from object space could be produced. The development of a focal plane array by placing many detectors adjacent to each other in a matrix eliminated the need for a mechanical scanning system (Orlove 1994).

Recently, a new generation of imaging systems or infrared cameras has been developed based on the uncooled microbolometer detector technology. These systems incorporate the focal plane array method and have eliminated the need for the troublesome detector cooling system used by photon detectors. Instead, temperature stabilization provided by a thermoelectric cooler as part of an automatic temperature compensation system is used to keep track of the internal radiation from internal parts of the measuring device (Kastberger and Stachl 2003). These systems have the advantage of low cost, small size and weight, real time (30 frames per second) digital output, and low power requirements (Zalameda and Winfree 2005). Additionally, advances in camera design, image analysis software, and processor technology have meant increases in system stability, reliability, resolution, and speed (Kastberger and Stachl 2003). These cameras save the object signal, which is the non-calibrated value related to the amount of radiation received by the camera from the object, in digital image format. Therefore, images are fully radiometric in that the object parameters such as emissivity, ambient temperature and distance can be adjusted even after image capture. The object temperature is then calculated using calibrated measurement formula algorithms (FLIR Systems AB 2003). Image saving and transfer protocols allow real-time capture of multiple images, especially important when dealing with a movable biological subject.

1.3.2 IRT applications in livestock production

There are several inherent advantages of infrared thermography for livestock applications. The surface temperature distribution is seen almost instantaneously and in greater detail than with a thermocouple or spot radiometer. It allows the non-contact measurement of objects with a low heat capacity, such as animal coats, where the physical attachment of a probe may give false readings. Thermography is non-destructive and measurement of inaccessible objects is possible, where a physical probe could not be attached. Lastly, the non-invasive measurement of temperature is possible where the proximity of an observer could otherwise disturb the object of measurement (Cena 1973). Cena and Clark (1973) considered that the principal disadvantage of infrared thermography is low accuracy compared to conventional thermometry. They found that absolute temperature measurements are within about ± 1° C but comparative measurements were more precise (Cena and Clark 1973). The potential for accuracy in measurements has improved with advances in imaging systems but accuracy still depends on the skill of the operator and the willingness of the subject to remain still.

For infrared thermography of the relatively low temperature of biological subjects, calculation of the peak emitted radiation using Planck's curves and Wien's displacement laws indicates that the mid wave (3-5 µm) and long wave (8 to 14 µm) band is preferred (Kastberger and Stachl 2003). In addition, due to the scattering effects of atmospheric water vapour and carbon dioxide, transmission of infrared energy drops substantially at wavelengths outside of these two bands. For the measurement of biological materials, imaging system designers generally agree that the long wave spectral band offers the least signal attenuation of the two (Orlove 1994). With regards to the emissivity correction factor, Porter and Gates (1969) studied the thermodynamic equilibrium of animals with environment and stated that the absorptivity to sunlight and skylight of various animals may vary from as low as 0.2 to nearly 1.0, but the absorptivity to infrared thermal radiation (and therefore the emissivity) is almost always between 0.95 and 1.0 (Porter and Gates 1969). Several other sources consider the emissivity value of biological materials such as bare skin to be very high (0.98) and independent of the surface colour in the visual spectrum (Steketee 1973; Wolfe and Zissis 1978; FLIR Systems AB 2003). The emissivity of dry fur is relatively uniform in mammals, in the range of 0.98 to 1.0 (McCafferty 2007). Speakman and Ward (1998) suggested the high emissivity of biological materials is due to the very high water content (generally greater than 65%) and water has an absorptivity of about 0.96 in the infrared range. A caution exists, that minor changes in the apparent surface temperature might instead represent alterations in surface emissivity of an object which actually has a uniform surface temperature (Speakman and Ward 1998). But small differences in emissivity can be shown by calculation (with the Stefan-Boltzmann equation) to account for less than 0.5°C at typical coat temperatures (McCafferty 2007).

The angle at which an object is viewed also influences the intensity of radiation received. Since electromagnetic waves travels in straight lines, an object viewed at a very shallow angle relative to the emitting surface will have a reduction in the intensity of thermal radiation received. But this effect is negligible for objects with rough surfaces, such as animals, unless the viewing angle is less than 10° (Speakman and Ward 1998). The intensity of radiation detected also declines with increasing distance between the object and the sensing device. The decline in radiation detected follows the inverse square law. At longer distances, absorption of radiation by the surrounding atmosphere becomes substantial. However, this factor is relatively trivial at the distances (typically less than 10 m) used in infrared thermography on animal subjects (Speakman and Ward 1998). Nevertheless, for the comparison of radiated energy from any object including animal subjects, it is important to consider standardizing the viewing distance and angle.

For the field of animal science, infrared thermography has been used to investigate numerous aspects of animal physiology and as such has demonstrated utility in a number of applications (Palmer 1981; Kastberger and Stachl 2003; Knizkova et al. 2007; McCafferty 2007). Our own lab or within collaboration with others has also demonstrated several aspects of utility with infrared thermography, including joint soundness (Haley et al. 2005), disease onset (Schaefer et al. 2007), meat quality attributes (Schaefer et al. 1988; Schaefer et al. 1989; Tong et al. 1995), and fundamental measures of stress and pain (Stewart et al. 2005; Stewart et al. 2008).

1.3.3 Thermoregulation and energy balance concepts

Thermoregulation deals with the vast array of coping mechanisms used by all animals to survive and prosper within their environment. The concepts of thermoregulation have been studied extensively in cattle (Kleiber 1961; Webster 1971; Mount 1979; Young et al. 1989). In homeothermic animals, thermoregulation is a balance between heat production and heat loss. Heat production is generally considered to be the result of intermediary metabolism, protein synthesis, ion exchange, and mechanical work. Heat loss is generally understood to be composed of evaporative, convective, conductive, respiratory and radiated mechanisms as discussed by Kleiber (1961). Cattle, being homeothermic, desire to maintain a stable deep body or core temperature despite fluctuations in environmental temperatures and differences in activity. The core temperature may only fluctuate slightly in a diurnal pattern over a 24 hour period while the peripheral tissues and limbs may respond more drastically to changes in temperature. In cold weather, the zone of core temperature shrinks and the peripheral tissues and limbs will be maintained at a colder temperature. Likewise, in hot weather, the zone of core temperature expands and the peripheral tissues and limbs may approach the core temperature (Robertshaw 2004). For the objective measurement of efficient use of energy, irrespective of the technology used, there is a preference that the animal is in a thermoregulatory steady state while being monitored. This concept is referred to as the thermal neutral zone and is defined as the range of ambient temperature within which an animal's metabolic heat production is, over the short term, independent of ambient temperature (Young et al. 1989).

In energy balance studies, due to the difficulty in separating the individual components of heat exchange by conduction, convection, and radiation, the usual practice was to combine all three as one term called sensible heat loss. Determination of the individual contribution of radiated heat loss became possible as technology progressed. Early work by Hardy and Du Bois (1938a) studied basal metabolism of human subjects (the authors) in a respiration calorimeter at various atmospheric conditions. They attempted to separate heat loss by convection and radiation by an radiometer of their own design using blackened tinfoil receiving elements with thermocouples (Hardy and Du Bois 1938a). The radiometer device was calibrated to measure the intensity of the infrared radiation from a skin surface and thereby the radiated temperature of that surface (Hardy and Du Bois 1938b). At lower temperatures the surface layer of the body cooled rapidly and heat loss greatly exceeded heat production. Radiation accounted for about 70% of the total heat loss at 22°C to 26°C. At higher temperatures as skin and air temperature approached each other, the percentage due to radiated heat loss declined rapidly to zero while heat loss due to vaporization increased (Hardy and Du Bois 1938a).

In livestock, the accurate determination of radiated heat loss has been difficult. Blaxter et al. (1959) studied the components of heat loss at various temperatures in sheep and found that the sensible loss of heat (radiation, convection and conduction) decreased as environmental temperature rose. The heat loss by radiation in this case was computed from mean skin and air temperatures determined with thermocouples and was subject to systematic errors of up to ±10%. It was still determined that heat loss by radiation makes up some 55-65% of the total sensible heat loss. Joyce et al. (1966) studied the exchange of heat by long-wave infrared radiation for sheep in modified respiration chambers. The ultimate objective was to improve the prediction of the energy requirements of sheep in outdoor environments. Highly reflective walls were used in one respiration chamber and highly absorptive walls were used in the other chamber. This created an emissivity difference which would differentially reflect or absorb the radiated heat emitted by the sheep. The radiated heat loss of the sheep was then indirectly measured by measuring the temperature of the walls by thermocouples. This method, despite its indirect nature of the measurements, indicated that radiation accounts for about 50% of the total sensible heat loss (Joyce et al. 1966).

The effects of environmental temperature on sensible heat loss of cattle (without separating out the radiated component) was done on steers (Blaxter and Wainman 1961) and calves (Gonzalez-Jimenez and Blaxter 1962). Both studies found evidence of variations in cutaneous vasoconstriction occurring at different surfaces of the body within the thermal neutral zone. Piloerection increasing the insulative value of the hair coat also accounted for a large part of a lower conductance of heat below the critical temperature. Whittow (1962) used attached thermocouples to measure skin surface temperatures of bull calves. Measurements of the temperatures of the various sites on the extremities and trunk, along with rectal temperatures, respiratory rates and heart rates during exposure to environmental temperatures (-5° to 45°C) were made. Large variations between the skin temperatures of the extremities and the trunk were observed at -5° to 25°C but were similar at higher environmental temperatures. Variations in the skin temperature of the extremities were brought about by changes of blood flow to these parts. They concluded that variations in the skin temperature of the extremities have an important thermoregulatory function (Whittow 1962). In support, McArthur (1981) found the relationship between sensible heat loss and environmental temperature was not linear at high and low temperatures. It was suggested to be due to neural vasomotor action (vasodilation and vasoconstriction) and differences of thermal resistance values of the trunk and extremities. A more realistic model of heat loss could be possible if the trunk and extremities are considered separately (McArthur 1981). In cattle, Webster (1971) described heat losses in cold, outdoor environments without necessarily partitioning out radiation losses. The net effect of the external environment was assessed using an artificial ox “Moocow” (model ox observing cold outdoor weather). A general equation was derived which illustrated the extent to which wind and radiation exchanges can influence heat losses from cattle (Webster 1971).

1.3.4 IRT applications with feed efficiency

With respect to the mechanisms of heat loss, of particular interest and relevance to the current study is radiated heat loss, which represents a significant proportion (40-60%) of the energy budget of homeothermic animals (Kleiber 1961). There is an increasing interest in using infrared thermography to study radiated heat losses and feed efficiency. Clark et al. (1973) developed a method to determine insulation resistances for heat transfer in animal coats and human clothing with the use of an infrared imaging system. Temperatures measured on sheep’s fleece and human clothing was linearly related to local net radiation. The method was suggested to be a useful complement to calorimetric studies of the energy balance in relation to metabolism, and could also provide a more realistic basis for relating metabolic rate to climate. Local values of convective and radiative heat loss from appendages could be measured separately from the rest of the body to find the total sensible heat loss from the animal in a given environment (Clark et al. 1973)

Shuran (1988) validated the ability of a liquid nitrogen cooled detector imaging system to measure energy expenditure in human subjects. Radiated heat loss was quantified directly using the camera on human subjects during fasting, fed and intraprandial states but the accuracy was found to be poor (±20%). Despite the accuracy concerns, IRT was also demonstrated to be a valid method to determine radiated heat loss from post-surgery patients receiving total parenteral nutrition (Shuran 1988).

In cattle, Scott et al. (2002) created environmentally induced changes in metabolic heat production and growth efficiency. Beef heifers were placed in environmental chambers for 21 days at either -18C or 18C and ad libitum pelleted feed was offered. Individual feed intake and live weight gain was determined. Indirect calorimetry measurements were taken on day 22 in a thermoneutral environment along with dorsal, lateral, and distal infrared images of the animal to determine total radiant heat loss. Feed efficiency significantly ranked (Spearman correlation) with radiant heat loss determined by infrared thermography. Heifers with the highest growth efficiencies displayed the lowest radiant heat loss values. It was concluded that heat loss as measured by IRT can be used as an index of feed efficiency in cattle (Scott et al. 2002). However, while it is recognized that indirect calorimetry is a very accurate method of determining energetic efficiency and heat production differences, this methodology is not very practical for large numbers of animals. It is known that heat production of animals in thermo neutral conditions may differ substantially as functions of feed intake, physiological state, genotype, sex, and activity (NRC 1996). The determination of RFI in feedlot settings appears to be more practical in this respect. Both methods of determining energetic efficiency appear to be comparable. Comparison of high, medium and low RFI animals by Nkrumah (2006) in digestibility and calorimetry trials found significant positive associations between RFI previously determined in a feed trial and heat production determined by indirect calorimetry. Heat production was 10 and 21% higher in medium and high RFI steers respectively, than low RFI steers (Nkrumah et al. 2006).

1.4 IRT applications in RFI research

IRT measures of the radiated surface temperature of an animal could be related to this increased heat production, similar to the findings by Scott et al. (2002) mentioned before. This approach was investigated by Schaefer et al. (2005) on mature cows using a cooled detector imaging system. IRT images to measure the dorsal surface radiated temperature on three dates were collected during an 84 day RFI trial. Following the feed trial, cows were classified into low, intermediate, and high RFI groups. The maximum dorsal surface temperature was significantly lower in low RFI classified cows compared to high RFI cows. The data suggested that the use of infrared thermographic scans could display utility in the assessment of feed efficiency in cattle (Schaefer et al. 2005).

Brown (2005) studied dorsal, cornea, eye, forehead and nose temperatures measured by infrared thermography at the start of a RFI trial on growing steers. No significant correlations were found for dorsal thermal images to subsequent growth performance or feed efficiency traits, including RFI. However, there were some negative correlations with ADG and DMI with eye, forehead and nose thermal images. In addition, hair density, curvature and fibre measured at the start of test were not different between high and low RFI steers. The results suggested that thermoregulation does not differ between high and low RFI animals, although additional research is warranted (Brown 2005).

Montanholi et al. (2006) measured hind temperatures using IRT on beef cows fed differing levels of wheat straw. RFI was calculated for each group after a nine week experiment. Both within and across dietary treatments, hind temperature measured by an uncooled microbolometer thermal camera tended to be greater for cows with high RFI. High and low RFI cows also showed a small negative correlation to hind temperature.

They suggested that as the use of IRT technology progresses, infrared images may be useful in the assessment of dietary treatment effects and have some predictive abilities for feed efficiency (Montanholi et al. 2006).

The relationship between RFI of feedlot steers from three different sire breeds and IRT of specific body locations taken at the start and end of the feed trial was investigated later by the same group (Montanholi et al. 2008; Montanholi et al. 2010). Low and medium RFI steers had lower maximum eye temperatures than high RFI steers for thermal images taken at the end of the RFI trial. Piedmontese sired steers had a lower hind temperature at the start of the feed trial than either Angus or Charolais sired steers. They suggested that breed effects when evaluating potential predictors of feed efficiency, such as thermography, should be considered (Montanholi et al. 2008).

Infrared temperatures of the eye, cheek, and feet taken at the end of the feed trial were positively correlated with RFI in beef bulls (Montanholi 2009). However, infrared images of the rib area, rear area and scrotum were not related to RFI. This suggested that thermographs of body extremities, with the exception of the scrotum, may be a better indicator of RFI than core body locations (Montanholi et al. 2009).

Infrared thermal imaging of the rib section on yearling Angus bulls, with hair or with hair removed by clippers, have been compared to feed intake, ADG, and RFI. Residual feed intake was not correlated with any of the temperature measures. Of interest, there were some significant correlations using the temperature difference in clipped and unclipped rib areas with daily DMI and ADG (Huntington et al. 2012).

The relationship of IRT measures of radiated heat loss to RFI on beef heifers has not been investigated. Since heifers will become the future cow herd, their feed efficiency and subsequent lifetime feed consumption is an economically relevant trait to consider. However, determining RFI requires specialized equipment for the measurement of individual feed intake. The cost, complexity and availability of this equipment are still a limiting factor for wider scale selection for feed efficiency in the beef industry. If IRT can be shown to have a predictive value for feed efficiency in heifers, selection programs could be developed to reduce the need for measuring individual feed intake.

The relationship of IRT of selected body locations to RFI initiated by Montanholi (2009) deserves more study. Initial studies by Schaefer et al. (2005) and Scott et al. (2002) concentrated on whole body views such as the dorsal view of the animal. This method presents some difficulties, mostly due to the height the camera needs to be mounted in order to obtain a full dorsal view. Also, for imaging of animals in a handling system, the preferable placement of the camera would be directly above the squeeze chute in order to ensure animal identification and minimize animal movement. However, structural components of the chute will often obscure a clear view of the animal. Another difficulty of whole body views is the thermal image aberrations common with this view. Physical contact with part of the handling system or another animal can temporarily alter the thermal image. For example, if the head of the next animal in line is pressing on the hip of the subject animal, the physical contact and warmer exhaled breath alter the surface temperature of the subject animal. Thermal images of the head region while restrained in a head gate could be acceptable as long as the head remains clean after following a preceding animal. Imaging of the skin surface associated with the inner canthus of the eye, especially the posterior border of the eyelid and *caruncula lachrymalis*, is easily accessible and has the advantage of a lack of hair coat. This site is also highly vascular and typically warmer than the surrounding tissue. Imaging of the eye has shown utility as an anatomical landmark in thermal imaging for detection of bovine respiratory disease in calves (Schaefer et al. 2007).

1.4.1 Handling stress implications

In all procedures involving livestock, there is the possibility that the stress associated with data collection can affect the data itself. While IRT is regarded as a non-invasive method as discussed by Stewart et al. (2005), the cumulative effect of handling stress impacting the radiated temperature of an animal is also an important consideration. The stress associated with chute side collection of data on a group of animals could alter a potential relationship of IRT to RFI. The utilization of an automated system to capture infrared images as animals attend a water station (Schaefer et al. 2012) is currently being investigated.

1.4.2 Insulation differences

The influence of the hair coat on the relationship of RFI and IRT is potentially an important factor. The net radiative exchange is defined as the sum of all coat and tissue radiative exchanges with the environment. A thermal imaging camera detects this radiative exchange of energy at a point slightly below the hair surface depending on the thermal resistance of the hair coat (Clark et al. 1973). But thermal resistance is dependent on the hair thickness, density and length as well as the degree of piloerection. None of these microclimate factors can be assumed to be uniform over the whole body or between animals. Gilbert and Bailey (1991) studied diet and breed differences in hair coat characteristics and the relationship to postweaning gain. Although measures of hair coat weight were moderately heritable, none of the hair coat characteristics were strongly associated with postweaning gain. Unfortunately, no individual feed intake measurements were available to test any hypotheses regarding energetic efficiency (Gilbert and Bailey 1991).

There is a lack of evidence showing whether there is a hair insulation differences between RFI groups. Luiting et al. (1994) did observe that low RFI hens have smaller unfeathered body areas through which they can lose energy and tend to be slightly better feathered. However, Basarab et al. (2003) found no improvement in the regression model to calculate expected feed intake with the inclusion of an insulation index as an additional energy sink. The insulation index was determined only at the beginning of the RFI trial by measuring hair cover over the rump region.

Brown (2005) also measured hair fibre, curvature, and density for steers at the start of a RFI trial but subsequently found no relationship to any measures of efficiency including RFI, ADG, DMI, FCR, or PEG (partial efficiency of growth).

Richardson et al. (2001) found that following a single generation of selection for improved post weaning RFI, the weight of external organs (hide, head, hooves and tail) did not differ between low and high RFI groups. However, when expressed as a percentage of the final liveweight, external organs were significantly heavier in low RFI steers (Richardson et al. 2001). This was suggested to be a reflection of different patterns of maturity rather than mature cow size and differences in protein turnover. It is interesting to note the role these external organs could contribute to the insulative factor of the animal.

Determining the insulative resistance to heat transfer by measurements of hair thickness, length and density could be used to determine the net radiative heat flux but would be difficult and time consuming. This approach has been attempted by several investigators (Cena and Monteith 1975a; Cena and Monteith 1975b; Bakken 1976; Gebremedhin 1987) but the equations are very complex. An alternative might be to remove or standardize the hair coat overlying the region of interest and compare the radiated temperature at the skin surface to the radiated temperature at the hair surface. As stated before, the inner canthus of the eye is also devoid of hair and could be used as a comparison site to measure radiated skin temperature without having to alter or disturb the animal.

1.4.3 IRT image analysis

Due to the limitations of image capturing technology, the determination of radiated temperature by IRT has generally been based on a limited number of saved images. The moment to moment displayed thermograph can fluctuate from true variation in radiated heat emission but also due to a variety of other factors including air movement, animal movement and position. There is a time delay associated with waiting for an animal to stop moving long enough so the camera operator can assess that first, the live image is suitable to be frozen; and second, saving the frozen image. The question arises, will an image saved in this manner represent the best estimate of radiated temperature. Real time capture of images at a fast frame rate has allowed for an alternative method of scanning animals. Capturing all images and determining the suitability of each one at the time of image analysis removes the onus of searching for the best image previously placed on the camera operator. A greater number of saved images allows for the use of statistical procedures to determine the best estimate of radiated temperature.

1.5 Hypothesis

The hypothesis of the present thesis is that infrared thermography can be used to rank and identify beef heifers displaying differences in metabolic efficiency as measured by RFI. As a corollary, it is also hypothesized that handling stress, measured by chute order cortisol level will impact infrared thermography values.

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CHAPTER 2

Relationship of radiated heat loss measured by infrared thermography to residual feed intake in beef heifers

2.1 Introduction

Profitability in livestock production is an elusive goal, it can be gained or lost by countless combinations of revenue and expenses. Since feed is a major expense in beef production systems (Ferrell and Jenkins 1985), reductions in either the volume used or price make best sense as long as production can be maintained. Maintaining the level of production is a key point, there is no overall savings in reducing inputs if the output is also lower. The inverse is true as well; greater production is generally expected to be accompanied by higher inputs. The traditional use of feed conversion ratios to measure efficiency has been largely proven to be ineffective for selection (Archer et al. 1999; Johnson et al. 2003). More recently, the concept of residual feed intake (RFI) has improved the potential for feed efficiency improvement (Arthur et al. 1997; Archer et al. 1999; Basarab et al. 2003) but the cost and effort required to collect individual feed intake must be considered (Crews 2005). An indirect non-invasive method to estimate feed efficiency may be useful. It has been demonstrated that a portion of the differences in RFI are due to considerable variation among cattle in energy use and partitioning, particularly differences in heat production (Nkrumah et al. 2006). A portion of the heat production by any warm homeothermic animal in a colder environment must be lost to that environment in order to maintain equilibrium. It has been shown that heat loss by radiation is substantial avenue for temperature regulation especially when the ambient temperature is less than the animal's surface temperature (Kleiber 1961). Infrared thermography has been used to investigate numerous aspects of animal physiology and as such has demonstrated utility in a number of applications (Kastberger and Stachl 2003; Knizkova et al. 2007; McCafferty 2007). Infrared thermography has also been demonstrated as having predictive abilities for feed efficiency on mature cows (Schaefer et al. 2005; Montanholi et al. 2006) where the feed energy for cow maintenance represents 65-75% of total feed energy requirements (Ferrell and Jenkins 1985; Montano-Bermudez et al. 1990). A higher proportion of heifers within a herd will ultimately join the cow herd than a young bull being selected as a herd sire. Despite this, seedstock producers are more likely to be measuring young bulls for feed intake and RFI in order to develop multiple trait selection schemes that include feed efficiency (Crews et al. 2006). Especially for heifers, a non-invasive technology such as infrared thermography to indirectly assess feed efficiency would have a positive effect on the livestock industry. Therefore, it is being proposed that infrared thermography can be used to rank and identify beef heifers with differences in feed efficiency as measured by RFI. Specifically, the relationship between RFI and multiple IRT images collected in real time from specific anatomical sites with and without hair cover was investigated. In addition, the impact of handling stress as measured by glucocorticoid levels on the relationship of IRT to RFI was investigated.

2.2 Methods and Materials

2.2.1 Animals

Sixty one weaned crossbred replacement heifers from the 2006 spring calf crop of the Lacombe Research Centre were used to study the relationship of radiated heat loss determined by thermographic images to residual feed intake. Heifers were cared for according to the guidelines of the Canadian Council on Animal Care (Canadian Council on Animal Care 1993). Management of the cow-calf herd has been previously described by Basarab et al. (2007). Dams varied in breed type composition but were all aged from 4-12 years old. Aberdeen Angus-Hereford and Aberdeen Angus dams mated to 6 Hereford sires and 1 Aberdeen Angus sire produced 35 heifer calves for the study. Charolais-Simmental, Charolais-Red Angus, and Charolais-Maine Anjou dams mated to 4 Red Angus sires and 1 Hereford sire produced an additional 26 heifer calves. Because of the use of only British breed sires, all 61 heifers were at least 50% British, the remainder depending on the varied breed compositions of the dams. The average overall breed composition of the 61 heifers can be described as being 81.6% British breed types (Hereford, Aberdeen Angus, and Red Angus combined) and 18.4% Continental breed types (Charolais, Simmental, Maine Anjou combined). After fall weaning, the normal processing protocols for vaccinations and deworming used by the research station staff were completed. The heifers were placed into an open feedlot pen and fed barley silage once daily. Growth promoting implants were not used at any point.

2.2.2 RFI test procedure

Heifers were then moved to an outdoor feedlot pen (86 m by 46 m; 65 m^2 per animal) equipped with the GrowSafe® (GrowSafe Systems Ltd., Airdrie, AB) feeding system for automatic monitoring of individual feed intake and feeding behaviour. A pre-trial adjustment period of approximately one month allowed for acclimatization to the GrowSafe® feed bunks and a move to twice daily *ad libitum* feeding of 90% barley silage and 10% barley grain. Wood chips and shavings were used as bedding and replenished as needed during the pre-trial and test period. For the trial period, heifers continued to be offered *ad libitum* a growing ration of 90% barley silage and 10% barley grain providing 9.85 Mcal/kg ME DM for 113 days during the winter feeding season (Jan. 9th to May 2nd). Heifers were weighed on two consecutive days at the start and end of the feed trial and at 28-d intervals (days 0, 1, 27, 56, 84, 112, 113). Body weights were collected every 28 days and individual daily feed intake was collected using the GrowSafe® feeding system. The GrowSafe® feeding system uses a half-duplex radio frequency transponder button for identification of each heifer and a series of tag reader antennas coupled to sixteen individually weighable bunk feeders to measure feed consumption.

Ultrasound measures of backfat, ribeye area, and marbling between the 12-13th rib was collected by a certified ultrasound technician using procedures described by Brethour (1992) at the start and end of the feeding trial using an Aloka 500V diagnostic real-time ultrasound camera with a 3.5 MHz 17cm linear array transducer (Overseas Monitor Corporation Ltd., Richmond, BC). Ultrasound data at the start of test was missed on one heifer.

2.2.3 Infrared thermography procedure

Real-time recording of infrared images were collected for analysis while the heifer was restrained in an indoor hydraulic chute on four weigh dates (day 0 27 94 112) during the feed trial. Cattle handling on weigh dates started at about 8:30am prior to feed delivery. Heifers were moved as a group from the outdoor feedlot pen to an outdoor holding pen and sweep tub. From the sweep tub, heifers moved single file down an indoor alley system to the hydraulic chute. The capacity of the alley allowed a random subset of 10-15 animals to be inside waiting before entering the chute to be processed. Overhead radiant heaters were turned off well in advance of cattle processing to prevent their heat emission from interfering with the infrared image collection. Animal entrance and exit doors were left open in order to allow free air flow.

For image capture, a FLIR S60 camera (FLIR Systems AB, Danderyd, Sweden) was interfaced to a portable computer by a FireWire connection and the FLIR Researcher infrared image capture module was used. The camera was focussed clearly on the region of interest at a distance of one meter. Recording of the raw images was accomplished while the animal was restrained in the squeeze chute but before blood collection. Generally, there was a brief struggle caused by being restrained followed by a period when the animal held still. For the first date (day 0), the 60Hz or 30 frames/second image capture frame rate setting was used. The 7.5Hz or 3.25 frames/second setting was used for the subsequent three dates (day 27 94 112). Recording of a sequence file allowed the capture of a 5-10 second time period of individual infrared images. In order to make ambient and reflected temperature image corrections for the subsequent analysis, ambient temperature and relative humidity values were recorded. This was done during the whole time period while the animals were being processed using the auto save function of a Kestrel 4000 datalogger (Nielsen-Kellerman, Boothwyn, PA). For the first date, these parameters were recorded every two minutes, thereafter it was recorded every five minutes. Average daily and hourly environmental conditions were also recorded from the AAFC-AAC weather station located <1 km from the feedlot pen. This weather station also has available long term data collected for the past 20 years for comparison.

2.2.4 IRT anatomical sites

At the start of the trial (day 0) infrared image capture was limited to the side of the heifer's head in order to measure radiated heat loss from the eye and cheek regions. The hair coat was left undisturbed, no brushing, clipping, or cleaning was done. For the second weigh date (day 27) imaging was limited to the heifer's left side midsection. The hair coat was clipped to length of 2mm over the 12-13th rib section starting at a point which would encompass the ventral end of the ribeye muscle and following the natural rib curvature dorsally to the midline. This mimics the accepted starting location for placement of an ultrasound probe for cross-sectional ribeye area ultrasound image collection in beef cattle. The area of hair removed was approximately 10-15cm wide by 20-25cm long. The hair removed was discarded; no attempt was made to measure hair coat density or weight. The camera was positioned to collect simultaneous images of this clipped area and an undisturbed hair coat area located posterior to the clipped area. The undisturbed hair coat area was overlying the position of the ribeye muscle along the lumbar vertebrae. Simultaneous measurement of both areas on each image allowed measurement of the radiated heat loss from the midsection with and without the hair insulation. On April 13th (day 94) and May 1st (day 112) imaging was done of both the head and midsection regions. However, the hair coat on the midsection region was not re-clipped on these dates. A rectal temperature measurement was also collected on the last two dates with a GLA M525/550 digital feedlot thermometer (GLA Agricultural Electronics, San Luis Obispo, CA).

2.2.5 Handling stress measurement

On all four dates, following infrared imaging but before chute release, a blood sample was collected by jugular venipuncture for the determination of cortisol levels. Cortisol levels were determined in order to study the impact of handling stress on the infrared thermal parameters. On Day 0 blood was collected in serum tubes. On the subsequent dates blood was collected in sodium heparin tubes for the collection of plasma. Each blood sample was centrifuged using an Omnifuge RT (Osterode, West Germany) at 1600 x *g* for 20 minutes at 4ºC. Following centrifugation, the plasma or serum was fractioned into a 1.2ml bio tube and then frozen at -80ºC until needed for analysis. A commercial serum cortisol assay kit (recommended by a provincial endocrinologist, Dr. N. Cook, personal communication) was used for all serum and plasma samples. Cortisol was analyzed using reagents supplied by R&D Systems (Minneapolis, MN, USA; catalog number KGE008). The sensitivity of the kit is stated as 0.071 ng ml^{-1}. Cortisol concentrations were quantified by competitive enzyme immunoassay using a PowerWaveX-I Microplate reader (Bio-tek Instruments, Inc., Winooski, VT, USA) measuring absorbance at 450nm. Intraassay CV for cortisol at 7.66 and 3.85 ng ml^{-1} was 4.6 and 7.9% respectively. The corresponding interassay CV was 5.4 and 8.7%.

2.3 Calculations

2.31 Residual feed intake

The methodology for calculating residual feed intake using the GrowSafe System (GrowSafe Systems Ltd., Airdrie, AB) has been previously described (Basarab et al. 2003; Basarab et al. 2007). The on-test weight (STWT), midpoint metabolic weight (MMW) and average daily gain (ADG) for each heifer was calculated using a linear regression of the recorded weight for each weight date against the number of days on-test. The coefficient of determination (R^2 X 100) indicated a linear growth curves as would be expected for the phase of growth observed in the feed trial (mean = 99.1%, SD= 0.7, range 96.8 to 99.9%)

Based on the dry matter (DM) and metabolizable energy content (ME) of the diet (shown in Table 2-1) the average daily feed intake of each heifer over the test period was converted first to total dry matter intake (DMI) and then to total metabolizable energy intake (MEI). In order to standardize with previous trials, the total MEI was divided by 10 to give total DMI standardized to an energy density of 10 MJ ME kg^{-1} DM. This value was then divided by the DM content of the diet to give a total standardized feed intake value. This value was finally divided by the number of days on test to give average standardized daily feed intake (SFI, kg d^{-1}).

Stepwise multiple regression analysis (SAS Institute Inc 2000) indicated that final ultrasound backfat thickness (BF*end*) as an independent measure of body composition would significantly account for additional variation in SFI and was included in the model. Therefore, the SFI of each heifer was regressed against ADG (kg d^{-1}), MMW ($kg^{0.75}$), and BF*end* (mm) using PROC GLM (SAS Institute Inc 2000) and the following model;

Model 1: $Y_i = ß_0 + ß_1ADG_i + ß_2MMW_i + ß_3BF\mathit{end}_i + e_i$

where Y_i, ADG_i, and MMW_i are observations on the *i*th animal. $ß_0$ is the intercept of the model, $ß_1$ and $ß_2$ and $ß_3$ are linear regression coefficients and e_i is the residual error of the *i*th animal. Model 1 resulted in an equation that accounted for 78.2% ($P < 0.0001$) of the variation in SFI and was used to predict expected feed intake (EFI_{fat}).

Residual feed intake was calculated as the difference between actual and expected feed intake ($RFI_{fat} = SFI – EFI_{fat}$). Heifers were grouped into high-RFI_{fat} (>0.39 kg as fed d^{-1}), med-RFI_{fat} (≤ 0.39 to ≥ -0.39 kg as fed d^{-1}), and low-RFI_{fat} (< -0.39 kg as fed d^{-1}) groups based on ±0.5 standard deviation around the mean.

2.3.2 Infrared thermographic images

For all the infrared image sequence files, temperature analysis was done using the FLIR Researcher software (FLIR Systems AB 2003). The environmental parameters collected by the Kestrel datalogger corresponding to the time period each heifer was restrained in the chute were used for a correction of the ambient and reflected temperature and the relative humidity parameters within the Researcher software. The ambient temperatures inside and outside the handling facility for each collection date is shown in Figure 2-1. Emissivity was fixed for all images at 0.98, the recommended value for biological tissue (McCafferty 2007). Each subsample image of the sequence file was visually evaluated for the proper focus, position, clarity, and lack of motion. Any subsample images not meeting these requirements were rejected and the thermal data was not saved.

The FLIR Researcher circle analysis tool was used for each suitable subsample image to display the mean and standard deviation of radiated temperature values of all pixels within the region of interest (ROI). The minimum and maximum radiated temperature within the ROI was also displayed; however, the value could possibly be from a single pixel. All these temperature parameters were saved for subsequent analysis.

For the head images, the first ROI chosen was a circle analysis tool placed over the eye and surrounding orbital tissue. This circle was kept approximately twice the size of the eyeball and resized when needed. A second ROI used another circle tool to measure an area from the lower edge of the first ROI circle to the edge of the jawbone in order to measure the cheek region. These were moved and resized as needed in order to track slight movement and changes in position however similar circle diameters for all images were used. An example of the head region infrared images from two heifers and the analysis tools used is given in Figure 2-2. For the midsection images, the first ROI used a circle tool in order to fit only within the clipped area. The second ROI used a circle similar in size to the first and placed to measure an unclipped area slightly posterior of the first circle. These also were moved and resized as needed in order to track movement and changes in position. In order to have a measurement of the insulating properties of the hair coat on the midsection, the difference in the mean temperature of the clipped and unclipped ROI for each suitable subsample image was also saved. An example of midsection infrared images from two heifers and the circle tools used for temperature measurement is shown in Figure 2-3.

Therefore, for each heifer on each collection day, there were multiple sequential individual images taken. Each of the ROI within the images has a set of the basic statistics (*mean, standard deviation, min*, and *max*) describing the temperature profile within the total pixel area selected by the circle analysis tool. An example of the image to image variation in mean temperature of the cheek for a single heifer is shown in Figure 2-4. In order to reduce the dataset to a single value for each heifer for a best estimate of the temperature profile for each day, a pooled average of all the means, standard deviations, minimums, and maximums for each day was calculated. Use of a pooled average was intended to reduce the influence of any single image. The tremendous volume of data created by this methodology of infrared imaging has potential for a great deal more analysis and discussion later but priorities needed to be established for the scope of analysis and discussion within this thesis. For eye images, the surface area has a variety of angled surfaces, both convex and concave, plus a variable amount of cooler eyelashes and other hair cover that increase the temperature variation. As well, close attention must be given to maintaining the relative size of the analysis circle to the size of the eye area. If the circle is made smaller, the mean temperature value tends to increase because less area with cooler hair cover is included. Measuring the maximum temperature displayed within the eye images has a couple of key advantages over measurements of the larger more variable eye area. The inner canthus of the eye is generally the anatomical site of the warmest radiated temperatures displayed. This is partly due to the complete lack of hair cover to interfere with temperature measurements. The surface shapes of the tissues which make up the inner canthus, the posterior border of the eyelid, and the *caruncula lachrymalis* are also similar to a concave cavity. Measurements taken within a cavity is commonly used in thermography to aid in the consistent and accurate temperature measurements of difficult materials (Dereniak and Boreman 1996). The maximum infrared temperature detected at this site could be comparable to the radiated temperature of skin surfaces without the need for clipping. However, the limitation may be that maximum temperature value displayed could be from a single pixel only. This limitation is the main rationale for taking multiple images and calculating a pooled average. Therefore, for these reasons both the mean and max temperature of eye images will be discussed. For the cheek region, the analysis circle measures the radiated temperature from a relatively uniform and flat area with less angle variations than eye images. However, due to variations which might exist in hair cover that may affect the maximum and minimum values, only the mean temperature will be discussed. The range in temperature variation, the number of images used, and the time span contributing to these pooled estimates is shown in Table 2-5a for head region images. For the midsection clipped and unclipped regions, these are once again a relatively flat and uniform surface area with a lower expected temperature variation. The mean temperature of the clipped and unclipped area and their temperature difference will be discussed. The range in temperature variation, number of images used, and time span for midsection images is shown in Table 2-5b.

Eye and cheek temperatures were collected on 3 dates (day 0, 94, 112) and the clipped and unclipped rib temperatures were also based on 3 dates (day 27, 94, 112). Collection of the infrared image sequence files for 6 heifers on Apr 13th (day 94) was missed due to a camera to computer connection malfunction. Therefore, the overall trial averages of infrared temperatures for correlation analysis are based on 55 heifers instead of 61 heifers. A single blood sample collected on Day 0 was removed from the cortisol analysis due to problems with the assay. The overall trial average for cortisol levels used 60 heifers over 4 sampling dates (Day 0, 27, 94, 112). The overall trial average for rectal temperature data used 61 heifers over 2 sampling dates (Day 94, 112).

2.4 Statistical Analysis

Data were checked for normality and homogeneity of variance by histograms, scatter plots, and formal statistical tests (Shapiro-Wilk) as part of the UNIVARIATE procedure of SAS (data not shown). The cortisol and inside ambient temperature were found to be non-normally distributed and natural logarithmic transformations were attempted. However, this data remained skewed even after transformation and analysis continued on the raw values.

Generalized least squares analysis using the MIXED procedure of SAS (Littell et al. 1996; SAS Institute Inc 2000) was used to examine the fixed effect of RFI_{fat} group (high, medium, and low) on growth performance, feed intake, feed conversion, and ultrasound body composition. Percentage of British breeding and heifer age was used as a covariate for all independent variables. Percentage of British breeding and heifer age were analyzed similarly, but were removed as a covariate in the model as needed.

The MIXED procedure of SAS was also used to examine the effect of RFI_{fat} group on the repeated measures of infrared temperatures, cortisol level, and rectal temperature. This model included fixed terms for RFI_{fat} group, day of test (0, 27, 94 and 112), and the interaction. For the repeated measures, covariates included chute order, the inside ambient temperature during image collection for each animal, and the heifer's percentage of British breeding. Animal identification was set as the repeated subject. Several variance-covariance structures were tried including compound symmetry (CS) and unstructured (UN). The spatial power law (SP(POW)) variance-covariance structure was ultimately chosen due to the lower magnitude of the Akaike information criterion (AIC) and since this structure is also deemed more appropriate for unequally spaced data (Littell et al. 1996). Differences in the main effects were determined by *F*-tests using Type III sums of squares. The PDIFF option and Tukey test was applied for pairwise comparisons. Pearson correlation coefficients were computed using CORR procedure of SAS (SAS Institute Inc 2000) separately for Day 0, 27, 94, 112 and for the overall trial averages of the relationships between RFI, SFI, production traits, infrared temperature means, cortisol levels and rectal temperature.

2.5 Results

Summary statistics of the start, end, and on-test period for the 61 heifers are given in Table 2-2. During the 113-d test period, heifers grew at an average of 1.02 kg d^{-1} and consumed 8.18 kg DM $head^{-1}$ d^{-1} resulting in a feed conversion ratio (FCR) of 8.10 kg DM kg $gain^{-1}$ and an off-test ultrasound backfat thickness of 6.51 mm. Residual feed intake adjusted for off-test ultrasound backfat thickness (RFI_{fat}) averaged 0.0 as should be expected and ranged from -1.55 to 2.19 kg as fed d^{-1} (SD=0.78).

Pearson correlation coefficients for measures of performance, feed intake, ultrasound, and feed efficiency are given in Table 2-3. As expected and by design, RFI_{fat} was not phenotypically correlated with ADG, MMW, or final ultrasound backfat since these traits were used in the regression model. RFI_{fat} was also not correlated with heifer age, percentage of British breeding, initial or final body weight, or any initial or final ultrasound measures. As expected, RFI_{fat} was phenotypically correlated ($P<0.001$) with

DMI (r =0.47) and FCR (r =0.42). Dry matter intake was correlated (P<0.0001) with heifer age (r =0.59), initial weight (r =0.79), MMW (r =0.84), final weight (r =0.86), and ADG (r =0.62). Dry matter intake was also positively correlated (P<0.05) with all of the initial and final ultrasound measures but not percentage of British breeding. FCR was negatively correlated (P<0.0001) with ADG (r = -0.67). As expected, MMW was strongly related (P<0.0001) to both initial (r =0.99) and final weight (r =0.99) due to MMW being derived from their difference. MMW was also positively correlated (P<0.001) with age (r =0.60) initial and final ultrasound measures of backfat (r = 0.48, r = 0.47) and ribeye area (r = 0.50, r =0.56). MMW was also correlated (P <0.05) to the final ultrasound marbling score (r =0.30).

Summary statistics of the infrared traits, cortisol levels, rectal temperatures, and inside ambient temperatures for Day 0, 27, 94, and 112 are given in Table 2-4. Of the infrared measures, eye-max temperature has the lowest variation across heifers, while hair-rib-mean and rib-difference-mean were the highest. The variation in clipped-rib-mean temperature across heifers was lowest on Day 27 when the hair was initially removed, but increased on Day 94 and Day 112 as the hair coat regrew.

The capture of sequential infrared image clips in order to derive pooled averages of the radiated temperature from each anatomical site appears to be feasible technique in this study. Of interest was the variation across individual images used for each infrared measure as given in Table 2-5a for the eye and cheek measures and in Table 2-5b for the rib section measures. While the image to image variation in temperatures observed decreased over the length of the trial for all measures taken, the variation was still great enough to suggest that relying on single infrared images as an estimate of radiated temperature should be avoided.

Differences in intake, performance, and feed efficiency traits for heifers classified into low, medium, and high RFI_{fat} groups as described previously are presented in Table 2-6. DMI and MEI for low-RFI_{fat} and medium-RFI_{fat} heifers were similar but both were significantly different from high-RFI_{fat} heifers. Low-RFI_{fat} and medium-RFI_{fat} heifers consumed 7.5% and 6.5% less DMI and MEI than heifers ranked as high-RFI_{fat} ($P=0.0004$). Heifer age and percentage of British breeding, ADG, initial BW, MMW, final BW, and all ultrasound measures did not differ ($P>0.05$) between the RFI_{fat} groups. FCR tended to increase across RFI_{fat} groups ($P=0.0574$) but only the low-RFI_{fat} and high-RFI_{fat} heifers were different from each other at this level of confidence.

Least square means for infrared, cortisol, and rectal temperature measurements for heifers with low, medium, and high RFI_{fat} are presented in Table 2-7. Low-RFI_{fat} and medium-RFI_{fat} heifers had similar cheek-mean radiated temperatures but both were significantly less than high-RFI_{fat} heifers ($P<0.0001$). Eye-mean temperature tended to increase across the RFI_{fat} groups ($P=0.0747$). All other infrared measurements, cortisol, and rectal temperature did not differ between RFI_{fat} groups. Infrared temperatures for cheek-mean and hair rib-mean increased ($P<0.0001$) for each date over the trial period. Eye-mean and Eye-max temperatures were lower ($P<0.0001$) for Day 0 compared to Day 94 and Day 112. Clipped rib-mean and rib-difference-mean temperatures decreased ($P<0.0001$) for each date over the trial period. Cortisol on Day 0, Day 27, and Day 112 were similar while cortisol measured on Day 94 was less ($P=0.0101$) than Day 0 or Day 27 but not different than Day 112. Rectal temperature was measured only on two occasions but was lower ($P=0.0074$) on Day 94 compared to Day 112. Inside ambient temperature collected at the time of infrared and blood sampling was significantly ($P<0.0001$) lower for Day 0 and 27 compared to Day 94, which in turn was lower than Day 112. There were no significant ($P<0.05$) RFI_{fat} by day of test interactions detected for any of the measures taken.

Pearson correlation coefficients for measures of performance, feed efficiency, and feed intake, with the trial average of data collected during infrared imaging are given in Table 2-8. Chute order was negatively related to ambient temperature recorded at the time of infrared imaging ($P<0.001$, $r = -0.58$). Chute order was also negatively related to eye-mean temperature ($P<0.05$, $r = -0.28$) and tended to be negatively correlated with eye-max temperature ($0.10 <P<0.05$, $r = -0.23$). Cheek-mean temperature was positively related to RFI_{fat} ($P<0.001$, $r =0.46$), DMI ($P<0.05$, $r =0.34$), FCR ($P<0.05$, $r =0.31$), and negatively with British percentage ($P<0.05$, $r = -0.34$). Cheek-mean temperature was not related to MMW, ADG, or chute order. Eye-mean temperature was positively related to RFI_{fat} ($P<0.05$, $r =0.27$), DMI ($P<0.01$, $r =0.40$), MMW ($P<0.05$, $r =0.32$) and chute order ($P<0.05$, $r = -0.28$). Eye-mean temperature also tended to be negatively correlated with British percentage ($0.10 < P < 0.05$, $r = -0.26$). Eye-max temperature was positively related to ambient temperature ($P<0.05$, $r = 0.33$). Eye-max temperature was unrelated to RFI_{fat}, DMI, MMW, and ADG but tended to be related to FCR ($0.10 < P < 0.05$, $r =0.23$) and chute order ($0.10 < P < 0.05$, $r = -0.23$). Infrared temperature measurements taken of the clipped rib section were not significantly correlated to any traits other than a positive trend with rectal temperature ($0.10 < P < 0.05$, $r =0.26$). Temperatures of the undisturbed hair site were negatively related to British percentage ($P<0.05$, $r = -0.33$) and tended to be positively related to FCR ($0.10 < P < 0.05$, $r = 0.25$) and cortisol ($0.10 < P < 0.05$, $r = 0.26$). The temperature difference between the clipped and undisturbed rib section was positively correlated with British percentage ($P<0.05$, $r = 0.30$) and tended to be correlated with RFI_{fat} ($0.10 < P < 0.05$, $r = -0.23$) and rectal temperature ($0.10 < P < 0.05$, $r = 0.25$). No significant ($P<0.05$) correlations were observed between rectal temperature and RFI_{fat}, DMI, FCR, MMW, ADG, or any of the infrared measures. However, rectal temperatures were positively correlated with chute order ($P<0.01$, $r = 0.34$), British percentage ($P<0.001$, $r = 0.43$) and negatively correlated with ambient temperature ($P<0.001$, $r = -0.33$). Cortisol also had no significant ($P<0.05$) correlations with any of the infrared measures but was positively correlated with rectal temperature ($P<0.001$, $r = 0.56$) and negatively correlated with MMW ($P <0.05$, $r = -0.26$).

2.6 Discussion

While feed efficiency in cattle production has always been an important issue, improvement has been slow. Selection based on the traditional measures of feed efficiency used until quite recently was often accompanied by undesirable changes in the mature size of the breeding herd. Measurement of feed efficiency using the RFI concept avoids this complication. A great deal of published beef research in feed efficiency now utilizes the RFI concept, but the adoption by industry continues to lag behind. The reasons for this are varied but the cost and complexity of RFI testing appears to be a major factor. The search for indirect measures of feed efficiency has been undertaken by many in order to avoid or reduce the need for individual feed measurement which is essential to the RFI concept.

The use of measuring radiant heat loss as part of the energy balance equation has shown utility as an indirect measure of RFI by a few labs equipped with both the combined expertise in livestock husbandry and infrared thermography. The proper collection and interpretation of IRT data is still very complex and continues to evolve even if the equipment to do so has become easier to work with. In the current study, the use of a state of the art infrared thermographic system and some novel ideas to improve the measurement of radiated heat loss to indirectly measure feed efficiency will be discussed.

2.6.1 RFI component

Before the discussion can be made about the usefulness of any indirect measures of energetic efficiency, the accuracy and quality of collection of the variables involved must be discussed. In this study the dependant variable of most importance is the residual feed intake value. The 112-d length of the test and the collection of live weights at 28-d intervals is considered adequate to allow the accurate determination of average daily gain and average daily feed intake for all heifers (Wang et al. 2006; BIF 2010). The 57 day range of age for the heifers at the start of test was also within the 60 day range of age recommended (BIF 2010). Collection of the individual feed intake with the Growsafe® system was excellent; the mean assigned feed disappearance was 99.7%. There were 14 days excluded from the feed intake data set because of system malfunctions, non-detection of consumed feed, and other problems. This also included days where the normal feeding pattern was disrupted by removal of heifers from the pen on weigh-dates. The regression of body weight on time indicated that growth curves were linear with a coefficient of determination (R^2 X 100) averaging 99.1 % and no heifers less than 95%.

As desired, this indicated growth occurred normally; morbidity and nutritional restrictions were not a factor.

The RFI_{fat} regression model used accounted for 78.2% of the variation in standardized as-fed feed intake. As expected, MMW accounted for the largest proportion of variation at 69.8% ($P<0.0001$), with ADG contributing an additional 4.7% ($P=0.0010$). The addition of final ultrasound backfat added an additional 3.8% ($P=0.0027$) to the overall model**.** The model fit was extremely good, and the phenotypic variation in heifer RFI_{fat} ($SD=0.78$) compared favourably with other studies (Arthur et al. 2001; Kelly et al. 2010). Only 21.8% of the variation in feed intake was not explained by the overall model. This remainder can be attributed to unknown factors, of which thermoregulation may be involved. A great deal of efficiency studies utilizing the residual feed intake concept have used the base model for RFI, that is, variation in feed intake accounted for by MMW and ADG. RFI_{fat} was chosen as the measure of feed efficiency in this study because of the possible role of body composition differences also playing some part in thermoregulation. RFI_{fat} was calculated on a standardized as-fed basis comparable to the method used in an earlier paper on feedlot steers (Basarab et al. 2003) while most recent studies express RFI on a DM-basis. The range in RFI_{fat} is similar to other studies where a measure of body composition is used to account for additional variation in feed intake in growing bulls (Lancaster et al. 2009), growing steers (Basarab et al. 2003), and growing heifers (Kelly et al. 2010).

Moderate to strong positive correlations of DMI on ADG, MMW, and final backfat were observed, indicating that larger, faster growing heifers consume more feed and gain more subcutaneous fat. A moderate positive correlation of FCR to RFI_{fat} was also observed.

However, the lack of a significant difference in DMI between the low-RFI_{fat} and med-RFI_{fat} group may be related to the limited number of heifers, being only 61 head. Grouping based on ±0.5 of the standard deviation around the RFI_{fat} mean in this study was done similarly to other studies (Basarab et al. 2003; Nkrumah et al. 2004; Kelly et al. 2010; Shaffer et al. 2011). An alternative may be to classify animals into only two RFI groups, positive and negative (Basarab et al. 2011; Shaffer et al. 2011) or arbitrarily selecting RFI values to give equal group sizes (Montanholi et al. 2010).

2.6.2 Collection of Infrared data

The recommended procedures for collection and analysis of IRT images are well established for other applications of IRT such as electrical component scanning (Orlove 1994). Live animal thermography is a relatively new practice; however some of the same principles and guidelines apply. For any thermography, overall focus of the image is crucial, as well as maintaining a constant distance and orientation to the subject. Compensation of the image for incidental sources of radiated heat is also necessary for the accurate determination of radiated temperature of the subject. In the current study, adjustments in focus, orientation, and distance were accomplished at the time of image collection while heifers were in the chute. The use of collection of multiple images in a sequence file which could be viewed as many times as needed also allowed the opportunity to discard individual images which were unsuitable. Compensation for background radiation on earlier infrared systems needed to be done at the time of image collection. However, the system used in this study allowed for post collection adjustments. Collection of multiple images for each date and the use of a pooled average to determine a best estimate of radiated temperature on a live subject is a novel approach. Other studies have generally not reported how many images were used in the determination of radiated temperature (Brown 2005; Schaefer et al. 2005; Montanholi et al. 2008; Montanholi et al. 2009; Montanholi et al. 2010). But based on the variation as seen in Figure 2-4 and Table 2-5a and 2-5b, the number of images needed to determine a best estimate of radiated temperature requires consideration.

2.6.3 Chute order and capture implications

The difficulty in determining a best estimate of radiated temperature also extends to the choice of when and where thermography is collected. Being a non-contact and non-invasive technology, the actual act of collecting infrared images in this study was not stressful to the animal. But in order to collect images, the camera operator did have to approach the animal's head within one meter, and some animals did object by struggling. These reactions and the subsequent changes in head positioning contributed partly to the variability of temperatures seen in Table 2-5a. As well, midsection imaging was affected by heifers observed to be breathing heavily following the initial capture and struggle. Besides this, the stress associated with moving all the heifers from the home pen to the handling facility, the subsequent crowding, capture, and restraint of each heifer could have an impact on the radiated temperatures observed. Additionally, even though heifers were moved into the handling system randomly and quietly as possible on each date, their individual temperament and willingness to enter the system could contribute to their overall stress level. For these reasons, determination of plasma cortisol levels while each heifer was restrained and recording of the chute order for each date was an attempt to determine the handling stress placed on the heifers. But the averaged values across dates as shown in Table 2-8 show no relationship of plasma cortisol levels to chute order or radiated temperatures. While it is of interest that chute order was negatively correlated to eye-mean and eye-max radiated temperature, ambient temperature showed an even stronger negative correlation with chute order. This chute order effect is likely only due to the initial ambient temperature decline over the image collection periods as shown in Figure 2-4. Presenting this data as the overall trial averages suggests that the handling stress relationship with the chute-side infrared temperatures is inconclusive. Of interest, however, plasma cortisol was positively correlated ($r=0.46$, $P = 0.0002$) to chute order on Day 0 suggesting an increase in handling stress at least on that occasion (data not shown). This relationship was not seen again for subsequent dates. Chute-side infrared imaging has the advantage that all subjects can be studied in a short time period under similar handling and ambient conditions. However, the possibility of handling stress impacting on the best estimates of radiated temperature suggests that the method is not completely non-invasive as hoped. For this reason, development of an automated system at a water station to collect infrared eye radiated temperatures has been studied (Schaefer et al. 2010). This system has shown utility with the detection of bovine respiratory disease and potentially could be used to study energetic efficiency similar to the current study. The potential advantage of this automated method would be that the images are collected while the animals are in a steady state under pen conditions and comparisons could be done at a variety of ambient conditions. Radiated temperature of animals with different energetic efficiencies may be more diverse than seen in this study.

2.6.4 Thermal response

Of all the infrared measures, cheek-mean temperature was discovered to be the most supportive of the hypothesis of a relationship between radiated heat loss measured by infrared thermography and feed efficiency measured by residual feed intake in growing beef heifers. In this study, cheek-mean infrared temperature was found to be moderately and positively correlated with RFI_{fat}, DMI, and FCR but not ADG or MMW. Low-RFI_{fat} and Mid-RFI_{fat} heifers had a lower cheek-mean temperature than High-RFI_{fat} heifers. This finding is mostly in agreement with Montanholi (2009) who also found positive correlations of infrared cheek temperature in beef bulls with different measures of RFI as well as DMI and ADG but also ultrasound backfat thickness, ribeye area, and marbling score. In another study, Montanholi et al (2010) found cheek temperatures were correlated positively with RFI, DMI, ADG, FCR in beef steers. In this study, the next best infrared measurement site related to RFI_{fat} observed was the eye-mean temperature. It is noteworthy that the cheek-mean and eye-mean measurement sites are both taken on a portion of the animal’s extremities. The extremities, including the head and limbs, have a significant role in body heat dissipation in cattle (Whittow 1962; Montanholi 2009). In comparison to the cheek-mean temperature, eye-mean infrared temperature was found to have a lower positive correlation with RFI_{fat} while the relationship of eye-mean temperature to DMI was stronger. However, there was no significant difference between RFI_{fat} heifer groups for eye-mean temperature. The eye-mean site does include a mixture of pixels measuring the warmer eye socket itself plus an area of cooler surrounding skin and hair. This surrounding skin and hair appears to have a surface temperature which is more similar to that observed on the cheek site. Therefore, the eye-mean infrared temperature value seems to be intermediary to both the cheek-mean and eye-max temperature measures. This is supported by the finding that eye-max temperature showed no relationship with RFI_{fat} or any of the other measures except for a positive correlation with ambient temperature. It has been observed in this study and others (Stewart et al. 2008; Schaefer et al. 2012) that the infrared maximum temperature of the eye region is usually situated at the medial posterior palpebral border of the lower eyelid and the lacrimal caruncle (Stewart et al. 2008). This area is highly innervated and vascularized, along with being closely situated to the tear ducts and associated lacrimal apparatus. In humans, the lacrimal gland structure and function is impacted by hormones from the HPA axis and can become a target of the immune system, showing signs of inflammation (Zoukhri 2006). In cattle, the infrared eye-max temperature including the lacrimal gland area has been reported as useful in the detection of bovine respiratory disease (Schaefer et al. 2007) and bovine viral diarrhoea (Schaefer et al. 2004). It has also been used as a method for detecting fear-related responses of cattle to handling procedures (Stewart et al. 2008). This lack of a relationship between eye infrared temperature measures and RFI has been previously reported in beef steers (Montanholi et al. 2010) and beef bulls (Montanholi et al. 2009).

Infrared thermographic measurements taken of sites with less hair coat exhibited higher radiated surface temperatures indicating increased heat loss. In fact, the radiated eye-max temperature was consistently the highest infrared temperature recorded. But this would be expected, being that the eye-max temperature value could come from one single pixel situated on a spot with no hair cover. The influence of the hair coat in radiated heat loss can be seen in the values obtained of the midsection region on Day 27, Day 94, and Day

112. The infrared rib-difference value (12.90° C) was highest on Day 27 when the hair was first removed. This was due to the clipped-rib temperature measurement on Day 27 being essentially a skin temperature measurement with the removal of hair cover. The clipped-rib temperature value for Day 27 was the highest seen of any of the midsection infrared measurements despite having the coldest ambient temperature of any of the infrared measurement dates. At the same time, the hair-rib measurement taken on Day 27 was the lowest of the midsection temperature measurements mirroring the low ambient temperature conditions and was likely at a point of full winter hair cover. However, since no attempt was made to quantify hair thickness or density, this cannot be verified. On Day 94 and Day 112 radiated heat loss measurements of clipped-rib site were compromised by hair regrowth while at the same time radiated heat loss over the hair-rib site was likely increasing due to winter hair coat shedding. In addition, increasing ambient temperatures conditions over the length of the trial was occurring. Due to these reasons, the infrared rib-difference value was less over the two subsequent dates (6.28° C and 3.81° C for Day 94 and Day 112, respectively) but still remained positive. Since the ambient temperature conditions and the shedding of the winter coat cannot be controlled, it may have been preferable to have re-clipped the hair regrowth from the clipped-rib site on Day 94 and Day 112. This may have aided in maintaining a more true radiated heat loss gradient between the clipped-rib and hair-rib sites for comparison across dates. Nevertheless, none of the infrared measures taken of the midsection, with hair or not, were correlated ($P < 0.05$) with measures of RFI_{fat}, DMI, or FCR. This is in agreement with other studies investigating the relationship of RFI measures with midsection IRT scans on unaltered hair coats taken laterally (Montanholi 2009; Montanholi et al. 2010),

and dorsally (Brown 2005) in young cattle similar to the present study. However, Schaefer et al. (2005) did find differences in dorsal surface temperatures with infrared scans taken on mature cows. Maximum dorsal infrared temperature was higher in cows with RFI greater than 1 kg as fed per day compared to cows with RFI less than -1 kg as fed per day (Schaefer et al. 2005). The lack of a significant relationship of clipped-rib, hair-rib, and rib-difference infrared temperature with RFI_{fat} in this study is also consistent with a multiyear study using Angus bulls utilizing a similar method (Huntington et al. 2012). Hair was clipped from a rectangular area on the left ribs and digital infrared thermal imaging (DITI) was taken of this area along with an unclipped rib area of similar surface area. The difference between the clipped and unclipped rib area was also calculated. The finding of low to moderate correlations ($-0.28 < r < 0.33$, $P < 0.05$) between surface temperatures and DMI, ADG, and G:F suggested that DITI could be used to assess the rate and efficiency of gain but not RFI (Huntington et al. 2012). In the present study, it is of interest the rib-difference measurement tended to be weakly correlated with RFI_{fat} ($r = -0.23$, $P < 0.10$). That is, heifers with lower, more desirable values of RFI_{fat} tended to have a greater difference in radiated temperature between the clipped-rib and hair-rib. While this is only a trend, the insulating effect of the hair coat may warrant more investigation. The hair coat as an insulation factor has been rarely mentioned in other RFI studies (Basarab et al. 2003; Brown 2005) but to this author’s knowledge no differences have been reported yet. Gilbert and Bailey (1991) did study the relationship of a large variety of hair coat characteristics with post weaning growth in young cattle. While heritability of many of the hair coat characteristics were sufficient to expect a response to selection, no useful relationship was found with post weaning growth (Gilbert and Bailey 1991). It may be interesting to revisit these hair coat characteristics in relation to RFI testing and IRT measures for energetic efficiency.

2.7 Conclusion

The efficiency and cost effectiveness of raising food animals is an important agronomic issue particularly as competition for resources increases. Clearly the identification of animals exhibiting superior metabolic efficiency would be desirable. For this purpose, the current study hypothesized that the radiated energy as measured by IRT from an animal could be used to rank metabolic efficiency. Toward this end, infrared thermography was used to compare animals of known feed efficiency as determined by the RFI method. Sixty one heifers were studied in a post-weaning trial over a period of 112 days during which time RFI_{fat} scores were determined and measurements of infrared radiated temperatures on several anatomical sites were collected. Moderate and positive correlations were found between RFI_{fat} and IRT. Of notable interest in the collection of this data was the observation that chute order and the stress of handling could have an impact on thermal response. This observation would advocate for the standardization of a non-invasive collection of infrared data to improve precision and accuracy. It was also of interest that the extremities (head region) showed greater variation than the trunk (rib section) and in this regard cheek-mean temperature was superior to the eye-max temperature as a preferred thermal collection site. In addition, the impact of environmental conditions such as ambient temperature and seasonal impacts were apparent. Standardizing or correcting for these factors may improve precision and accuracy in the thermal measures. Overall, this data is consistent with ongoing research at the Lacombe Research Centre, Alberta, Canada and independent studies at the University of Guelph, Ontario, Canada. Infrared thermography demonstrates utility in identifying animals with different metabolic efficiency.

Table 2-1. Ingredient and nutrient composition of diet for beef heifers

Items	
Ingredient composition, % as fed basis	
Barley silage	90
Steam rolled barley	10
Nutrient composition, DM basis[z]	
Dry matter, %	40.07
Acid detergent fiber, %	29.63
Total digestible nutrients[y], %	65.25
Metabolizable energy[x], MJ kg^{-1}	9.85
Crude protein, %	12.48
Calcium, %	0.53
Phosphorus, %	0.29

[z] Samples of the total mixed diet were collected weekly, pooled and analyzed monthly.

[y] TDN(%) =96.03 – [1.034 x ADF, %] (Norwest Laboratories, 3131-1 Ave. South, Lethbridge, AB, Canada T1J 4H1).

[x] ME, MJ kg^{-1} DM = (TDN, %/100) x 4.4 Mcal kg^{-1} TDN) x 4.184 MJ DE Mcal^{-1} x 0.82 MJ ME MJ^{-1} DE (NRC 1996)

Table 2-2. Descriptive statistics of performance, feed efficiency and ultrasound traits for beef heifers

Trait	Mean	SD	Min	Max
Start of post-weaning test				
Age, d	265.4	13.1	229	286
Body weight, kg	296.7	30.5	213.7	382.7
Backfat thickness, mm	4.23	1.12	1.55	6.22
Ribeye area, cm^2	42.52	4.86	30.77	54.64
Marbling score	4.47	0.50	3.50	5.85
End of post-weaning test				
Body weight, kg	411.5	36.7	306.9	518.9
Backfat thickness, mm	6.51	1.81	2.38	10.95
Ribeye area, cm^2	62.10	5.36	52.31	75.51
Marbling score	4.74	0.42	3.55	6.00
On-test period				
ADG, kg d^{-1}	1.02	0.11	0.76	1.28
DMI, kg DM d^{-1}	8.18	0.68	6.47	10.09
MMW, $kg^{0.75}$	81.6	5.7	64.8	97.8
FCR, kg DM kg^{-1} gain	8.10	0.70	6.27	9.67
RFI_{fat}, kg as fed d^{-1}	0.00	0.78	-1.55	2.19

RFI_{fat} is adjusted for end of test ultrasound backfat thickness

Table 2-3. Phenotypic correlations among measures of performance, feed intake, ultrasound, and feed efficiency for beef heifers

Trait	ADG	DMI	MBW	FCR	RFI$_{fat}$
Age, d	0.26*	0.59***	0.60***	0.21	0.15
British breeding, %	0.15	0.12	-0.02	-0.11	-0.03
Start of post-weaning test					
Body weight, kg	0.36**	0.79***	0.99***	0.29*	0.00
Backfat thickness, mm	0.16	0.50***	0.48***	0.24†	0.06
Ribeye area, cm^2	0.01	0.38**	0.50***	0.34**	0.09
Marbling score	0.18	0.32*	0.24†	0.08	0.04
End of post-weaning test					
Body weight, kg	0.63***	0.86***	0.99***	0.01	0.00
Backfat thickness, mm	0.25†	0.57***	0.47***	0.21	0.00
Ribeye area, cm^2	0.34**	0.52***	0.56***	0.06	0.15
Marbling score	0.21†	0.30*	0.30*	0.00	-0.09
On-test period					
ADG, kg d^{-1}		0.62***	0.51***	-0.67***	0.00
DMI, kg DM d^{-1}			0.84***	0.16	0.47***
MMW, kg$^{0.75}$				0.14	0.00
FCR, kg DM kg^{-1} gain					0.42***

† $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Table 2-4. Descriptive statistics of infrared, cortisol, ambient temperature and rectal temperature traits for beef heifers

Trait	Mean	SD	Min	Max
Day0				
Eye-max, °C	35.64	0.74	33.93	37.16
Eye-mean, °C	26.01	1.65	21.64	30.26
Cheek-mean, °C	13.16	1.50	9.87	17.37
Cortisol, ng/ml	22.56	10.48	3.66	54.44
Inside ambient temp, °C	7.65	2.07	4.8	12.8
Day27				
Clipped rib-mean, °C	31.32	0.70	29.95	32.97
Hair rib-mean, °C	18.11	2.11	14.12	21.91
Rib-Difference-mean, °C	13.21	2.07	9.20	17.69
Cortisol, ng/ml	21.58	10.61	4.61	47.37
Inside ambient temp, °C	7.60	2.32	5.4	16.4
Day94				
Eye-max, °C	37.69	0.62	36.47	39.00
Eye-mean, °C	31.21	1.32	27.48	33.59
Cheek-mean, °C	23.14	1.31	19.90	25.92
Clipped rib-mean, °C	30.20	1.22	27.12	32.59
Hair rib-mean, °C	23.99	1.65	21.02	27.54
Rib-Difference-mean, °C	6.21	1.74	1.19	10.21
Cortisol, ng/ml	18.47	9.11	4.35	56.73
Rectal temp, °C	38.95	0.34	38.22	40.39
Inside ambient temp, °C	10.67	0.51	10.0	12.5
Day112				
Eye-max, °C	37.86	0.55	36.59	39.29
Eye-mean, °C	31.81	1.12	28.38	33.56
Cheek-mean, °C	25.24	1.34	20.95	27.61
Clipped rib-mean, °C	28.46	1.42	24.68	30.81
Hair rib-mean, °C	24.96	1.61	21.89	29.33
Rib-Difference-mean, °C	3.50	1.86	-0.42	7.36
Cortisol, ng/ml	21.13	10.26	5.98	56.05
Rectal temp, °C	38.98	0.31	38.22	39.78
Inside ambient temp, °C	12.48	0.74	11.9	15.5

Table 2-5a. Variation across individual sequential infrared images used to derive heifer eye and cheek pooled average temperatures

Trait		Mean	SD	Min	Max
Day0	(*n*=61)				
Eye					
Images used		271.4	93.1	63	443
Time range, sec		15.4	4.3	6	28
Eye-max	SD, °C	0.27	0.11	0.11	0.64
	Range, °C	1.24	0.41	0.5	2.3
Eye-mean	SD, °C	0.67	0.31	0.12	1.34
	Range, °C	2.74	1.10	0.7	6.6
Cheek					
Images used		318.7	108.8	73	558
Time range, sec		16.1	4.5	7	27
Cheek-mean	SD, °C	0.43	0.26	0.19	1.97
	Range, °C	1.90	0.84	0.8	5.2
Day94	(*n*=55)				
Eye					
Images used		38.2	15.0	10	84
Time range, sec		7.6	3.1	2	16
Eye-max	SD, °C	0.26	0.12	0.09	0.58
	Range, °C	0.96	0.40	0.3	2.3
Eye-mean	SD, °C	0.35	0.27	0.08	1.74
	Range, °C	1.26	0.77	0.2	4.3
Cheek					
Images used		50.4	16.0	16	88
Time range, sec		8.9	3.5	2	19
Cheek-mean	SD, °C	0.28	0.11	0.10	0.55
	Range, °C	1.11	0.41	0.4	2.4
Day112	(*n*=61)				
Eye					
Images used		42.5	12.1	24	84
Time range, sec		8.0	4.0	3	26
Eye-max	SD, °C	0.23	0.10	0.06	0.46
	Range, °C	0.83	0.32	0.2	1.6
Eye-mean	SD, °C	0.28	0.16	0.08	0.80
	Range, °C	1.04	0.59	0.3	2.9
Cheek					
Images used		50.9	16.2	28	108
Time range, sec		9.0	5.3	3	36
Cheek-mean	SD, °C	0.27	0.16	0.04	0.64
	Range, °C	0.99	0.50	0.2	2.5

Table 2-5b. Variation across individual sequential infrared images used to derive heifer rib section pooled average temperatures

Trait		Mean	SD	Min	Max
Day27	(*n*=61)				
Rib					
Images used		84.0	39.1	26	285
Time range, sec		13.9	9.9	4	84
Clipped-mean	SD, °C	0.16	0.12	0.06	0.79
	Range, °C	0.63	0.30	0.3	2.1
Hair-mean	SD, °C	0.28	0.18	0.09	1.17
	Range, °C	1.11	0.56	0.3	3.2
Diff-mean	SD, °C	0.29	0.14	0.11	0.79
	Range, °C	1.19	0.52	0.4	3.4
Day94	(*n*=55)				
Rib					
Images used		81.5	21.9	28	132
Time range, sec		13.6	4.8	6	26
Clipped-mean	SD, °C	0.15	0.10	0.04	0.65
	Range, °C	0.55	0.26	0.1	1.6
Hair-mean	SD, °C	0.23	0.11	0.08	0.65
	Range, °C	1.02	0.40	0.3	2.0
Diff-mean	SD, °C	0.25	0.11	0.09	0.58
	Range, °C	1.07	0.40	0.3	2.2
Day112	(*n*=61)				
Rib					
Images used		59.7	16.2	31	111
Time range, sec		9.1	2.7	4	17
Clipped-mean	SD, °C	0.12	0.08	0.04	0.63
	Range, °C	0.47	0.30	0.1	2.1
Hair-mean	SD, °C	0.20	0.09	0.08	0.48
	Range, °C	0.83	0.34	0.3	2.1
Diff-mean	SD, °C	0.23	0.13	0.07	0.73
	Range, °C	0.92	0.45	0.3	2.4

Table 2-6. Characterization of intake, performance, and feed efficiency traits in beef heifers with low, medium, and high backfat adjusted residual feed intake (RFI_{fat})

	RFI_{fat} group[1]				
Trait	Low	Medium	High	SE[2]	P-value
Number of heifers	17	27	17		
Age at start, d	266.9	262.0	269.2	2.94	0.1905
British breeding, %	76.2	87.8	77.0	5.01	0.1638
Start of post-weaning test					
Initial BW, kg	305.0	290.5	298.2	5.51	0.1803
Backfat[3], mm	4.15	4.25	4.28	0.23	0.9239
Marbling score[3]	4.49	4.41	4.54	0.11	0.6988
L. thoracis area, cm^2	43.77	42.05	41.97	1.03	0.4175
End of post-weaning test					
Final BW, kg	421.2	403.2	415.0	6.79	0.1625
Backfat, mm	6.86	6.19	6.67	0.31	0.2892
Marbling score	4.81	4.71	4.71	0.09	0.7102
L. thoracis area, cm^2	61.59	61.32	63.82	1.10	0.2471
On-test period					
ADG, kg d^{-1}	1.03	1.00	1.03	0.02	0.5157
DMI, kg DM d^{-1}	7.96^{a}	8.05^{a}	8.61^{b}	0.11	0.0004
ME intake, MJ d^{-1}	78.40^{a}	79.28^{a}	84.82^{b}	1.09	0.0004
MMW, $kg^{0.75}$	83.13	80.33	81.97	1.04	0.1621
FCR, kg DM kg^{-1} gain	7.80^{a}	8.13^{ab}	8.36^{b}	0.15	0.0574
RFI_{fat}, kg as fed d^{-1}	-0.93^{a}	0.03^{b}	0.89^{c}	0.08	<0.0001

[a-c] Least squares means within a row with different superscripts differ ($P<0.05$).

[1] Low = RFI_{fat} was <0.5 SD below the mean; medium = RFI_{fat} was ±0.5 SD around the mean; high = RFI_{fat} was 0.5 SD above the mean.

[2] SE = pooled SE.

[3] initial ultrasound measures based on 60 animals (1 animal missing data in RFI_{fat} = medium group)

Table 2-7. Characterization of thermographic temperature measurements, cortisol levels, rectal temperature, and ambient temperature during image collection for beef heifers with low, medium, and high backfat adjusted residual feed intake (RFI_{fat})

	RFI_{fat} group[1]				Day					P-value		
Trait	Low	Medium	High	SE[2]	0	27	94	112	SE[2]	RFI	Day	P x D[3]
Number of heifers	17	27	17		61	61	55	61				
Cheek-mean, °C	19.88^{a}	20.40^{a}	21.29^{b}	0.19	13.75^{a}		23.03^{b}	24.79^{c}	0.23	<0.0001	<0.0001	0.2163
Eye-mean, °C	29.36	29.61	30.12	0.22	26.39^{a}		31.16^{b}	31.53^{b}	0.24	0.0747	<0.0001	0.1482
Eye-max, °C	36.99	37.05	37.13	0.09	35.96^{a}		37.64^{b}	37.57^{b}	0.12	0.5781	<0.0001	0.6383
Clipped rib-mean, °C	30.15	29.83	30.05	0.16		31.27^{a}	30.20^{b}	28.56^{c}	0.19	0.3388	<0.0001	0.4230
Hair rib-mean, °C	22.08	22.42	22.50	0.29		18.40^{a}	23.87^{b}	24.73^{c}	0.30	0.5897	<0.0001	0.5637
Rib-Difference-mean, °C	8.02	7.43	7.54	0.34		12.90^{a}	6.28^{b}	3.81^{c}	0.31	0.4392	<0.0001	0.1662
Cortisol, ng/ml	19.58	21.85	20.93	1.59	23.88^{a}	23.21^{a}	17.43^{b}	18.64^{ab}	1.54	0.5926	0.0101	0.1736
Rectal temp, °C	38.97	38.96	38.96	0.06			38.85^{a}	39.08^{b}	0.05	0.9751	0.0074	0.8055
Ambient temp, °C	9.70	9.46	9.68	0.15	7.68^{a}	7.64^{a}	10.67^{b}	12.46^{c}	0.18	0.4263	<0.0001	0.4712

[a-c] Least squares means within a row with different superscripts differ ($P<0.05$).

[1] Low = RFI_{fat} was <0.5 SD below the mean; medium = RFI_{fat} was ±0.5 SD around the mean; high = RFI_{fat} was 0.5 SD above the mean.

[2] SE = pooled SE.

[3] P x D = phenotype (low RFI_{fat}; medium RFI_{fat}; high RFI_{fat}) x day (0 d; 27 d; 94 d; 112 d) interaction

Table 2-8. Correlations of performance and feed efficiency traits with thermographic temperature measurements for beef heifers

Trait	RFI_{fat}	DMI	FCR	MMW	ADG	Rectal temp	Cortisol	Chute order	Ambient temp	British %
Cheek-mean	0.46^{***}	0.34^{*}	0.31^{*}	0.18	0.01	-0.21	0.02	-0.13	0.21	-0.34^{*}
Eye-mean	0.27^{*}	0.40^{**}	0.12	0.32^{*}	0.20	-0.20	-0.02	-0.28^{*}	0.16	$-0.26^{\dagger}$
Eye-max	0.10	0.09	$0.23^{\dagger}$	0.09	-0.12	-0.14	-0.02	$-0.23^{\dagger}$	0.33^{*}	0.04
Clipped rib-mean	-0.19	-0.01	0.11	0.10	-0.11	$0.26^{\dagger}$	0.21	0.15	-0.08	-0.02
Hair rib-mean	0.14	0.01	$0.25^{\dagger}$	0.04	-0.19	-0.09	$0.26^{\dagger}$	-0.02	0.17	-0.33^{*}
Rib-Diff-mean	$-0.23^{\dagger}$	-0.01	-0.18	0.01	0.12	$0.25^{\dagger}$	-0.14	0.09	-0.20	0.30^{*}
Rectal temp	-0.08	-0.11	-0.10	-0.20	-0.03		0.56^{***}	0.34^{**}	-0.33^{**}	0.43^{***}
Cortisol	0.12	-0.17	0.10	-0.26^{*}	-0.20			0.21	-0.05	0.09
Chute order	-0.10	0.11	-0.18	0.14	$0.22^{\dagger}$				-0.58^{***}	0.21

† $P < 0.10$; * $P < 0.05$; ** $P < 0.01$; *** $P < 0.001$.

Figure 2-1: Inside and outside temperatures on IRT collection dates

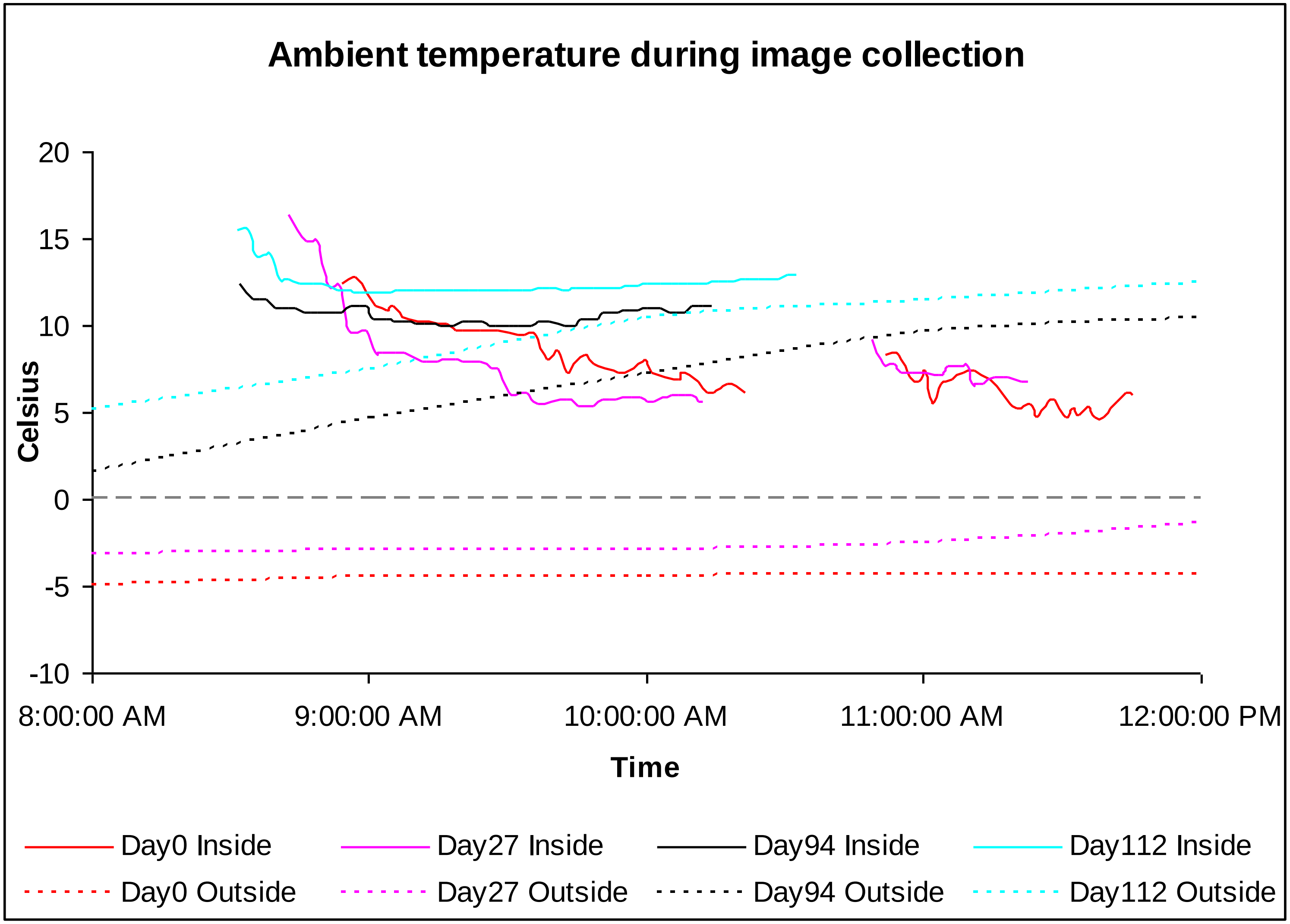
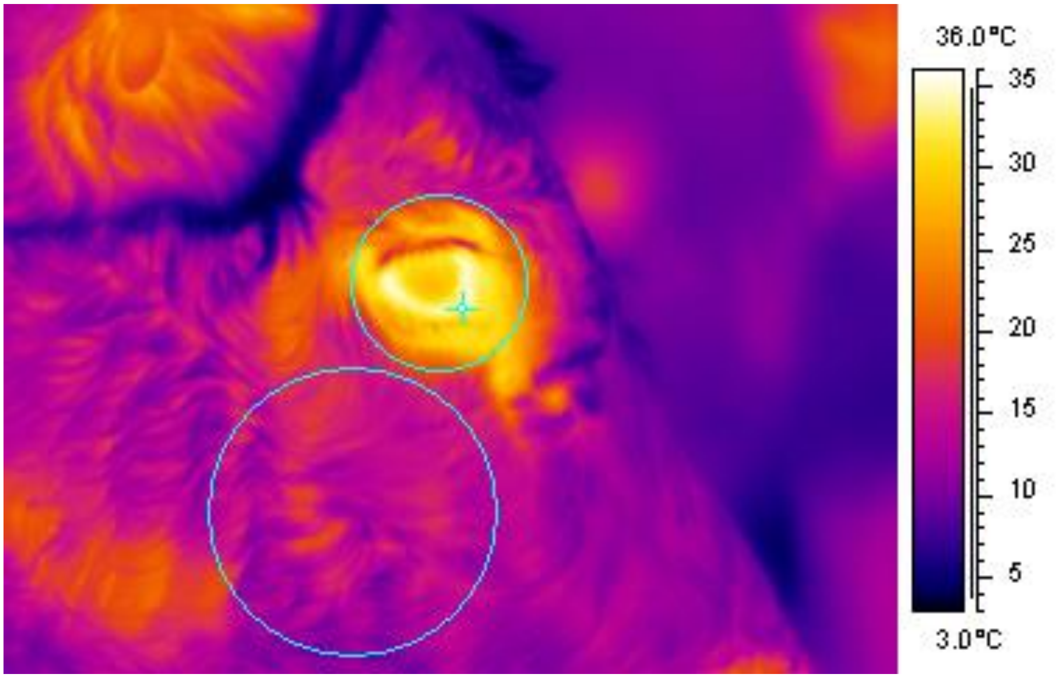
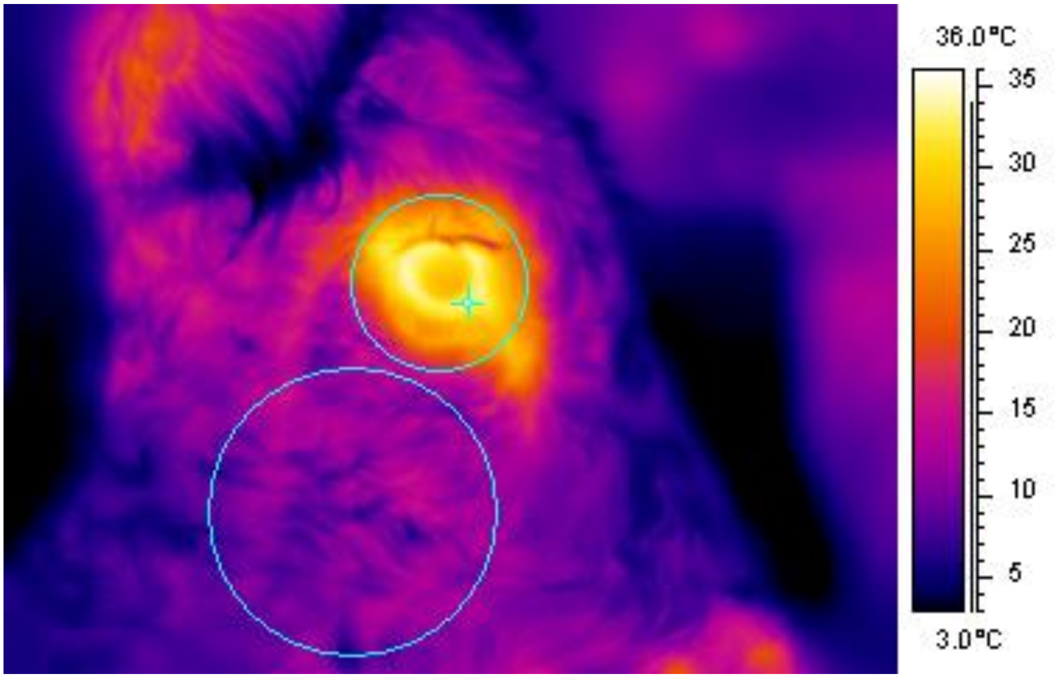


Figure 2-2: Examples of two heifers' head region infrared images and the analysis tools used. Mean cheek temperature (Cheek-mean) for each image is determined by the average of all pixels within the larger circle. Mean eye temperature (Eye-mean) is determined from the smaller circle. Maximum eye temperature (Eye-max) is the highest temperature reading seen within the eye circle tool as shown by the cross-hairs tool.

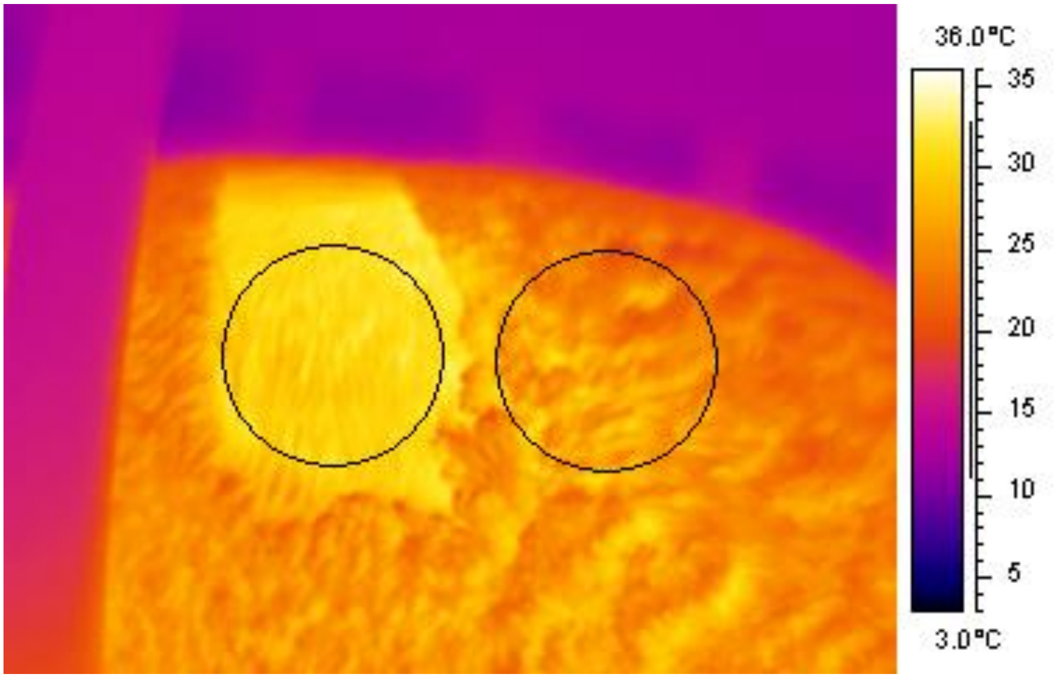


Cheek-mean: 14.5°C, Eye-mean: 27.0°C, Eye-max: 35.4°C

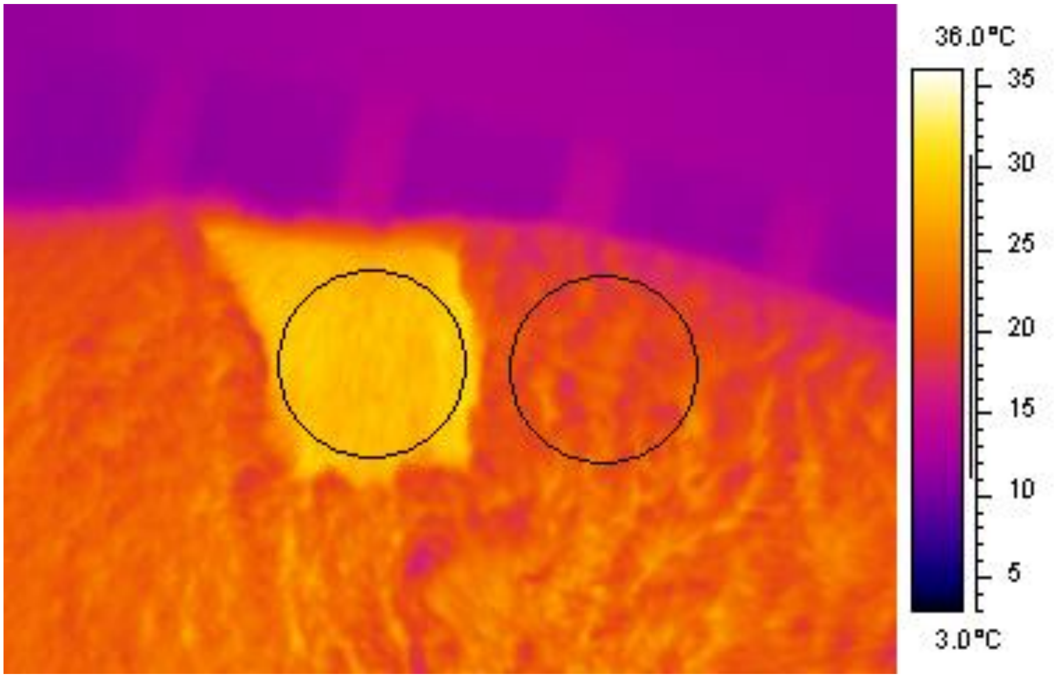


Cheek-mean: 11.0°C, Eye-mean: 26.3°C, Eye-max: 34.5°C

Figure 2-3: Examples of two heifers' rib section infrared images and the analysis tools used. Left circle determines the mean temperature of all pixels within a previously clipped area (Clipped rib-mean). Right circle determines the mean temperature of all pixels within a undisturbed area with normal hair cover (Hair rib-mean). The difference in mean temperature between the two circles (Rib diff-mean) can then be calculated.

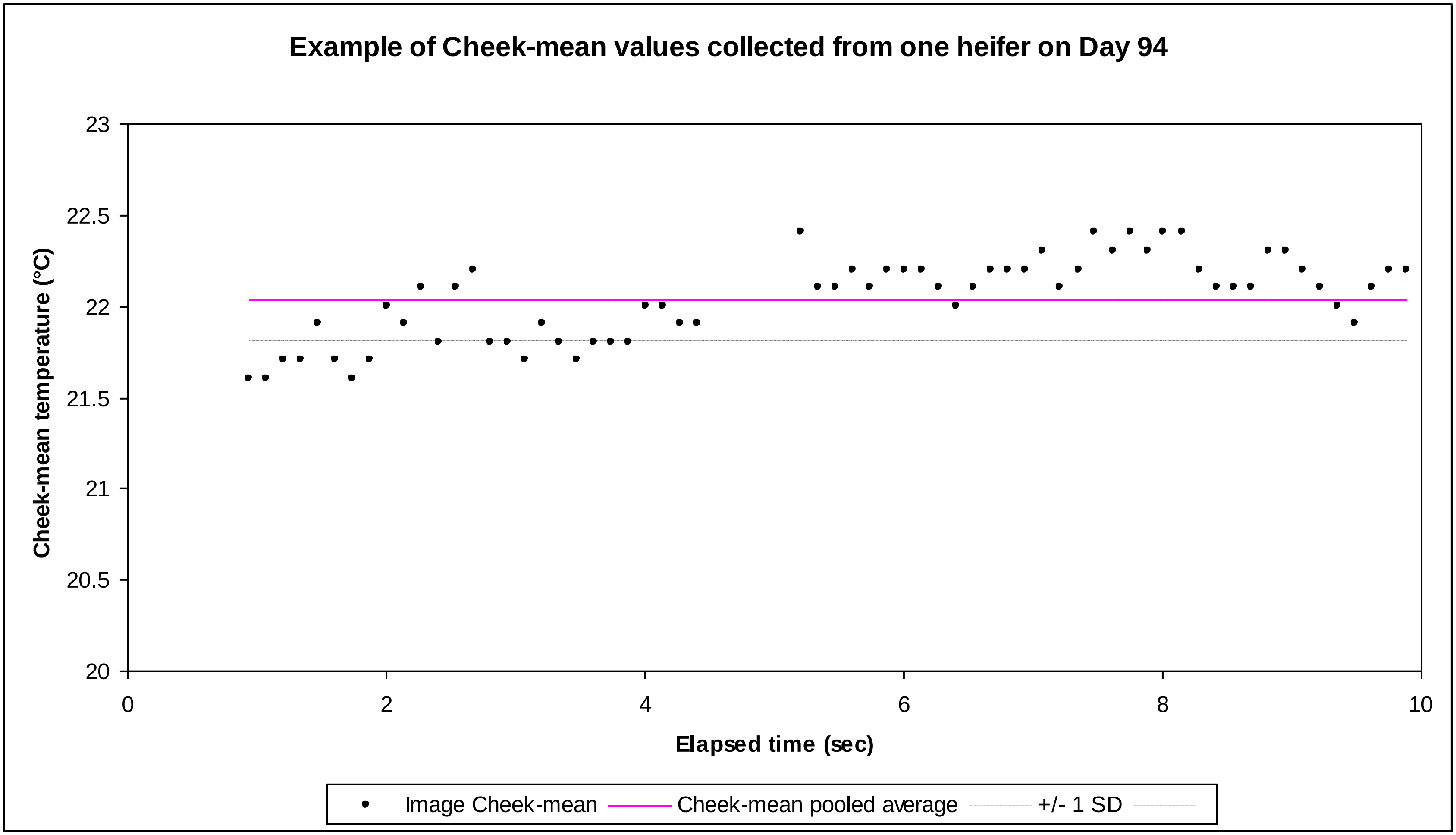


Clipped rib-mean: 30.4°C, Hair rib-mean: 25.9°C, Rib diff-mean: 4.5°C



Clipped rib-mean: 28.5°C, Hair rib-mean: 20.2°C, Rib diff-mean: 8.3°C

Figure 2-4: Typical individual image temperature variation



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CHAPTER 3

General Discussion Summary and Conclusions

3.1 Summary

The hypothesis for this thesis was that infrared thermography can be used to rank and identify beef heifers displaying differences in metabolic efficiency as measured by RFI. An increased mean infrared temperature of the cheek region was observed in high-RFI_{fat} heifers compared to low and medium RFI_{fat} heifers. The mean infrared surface temperature taken on the rib section of the trunk, regardless of hair cover, was not related to RFI_{fat}. As well, the maximum infrared temperature of the eye region was also not related to RFI_{fat}. It was also hypothesized that handling stress, measured by chute order cortisol level will impact infrared thermography values. No relationship was observed between a measures of blood cortisol collected at the time of handling and infrared measures.

3.1.1 Why the cheek?

Why the cheek was an effective site for measuring heat loss related to feed efficiency is a relevant question. The cheek could be classified as being part of the body extremities. Compared to the rib section region, the cheek region is more highly innervated and vascularized, but also has less subcutaneous fat cover overlaying an active muscle group. Certainly the facial muscles are more active considering their function in mastication compared to the spinal muscle groups normally involved only with maintenance of and changes in posture. These differences in anatomical expression and function allow the cheek as well as other body extremities such as the legs, ears, and nose to be major sites of thermoregulation. Thermoregulatory mechanisms available to an animal within a thermal neutral zone include vasodilation and vasoconstriction as well as piloerection in conjunction with differences in hair insulation parameters. All of these mechanisms play a role in the effectiveness of the transfer of excess heat generated within an animal. Using the equation of ME=RE + HP (NRC 1996) it can be demonstrated that high-RFI animals with a higher metabolizable energy intake but no increase in retained energy must therefore have increased heat production. Differences in heat production can be attributed to factors related to the heat increment of feeding and also to basal metabolism, voluntary activity, and thermal regulation. The sum of all these metabolic activities generates heat which must be managed in order to maintain a homeothermic condition. Within the thermal neutral zone, the main avenue for dissipating excess heat is through radiated heat loss using a combination of thermoregulatory mechanisms at efficient thermoregulatory sites. In this thesis, the ability of infrared thermography to measure the radiated temperature and subsequently predict the feed efficiency by RFI appears to be strongest for the cheek region.

3.1.2 Handling stress impact

No relationship was found between cortisol and IRT. This was unexpected since the maximum temperature of the eye determined by IRT has shown utility as an indication of handling stress (Stewart et al. 2005). There are several possibilities why no relationship was found. The handling stress may not have been sufficient to evoke a cortisol or IRT response. The observation of a positive correlation between cortisol and chute order on Day 0 but not seen on subsequent dates may support this. The handling the heifers received on Day 0 was certainly a novel stress for them, whereas subsequent weigh days may have become less stressful with habituation. There is also the possibility of a timing issue of the HPA cortisol response to the handling stress and the infrared temperature response. Considering that activation of the HPA takes minutes to respond and that the most stressful activity in the chute may indeed have been the collection of the blood sample, it is possible that an IRT detectable response may not have occurred until the heifers were back in their home pen. There is also the possibility that a fear-related response was occurring, where the eye-max temperature declines for a short period (Stewart et al. 2008). Lastly, the cumulative handling stress over the entire time period from when the heifers were removed from their pen until they were captured in the chute may have already had the maximum effect on IRT measures. However, without monitoring baseline values for both, this cannot be explored further. Cortisol and IRT may be related but the experimental design used in the collection of this data may not be suitable to investigate any relationship.

3.2 Standardizing a IRT collection procedure

With regards to predicting energetic efficiency, the need to consider a standardized operating procedure for IRT collection is evident. For the chute side collection of IRT images, it would be desirable to be within the thermal neutral zone of the animals while maintaining constant environmental conditions. Using ambient temperature as a covariate with this data set was deemed useful to remove the impact of differences in ambient temperature. However, this method may not be suitable for rapidly changing environmental conditions or even conditions outside of the thermal neutral zone.

Certainly, the effects of solar loading and the impact of absorbed solar radiation on the surface temperature of the animals cannot be dismissed. In this study, heifers were brought inside to a thermal neutral environment away from the radiant heat of the sun before images were taken. In the same way, it would be preferred that the location where images are taken not have a source of radiant energy that will impact on the images. In this regard, overhead heaters should be turned off well before animals are brought in to be imaged as was done in this study. As discussed above, although the impact of handling stress on the relationship of IRT to RFI is inconclusive, it also merits consideration. It would be preferred that for the chute-side collection of IRT images, animals should be handled as quietly and efficiently as possible. The time of day that IRT images are collected must also be considered, circadian patterns and the impact of time of feeding on IRT may also be important. In this study, heifers were removed from the pen before feeding; only orts remained in the bunk. This would be a preferred procedure as the access to fresh feed and a possible expected rise in energy expenditure due to the heat increment of feeding (HIF) may cause an increase in radiated temperature. The use of a water station IRT system (Schaefer et al. 2012) where the animals are allowed to self-assess may offer the opportunity to investigate concerns about the impacts of stress, time of day, feeding, and environmental conditions.

The cheek site used was left undisturbed, fortunately the heifers stayed relatively clean and there was no need to brush or clean debris in this data set. However, it is recognized this may not always be possible. Preparation or alteration of hair coat at the cheek site may be necessary. For example, if hair loss is evident then clipping to standardize the hair coat may be considered. Whether a relationship of IRT cheek-mean temperature to RFI remains after hair clipping deserves more study. In conjunction with this, collection of a hair sample from IRT measured sites to measure hair length and density properties may be useful. Although not done in this study, a more accurate estimate of hair insulation differences by IRT may have been possible if the removal of hair from the rib section had been repeated on Day 94 and 112. However, as shown, IRT temperatures of the rib section, with hair or not, may not be as useful as the cheek site.

3.3 IRT image analysis

This study investigated the use of real time collection of multiple IRT images in order to determine a ‘best estimate’ of radiated temperature. This method allowed the camera operator to concentrate mainly on capturing properly focussed images at the appropriate distance. This is a novel technique for the capture of images which has evolved with the advancements in computer and camera technology. Unfortunately, a communication issue between the camera and computer resulted in some data loss on one occasion. The advantage of being able to replay the sequence file as often as required during the analysis is substantial. However, the time required to analyze the multitude of images was also tiresome and tedious. Certainly this became evident when the fastest frame rate of image transfer was used on Day 0, subsequent dates utilized a slower frame rate. However, the question of how many images are needed to determine the ‘best estimate’ still remains. Although not investigated in this thesis, a within animal repeatability analysis similar to method used to determine the length of test duration needed to determine RFI (Wang et al. 2006) is possible. Repeatability of the IRT measures can also be determined by the ratio-of-variances estimation used previously in a feed efficiency trial with beef bulls to investigate feeding behaviour traits over a finishing phase (Kelly et al. 2010). Other image parameters and statistical methods warrant further investigation. For example, perhaps the temperature variation within the region of interest is revealing. Moving beyond the relatively simple approach of a pooled average of the mean temperatures, stepwise multiple regression models using IRT could be utilized to predict energetic efficiency. Other measures of efficiency using the residual concept which are now being proposed are residual gain (RG) for growth efficiency (Crowley et al. 2010) and a combination of residual feed intake with residual gain (RIG) (Berry and Crowley 2012). These proposed measures of efficiency can be calculated for this dataset as well. The relationship of IRT measures already collected in this study to RG and RIG warrants future investigation.

3.4 Limitations of the study

Briefly, limitations other than those suggested related to the standardization of the infrared technology discussed above would include; increasing the number of animals, examine the impact of the number of IRT collection dates, further assessment of the impact of breed type, consideration of any effects of puberty and evaluation of illness effects such as bovine respiratory disease.

3.5 Implications

Notwithstanding these aforementioned factors the present study again demonstrated the utility in using infrared thermography to identify and rank beef heifers for metabolic efficiency. Economically, the decision process for selecting heifers to join the cow herd is often influenced by predicted input variables such as feed prices and availability, and output variables such as fed cattle prices. On a yearly basis, a manager may choose to keep more or fewer heifers depending on the future market predictions. One scenario may be to improve the overall feed efficiency of the herd by culling the inefficient heifers. Based on the data from the current study, using IRT to select and cull animals would have had a financial impact of approximately $22 per year per animal. To determine this impact, the following scenario was proposed as a starting point. For the 55 heifers which had a cheek-mean value for all three dates, an overall cheek-mean for the trial was determined. An upper threshold temperature of 21.1ºCwas determined, identical to the grouping method used for RFI_{fat} (μ+0.5sd). By this criterion, 19 heifers were identified as being possible culls based on having a consistently hotter cheek temperature. This cull group successfully identified 11 of the possible 17 high RFI_{fat} heifers. Assuming that the relative differences in feed intake as determined by the RFI procedure would continue on a yearly basis, it is estimated the 19 hot IRT heifers on average would have consumed an extra 145 kg per year. This results in an average $22 impact in feed costs at an estimated market value of feed at $0.15 per kg. By comparison, using the RFI score and culling the 17 high RFI_{fat} heifers directly would eliminate the animals consuming on average an extra 335 kg or $50 per year

Clearly, the savings possible are superior when based directly on the RFI score; however the estimated cost to determine a RFI score is approximately $500 per animal. Currently there are only a few facilities available to conduct RFI feed trials. Furthermore, the expertise needed and the quality control of collecting accurate feed intake data comes at an additional cost, animals must be transported to and from the test centres, the length of pre-test and test period is substantial, and the feed cost to the producer will be based on market prices. The estimated cost to determining RFI using current feed monitoring methodology in a group of beef heifers would be difficult to justify with the potential herd savings even when amortized over future calf crops

By comparison, the IRT method is estimated to cost $15 per animal using a chute side handheld camera system which can be used at multiple farms. This would likely be reduced further to approximately $5 per animal using an automated system. In addition, the time required to determine efficiency may be completed in days for IRT versus months for RFI. Hence IRT methodology has the potential to be a cost effective on-farm test to select for improved feed efficiency in beef heifers.

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