Identifying and managing low viable piglets for improved survival

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Abstract

Preweaning mortality is a major cost to the pork industry that, despite piglet management being a highly researched area, continues to increase. Low viability piglets are credited for a large percentage of this mortality, however, the terminology and measures used to identify these piglets is inconsistent. Therefore, we proposed to investigate existing and novel parameters to better identify these truly low viability piglets and potential management strategies for improved survival

Chapter 2 briefly summarises the previous knowledge of what a viable piglet has been defined as, and current commonly used management strategies for their management. The main outcomes of this chapter were that identification lies in the early evaluation of the complex relationship between a piglet's physical characteristics, temperature and colostrum intake. It also acknowledged the critical role of the sow in a piglets' starting viability.

Chapter 3 focused on piglet morphology and identified that rather than an individual trait, the proportion of crown to rump length and abdominal circumference are indicative of survival and performance. Chapter 4 focussed on sow transition phase feeding manipulation for increasing born alive and showed that with decreasing farrowing duration through increased feeding frequency the number of piglets born alive increased, suggesting higher litter viability at birth.

Chapters 5 was an initial look into the temperature profile of piglets from birth to 24 h using rectal and surface temperature to determine if monitoring temperature change was a critical identifying factor. Repetitive rectal temperature measurements were deemed stressful and impractical for production application. Therefore, we investigated surface temperature further as, based on the findings from Chapter 5, it was highly variable at birth and 24 h, which are critical timepoints for interventions. Chapter 6 was a comparison of three surface locations; base of ear, tip of ear and eye to rectal temperature for correlation and practicality. We determined from the outcomes of Chapters 5 and 6 that temperature monitoring is an important indicator but, under production conditions, surface temperature is too unreliable for identifying at-risk piglets.

Currently, temperature interventions are largely based around providing energy supplements which reduce available stomach volume for colostrum, and or external warming methods like heat lamps which are stationary and drying which has had short term temperature

improvements. Chapter 7 introduced a warming method used in human surgeries to reduce risk of postoperative hypothermia. A warm saline bolus was injected into the intraperitoneal space of piglets, and this improved subsequent temperature and survival especially in low-birth-weight piglets. Collectively, the findings of this thesis present novel identification and management strategies for improved piglet survival and evaluate existing methods for production application. This research has enabled the stimulation of a change in perspectives of piglet management research, adding strength to the need to reanalyse how we identify low viability at-risk piglets for improved survival.

Declaration

I certify that this work contains no material which has been accepted for the award of any other degree or diploma in my name, in any university or other tertiary institution and, to the best of my knowledge and belief, contains no material previously published or written by another person, except where due reference has been made in the text. In addition, I certify that no part of this work will, in the future, be used in a submission in my name, for any other degree or diploma in any university or other tertiary institution without the prior approval of the University of Adelaide and where applicable, any partner institution responsible for the joint-award of this degree.

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I acknowledge the support I have received for my research through the provision of an Australian Government Research Training Program Scholarship.

Signed: ___

Bryony Tucker

Date: 04/08/2022

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List of Publications Included in this Thesis

Tucker, B. S., J. R. Craig, R. S. Morrison, R. J. Smits, and R. N. Kirkwood. 2021. Piglet Viability: A Review of Identification and Pre-Weaning Management Strategies. Animals 11(10):2902. doi: 10.3390/ani11102902

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Conference Abstracts during Candidature

Tucker, B. S., J. R. Craig, R. S. Morrison, R. J. Smits, and R. N. Kirkwood. 2021. Sizing up piglets for survival: A novel spin on a novel approach. Animal - Science Proceedings 12(2):172. doi: 10.1016/j.anscip.2021.09.095

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Gratefully yours,

Bryony Tucker

Chapter 1:

Introduction

Background

Viability is a combination of performance and the ability to thrive and survive. Throughout this thesis I will use this term to generalise a piglet's level of ability to thrive and survive, although acknowledging these are independent. In the context of a foetus, viability is the ability to survive outside the uterus (Merriam-Webster). However, although a simple definition, the accuracy and or repetitive ability of people to determine the viability of piglets at and around birth is contentious. Piglets of low or no viability are terms usually interchanged with low-birth-weight piglets, although a definitive cut off for what constitutes a low birth weight also varies in the literature and in pig production generally. This variation may reflect differences in genetics and or management systems, however, the absence of a universally agreed identification method or measure for piglet viability continues to contribute to the inaccurate identification of piglets with a predisposition to impaired survival. Piglet preweaning mortality (PWM) is one of the largest causes of loss to the global pork industry (Tuchscherer et al., 2000; Kirkden et al., 2013). Although attempts to reduce PWM through multipronged research is ongoing, it continues to rise (Edwards, 2002). Non-viable or low viability piglets are documented to be some of the greatest contributors to PWM (Pandolfi et al., 2017).

The continual increase in PWM indicates current methods to identify and manage true low viability piglets are inadequate (Koketsu et al., 2021). What is known is that there are important relationships among weight gain, colostrum intake and temperature regulation when considering piglet mortalities. Therefore, this thesis addresses some of the main areas in question regarding the prediction of piglet survival and viability. Firstly, are there physical determinates that better predict who is going to be a poor survivor, secondly, how can we monitor and/or manipulate their body temperatures to mitigate these physical determinates and, thirdly, we examine pre-natal sow level factors impacting piglet viability. In summary, this thesis outlines details of alternative ways to better identify low viability subgroups of piglets and some intervention protocols for monitoring and manipulating piglets for improved survival.

Thesis Format

Chapter 2 covers the general background of the topics covered in the thesis, thesis chapter format and overall aims. It also includes a literature review titled "Piglet Viability: A Review of Identification and Pre-weaning Management Strategies" published in the journal, Animals.

The review was structured to evaluate current methods for predicting viability, key contributing factors to low viability, and management strategies for improving piglet survival. Preweaning management is an extensive topic that has been reviewed previously however as it is a highly important area, with increasing litter size and changes within industry, the approach to research must also reflect this to benefit the producers. The purpose of this review was to approach pre-weaning mortality from the view of lower viability piglets, which are increasing in presence, although a singular definition of what constitutes a low viability pig is still uncertain. This review was intended to stimulate thoughts and discussion about how current practices could be modified or combined in novel ways to serve piglets more efficiently. This highlighted key areas to be investigated further within the experimental chapters.

Chapter 3 is a paper titled "Piglet morphology: indicators of neonatal viability? " Published in the journal, Animals. This chapter investigates the role of measures of piglet morphology in the prediction of survival and other key related performance indicators including colostrum intake and preweaning growth. As variation in individual piglet size is affected by birth litter size, among other factors, we reasoned that the morphology of piglets would also differ. It has been suggested that abdominal circumference and crown to rump length are good indicators of performance but have not been further investigated in relation to survival. Previous work has mostly involved very large litters, so this chapter aimed to determine if these measures are also applicable to a population with smaller litter sizes more reflective of Australian herds. Further, we wanted to investigate if, in addition to performance, measures of morphology are predictive of likely survival outcomes.

Chapter 4, entitled "Increased feeding frequency prior to farrowing: effects on sow performance", will be published in Translational Animal Science and looked prospectively at the concept of energy but from a sow management perspective. It is known that the duration of farrowing can determine the viability of piglets at birth including whether born alive or stillborn. This chapter investigated if manipulation of feeding during the transition period to reduce the time from last feed to the farrowing of smaller litters than those previously demonstrated in Denmark, and whether it results in fewer stillborn piglets and improved litter viability.

Chapter 5, entitled "Associations between surface and rectal temperature profiles, body weight, and pre-weaning survival in low-birth-weight piglets" briefly investigates the relationship between rectal and skin temperatures during the first 24 h of life, and contributing factors to the values observed. Temperature is an indicator of thermoregulatory function and a key predictor of piglet survival. However, repetitive measuring of temperature can be stressful for the piglets and labour intensive. Therefore, this chapter considers the temperature drop of neonatal piglets of different body weights from birth to 24 h, and comparing surface and rectal temperatures under commercial conditions to determine if skin temperature is an appropriate replacement for on-farm use. As expected, birthweight was a significant determinant of initial temperature drop and subsequent recovery. Both methods of temperature collection were able to detect a significant difference between piglets obtaining sufficient colostrum or not. We were also able to determine that the agreeance between surface and rectal temperature at certain time points could be used to further indicate a piglet's ability to survive when considering bodyweight and colostrum interaction. It was also identified that at birth and 24 h, piglet skin and rectal temperature were least correlated. This led to questions as to how accurate skin temperature is at indicating piglet core temperature when presented with different conditions, especially at these times. This experiment only measured skin temperature at one location. Therefore, we subsequently expanded the surface temperature recording locations (Chapter 6) to investigate the location of surface temperature measurement as a potential alternative to rectal temperature at the most challenging time points, birth and 24 h, to test the applicability of a handheld infrared camera for use in production.

Chapter 6, entitled "Using a handheld infrared camera to assess potential for thermal windows in neonatal piglets to substitute for rectal thermometers in monitoring post-natal temperature change", was designed to compare three of the main surface thermal locations suggested in the literature, namely base of ear, tip of ear and eye, for their correlation to rectal temperature at two of the least correlated time points (birth and 24 h). The use of a handheld infrared thermal camera allowed a comparison of temperature values derived from the camera automatic temperature reading and an algorithm that extracted the maximum temperature from the area specified in the thermal image. Although the base of the ear and eye showed promise in repeatability they were only moderately correlated to rectal temperature in a production (less controlled) environment. We determined that, currently, the use of a handheld infrared thermal camera to monitor skin temperature at the base of ear and or eye is not appropriate under production constraints.

Chapter 7, entitled "Neonatal piglet temperature changes: effect of intraperitoneal warm saline injection", was undertaken to determine whether we can reduce the postnatal temperature drop or reduce the duration of lower temperatures. Current intervention strategies such as an oral gavage of milk or other energy substrate reduce available stomach volume for colostrum ingestion. Therefore, this experiment was designed to replicate a human practice of administering warm fluids to a patient to treat hypothermia, without reducing stomach space. The results suggest that providing an internal source of heat potentially reduces the amount of energy a piglet must use to maintain and recover their temperature to thermoneutrality, thus leaving more for storage and use to compete for teats and successfully suckle.

Chapter 8 is the discussion chapter connecting the previous chapters visually through a diagram and discusses the outcomes and implications of the research as well as the future directions.

Project Aims

The overarching aim of this thesis was to determine if there were better indicators of low viability piglets, such as characteristics of morphology or temperature. This information can then be used to better understand the level of assistance piglets require to survive and assist in more efficient application of current and new management strategies. The individual experiments within this thesis aimed to determine if:

1) suggested morphological measures can be used in Australian pigs for indication of likely performance and survival
2) reducing farrowing duration by increasing sow feeding frequency can reduce stillbirth numbers and or improve sow and piglet performance in lactation
3) skin temperature could be an adequate replacement to repetitive rectal temperature recording in monitoring piglet thermoregulation
4) the location of the skin temperature reading, and the IRC derived (pointer) temperature is a good method for survival prediction
5) an internal warming method, via intraperitoneal injection of warm saline, can improve thermoregulation in piglets of different sizes and improve their subsequent survival

Chapter 2:

Piglet Viability: A Review of Identification and Pre-Weaning Management Strategies

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Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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animals

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Review

Piglet Viability: A Review of Identification and Pre-Weaning Management Strategies

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Simple Summary: Neonatal piglet viability is decreasing in concert with the selection for ever-greater numbers of piglets born per sow per year. Their survival depends on the early intervention and management strategies used by production staff. This paper will review current and novel methods used to identify these piglets, some of the factors affecting their viability, and management strategies commonly used within production systems to improve their survival.

Abstract: Increased attention on the effects of the global push for a larger litter size has focused on the increased occurrence of piglets with decreased viability, which have lighter birthweights and a reduced ability to thrive in early life. To improve their odds of survival, interventions must be timely and targeted. This requires the early identification of low-viability pigs and appropriate strategies to manage them. Using novel measures such as abdominal circumference and crown to the rump length in conjunction with birth weight may provide an improved protocol for the identification of those at most risk of preweaning mortality. Further, identifying these at-risk piglets allows interventions to increase their colostrum intake and heat provisions shortly following birth. The appropriate management of the pre- and post-partum sows will improve the chances of decreasing the number of piglets born with lower viability. However, this outcome is constrained by limitations in resources such as technology and staffing. If these challenges can be overcome, it will allow for greater control and increased effectiveness in the implementation of current and new management strategies.

Keywords: piglet; viability; management; preweaning survival

1. Introduction

Pork industries worldwide face loss of profit due to high piglet pre-weaning mortality (PWM), which can account for 10% to 20% of all live born piglets [1,2]. Attempts to reduce PWM are ongoing through research and the formulation of new industry guidelines. However, this PWM continues to increase, with 80% of deaths occurring within the first 72 h of life [3]. There are many factors that impact PWM, although non-viable or low-viability piglets are a major contributor (Figure 1), second only to the occurrence of stillbirths [4]. The term viable, when referring to a foetus, is the ability to survive outside the uterus [5]. However, although the term viable, per se, is simple, the accuracy of measures used to determine the viability of piglets at birth is contentious. The absence of universally agreed measures for piglet viability contributes to the inaccurate prediction of survival and subsequent PWM. This raises concerns for the accuracy of identifying factors contributing to low viability and the effectiveness of associated remedial management strategies. Evidence within the literature strongly suggests that increased litter size, largely due to genetic selection to increase the number of piglets born, is the major contributing factor for the greater occurrence of low-viability piglets and the consequently increased PWM [6–8]. The continual increase in PWM indicates current methods to identify and manage low viability piglets are inadequate [9]. The aims of this review are to identify how the literature defines low-viability piglets and to evaluate the management strategies implemented to improve PWM. A variety of neonatal measures for viability, contributing factors and current management strategies will be discussed within this review (Figure 1).

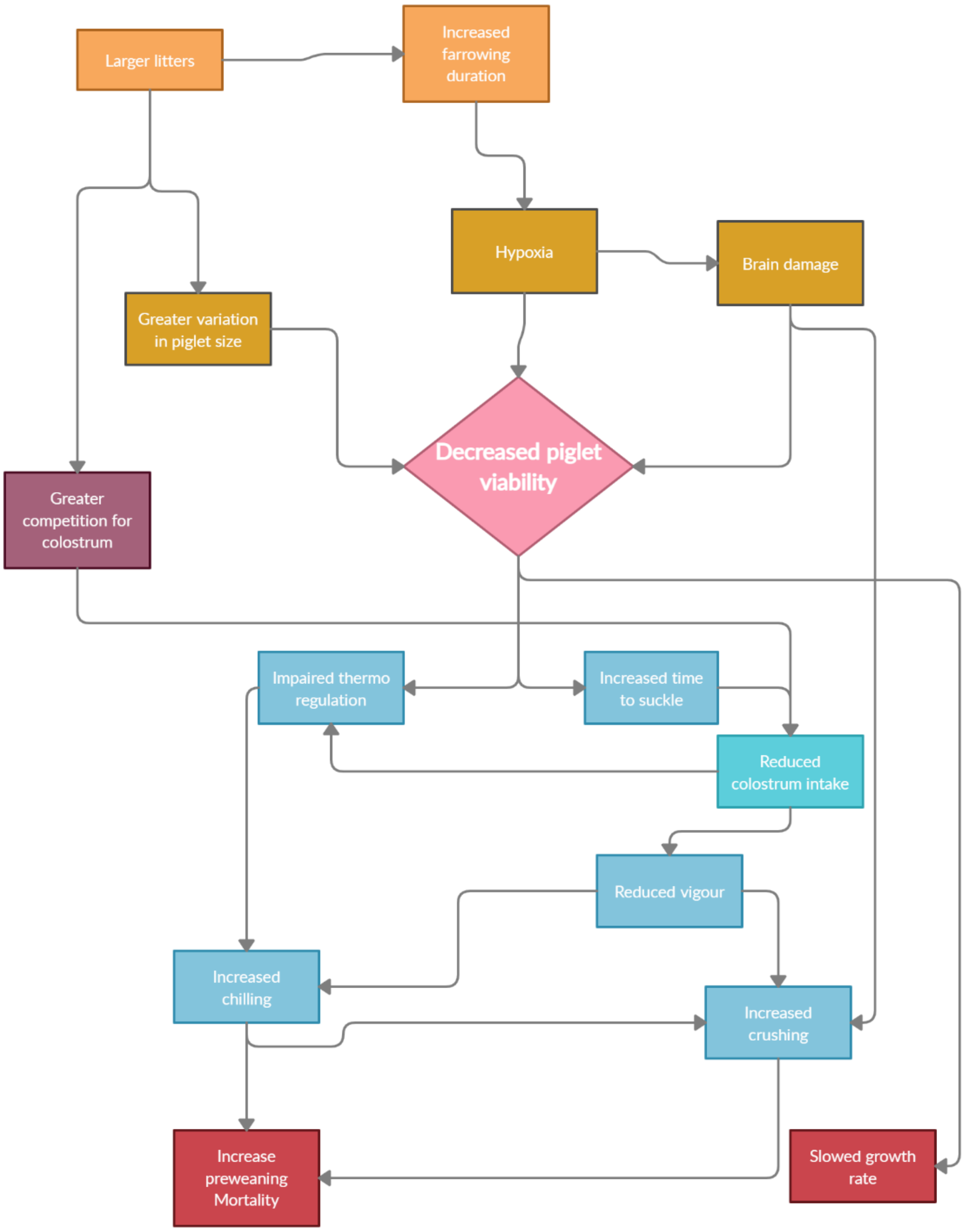

Figure 1. Factors influencing piglet viability and possible outcomes.

2. Materials and Methods

2.1. Birth Weight (BW)

In commercial practice, BW is the most commonly used indicator of a piglet's ability to survive until weaning [1,10–14]. The long-term effects of low BW on piglet survival and growth have been investigated, but with contradictory findings on the ability of piglets to compensate and catch up to littermates in terms of growth. It was documented that the lightest-BW piglets could compensate during postnatal growth [15] although others have stated that low-BW piglets have a higher chance of demonstrating poor pre-weaning growth and a lower BW at weaning [16]. Further, lower-BW piglets exhibit poorer lifetime growth rates and increased days to market weight compared to their heavier-BW littermates [6,15].

Low-BW piglets have been categorised based on their number of standard deviations (SDs) from the mean BW of the batch [11]. Within the experimental population of that study, piglets with a BW that was within 2.5 SDs of the mean BW of the population had the potential to compensate growth in other stages. However, piglets with a BW more than 2.5 SDs below the mean did not show compensatory growth. Regardless of the BW category, not all piglets showed improved performance, suggesting that the BW is not the sole predictor of pre-weaning growth and survival [11]. Some of the variation in performance may be the result of intrauterine growth restriction (IUGR). Many small foetuses are genetically small but are normal, while others are the result of placental insufficiency, often termed IUGR piglets. These IUGR neonates are a major contributor to perinatal mortality across many species. In humans, there are cut-off birth weights, and other morphological measures are used to identify IUGR babies [16]. There are two types of delayed foetal growth, asymmetric and symmetric. With asymmetric growth the body is disproportionately small for the head size, while with symmetric growth, heads are proportionally affected. The most commonly identified IUGR piglets are asymmetrical, identifiable by the so-called dolphin-like head shape [17,18]. These IUGR piglets grow at a slower rate than their littermates, with an impaired energy supply, underdeveloped organs and impaired gastrointestinal and skeletal development [19–23]. Symmetrical foetal growth restriction is harder to identify and, as such, possibly influences the performance reported for low-BW piglets in the literature. Only asymmetric IUGR is referred to in the literature for pigs, and the degree of IUGR severity can be identified by the use of morphological measures of the head [21,24]. However, the assessment of these head characteristics is subjective, and consequently, the identification of IUGR piglets using head morphology is often inconsistent. Thus, the validation of more objective measures of the head would improve the validity of classification. Head morphology is not the most robust method for identifying IUGR piglets. Clearly, the parameters used to classify piglets as having low viability require further clarification to improve the relevance and effectiveness of early intervention strategies for these low-viability piglets.

2.2. Novel Predictors

In humans, morphological measures have been recorded for newborns as being better indicators of potential growth and development than BW alone [16]. As such, the morphology of piglets at birth potentially may provide relatively novel predictors of their potential postnatal growth and development [18,21,23,25]. A variety of morphological measurements which improve the prediction of a piglet's ability to survive have been identified. The body mass index (BMI = weight (kg)/crown – rump (cm)^2) and the abdominal circumference (AC) have been identified as the most accurate predictors of piglet growth from days 1 to 28 of life, and thereafter, the AC and the ponderal index (PI = weight/crown – rump^3) are the best predictors of growth from days 28 to 70 [25]. These findings are supported by Huting et al. [18], who found the BMI is associated with pre- and post-weaning average daily gain.

2.3. Colostrum Intake

Sufficient colostrum intake within the first 24 h of life is a well-established determinant for continued survival. Colostrum provides piglets with energy for thermoregulation and weight gain, passive immunity and growth factors [26–28]. It is recommended that to survive and thrive before and after weaning, a colostrum intake of at least 250 g per pig is required [29]. Accordingly, sufficient intake could be the most appropriate measure of viability. Amdi et al. [17] identified a large variation in stomach weight and capacity in both IUGR and normal piglets at birth. Under artificial feeding conditions, the maximum capacity of a newborn IUGR piglet's stomach was ~50 mL per kg/BW [30]. This would require the feeding of colostrum at least 5 times within the first 24 h to achieve appropriate intake for improved survival. Piglet stomachs grow rapidly, and increases in functional maturation occur within the first 3 days post-partum [31], with gut closure occurring by about 24 h of life [27]. The rapid developmental changes in the stomach of the piglet highlights the importance of time relative to birth, if management strategies are to be implemented with optimal outcomes. However, applications within many production systems are currently impractical, as the sufficiently precise prediction of birth time is not possible, with approximately 15 h of the day (i.e., overnight) being unstaffed on most farms.

Regardless of the stomach capacity or frequency of feeding, recent studies have questioned the ability of the gastrointestinal tract of low-viability piglets to digest and absorb the colostrum components ingested [32,33]. The poorer nutrient absorption and potential lack of organ maturation in IUGR or low-viability piglets [17,34] could reduce the effectiveness of supplemental feed. Therefore, a measure of colostrum absorption requires research into the gut function of low-viability piglets as their ability to uptake colostrum is crucial. Intestinal closure is where the ability of intestinal cells to uptake macromolecules into the lymphatics and blood decreases. In the pig, this process begins at about first 6–12 h post-ingestion of colostrum and is complete at 24–36 h [35,36]. During the time when the gut is "open", the piglet can obtain necessary immunoglobulins and other immune elements required to acquire their passive immunity [37]. This highlights the importance of timely intervention and the availability and uptake of sufficient colostrum. Additionally, when farrowings are unattended, a way to record the time of birth would aid in the timely implementation of effective management strategies.

2.4. Piglet Body Temperature

Piglets are born with a limited energy supply, having little readily mobilizable adipose tissue and no brown fat that plays an important role in thermoregulation in many other species [38]. Piglets must rely on their ability to access a teat to suck and thermoregulate. The in-utero temperature fluctuates between 38 and 40 °C [39] and is influenced by sow parity [40]. The minimum temperature of the environment immediately following birth must be 34–35 °C for thermoneutrality [41]. Ambient temperature varies greatly with the geographical location, and the temperature at the piglet level will be influenced by the type of production system. Commercial production facilities often operate with suboptimal environments for piglets, with draughts, skin wetness and cold flooring being contributing factors to PWM. This environment can directly impact the severity of the initial temperature drop and the time for piglets to recover to near the optimal temperature [42]. At their birth, farrowing house temperatures are often 10–12 °C lower than a piglet's lower critical temperature of ~34 °C [39], accentuating reductions in piglet temperatures with near normal body temperatures not being achieved for several hours (Figure 2) [42]. Being born into a suboptimal environment could further negatively impact the chance of survival for a piglet already disadvantaged in utero. The ability of piglets to thermoregulate is directly related to their weight, and as such, their body temperature at 24 h post-partum may be a good predictor of early-lactation piglet performance [12,38]. Caldara et al. [43] showed that at 30 to 45 min post-partum, as weight increased, so did skin temperatures. This indicates less of a postnatal drop in body temperature of heavier piglets (≥1.4 kg) compared to that of lighter-weight piglets [44]. Further comparisons between weight groups were not reported, likely due to the small sample size (*n* = 4 sows) used in the study. Small piglets have a higher surface area-to-volume ratio than large piglets; thus, heat loss is proportionally greater. It has been suggested that a birth weight less than 1.1 kg in European breed piglets predisposes to an impaired ability to thermoregulate [39]. This may be explained by IUGR piglets usually being under 1.1 kg at birth and having a lower rectal temperature than normal-weight piglets [17,44]. There is potential for these measures to act as indicators for piglet survival in the immediate postnatal period and could influence decisions on the distribution of farrowing house resources and fostering movements.

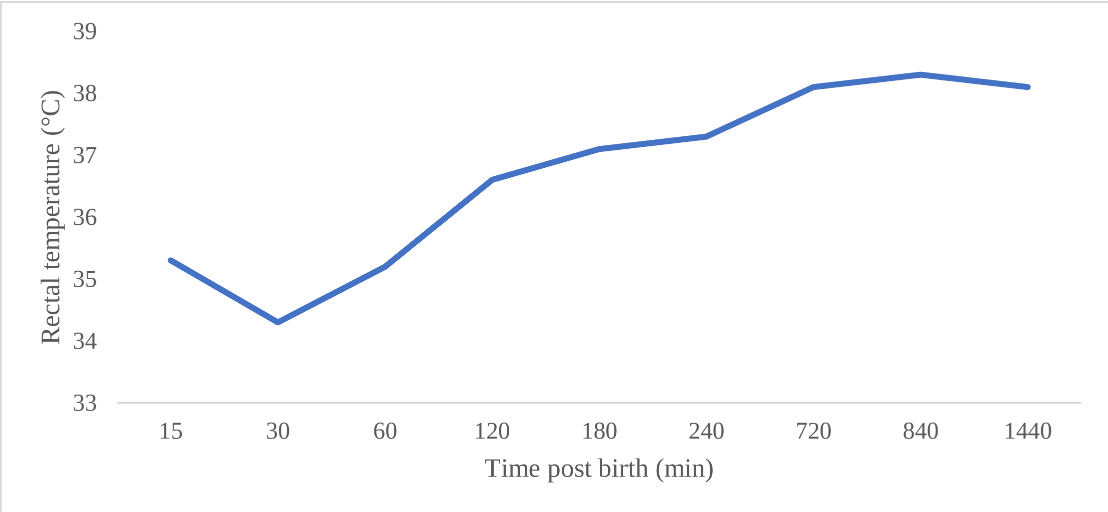

Figure 2. Piglet rectal temperature change from 15 min to 24 h post-partum. Modified from Anderson et al. [42].

3. Contributing Factors to Low Viability

3.1. Selection for Larger Litters

Many studies have focused on increasing the reproductive output of the sow, with increasing litter size at the forefront of industry research. Modern Danish sows have the capability to produce an average of 16.9 piglets born alive per litter [45], which is significantly greater than the available teat capacity. It is well established that larger litters at birth have a higher within-litter BW variation and a higher proportion of low-viability piglets [6,46]. This means that, despite higher numbers of piglets produced, piglets born alive are more likely to be relatively small, underdeveloped and at higher risk of mortality. The size of piglets from large litters is impaired in utero, because there is a greater competition for available resources [47,48]. The increased energy requirement of a large litter can also accentuate a lack of energy in the sow, contributing to an increased PWM due to difficulties during farrowing and inadequate colostrum and milk supply [49–51]. Extended farrowing durations as a result of a larger litter size can increase the incidence of intrapartum hypoxia, leading to higher stillbirth rates [52,53] and/or permanent brain damage in live born pigs (Figure 1) [54,55]. The increased occurrence of stillbirth is exacerbated in higher parity sows, as their uterine contractility may decrease, possibly due to older sows experiencing poorer calcium homeostasis, limiting the ability of the sow to expedite piglet delivery [56,57]. Although Australia lags behind many countries in terms of litter size, there is evidence that even with smaller litters there are trends in commercial herds for an increased total born alive per litter, with the Pork CRC reporting an increase of total piglets born from 12.4 to 12.8 between 2013 and 2016 and a similar trend also seen in the Australian average piglet PWM, being 10.9% and 11.5% for 2013 and 2016, respectively [58]. These reported figures indicate that although a slight increase in litter size was achieved, the net effect on overall productivity would be minimal given the higher mortality rate, as also described by others [59]. Accordingly, the increased presence of low-viability piglets in larger litters has encouraged the industry to develop better fostering and management techniques, but there are still a growing number of piglet deaths due to increased litter sizes and associated lower viability at birth.

3.2. Farrowing Induction

Induced farrowing is used to increase the likelihood of the sow farrowing during supervised hours [60,61]. Indeed, supervision is recommended when inducing farrowing, as several potential negative side effects have been reported [62,63]. Some studies report an increase in stillbirths, but this is largely considered a result of extended farrowing duration due to dystocia [52,63]. Regardless, if not timed correctly, inducing sows to farrow has been associated with an increase in PWM [62]. Premature piglets born as a result of inappropriately timed farrowing induction are born lighter and have a lower average daily gain than those born to non-induced sows [53]. The induction of farrowing uses prostaglandins and/or oxytocin, and globally, consumers are becoming more interested in animal industries and how medication and hormones are used [64]. Therefore, the practice of inducing sows is not universally viewed favourably, so induction protocols should be assessed to better suit the developmental needs of the piglet.

3.3. Transition into Parturition

Farrowing can be long and problematic for the sow and her piglets. Parity, nutrition and the sow's environment may influence the farrowing outcome [48,65,66]. Traditional research typically focused on the gestation and lactation periods as separate phases, defined as being before and after farrowing is complete, respectively. More recently, research has redefined the period of change from gestation to lactation as a separate state categorised as the transition period with its own management challenges, including nutritional. A relationship between the time from the last feed to the onset of farrowing and the duration of farrowing has been documented [67]. Specifically, farrowing duration was 3.8 ± 1.5 h, if farrowing started within 3.1 ± 0.34 h of the last meal. However, if farrowing commenced more than 3.13 h after the last feed, there was a decrease in arterial glucose concentrations and an increase in farrowing duration to 9.3 h if farrowing commenced 8 h after the last feed. To our knowledge, only one other study by Gourley et al. [68] has focused on the time from feed to farrow intervals. There was no decrease in farrowing duration recorded, when the feed-to-farrow interval was reduced by more frequent feeding sessions. The difference between the two studies has been suggested to be due to the difference in average farrowing duration and born alive for the study populations. This highlights that although some sows may still farrow within a safe timeframe, with the selection for larger litter sizes farrowing duration is likely to increase as will the possible negative effects of prolonged farrowing duration on stillbirth rate and neonatal viability [52,69,70]. Extended farrowing durations increase the incidence and degree of hypoxic events experienced by piglets [12]. Hypoxia slows the responses of piglets to their environment, increases their chance of being overlaid by the sow and/or reduces their ability to compete for sufficient colostrum and milk, lowering their chance of survival. The findings of Langendijk et al. [52] and Feyera et al. [67] highlighted the importance of developing better sow and piglet management strategies during the transition period. Further research into the mechanisms behind the relationship between the time from the last feed to the onset of farrowing and the farrowing duration is crucial for reducing the impact of farrowing duration on piglet viability.

4. Management Strategies for Improving Piglet Survival

4.1. Sow-Specific Diets

Extensive research has explored numerous diet compositions for sow gestation and lactation feed which may influence sow and piglet performance [71,72]. However, the use of feed additives by producers is limited, as the associated costs can outweigh the benefit. There are generally three main phases targeted for gestation-specific diets, which differ between gilts and sows, with these being early gestation (days 1–28), mid gestation (days 29–84) and late gestation (days 85–115). Early-gestation diets are targeted at priming the sow for optimal metabolic and endocrine conditions to develop and maintain good-quality embryos and foetuses [73]. Mid gestation feeding is focused on maintenance and maternal body gain, usually met by a gradual increase in feed and energy intake [74]. Late gestation is crucial for foetal and mammary growth and influences the production of colostrum and sow performance throughout lactation [75,76]. Despite the transition period from late gestation into lactation being critical for sow performance and piglet development, there is a paucity of research in this area. The transition from gestation to lactation is traditionally considered to occur, after the sow farrows; however, recent research has put more importance on the lead up to farrowing as a part of the transition period to prime the sow to be in a positive energy state prior to farrowing [67]. Parturition requires large amounts of energy, but sows consume little or no feed immediately prior to or during farrowing. Extended farrowing durations reduce piglet viability and increase stillbirth rates. Recent research documented a significant positive association between the time interval from the last feeding to the onset of farrowing and the farrowing duration [67]. These authors suggested the relationship is directly related to a depleted energy supply if the interval between eating and farrowing is more than 3 h. Others have found that farrowing duration, stillbirths and 24 h mortality are not impacted by increased feeding frequency or amount offered in the 2–3-day prepartum, although there is a decrease in overall PWM [77]. Another contributing factor to farrowing difficulty and extended farrowing durations could be weak muscle tone reducing the effectiveness of muscle contractions, and a decline in blood calcium levels may result in insufficient calcium for optimal myometrial contraction and result in the delayed expulsion of piglets. A deficit in calcium can also reduce the effectiveness of both endogenous and exogenous oxytocin, which also may impair myometrial contractions [78]. There are reports of calcium supplementation reducing stillbirth rates, presumably by reducing the duration of farrowing [77,79]. One method for increasing the calcium mobilisation from bone and the uptake from the gut is by manipulation of the dietary cation-anion differences (DCAD) [80]. Negative-DCAD-transition diets are used extensively in the dairy industry to increase milk production and reduce the occurrence of post-parturient hypocalcaemia [80–82]. Negative-DCAD diets contain larger amounts of negatively charged ions which when absorbed into the blood cause a mild acidaemia that promotes parathyroid sensitivity and increased mobilisation of calcium from bone, increased renal vitamin D activation and increased calcium uptake from the intestinal tract. Studies have shown that the effects of feeding negative-DCAD diets for an extensive time prior to calving have minimal negative effects on the cow [83,84]. However, one recent study showed that calves born to cows fed a negative-DCAD diet had a lower BW and an average daily weight gain than calves from cows fed positive-DCAD diets [85]. We are not aware of any published research investigating the feeding of negative-DCAD diets on the sow farrowing duration and the stillbirth rate. However, as sows produce litters of multiple young as opposed to singular young in dairy cows, the same effect may not be clear on the individual offspring. These studies identify the importance of sow nutrition immediately prior to farrowing, both in diet content and feeding frequency, for the optimal farrowing performance.

4.2. Interventions at Farrowing

Supervision during farrowing is recommended but often not implemented due to the relatively unpredictable timing of piglet delivery. Behavioural indicators, such as bar biting, pawing and nest building attempts in conjunction with colostrum leakage, are the typical indicators for impending farrowing. Unfortunately, the presentation of these signs varies greatly in degree and timing relative to the onset of piglet delivery [86]. Further, these indicators are reliant on a person being present to observe and are used to monitor their progress. Piglet mortality in the neonatal period is significantly reduced by the presence of staff during the farrowing [63,87]. However, to reduce overall PWM, ongoing supervision for at least three days is recommended [63,88]. Supervision allows the use of practices such as timely manual delivery assistance, drying and rubbing of piglets and fostering techniques [65,88]. The ability of production systems to implement the adequate supervision of farrowing may be constrained by labour costs and staff availability. However, modern technology can be used to supervise farrowing and reduce piglet mortality without increased labour costs. With the increasing interest in smart farming technologies across multiple agricultural sectors, there have been growing numbers of studies conducted to develop and demonstrate the use of technology such as movement sensors that detect postural changes or patterns of behaviour to predict the onset of farrowing. It has been noted, however, that most of these technologies require large amounts of power resulting in a need for frequent battery changes and are currently not ready for applications within commercial production [89,90]. Further, these examples are focused on detecting the onset, but not the process of farrowing, which does not replace the labour needed for the adequate supervision of farrowing. Other promising systems, such as thermal cameras which use the detection of heat differences to notify personnel when a sow has not had a piglet in a set interval, would allow for timely assistance and potentially piglet assistance prior to the onset of hypothermia.

The standard farrowing crate design includes a creep area often with some sources of heat such as heat lamps, mats and/or bedding [91,92]. However, piglets prefer to lie close to the udder of the sow during the first 24 h of life, when the risk of hypothermia is greatest [93]. Piglets naturally adapt their behaviours to reduce heat loss by huddling with littermates and shivering [38]. The intensity at which they are able to shiver is inversely related to the body temperature down to 34 °C, but below this, the shivering intensity does not increase and heat production decreases [38]. The early re-warming of a hypothermic piglet can reverse some of the biological reactions and metabolism restrictions associated with the drop in temperature [38]. In human medicine, warm intravenous fluids are given to hypothermic patients to increase their core temperature [94]. This is standard practice during surgical operations as well as in cases of severe hypothermia [95]. Administering warm fluids (65 °C) to hypothermic dogs has been shown to increase their temperature with no adverse reactions [96,97]. To our knowledge, there has been no published research on the administration of warm fluids to piglets as a treatment for hypothermia. Current applied interventions such as drying and rubbing of piglets have been shown to be highly effective in increasing rectal temperature if applied at birth [98]. However, this requires personnel to be present at birth to apply these techniques within an effective time frame. With litter sizes continuing to increase, improved supervision practices will become necessary to maintain piglet neonatal survival and to reduce PWM.

4.3. Management during the First 24 h post-Partum

Fostering is used to increase piglet access to colostrum, milk and warmth, when these essential resources are limited for a piglet to thrive. Various fostering techniques have been developed, but those commonly used are cross-fostering and the use of nurse sows [99–101]. Cross-fostering is a standard practice, as it permits the equalising of piglet numbers per litter, allowing more equitable teat access, generally with the minimal movement within a farrowing house. However, if most sows are producing greater numbers of piglets than their teat capacity, then there are limited options to move piglets to available teats. The implementation of split suckling protocols and the use of nurse sows are becoming more popular to ensure piglets in large litters consume sufficient colostrum and milk [88,102]. Split suckling involves the temporary removal of larger piglets from the udder for a series of milk let down events to provide smaller piglets with opportunities to suckle, allowing all piglets to remain with their birth mother [99]. Unlike split suckling, cross-fostering is the movement of piglets from one litter into a new litter to increase their access to colostrum and milk [88]. The proper implementation of split suckling prior to gut closure requires a greater presence of personnel in a farrowing house than does cross-fostering. To ensure lower viability, piglets get the greatest opportunity to consume sufficient colostrum (250 g minimum) and survive, and further investigations into new piglet management options are required.

One-third of sows do not produce enough colostrum to provide 250 g to each of their piglets [29]. The quality of colostrum available to the piglet, rather than the quantity and the amount of colostrum produced per sow, is often not considered, and it has been shown that colostrum quality has not increased with litter size [103,104]. To offset the gap, many energy and milk supplements have become available, but their effectiveness for supporting low-viability piglets is largely undocumented. The main goal of these products is to supply a "boost" of energy to provide piglets with greater opportunities to suckle and obtain colostrum [105,106]. Studies suggest that low-viability and IUGR piglets have underdeveloped gut function, potentially impairing their ability to digest colostrum and supplementary products efficiently [32–34]. If the gut is impaired, regardless of the amount of colostrum or energy supplied, nutrient and immunoglobulin uptake from the gut will be reduced. The development of a supplementary product that not only provides energy but also improves the gut function of piglets would be beneficial. As the litter size continues to increase, the need for more research and development in the management of neonatal low-viability piglets becomes increasingly urgent.

5. Conclusions/Summary

Figure 1 summarises various interactions impacting PWM. Low-viability piglets are increasingly the result of pressure to drive economic growth by increasing larger litter sizes. The lack of consistency in the definition of low-viability piglets increases the confusion when comparing methods for identifying low-viability piglets and the efficacy of management strategies to improve their survival. The Danish pig industry has proven that selection can successfully increase litter sizes. However, sows may not be able to supply adequate support immediately following birth to nurse them to weaning. Staff attendance and supervision is critical, but the availability of appropriately trained personnel is often the largest production constraint. To optimise the number of high-quality pigs weaned per sow, solutions and management strategies need to be developed to reduce the occurrence of low-viability piglets and improve their survival and growth to weaning. The findings of this review suggest that the current measures used to define low-viability piglets and the focus of management practices to improve their performance and pre-weaning survival rates require further refinement. This review has highlighted the lack of consistency of definitions for low-viability piglets used within the literature which, in turn, questions the effectiveness of a number of these research outcomes for industry applications.

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Chapter 3:

Piglet Morphology: Indicators of Neonatal Viability?

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animals

Article

Piglet Morphology: Indicators of Neonatal Viability?

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Simple summary: Early identification of poor-performing and non-viable piglets is important for effective interventions. Weight has been the consistently used indicator of likely survival in commercial production. We found that piglet survival increased with increasing abdominal circumference (girth) and crown to rump length. When a piglet was proportionately long and wide, they were more likely to be heavier at 24 h and survive until weaning, unless they were a small piglet. Small piglets that were disproportionate were more likely to survive than the proportionate small piglets, especially when they consumed more than 200 g of colostrum. We suggest that the girth and length of the piglet should be used when making production decisions for small piglets.

Abstract: The morphological measures, crown-to-rump length (CR), and abdominal circumference (AC) have been suggested to be as good, if not better, than birth weight for predicting piglet performance. We explored the relationships between CR and AC, and piglet weights at birth and 24 h, to investigate their predictive value for piglet survival. Piglet weight and AC at birth and 24 h, and CR at 24 h were recorded for 373 piglets born to 31 sows. Morphological measures were categorised into two levels for weight and three levels for AC and CR. Further, AC and CR groupings were concatenated to create a new variable (PigProp) to describe the proportionality of piglet morphology. Proportionate piglets had equal CR and AC levels, and disproportionate piglets had contrasting levels. Birth AC was a good predictor of colostrum intake ($p < 0.001$) when accounting for birth weight, but 24 h weight and PigProp were good indicators of actual colostrum intake ($p < 0.001$ for both). The significant interaction of colostrum and PigProp showed that within the smaller piglet groups, those who had greater than 200 g of colostrum had higher 24 h weight and survival ($p < 0.001$ both). As expected, as body weight and colostrum intake increased, so did weight change to d 21 (P = 0.03 and trend at $p = 0.1$, respectively). A similar pattern was seen with increasing PigProp group ($p < 0.001$); however, piglets from the disproportionate group 1,3 had the greatest observed weight change (5.15 ± 0.06 kg). Our data show morphological measures may be more predictive of piglet viability in terms of both performance and survival than weight and there may be subgroups that have higher than expected chances of survival.

Keywords: abdominal circumference; crown-to-rump length; low birthweight; piglets; pre-weaning survival; proportion

1. Introduction

Pre-weaning piglet mortality is a prevalent economic and welfare issue for the swine industry [1,2]. Despite extensive research on ways to improve the survival of piglets using genetic selection, environmental improvements, and management routines, pre-weaning mortality remains high [3–5]. Multiple factors interact to influence a piglet's ability to survive, including their birth weight, colostrum intake, and viability at birth, as well as factors inherent to the sow, such as her gestation environment and her post-partum management [2,6,7].

Selection for larger litter sizes in recent years has increased the within litter birth weight variation and, consequently, competition between littermates for colostrum in the first 24 h of life [7–11]. Furthermore, often a sow's teat number is inadequate to support such a large litter without interventions such as supplemental colostrum and (or) milk for her piglets. For these reasons, although selection for larger litter sizes has resulted in a higher number of piglets weaned per sow, it has also contributed to a greater incidence of pre-weaning mortality [12].

Piglet birth weight is a production indicator for pre-weaning growth and survival with lower birth weight piglets underperforming [9,13–15]. However, recent research has raised questions as to the utility of using only birth weight [7], which in commercial settings is usually estimated visually, as a criterion for informing management decisions such as fostering [16,17]. Other more specific measures of piglet morphology at birth could serve as potential early life indicators for pre-weaning performance and survival.

Recent studies have suggested that a piglet's morphology may be more indicative of performance [16–19] than birth weight alone. A key paper by Douglas et al. [19] found that piglet crown to rump (CR) length, abdominal circumference (AC), and body mass index are good predictors of growth performance, although they rely heavily on body weight and the age of the piglet. However, that study did not investigate if these same morphological measures could be used to indicate survival. Since that study, to our knowledge, no other paper has considered these morphological measures as indicators of performance. This is surprising as these morphological measures are used commonly in humans to estimate foetal development and childhood growth potential [20,21]. Interestingly, among other factors, human ethnicity can influence gestation day foetal and neonatal measures, such as estimated weight, long bone length, and AC, with racial/ethnic-specific measures providing greater accuracy [22]. The authors surmised that, like in humans, these morphological measures may be different across pig genetic lines and countries. The previous study was conducted in the UK where the average litter size was 13.6 piglets per litter [19,23]. This is greater than the reported Australian litter sizes of between 11.1 and 12.9 piglets per litter [24]. It is well known that with increased litter size uterine space becomes limiting and piglet variation increase [9,10]. Therefore, it is not unreasonable to assume that the morphological measures as indicators of performance and survival would be different for a herd with lower litter size. Further, the present study focuses on how morphology influences performance of different weight piglets, as opposed to across the population, in conjunction with weight in addition to its prediction of survival.

Therefore, the present study tested the suggestion that measures of neonatal piglet morphology such as AC and CR are indicative of a piglets' chance of survival to weaning under Australian commercial conditions. It was hypothesised that a longer crown to rump length indicates likely improved survival while a shorter abdominal circumference indicates a lower potential colostrum consumption and, thus, compromised survival.

2. Materials and Methods

2.1. Experimental Design

All experimental sows farrowed over a 3-d interval, having 452 live and 38 stillborn piglets in total. From the piglets born alive, 79 piglets were not considered for inclusion within the trial due to the time of birth being outside of observation hours. At farrowing, a total of 373 piglets born to 31 mixed parity sows (birth parities 2 to 9) were selected for inclusion in the study from litters that were born between 0700 h and 2000 h, for the collection of morphological measures.

Sow parity, day of farrowing, and estimated piglet birth time by visual observation were recorded. Within 5 min of birth, piglets were sexed, ear-tagged, weighed, and had their abdominal circumference (AC) recorded. The AC was determined using a standard measuring tape to an accuracy of 0.5 cm on the basis of the smallest clear measure on the measuring tape at the widest point around the piglet's trunk, posterior to the umbilicus [19]. Once AC had been measured, the piglets were placed back with their sow under a heat lamp in the creep area, and no additional assistance other than standard production protocols was provided.

At 23 to 26 h after delivery of the first piglet, all piglets were individually weighed, and their crown-rump length (CR) and AC were recorded. The CR was measured from the base of the tail to the crown of the head using the same measuring tape as for AC. The morphological measures were performed by the same technical staff for the duration of the experiment to reduce individual bias. All mortalities and removals were recorded from birth until weaning on day 21 (± 2 d). Piglets were individually weighed at weaning.

2.2. Animals and Housing

Sows were housed in groups of 40 sows per pen from mating until confirmation of pregnancy at day 28 of gestation via ultrasound, following which sows were moved to pens of 80 sows per pen equipped with electronic feeders supplying 2.5 kg/d of a standard gestation feed formulated to provide 13.8 MJ digestible energy (DE)/kg, 14.3% crude protein (CP), and 0.4% standardised ileal digestible (SID) lysine. Sows were moved into individual slatted floor farrowing crates at 110 d (± 2 d) gestation and a fed standard lactation diet, formulated to provide 15 MJ DE/kg, 16.7% protein and 0.90% SID lysine, at 3.8 kg from entry to farrowing and ad libitum from farrowing until weaning, with any spoiled feed removed daily. Sows were monitored daily for general health and welfare throughout the study. Each farrowing crate was equipped with sow and piglet level nipple drinkers, a solid floored creep area from the back to the middle side of the crate with a heat lamp positioned centrally over the creep.

All sows farrowed without induction. No sow on trial required manual assistance with farrowing as per production protocol (farrowing assistance provided if sows showed signs of distress during farrowing and or if 45 min had elapsed from birth of the last piglet with no farrowing progress evident).

Minimal fostering occurred, with stock people moving only non-tagged pigs, when necessary (within the first day), on to sows not on trial. Piglets were processed at day 4, receiving an iron injection, tail docking, and toltrazuril (Baycox®; Bayer Animal Health, Manheim, Germany) drench.

2.3. Statistical Analysis

All statistical analyses were performed using SAS version 9.4 (Statistical Analysis Software, Cary, NC, USA). The variables were categorised as follows: AC (3 levels) and CR (3 levels) at birth, and 24 h where applicable (Table 1). Weight was originally categorised into groupings of 5 levels; however, this was later modified, and the data were pooled into 2 groups on the basis of the analysis showing no differences between weight classes > 1.1 kg. The 24 h AC and CR groups were concatenated (CR level, AC level) to create a new variable grouping, Piglet Proportions (PigProp: 9 levels: Table 1), where proportionate piglets had equal CR and AC levels and disproportionate piglets had contrasting levels.

Table 1. Definition of categorised variables of interest: piglet body weight (W) and abdominal circumference (AC) at birth, and piglet body weight, crown to rump length (CR), and Piglet proportions (PigProp) at 24 h.

Morphological Measures	Birth			24 h	
	Group	**N**	**Range**	**N**	**Range**
W (kg)	1	103	0.50–1.10	86	0.50–1.10
	2	270	1.12–2.20	262	1.12–2.40
AC (cm)	1	131	16.0–22.0	145	18.0–25.0
	2	141	22.5–25.0	117	25.0–27.0
	3	101	25.5–30.0	86	27.0–32.0
CR (cm)	1	-	-	116	17.0–23.5
	2	-	-	131	24.0–26.5
	3	-	-	101	27.0–32.0
	Group	**N**		**CR group (cm)**	**AC group (cm)**
PigProp	1,1	81		17.0–23.5	18.0–25.0
	1,2	28		17.0–23.5	25.0–27.0
	1,3	7		17.0–23.5	27.0–32.0
	2,1	47		24.0–26.5	18.0–25.0
	2,2	55		24.0–26.5	25.0–27.0
	2,3	29		24.0–26.5	27.0–32.0
	3,1	17		27.0–32.0	18.0–25.0
	3,2	34		27.0–32.0	25.0–27.0
	3,3	50		27.0–32.0	27.0–32.0

Colostrum intake (CI) was calculated using the equation developed by Devillers, et al. [25]:

$$CI = -\,217.4 + 0.217 \times t + 1{,}861{,}019 \times \frac{W}{t} + BW \times \left(\frac{54.8 - 1{,}861{,}019}{t}\right) \times (0.9985 - 3.7 \times 10^{-7} \times t_{fs}^{2})$$

where CI = colostrum intake (g), W = piglet body weight at 24 h (kg), BW = piglet body weight at birth (kg), t = age (min), and t_{fs} = time elapsed from birth to first sucking (min). On the basis of Devillers, et al. [25] research, t_{fs} is assumed to be 30 min and t is 1440 min.

Colostrum intake was also categorised into 2 levels (CIc) on the basis of 200 g being the recommended minimum amount of colostrum needed to survive (level 1 includes piglets who consumed <200 g of colostrum and level 2 includes piglets who consumed ≥200g).

Correlations between measures at birth and 24 h were tested using PROC CORR with the output being the Pearson's correlation coefficient and the respective 95% confidence intervals. Correlation was considered to be very high if $r \geq 0.90$, high if $r = 0.7$ to 0.89, moderate if $r = 0.5$ to 0.69, low if $r = 0.3$ to 0.49, and negligible if $r < 0.3$ [26].

The effect of PigProp category on 24 h weights was estimated using a mixed model in PROC MIXED, as presented in Equation (1):

$$24\ weight = CIc_{\ af,bo,ls,p,\ s} \times PigProp_{af,bo,lg,ls,p,s} \tag{1}$$

where fr = farrowing room, bo = birth order, gl = gestation length, ls = litter size, p = parity, and s = sow.

The effect of birth weight category and PigProp category on weight change was estimated using a Mixed model in PROC MIXED, as presented in Equation (2):

$$Weight\ change = BWc_{af,bo,gl,p,s} + PigProp_{afbo,gl,p,s} + CIc_{afbo,gl,p,s} \tag{2}$$

where fr = farrowing room, bo = birth order, gl = gestation length, ls = litter size, p = parity, and s = sow.

The effect of birth weight and birth AC on colostrum intake was estimated using a mixed model in PROC MIXED, as follows:

Birth factors predicting colostrum intake, Equation (3):

$$Colostrum\ intake\ (g) = BWc_{af,bo,gl,p,s} + BACc_{af,bo,gl,p,s} \tag{3}$$

Twenty-four-hour factors indicating colostrum intake, Equation (4):

$$Colostrum\ intake\ (g) = 24Wc_{af,bo,gl,p,s} + PigProp_{af,bo,gl,p,s} \tag{4}$$

where fr = farrowing room, bo = birth order, gl = gestation length, ls = litter size, p = parity, and s = sow.

For all mixed models, piglet sex was tested in the preliminary model but removed as nonsignificant. The outputs were the means and their respective standard errors. Significance was assessed at the $p = 0.05$ level.

The effect of PigProp on survival from day 1 to day 21 (weaning) was estimated using a linear regression in PROC GLIMMIX as presented in Equation 5:

$$Survival = (CIc \times PigProp)_{gl,s}$$

where gl = gestation length and s = sow. Farrowing room, parity, litter size, birth order, and sex were tested in the preliminary model but were found to be not significant and as such removed from the final model. The outputs of all linear regressions were geometric means and their respective 95% confidence intervals.

3. Results

The analysed dataset included 373 piglets born alive within observation hours. The mean stillborn rate was 1.22 piglets per litter and the mean total litter size was 14.6 (±2.89) piglets per litter. Twenty-five experimental piglets died between birth and 24 h, and an additional 56 piglets died between 24 h and weaning. Therefore, the analysis included the records of 373 piglets born alive of which 348 survived to 24 h and 292 to weaning (d 21). Mean colostrum intake was estimated at 218.2 ± 167.5 g, and the mean litter size at 24 h was 11.6 ± 3.2 piglets. Descriptive of morphological measures within the dataset displayed in Table 2.

Table 2. Descriptive summary statistics (mean ± SD) of the raw dataset for piglet bodyweight, abdominal circumference (AC), and crown to rump length (CR).

Morphological Measures	Birth	24 h	d 21
N	373	348	292
W (kg)	1.33 ± 0.34	1.38 ± 0.36	6.25 ± 1.61
AC (cm)	23.59 ± 2.63	25.45 ± 2.81	-
CR (cm)	-	24.83 ± 2.98	41.34 ± 4.32

The distribution of piglets across the concatenated CR and AC groupings at 24 h showed that more piglets were born with proportionate CR and AC sizes than disproportionate (Table 1). The least likely to occur were highly disproportionate piglets with high CR and low AC (group 3,1) or low CR and high AC (group 1,3).

3.1. Correlation of Morphological Measures

All individual birth and 24 h measures were positively correlated, with a moderate to a very high degree of correlation occurring between measures (Table 3). A very high degree of correlation between birth and 24 h weight and moderate correlation between 24 h CR and AC at birth, as well as at 24 h, were observed. AC change from birth to 24 h showed mostly negligible correlations with piglet measures, except a moderate correlation with 24 h AC.

Table 3. Pearson's correlation coefficients and respective 95% confidence intervals for the relationship between morphological measures: bodyweight (BW = birth weight, W = 24 h weight), abdominal circumference (AC) at birth and 24 h, and crown to rump length (CR) at 24 h.

Measures	BW	BAC	W	24 h AC	24 h CR	CI
BAC	72.0 (66.7–76.6)	-				
W	93.6 (92.1–94.8.)	72.1 (66.6–76.8)	-			
24 h AC	77.8 (73.2–81.6)	64.6 (58.1–70.4)	81.9 (78.1–85.1)	-		
24 h CR	72.6 (67.3–77.3)	64.4 (57.8–70.1)	73.1 (67.8–77.7)	65.1 (58.6–70.8)	-	
CI	20.2 (9.9–30.0)	28.9 (18.1 –37.5)	53.4 (45.4–60.5)	41.0 (31.9–49.4)	29.0 (19.0–38.3)	-
AC change	14.5 (4.0–24.6)	−32.8 (−41.9–−23.1)	19.2 (8.90–29.1)	48.7 (40.3–56.3)	7.60 (−2.9–18.0)	18.4 (8.0–28.4)

3.2. 24 h Weight

All piglets showed increasing mean 24 h weights when they obtained greater than 200 g of colostrum, regardless of PigProp grouping, except 1,3 ($p < 0.001$; Figure 1). This difference is greatest in 1,1 piglets having significantly higher 24 h weight when they consumed more colostrum ($p < 0.001$).

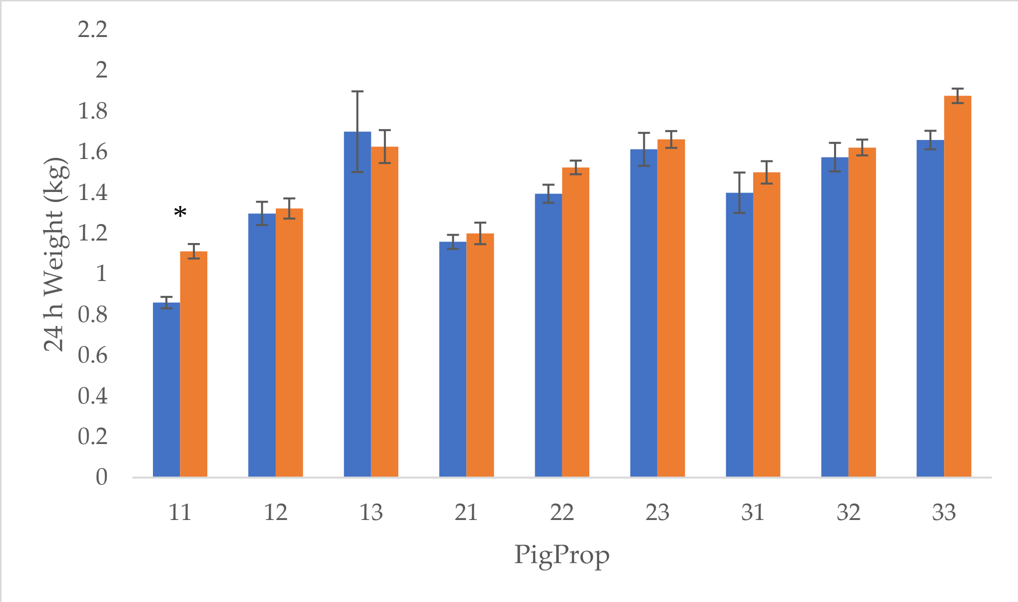

Figure 1: Mean ± standard error for 24 h weight for 348 piglet records for colostrum intake category PigProp interaction. Blue represents piglets who consumed < 200 g colostrum. Orange represents piglets who consumed ≥ 200 g colostrum. Adjusted for farrowing room, birth order, gestation length, litter size, sow, and parity. * Denotes a significant difference at $p < 0.05$ within the PigProp group.

3.3. Weight Change, 24 h to Weaning

Piglet weight change increased as birth weight and colostrum intake increased ($p = 0.03$ and 0.13, respectively; Table 4). In pigs that were from PigProp 1,1, 1,2, or 2,1, weight change was significantly lower ($p < 0.001$). Piglets from 1,3 showed the highest weight change. Piglets in group 2,2 and higher showed a weight change greater than 4.30 kg.

Table 4. Proportion and respective 95% confidence intervals of weight change from 24 h to d 21 for 348 piglets for birth weight category (BW), piglet proportions (PigProp), and colostrum intake. N = number of piglets per group. Adjusted for farrowing room, birth order, gestation length, litter size, parity, and sow.

Measure	Groups		N	Weight Change
BW (kg)		≤1.11	103	4.33 ± 0.31
		>1.12	270	4.88 ± 0.22
Colostrum intake (g)		<200	153	4.47 ± 0.27
		≥200	195	4.74 ± 0.24
PigProp	1,1	Proportionate	81	3.97 ± 0.27 [A]
	1,2	Disproportionate	28	4.14 ± 0.34 [AB]
	1,3	Disproportionate	7	5.15 ± 0.56 [BC]
	2,1	Disproportionate	47	3.93 ± 0.29 [A]
	2,2	Proportionate	55	4.79 ± 0.28 [C]
	2,3	Disproportionate	29	5.03 ± 0.34 [C]
	3,1	Disproportionate	17	4.97 ± 0.40 [C]
	3,2	Disproportionate	34	4.53 ± 0.34 [BC]
	3,3	Proportionate	50	4.91 ± 0.31 [C]

[A-C] Different superscripts indicate significant differences ($p < 0.05$) between groups.

3.4. Colostrum Intake

As birth weight and AC increased, so did the predicted potential colostrum intake ($p < 0.001$ for both; Table 5). Colostrum intake was higher in pigs with greater 24 h weight ($p < 0.001$; Table 6). As PigProp increased, so did colostrum intake, whereas, within the shortest pigs, those with larger AC consumed more colostrum (higher degree of disproportion) (Table 5 and 6).

Table 5. Mean ± standard error for predicted colostrum intake in 348 piglets. BW = birth weight category. BAC = birth abdominal circumference category. N = number of piglets per group. Adjusted for farrowing room, sow, litter size, parity, and birth order.

Measure	Groups	N	Colostrum Intake (g)
BW (kg)	≤ 1.11	86	195.7 ± 28.7
	> 1.12	262	222.5 ± 24.7
BAC (cm)	16.0–22.0	119	158.5 ± 26.6 ^{A}
	22.5–25.0	132	211.2 ± 27.0 ^{B}
	25.5–30.0	97	257.7 ± 29.5 ^{C}

$^{A\text{-}C}$ Different superscripts indicate significant differences (*p* < 0.05) between groups.

Table 6. Mean ± standard error for consumed colostrum intake in 348 piglets. W = 24-hour weight. Piglet proportions (PigProp) = concatenated crown to rump length and abdominal circumference categories at 24 h. N = number of piglets per group. Adjusted for farrowing room, birth order, litter size, sow, and parity.

Measure	Groups		N	Colostrum Intake (g)
W (kg)	≤1.11		86	148.3 ± 31.0 ^{A}
	>1.12		262	256.0 ± 23.0 ^{B}
PigProp	1,1	Proportionate	81	155.1 ± 26.7 ^{AB}
	1,2	Disproportionate	28	161.0 ± 34.5 ^{ABD}
	1,3	Disproportionate	7	281.4 ± 55.5 ^{CE}
	2,1	Disproportionate	47	104.6 ± 28.6 ^{A}
	2,2	Proportionate	55	190.5 ± 29.8 ^{BC}
	2,3	Disproportionate	29	211.0 ± 34.9 ^{BCE}
	3,1	Disproportionate	177	245.5 ± 40.1 ^{CE}
	3,2	Disproportionate	34	225.9 ± 33.9 ^{CE}
	3,3	Proportionate	50	244.5 ± 31.6 ^{E}

$^{A\text{-}E}$ Different superscripts indicate significant differences (*p* < 0.05) between groups.

3.5. Survival

Survival from 24 h to d 21 was significantly affected by the interaction between PigProp and colostrum intake (p < 0.001). When piglets consumed more than 200 g of colostrum, their survival increased substantially (Table 7). No piglets from groups 1,3 and 2,3 that consumed <200 g of colostrum died in this data set. Most improvement was observed for 1,1 piglets who consumed >200 g (p < 0.001). The mean survival also showed a similar increase for piglets in 1,2, 2,1, and 3,1 groupings when more colostrum was consumed.

Table 7. Proportion and respective 95% confidence intervals of survival rates from 24 h to d 21 for 348 piglets. Piglet proportions (PigProp) = concatenated crown to rump length and abdominal circumference categories at 24 h. N = number of piglets per group. Adjusted for farrowing room, birth order, gestation length, sow, and parity.

PigProp		CI (g)	N	% Survival
1,1	Proportionate	<200	50	48.0 (34.6–61.7)
		≥200	31	90.3 (73.9–96.9)
1,2	Disproportionate	<200	12	83.3 (52.1–95.8)
		≥200	16	87.5 (61.3–96.9)
1,3	Disproportionate	<200	1	100 (95.0–100.0)
		≥200	6	83.3 (36.7–97.7)
2,1	Disproportionate	<200	33	75.8 (58.4–87.4)
		≥200	14	100 (95.0–100)
2,2	Proportionate	<200	20	95.0 (71.6–99.3)
		≥200	35	94.3 (79.8–98.6)
2,3	Disproportionate	<200	6	100 (95.0–100)
		≥200	23	95.7 (74.6–99.4)
3,1	Disproportionate	<200	4	75.0 (23.6–96.7)
		≥200	13	84.6 (54.8–96.1)
3,2	Disproportionate	<200	8	87.5 (98.3–46.1)
		≥200	26	88.5 (69.6–96.2)
3,3	Proportionate	<200	19	94.7 (70.5–99.3)
		≥200	31	93.5 (77.5–98.4)

4. Discussion

We hypothesised that a longer CR length was associated with improved survival while a shorter AC was associated with lower potential colostrum/milk consumption, and thus compromised survival. On the basis of our data, we can partially accept our hypothesis. As overall piglet size increased (piglet proportions), so did colostrum intake and survival. Proportionate pigs showed increased survival as size increased and had less variation in survival than disproportionate pigs.

The degree of proportion or disproportion could be a better indicator for survival and performance than morphological measures alone.

4.1. Abdominal Circumference

Piglet AC had a linear relationship with body weight at both birth and 24 h, as previously documented for humans [27,28]. The high correlation observed between AC and weight may be related to successful suckling and post-natal consumption of colostrum and milk. Human infant AC was negatively correlated with time from the last feeding, which supports the linear relationship but also highlights the possible variability and low correlation with AC across time [29]. Although not measured in the present study, a similar relationship between time from feeding and AC in piglets may occur. Colostrum intake showed a negligible correlation with birth AC but an improved low correlation with 24 h AC. This correlation may improve if true time from last suckle was adjusted for. The design of this study only included those piglets born under observation, thus allowing for accurate recording at 24 h of age. Further, as the number of milk letdowns and successful suckling bouts were not recorded, the utility of these results is limited. If a strong relationship is present when true time from last suckle and or number of suckles is accounted for, AC change from birth to 24 h after birth could be used as a strong indicator for the successful consumption of sufficient colostrum [30].

Within this experiment, we assumed a 30 min interval from last suckle for each piglet and found that AC at birth when combined with birth weight was a good indicator of potential colostrum intake. These findings agree with the work of Douglas et al. [19], who showed that AC and birth weight were good predictors of performance. This is likely due to them being indicative of stomach capacity, which is greater in larger pigs allowing more milk and colostrum to be consumed at each let down [31,32]. Further, our second colostrum model supports this assumption as 24 h weight was a good measure of consumed colostrum when modelled with PigProp. As expected, when 24 h weight increased, so did colostrum intake. However, AC only influenced colostrum intake through PigProp and not individually. In light of these results, the true individual time from last suckle may have greater effect on smaller piglets.

In practice, the reproducibility of birth AC may be higher for prediction of colostrum intake than birth weight as it is unlikely to be as affected by factors difficult to account for like umbilicus (and its fluid) weight, although both measures cannot avoid influence by retained birth fluid. This could potentially distort the weight and or presumed empty stomach size; however, we assume this effect would be similar for both measures.

Although birth AC was a good indicator of potential colostrum intake, it could be significantly impacted by successful suckling and, as such, would require greater care for timing when measuring and applying in practice. AC at birth or 24 h alone did not influence survival, although its impact on colostrum intake, which does influence survival, suggests it should not be discounted as an indirect measure of survival as well as potential performance.

4.2. Crown to Rump Length

CR increased linearly with AC and weight at 24 h with a moderate correlation observed. It is commonplace in humans to use CR length during pregnancy and at birth in conjunction with AC, head circumference, and weight to gauge foetal development [20,21]. Interestingly, CR alone did not significantly influence weight, colostrum intake, or survival, contrary to our hypothesis. It was assumed that in larger litters with reduced individual uterine space, there would be greater variation in piglet size, and as a result, more piglets with shorter CR would be present and a difference would be observed. The lack of influence of CR preweaning is supported by the work of Douglas et al. [19], who found CR had no significant predictive value prior to weaning. However, our relatively small sample size may have precluded detection of a CR effect, which would explain the lack of litter impact. Unfortunately, CR was not measured at birth to reduce handling time immediately following piglet expulsion; however, it would have been interesting to compare the survival of piglets with different AC and CR at birth to those at 24 h, the former being a period of relatively higher piglet mortality [3,4].

It can be assumed that CR is not influenced by time from the last suckle, supported by its negligible correlation to colostrum intake, making it a more reproducible measure than AC and affected by less circumstantial factors. However, even in humans, CR is rarely used alone, often being combined with a waist to height ratio to diagnose foetal, infant, and childhood conditions such as growth retardation and obesity [33–35]. The previous pig morphology paper showed that CR can be used to calculate BMI, which was also a good performance indicator pre- and post-weaning. Therefore, CR is a good indicator of growth but could be a better survival indicator if combined with other morphological measures or used to calculate them.

4.3. Piglet Proportions (PigProp)

Previous studies have demonstrated that piglet body shape rather than birth weight had a greater influence on piglet performance [16,17,19], which was further expanded in this experiment for survival. The AC alone could be significantly affected by colostrum and (or) milk intake, while CR is not influenced by colostrum intake, which is critical to survival outcomes.

When considered together (i.e., PigProp), an interesting pattern of distribution across the groupings and survival was apparent. Proportionate piglets, being those that had the same grouped CR and AC (1,1; 2,2; 3,3 as defined in Table 1), occurred more frequently (53%) than the disproportionate groupings, with the greatest number being the smallest piglets. It is important to note that disproportion did not occur due to feeding and colostrum intake but was an important factor in determining survival. It could be suggested that the level of disproportion is an indicator of uterine growth performance such as intrauterine growth restriction (IUGR), which is well known to impact piglet viability at birth [18]. This is supported by the knowledge that as IUGR severity increases, CR decreases; however, it is not known if this effect remains when it is considered relative to AC.

Within the population, 12% of piglets were extremely disproportionate (1,3 and 3,1), resulting in a high error in the analysis. Therefore, we are unable to confidently determine what impact being highly disproportionate has on survival in comparison to more proportionate pigs. However, the remaining disproportionate piglets showed that having a slightly larger AC or CR can improve survival significantly in smaller pigs. As hypothesised, the smallest proportional piglets survived significantly less than did the other proportionate piglets and the disproportionate piglets. Although the influence of PigProp on colostrum intake was known, the survival difference within the smallest piglet grouping when more than 200 g of colostrum was consumed was greater than expected. Although subjective, we observed visually that differentiating between these slightly disproportionate piglets at 24 h was very difficult, lending support to the suggestion that accurate measuring of piglets at birth is valuable in determining viability.

As AC category increased within the same CR grouping, colostrum intake increased. A similar pattern was observed for increasing CR length but was not as definitive. Surprisingly, the piglets from 1,3 had the highest colostrum intake of all PigProp groupings, similar to the largest piglets. Bootstrapping was applied to test if this would remain true in a theoretical larger population, and this was supported. The authors suggest that this may have been due to these piglets having a disproportionately larger stomach capacity, and being able to obtain a full stomach early on provided them greater energy to outcompete their similar-sized poor-performing littermates. However, as stated above, the number of suckling bouts or a controlled allocation/administration of fluids was not tested in this study, and therefore relation to stomach capacity cannot be confirmed. Regardless, PigProp at 24 h may be used as an indirect measure of colostrum intake and continual feeding of the piglet.

The smallest proportionate piglets showed similar weight change to the disproportionate piglets of groups 1,2 and 2,1, and piglets from groups 1,3 showed similar weights to piglets from groupings 2,2 and greater. From these data, we can infer that within visually smaller piglet groupings usually designated as poor performers and survivors, there are piglets that have survival and growth rates similar to those of larger piglets. It would be interesting to further investigate a larger population on the basis of these findings to determine if within the smallest grouping (1,1), there are characteristics which can define the poorest performers once again without having to estimate or monitor colostrum intake. Surprisingly none of the models or the morphological measures showed influence of sex on survival, which is the same as in humans but contrary to previous research in pigs [36,37]. Sex has been shown to influence a piglet's chance of survival, with males tending to die from being overlain by the sow more than do females [37]. This sex effect was not evident in our study, although the suggested sex effect may be influenced more by the sex ratio of the litter rather than sex per se, as suggested by Seyfang et al. [38]. A larger investigation into morphological measures involving sex within litter effects would provide further evidence of the applicability of AC and CR as a tool for predicting survival and growth.

Although there is a standard growth chart for humans that is based on recurring measures or multiple measure types, there is not one for pigs, and it is known that there is a large variation in height and weight in humans due to race [39]. Although speculative, a similar degree of variation may exist between pig breeds for these morphological measures [21]. It is beyond the scope of this study to compare this; however, in comparison to studies from other countries, our mean CR and AC were smaller. Our mean CR and AC were similar to the means reported in light-weight pigs (AC = 23.3 ± 1.52 cm and CR = 24.0 ± 1.91) in the study by Douglas et al. [19]. However, we are unable to determine if this was due to uterine capacity as litter size was not reported. Despite this, another study did report greater mean CR (28 ± 0.26 cm) than our study, despite having higher mean litter size (16 ± 1.17) [40]. It is reasonable to assume that longer piglets need more space and thus with greater litter size, the capacity to reach this would be reduced. The disparity between our and other studies' findings further strengthen the argument that the variation seen between human races is replicated in pigs. Our findings support the hypothesis that not all small pigs will die, as even within the smallest poor-performing piglet group, there are still piglets that if they obtained sufficient colostrum can survive to weaning without additional intervention.

5. Conclusion

Current management decisions are based on the abundance of literature supporting the strong relationship between birth weight and pre-weaning growth and survival. Low birth weight piglets are treated as a uniform group assumed to underperform without additional intervention. The present study suggests that there may be more indicators of the potential risk to small piglets than just their weight, and that there may be subgroups that have higher than expected chances of survival. Disproportionately small piglets (either CR or AC one category higher than the other) show a much higher likelihood of survival than proportionally small piglets. However, these findings may be somewhat limited by the sample size as the effect for piglets greatly disproportionate (AC and CR in opposing extreme categories) could not be determined as they were born much less frequently. This strengthens the argument posed by previous research that birthweight alone may not be sufficient for an indication of performance and survival and novel measures such as AC and CR may be useful to assist with management decisions for post-natal piglet management when used in concert.

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Institutional Review Board Statement: This experiment was performed from June to August 2019 at a commercial piggery in Corowa, New South Wales, Australia, with the approval of the Rivalea Australia Animal Ethics Committee (protocol no. 19B014) under production conditions. All procedures were carried out according to The Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council, 2013).

Data Availability Statement : The data presented in this study are available on reasonable request from the corresponding author.

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Chapter 4:

Increasing feeding frequency prior to farrowing: effects on sow performance

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Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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i. the candidate's stated contribution to the publication is accurate (as detailed above);
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Increased feeding frequency prior to farrowing: effects on sow performance

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Abstract: Reducing the interval between the consumption of her last meal and the start of farrowing is suggested to increase the energy available to sows during farrowing, potentially reducing farrowing duration and easing piglet births. The present study aimed to examine whether increasing feeding frequency from one to two feeds within standard production hours (0700 to 1500) would produce a difference in farrowing duration and/or stillborn numbers. From entry to farrowing crates (110 ±1d gestation) to farrowing (116 ±1d gestation), multiparous sows (n = 118) were fed a daily fixed amount of feed either once at 0800 h or in two meals at 0800 h and 1300 h. Sow weights and backfat depths were recorded on entry and exit from the farrowing crate. Litter size and weight were recorded at 24 h after farrowing and at d 21 of lactation. Sows fed twice had shorter farrowing durations and fewer stillborn piglets than those fed once (2.21 ± 0.56 h vs 3.25 ± 0.52 h; $P = 0.001$). The interaction between treatment and farrowing duration showed that sows fed twice having a reduced farrowing duration had significantly lower stillborn rates than those fed once or those fed twice with longer farrowing durations ($P < 0.001$). These findings suggest that increasing feeding frequency prior to farrow can reduce farrowing duration and stillborn numbers in some sows, however, some sows remain with a high stillborn rate regardless of feeding frequency. Piglet average daily gain was greater in once-fed sows, but fewer of these sows remained in the herd at subsequent farrowing. Further, subsequent total born and born alive were higher in twice-fed sows. Feeding sows at a higher frequency can improve farrowing performance in some sows and could increase the longevity of the sow in the herd.

Keywords: Farrowing duration; Feeding frequency; Stillborn; Sow

Abbreviations:

SID, standardised ileal digestible
DE, digestible energy
EM, estimated marginal

Introduction:

Selection for larger litter sizes has resulted in a renewed focus on management strategies to prepare the sow for a faster farrowing to optimise born alive and piglet pre-weaning survival. A common problem associated with larger litters is a longer farrowing duration, which may result from an energy deficit in the sow and/or complications during the expulsion process (Manu et al., 2017; Manu et al., 2019). The relationship between a prolonged farrowing duration and increase stillbirth rate or reduce neonatal viability are well known (van Dijk et al., 2005; Oliviero et al., 2010; Langendijk et al., 2018). Arguably, stillbirth of piglets is one of the largest contributors to reduced litter size weaned and thus reduced production returns.

Gestation and lactation feeding strategies have been the focus of much nutritional research and management decisions (Campos et al., 2012). The transition period from gestation to lactation (7 d before to 7 d after farrowing) has recently been highlighted as an important phase for determining farrowing performance (Theil et al., 2011; Langendijk and Fleuren, 2018; Pedersen et al., 2020; Feyera et al., 2021). Increasing feeding frequency to transition sows resulted in a reduced time from last feed to farrowing and, in those sows having feed-to-farrow intervals less than 3.1 h, also higher arterial blood glucose concentrations and reduced farrowing durations (Feyera et al., 2018). In contrast, Gourley et al. (2020) found no reduction in farrowing duration or stillborn rate with increased prepartum feeding frequency. It is likely that geographic location, environmental conditions, genetics, and other management practices may have impacted the results of these studies, thus questioning how effective reducing time from feeding to farrowing is across different farms. Further, the difference between the two studies was suggested by Gourley et al. (2020) to be due to the sows of Feyera et al. (2018) having a higher mean farrowing duration and total born in their study population.

Gourley et al. (2020) fed their sows at 0100, 0700, 1300 and 1900 h. However, most farms are not set up or staffed to deliver feed at these times, especially when sows are required to be hand-fed. Therefore, our study was designed to test two feeding frequencies within a standard commercial production system with full staffing between the hours of 0700 and 1500 to determine whether a difference in farrowing duration and/or stillborn numbers occurred and, thus, be useful for farming practices. We hypothesized that increasing feeding frequency in the transition period before farrowing would reduce farrowing duration and number of piglets stillborn.

Materials and Methods:

This experiment was conducted under commercial conditions at Corowa, NSW, Australia, during August to September. The experiment was approved by the Rivalea Pty Ltd. Animal Care and Ethics Committee (Protocol 19B014) in accordance with the Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council, 2013).

Animals and Experimental Design

At entry to the farrowing house, 118 mixed parity (1 to 8) Large White x Landrace sows were allocated to a dietary treatment of either one feed at 0800 h, or two feeds at 0800 h and 1300 h, given each day until farrowing commenced. All feeds were provided before farrowing via hand feeding by one of two trained stock people. Sows were allocated to their treatment based on P2 backfat depth and parity at entry to the farrowing house, balanced across treatment groups. A daily allocation of 3.8 kg of a commercial lactation feed (Table 1) was provided to both treatment groups (as one feed or split as two 1.9 kg feeds).

For all sows that farrowed, number of piglets born alive and stillborn were recorded. A subset of sows (n = 33) who completed farrowing during extended staffed hours of 0700 h and 2000 h were recorded for farrowing duration measured from birth of first and last piglets. The day following completion of farrowing, gestation length, litter size, and litter weight (of live piglets) were recorded for each sow. Minimal fostering was permitted to standardize litter size to available functional teat number and the new litter size was recorded. Litter weight and litter size were recorded on d 21 of lactation for all litters, just prior to weaning. All sows were weighed and backfat depths recorded at weaning.

Housing and Management

Sows were moved into the farrowing house at d 110 (± 2 d) of gestation and their litters weaned at d 21 (± 2 d) of lactation. Prior to entry sows were weighed and backfat depth at the P2 position was obtained using an ultrasound machine and probe. Sows were individually housed in traditional slatted floor farrowing crates, each having a solid floored creep area with an infrared heat lamp for the piglets. Sows were monitored daily for general health and welfare throughout the farrowing house period. For this study, upon their due date sows were monitored for 13 h daily for onset of farrowing or farrowing difficulty. All sows farrowed naturally without exogenous hormonal induction. Farrowing assistance was provided if the sow showed signs of distress during farrowing and/or if 45 min had elapsed from the birth of the last piglet with no farrowing progress evident (Cowart, 2007). A piglet was considered live born if movement and/or breathing was detected following expulsion. During lactation, sows were fed to appetite the lactation diet as per standard production lactation management on this farm. After weaning, sows returned to the normal production system and subsequent reproductive data were collected from electronic farm data records.

Table 1: Composition of Lactation diet.

Item	% Of fed basis
Wheat	57.00
Barley	10.00
Mill Mix	6.70
Canola Meal, 38% CP	10.00
Meat Meal, 58% CP	3.33
Soybean Meal, 46%	2.5
Fish oil	0.40
Tallow	6.00
Betaine	0.40
Limestone	1.00
Magnesium sulphate	0.4
Potassium chloride	0.2
Lysine micro	0.43
Threonine micro	0.13
Tryptophan micro	0.04
Sows replace pak micro	0.2
Repro blend micro	0.05
Vitamin and mineral premix	0.47
Enzymes[1]	0.02
Antioxidant [2]	0.04
Phytase[3]	0.01
Yeast product[4]	0.01
Insoluble fibre[5]	0.67
Calculated composition:	
DE, MJ/kg	14.93
Crude Protein, %	16.04
Crude Fat, %	7.40
Crude Fibre, %	4.07
Ash, %	5.36
Available SID Lysine, %	1.01
Calcium, %	0.90
Phosphorus, %	0.98

[1]Commercial product Rovabio®Max (Adisseo, Antony, France). [2] Commercial product Endox™ Dry (Kemin Industries, Des Moines, Iowa, USA). [3] Commercial product Quantum Blue® (AB Vista, Marlborough, Uk). [4]Commercial products Proternative® 10 Titan (Lallemand Animal Nutrition, Australia). [5]Arbocel® (Rettenmaier & Söhne, Rosenberg, Germany).

Statistical Analysis

All statistical analyses were performed using SAS version 9.4 (Statistical Analysis Software, Cary, NC, USA). The data were analysed as two data sets: Subset (observed sows) = 33 sows observed to be farrowing during staffed hours; Main data set = 99 sows provided treatment within the 2 experimental sheds. For the statistical analyses, all data sets were bootstrapped at a root of 8 using PROC SURVEYSELECT subset = 164 sow observations and main data set = 509 sow observations for the analyses. The accuracy of the data was testing using PROC MEANS with all means of the bootstrapped data being similar to the original data to at least the second decimal point. Prior to the analyses, some data were manipulated:

- Farrowing durations were allocated to two categories based on results by Feyera et al. (2018); farrowing duration ≤ 3.47 = FD 1; farrowing duration > 3.47 FD 2.
- Total born was categorised into three levels; ls 1 = 7-9 piglets; ls 2 = 10-14 piglets; and ls 3 ≥ 15 piglets.
- P2 backfat change was categorised into three groupings; BF 1 < - 6 mm; BF 2 = – 6 to – 0.1 mm; BF 3 ≥ 0.1
- Sow weight at entry and change during lactation were corrected for estimated weight of conceptus using the equation by NRC (2012);

$$Weight\ of\ conceptus = \frac{[exp(8.621 - 21.02\ x\ exp(-0.053\ x\ gestaion, d) + 0.114\ x\ total\ born, n)]}{1000}$$

- Weight change was categorised into 4 groupings; Wt 1 < -13.68 kg; Wt 2 – 13.68 to – 6.07 kg; Wt 3 – 6.08 to 2.55 kg; and Wt 4 > 2.55 kg.
- Piglet birth weights were categorised into 4 groups; pbw 1 < 1.41 kg; pbw 2 1.41 to 1.59 kg; pbw 3 1.59 to 1.76 kg; pbw 4 > 1.76 kg.

The effect of treatment, litter size, days from entry to farrow and parity on farrowing duration were estimated using a mixed model in PROC MIXED for the subset, as presented in equation 1:

$$Farrowing\ duration = treatment_{p2,s} + litter\ size_{p2,s} + days\ from\ entry\ to\ farrow_{p2,s} + parity_{p2,s} \tag{5}$$

where p2 = p2 backfat at entry; s = room. The preliminary model also tested the effects of previous total born but it was found to be not significant (P > 0.1) and so excluded from the final model. The outputs of the model were least square means, their respective standard errors and difference between least square means. The level of significance was set at P < 0.05.

The effect of treatment, farrowing duration, litter size, days from entry to farrow and parity on stillborn number were estimated using a mixed model in PROC MIXED for subset and the main data set (where variables are applicable), as presented in equation 2:

$$Stillborn = treatment_{p2,s} + farrowing\ duration_{p2,s} + litter\ size_{p2,s} + days\ from\ entry\ to\ farrow_{p2,s} + parity_{p2,s} + (treatment * farrowing\ duration)_{p2,s} \quad (2)$$

where p2 = p2 backfat at entry; s = room. The preliminary model also tested the effects of previous total born but it was found to be not significant (P > 0.1) and was excluded from the final model. The outputs of the model were least square means, their respective standard errors and difference between least square means. The level of significance was set at P < 0.05.

The effect of treatment, sow P2 backfat and piglet birth weight category on average piglet weight gain were estimated using a mixed model in PROC MIXED for the main data set, as presented in equation 3:

$$Average\ piglet\ gain/day = treatment_{d,l,p,p2,s} + piglet\ birth\ weight\ category_{d,l,p,p2,s} \quad (3)$$

were d = days from entry to farrow, l = litter size, p = parity, p2 = sow backfat at entry and s = room. The preliminary model also tested the effect of previous litter size but was found to be not significant (P > 0.1) and so excluded from the final model. The outputs of the model were least square means, their respective standard errors and difference between least square means. The level of significance was set at P < 0.05.

The effect of treatment, litter size and weight change on P2 backfat change and weight change were estimated using a mixed model in PROC MIXED for the main data as presented in equations 4 and 5:

$$P2\ backfat\ change = treatment_{ap,p,p2,s} + litter\ size_{ap,p,p2,s} + weight\ change_{ap,p,p2,s} \quad (4)$$

$$Weight\ change = treatment_{ap,,p,p2,s} + litter\ size_{ap,p,p2,s} + P2\ backfat\ change_{ap,,p,p2,s} \quad (5)$$

where ap = average piglet weight change; p = parity; p2 = p2 backfat at entry; s = room. The preliminary model also tested the effects of previous total born, days from entry to farrow and farrowing duration, but these were found to be not significant (P > 0.1) and were excluded from the final model. The outputs of the model were least square means, their respective standard errors and difference between least square means. The level of significance was set at P < 0.05.

The effects of treatment, days from entry to farrow, litter size, average piglet weight change, parity, and weight change on subsequent wean to oestrus period, total born and born alive were estimated using a mixed model in PROC MIXED for the main data set, as seen in equations 5 to 7.

$$\begin{aligned} Wean\ to\ oestrus &= treatment_{fd,s} \\ &+ days\ from\ entry\ to\ farrow_{fd,s} + litter\ size_{fd,s} \\ &+ average\ piglet\ weight\ change_{fd,s} + weight\ change_{fd,s} + parity_{fd,s} \end{aligned} \tag{5}$$

$$\begin{aligned} Subsequent\ total\ born &= treatment_{fd,s} \\ &+ days\ from\ entry\ to\ farrow_{fd,s} + litter\ size_{fd,s} \\ &+ average\ piglet\ weight\ change_{fd,s} + weight\ change_{fd,s} + parity_{fd,s} \end{aligned} \tag{6}$$

$$\begin{aligned} Subsequent\ born\ alive &= treatment_{fd,s} \\ &+ days\ from\ entry\ to\ farrow_{fd,s} + litter\ size_{fd,s} \\ &+ average\ piglet\ weight\ change_{fd,s} + weight\ change_{fd,s} + parity_{fd,s} \end{aligned} \tag{7}$$

where fd = farrowing duration; s = room. The preliminary model also tested the effects of previous total born but it was found to be not significant ($P > 0.1$) and so excluded from the final model. The outputs of the model were least square means, their respective standard errors and difference between least square means. The level of significance was set at $P < 0.05$.

Chi-squared test in PROC FREQ was used to determine the number of sows removed from each treatment group in subsequent mating.

Results:

A summary of data set raw mean values are presented in Table 2.

Table 2: Mean ± standard deviation for raw dataset.

	N	Mean
Parity	118	3.3 ± 1.9
Days from entry to farrow	118	8.7 ± 1.4
P2 entry (mm)	113	21.2 ± 5.3
P2 backfat exit (mm)	112	17.3 ± 4.8
P2 backfat change (mm)	110	-3.9 ± 3.0
Weight entry (kg)	112	262.6 ± 25.3
Weight exit (kg)	112	256.0 ± 28.5
Weight change (kg)	112	-6.06 ± 13.7
Average piglet weight change (kg)	113	1.5 ± 0.4
Stillborn (%)	118	7.4 ± 7.4
Born alive (%)	118	92.6 ± 18.1
Litter size (born alive + stillborn)	118	14.9 ± 2.7
Farrowing duration (h)	33	4.02 ± 1.8
24 h Litter size	118	12.9 ± 2.1

24 h litter size is the post fostering litter size.

Farrowing data

Farrowing duration was reduced with increased feeding frequency (P < 0.001; Figure 1). Further, as litter size increased so did farrowing duration (P < 0.001; ls1 = 1.6 ± 0.86 h; ls2 = 2.8 ± 0.51 h; ls3 = 3.7 ± 0.44 h). As days from entry to farrowing increased from 6 to 9 d so did farrowing duration but, at 10 d, farrowing duration decreased (9 d 4.58 ± 0.7 h vs 10 d 2.53 ± 0.36 h; P < 0.001).

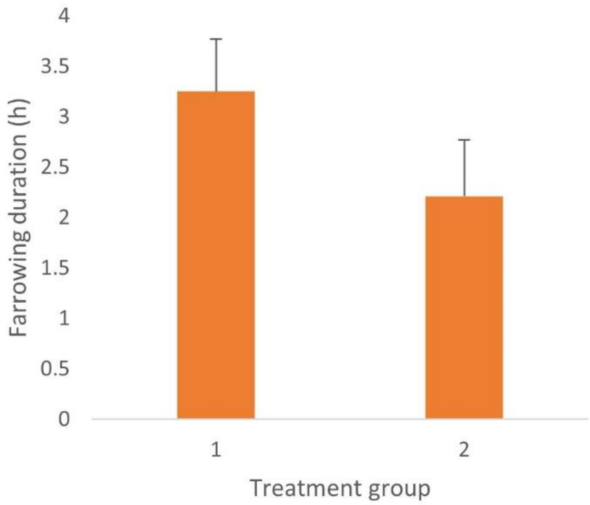

Figure 1: Means ± standard error of farrowing duration by treatment group for 33 sows bootstrapped at a root of 8 (164 sow observations). Treatment 1 = one feed per day. Treatment 2 = two feeds per day. Accounting for sow backfat at entry and room in the model.

Increased feeding frequency was associated with decreased stillborn in the subset of sows where farrowing duration was observed (*P* = 0.004; Figure 2). However, in the main dataset the reverse was true (*P* < 0.001). In both data sets, sows who spent 6 d from entry to farrow had higher stillborn numbers (subset = 2.68 ± 0.57 and the main data = 1.01 ± 0.33) than sows who spent longer prior to farrowing (subset 8 d, 0.59 ± 0.47; main data 8 d, 0.50 ± 0.23; *P* < 0.001). Sows with smaller litter sizes had lower stillbirth rates (*P* < 0.001).

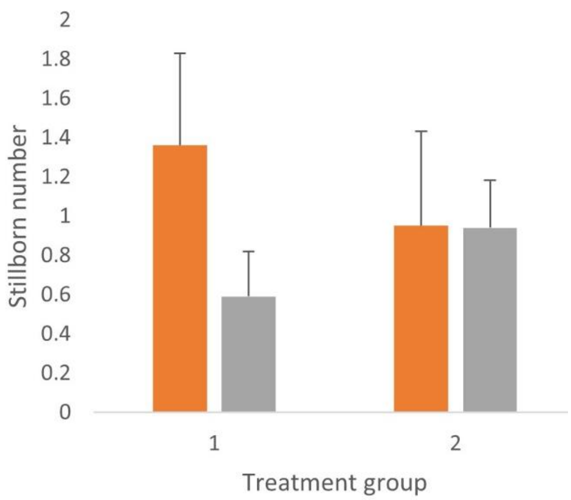

Figure 2: Mean ± standard error of stillborn number by treatment group two data sets bootstrapped at a root of 8; Orange = 33 sows whose farrowings were observed (164 sow observations) and Grey = 118 sows on trial (509 sow observations). Treatment 1 = one feed per day. Treatment 2 = two feeds per day. Accounting for sow backfat and room in the model.

Within the observed sows, the interaction of treatment and farrowing duration was shown to have an effect on stillbirths (P < 0.001). Sows fed twice with shorter farrowing durations had fewer stillborn than those fed once with shorter farrowing durations (Figure 3). However, sows with longer farrowing durations did not differ in stillborn numbers regardless of feeding frequency.

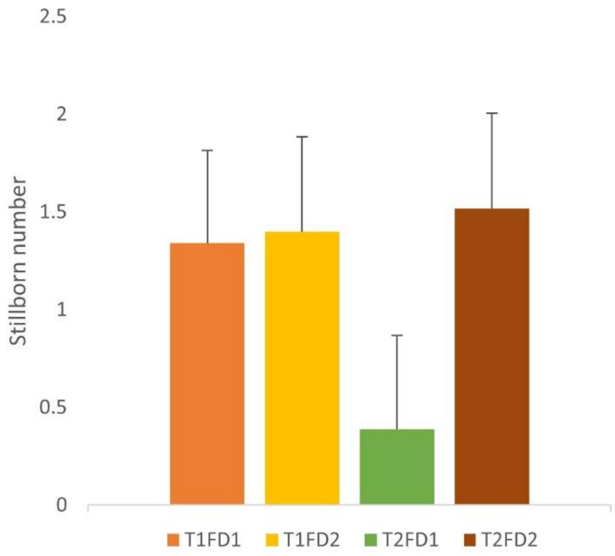

Figure 3: Mean ± standard error of stillborn number by the feeding treatment and farrowing duration for 33 sows bootstrapped at root of 8 (164 sow observations). Treatment 1 = one feed per day. Treatment 2 = two feeds per day. Farrowing duration 1, > 3.47 h. Farrowing duration 2, > 3.47 h. Accounting for sow backfat and room in the model.

Lactation

Average daily gain was increased in piglets from sows fed once per day compared to those from sows fed twice (Table 3).

Sows fed once per day lost more P2 backfat (0.56 ± 0.79 mm) than sows fed twice per day (0.02 ± 0.83; $P = 0.03$). However, the opposite was true for weight change, with twice-fed sows losing more weight to weaning than once-fed sows (1.31 ± 3.66 kg vs. 7.67 ± 3.73 kg; $P < 0.001$).

Table 1: Mean ± SE for average piglet lactation weight change by treatment, piglet birth weight and sow entry backfat depth for all trial sows, 509 sow observations after bootstrapping. Treatment one, one feed per day. Treatment two, two feeds per day. Piglet birth weight (Wt) 1 <1.41 kg; Wt 2 1.41 to 1.59 kg; Wt 3, 1.59 to 1.76 kg; Wt 4, > 1.76 kg.

		N	Average piglet weight change
Treatment	1	292	4.98 ± 0.24
	2	217	4.80 ± 0.25
Piglet birthweight	1	122	4.87 ± 0.25 [a]
	2	130	5.18 ± 0.25
	3	130	4.82 ± 0.25 [ab]
	4	127	4.66 ± 0.25 [b]

a-b denotes significance within piglet birth weight categories. Accounting for sow days from entry to farrowing, litter size, parity, sow backfat at entry and room in the model.

Subsequent reproduction

The wean to oestrus period was not significantly different between single or twice fed sows (9.97 ± 0.74 d and 9.23 ± 0.91 d; $P = 0.23$). As days from entry to farrow increased so did subsequent wean to oestrus interval (5 d, 4.8 ± 1.04 d; 7 d, 10.5 ± 1.20 d; $P < 0.001$).

The percentage of sows culled from the herd, based on subsequent farrowing, was higher in those from once-fed than twice-fed populations (25.4 % vs 15.6 %).

Subsequent total born was higher ($P < 0.001$) in twice-fed than once-fed sows (15.0 ± 0.50 vs. 16.3 ± 0.57), as was subsequent born alive (13.7 ± 0.34 vs. 14.4 ± 0.41; $P = 0.001$).

Discussion:

The current study showed a biologically relevant reduction in farrowing duration when the transition sow feeding frequency was increased from one to two feeds per day, supporting the suggestion that the sows fed only once may have begun to suffer from an energy deficit thus extending their farrowing duration (Pedersen et al., 2016; Feyera et al., 2018). The presence of this difference regardless of a higher total born occurring in twice-fed sows further strengthens this argument as larger litters would be expected to increase farrowing duration (van Dijk et al., 2005; Oliviero et al., 2010). Monitoring farrowing durations accurately both within and outside of normal staffed hours is a constraint on determining the effectiveness of management feeding strategies. Currently, few commercially available monitoring technologies exist for recording and reporting farrowing duration in production. Therefore, determining the benefit of increasing feeding frequency on an individual farm basis relies heavily on changes in stillborn numbers.

Stillborn number decreased in the subset of observed sows who received two feeds per day but not in the full dataset of sows. Sows in the full data set include sows that farrowed outside of observation hours thus, while speculative, it is possible that the lack of supervision resulted in a failure to intervene in unobserved dystocia with a resultant increased stillbirth. It is also important to note that these sows started farrowing later in the day and thus there would have been a prolonged period between their last feed and onset of farrowing. Based on the subset of data and previous research (Feyera et al., 2018; Gourley et al., 2020; Ju et al., 2021) it is possible that these sows had longer farrowing durations and associated increased stillborn. Interestingly, when the interaction of treatment and farrowing duration is considered in the subset, it was seen that two feeds did decrease stillborn rate in shorter farrowing sows. However, there was a proportion of sows that maintained a higher farrowing duration and thus stillborn number regardless of feeding frequency. This suggests that there is a proportion of sows which can have improved farrowing performance and stillborn number through feeding frequency management but there are other factors influencing farrowing duration and stillborn rate which are not affected by feeding frequency.

It is accepted that litter size, litter birth weight variation, and stillborn number all increase with increasing parity (Damgaard et al., 2003; Quesnel et al., 2008; Wientjes et al., 2012). Further, as litter size increases so does the total energy required by the sow to expel the piglets during farrowing (Oliveira et al., 2020). In contrast to previous studies, the mean litter size in our study was relatively small, suggesting that other factors may have influenced farrowing duration and/or the feed-to-farrow interval. It is well known that feeding strategies in previous lactations and gestation can impact lifetime performance, specifically sow condition and embryo quality (Bunter et al., 2006; Rozeboom, 2014). In the present study, although entry parity, backfat depth and body weight were used to allocate sows to treatment there was a large variation in backfat across the population. Feeding and management strategies are usually applied across the herd to maintain consistent condition and performance outcomes. However, as seen in the current study, variation does occur both in condition and performance of sows when a standard feeding strategy is used. Interestingly, Thongkhuy et al. (2020) suggested that backfat thickness at entry to the farrowing house does not impact farrowing duration but does influence stillborn number. The highest backfat score recorded prior to entry in their study was 24 mm which is at least 10 mm less than the highest recorded in the current study. Therefore, it is possible that sows with a higher backfat thickness at entry to the farrowing house could show a different effect on farrowing ease and output (Thongkhuy, et al., 2020).

Backfat depth has also been shown to impact glucose tolerance in sows, with higher values resulting in lower glucose tolerance (Cheng et al., 2020). Although not investigated in this study, sows with increased backfat depths may have benefited more from increased feeding frequency, by enhancing glucose tolerance as a result of distributing the nutrient load across the day. Prior to and during farrowing, glucose is critical for uterine contractions and colostrum synthesis. However, once the dietary glucose has been metabolised the sow must rely on stored energy to maintain her energy status (Serena et al., 2009; Feyera et al., 2018; Feyera et al., 2019). This is consistent with the literature reporting that decreasing time from last meal to onset of farrowing can reduce stillborn number (Feyera et al., 2018; Manu et al., 2019). This raises the suggestion that specific feeding regimes, such as increasing feeding frequency, could be used to tailor transition diets to the sow's needs to optimise her farrowing and post-farrowing performance.

Sows fed once had higher average piglet gains and backfat loss than sows fed twice, while sows fed twice lost more weight. This would suggest that once fed sows had better lactational performance than twice fed. However, the piglet average weight gain was similar for both treatment groups by commercial standards (Brandt, 1998; Collins et al., 2017). Therefore, this difference is not outstanding or concerning. Surprisingly, more twice fed sows were retained in the herd at subsequent mating and had higher subsequent total born and born alive than once fed sows. This suggests that although their current lactational performance was not as good as once fed sows, their longevity was improved. As an economic benefit to the producer this is of high value and could benefit long term reproductive outputs. It should be acknowledged that there are many management and external factors which impact lactational performance and subsequent reproduction, such as previous and subsequent feeding regimes, and as such the sow transitional feeding management should be considered in context.

The present study focused on increasing feeding frequency to better distribute the energy available to the sow across the day under production conditions. Previous studies suggested that increasing feeding frequency to at least three times per day would result in a clearer difference in farrowing duration and lactation performance (Feyera et al., 2018; Manu et al., 2019). A different approach to increasing energy available would be comparing increased feeding frequency to increased feed allowance. This would explore the effects of different total feed intake prior to farrowing and the time between feed and farrow. Gourley et al. (2020) found that four smaller meals per day, compared to one large meal, increased piglet weight gain from 24 h but when sows were fed ad libitum prior to farrowing, weight gain was further improved. Although speculative, the lack of greater differences between one and two feeds per day in our study may be due to the feeding frequency not being increased enough, even though it would be impractical for many producers to accommodate more than this level of hand feeding. Further to this, anecdotal observations suggested that the sows receiving one feed often stood and vocalised when the second feeding occurred for the twice fed sows. It could be suggested that the sows associated the stockperson pushing a cart with receiving food and when not in receipt of food became distressed and/or restless. This increase in activity without receiving the energy from a second feed may have further been detrimental there to energy reserves for farrowing (van Kempen, 2007; Feyera and Theil, 2017; Feyera et al., 2018). To minimise the impact of stockperson movements and association with food, whilst increasing the ability of production to implement greater feeding frequencies, an automated feeding system would be recommended. However, as the benefits of increasing feeding frequency to reduce farrowing duration are still not in strong agreement in the literature, the authors hesitate to suggest this to producers until further research is conducted.

The sample size of the subset of sows for farrowing duration observations was small, due to limitations of only being able to observe the sows in daylight hours which may limit the interpretation of these results. Despite this, the clear observation of a difference in farrowing duration suggests that more research into reducing the feed to farrowing interval is warranted. Although accounted for in all relevant statistical models, the occurrence of higher total born in sows receiving two feeds per day may obscure the effectiveness of increasing feeding frequency in this experiment. This is a universal problem for all pre-farrow management experiments as an accurate prediction of total born piglets is practically impossible prior to farrowing under production conditions.

Increasing feeding frequency as a management tool is constrained by production capabilities. However, it could be useful for herds with larger litters or those prone to longer farrowings. Having two feeding sessions per day may provide an economic benefit (e.g., sow longevity and piglet numbers) to a producer if their sows exhibit a long farrowing duration and larger litter size. An alternative approach would be ad libitum feeding or automatic feeding systems capable of delivering multiple small feeds per day. Ad libitum would allow sows to self-satisfy their appetite and potentially benefit low backfat sows, but could increase the labour required to provide this (Cools et al., 2014). Automation would allow more control for later feeding sessions, specifically overnight, however the cost of set up and maintenance may be impractical for some producers and could also potentially reduce the observation/pick up of sow issues due to less monitoring.

Conclusions:

The outcomes of this study show that increasing feeding frequency may reduce the duration of farrowing, and potentially energy demand, but not stillborn rate in a herd with short farrowing durations and smaller litter sizes. Feeding two times per day in late gestation did not improve sow body condition loss in lactation or reproductive output of sows compared to feeding once per day. Increasing feeding frequency should be considered for a system better designed to deliver feeding more accurately and automatically than does hand feeding. As litter sizes continue to increase, the applicability of research in transitional sow management and priority for production appropriate outcomes is becoming more evident. Future research should priorities effective monitoring technologies for accurate determination of the effects of sow transitional management changes on farrowing duration and stillborn numbers.

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Chapter 5:

Associations between surface and rectal temperature profiles, body weight, and pre-weaning survival in low-birth-weight piglets

Submitted to Livestock Science

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Contribution to the Paper	Conceptiualization, Methodology, Investigation, Writing, reviewing and editing		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
Signature		Date	18/05/2022

Co-Author Contributions

By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);
ii. permission is granted for the candidate in include the publication in the thesis; and
iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Associations between surface and rectal temperature profiles, body weight, and pre-weaning survival in low-birth-weight piglets

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Abstract: Rectal temperature is the gold standard for monitoring piglet body temperature but the requirement for piglet handling could potentially cause stress. The use of infrared cameras to record surface temperature has shown some promise in older pigs for detecting temperature changes but neonatal piglets are metabolically less mature and experience rapid temperature changes during their first 24 h. This experiment compared rectal temperature to surface temperature measured using an infrared camera for piglets of different body weights and colostrum intakes. During farrowing, 48 multiparous sows were monitored, and their piglet rectal and surface temperatures recorded for lower birthweight (≤ 1.2 kg) piglets. Temperatures were also recorded at 0.25, 0.50, 0.75, 1, 1.25, 1.50, 2, 3, 4 and 24 h, and piglets were re-weighed at 24 h. Piglet birthweights were assigned to one of three categories (BWC); BWC1 (≤ 0.80 kg), BWC2 (0.81 to 1.10 kg), and BWC3 (1.11 to 1.20 kg). Piglet colostrum intakes were calculated and categorised as either low (≤ 200 g) or normal (> 200 g), and piglet rectal temperatures at 1.25 h after birth were assigned to one of three categories; RC1 (≤ 32.0 ⁰C), RC2 (32.1 to 35.0 ⁰C), and RC3 (≥ 35.1 ⁰C). Rectal and surface temperatures were moderately correlated across all BWC and colostrum intakes. No BWC1 piglets obtained 200 g of colostrum by 24 h. At 1.25 h, BWC1 piglets reached a higher percentage of surface and rectal temperature agreeance than BWC2 or BWC3 piglets (BWC1 = 52.4% of piglets, BWC2 = 31.0% and BWC3 = 20.7%). However, this agreeance was not sustained to 24 h and fluctuated over time. The BWC3 piglets reached higher overall agreeance (89.1%; 84.4 – 92.5) but all piglet surface and rectal temperature agreeance dropped by 24 h (BWC1, 33.5%, BWC2, 55.1% and BWC3, 63.3%). At 9 d, fewer BWC1 piglets survived (25%) compared to BWC2 and BWC3 piglets (79 -100%). For BWC1 piglets, as their rectal temperatures at 1.25 h increased from RC1 to RC2, so did their survival (16.7 to 43.9%), while no association was detected with surface temperature. Although surface temperatures showed a similar recovery pattern to rectal temperatures within the first 24 h across all piglet birth weights, the decrease in correlation and agreeance at 24 h questions whether surface temperature would be an appropriate replacement for rectal temperature for use in commercial production.

Keywords: Temperature agreeance; Infrared thermal camera; low birth weight; Temperature recovery

1. Introduction:

Piglets are born wet and into an environment that is significantly cooler than their *in-utero* environment (38 – 40 °C: Kammersgaard et al., 2011; Andersen and Pedersen, 2016) and piglets experience a dramatic reduction in body temperature during the first 15 – 90 min from birth (Caldara et al., 2014; Vande Pol et al., 2020; Villanueva-Garcíaa et al., 2021). The average temperature recovery time from birth exceeds 4 h, a time during which it is critical for piglets to actively seek teats and consume sufficient colostrum to obtain energy for thermoregulation and acquire passive immunity (Xu et al., 2000; Rooke and Bland, 2002; Theil et al., 2014). In addition to inadequate passive immunity, failure to obtain adequate colostrum may result in hypoglycaemia and chilling, which can predispose them to be overlain by their sows (Edwards, 2002; Pandolfi et al., 2017).

The ability of a piglet to thermoregulate is related to its weight (Caldara et al., 2014) as smaller piglets have a greater surface area to volume ratio than heavier piglets and thus a proportionately greater heat loss. In consequence, heavier piglets experience a less severe postnatal drop in temperature than do smaller piglets (Cooper et al., 2019). Other factors, such as the parturition process, can impact piglet thermoregulatory ability. For example, piglets may be disadvantaged by a long expulsion phase resulting in hypoxia and decreased energy reserves (Feyera et al., 2018; Gourley et al., 2020). As piglets are born with little adipose tissue and no brown fat, they have a limited energy supply to thermoregulate (Herpin et al., 2002). To reduce the amount of energy mobilized to thermoregulate it is critical that piglets have an optimal environment. Farrowing house ambient temperatures are invariably below the piglet lower critical temperature and so piglets must rely on the use of additional heat sources or interventions to assist in regulating their temperature. Previous studies have tested a variety of interventions with varying effects on temperature change and (or) subsequent survival, such as energy supplements, drying and a warm saline injection (Andersen and Pedersen, 2016; Declerck et al., 2016; Moreira et al., 2020; Vande Pol et al., 2021; Tucker et al., 2022). Rectal temperature is the gold standard used across these studies as it is an internal temperature affected minimally by external factors and thus is reliable. However, repetitive rectal thermometer readings to monitor temperature changes and to identify critical periods for the piglets is an invasive process which can become stressful for the piglet and requires substantial piglet manipulation to measure temperature accurately. This manipulation usually requires removal from the crate environment or restraint resulting in exposure to different environmental temperatures, handling stress, and potential loss of suckling time. Recently, more research into the use of infrared cameras for the monitoring of piglet thermal status has been published (Kammersgaard et al., 2013; Schmid et al., 2021; Zakari et al., 2021). Automatic systems generating whole image analysis would be useful to monitor piglet thermal change, but handheld machines are more practical and easily employed in practice. There is evidence that rectal and surface temperatures show similar diurnal trends and that surface temperatures interact with piglet age and growth rate (Zakari et al., 2021). Interestingly, the use of an aural thermometer has shown high correlation with rectal temperature but also requires restraint so offers little benefits beyond that of rectal thermometers (Schmid et al., 2021).

Schmid et al. (2021) showed that a variety of different infrared thermometers and cameras can indicate core temperature but are affected by factors such as distance from the animal. In that study, the best target for the infrared camera was at the inner thigh and abdomen but this too required manipulation of the piglet. To minimise piglet handling, the aims of the present experiment were to compare rectal temperatures to surface temperatures measured using an infrared thermal camera at the base of the ear, of piglets with different body weights and colostrum intakes, and associations with colostrum intake and early piglet survival to determine if rectal and surface temperature could predict performance outcomes and survival. We hypothesised that rectal temperature would be highly impacted by body weight and colostrum intake and that surface temperature would be less sensitive to these factors.

2. Methods:

This experiment was conducted during September and October at a commercial piggery in southern New South Wales, Australia, and was approved by the local Animal Care and Ethics Committee (Protocol 20R027) in accordance with the Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council, 2013).

2.1 Housing and Management

Multiparous Large White X Landrace sows (mean parity 3.4 ± 1.2) were moved into their farrowing accommodations at approximately 110 d (± 2 d) of gestation, being housed in individual farrowing crates equipped with sow and piglet level nipple drinkers and a heat lamp positioned centrally over one side (creep area). The sows were fed 2.5 kg/day of a standard lactation diet formulated to provide 15 MJ DE/kg, 16.7% protein and 0.90% SID lysine from entry into the farrowing house until farrowing (116 ±1.5 d gestation). Once farrowed, sows were fed to-appetite via hand feeding twice per day until weaning (21 ± 2d of lactation).

All sows farrowed naturally without any intervention from stock people. Farrowing observations and measurements were conducted daily from 0600 h to 1900 h. At 4 d, piglets received an iron injection and a toltrazuril drench (Baycox, Elanco, Macquarie Park, NSW, Australia) and were tail docked with cauterisation.

2.2. Experimental Design

Piglets weighing < 1.2 kg at birth, born during normal working hours over a 3-d farrowing period were included on trial. Based on these constraints, 67 piglets born to 48 sows (parity 3.4 ± 1.2; litter size 14.3 ± 1.9 piglets; 36 female and 31 male) were included in the experiment. Within 3 min of birth (0 h), piglet surface and rectal temperatures were recorded after they were moved into a semi enclosed container positioned over a scale and were individually ear tagged, weighed, and sex recorded. Surface temperature was measured at the base of the right ear using a FLIR E8-XT thermal camera (Teledyne FLIR, Wilsonville, Oregon, USA) held approximately 30 cm from the piglet (using a generic ruler) and an emissivity value of 0.98 was pre-set in the camera (Soerensen et al., 2014). Surface and rectal temperatures were recorded at 0, 0.25, 0.50, 0.75, 1, 1.25, 1.5, 2, 3, 4 and 24 h. Piglets were weighed again at 24 h and percent piglet survival was recorded at 9 d of age. Colostrum intake (CI) was estimated using the equation developed by Devillers et al. (2004):

$$\mathrm{CI} = -217.4 + 0.217 * \mathrm{t} + 1861019 * \frac{\mathrm{BW}}{t} + \mathrm{BWb} * \left(\frac{54.8 - 1861019)}{t}\right) * (0.9985 - 3.7 * 10^{-7} * \mathrm{t}_{fs}^{2})$$

where CI = colostrum intake (g), BW = piglet body weight at 24 h (kg), BWb = piglet body weight at birth (kg), t = age (min) and t_{fs} = time elapsed from birth to first sucking (min) with t_{fs} and t assumed to be 30 min and 1,440 min, respectively.

2.3. Statistical Analysis

All statistical analyses were performed using SAS version 9.4 (Statistical Analysis Software, Cary, NC, USA). There were 737 piglet-related data point observations available for analysis. After bootstrapping the data at a root of 24 possibilities per piglet ID, 11,196 piglet observations were available for analysis. Some data were manipulated prior to analysis:

Piglet birth weights were assigned to one of three categories; BWC1 (≤ 0.80 kg), BWC2 (0.81 kg to 1.10 kg), and BWC3 (1.11 to 1.20 kg);

Piglet rectal temperatures at 1.25 h after birth were assigned to one of three categories; RC1 (≤ 32.0 ^{0}C), RC2 (32.1 ^{0}C to 35.0 ^{0}C), and RC3 (> 35.0 ^{0}C);

Piglet surface temperatures at 1.25 h after birth were assigned to one of three categories; SC1 (≤ 30.4 ^{0}C), RC2 (30.6 ^{0}C to 32.5 ^{0}C), and RC3 (> 32.0 ^{0}C);

Piglet colostrum intake was assigned to one of two categories, low (≤ 200 g) or normal (> 200 g);

Surface and rectal temperatures at moderately to highly correlated time-points were used to create a new binomial variable ('temperature agreeance'); 1 if surface temperature was within 2 °C of rectal temperature and 0 if it fell outside of 2 °C.

The correlation between the rectal and surface temperatures across bodyweight categories and colostrum intake categories were estimated using PROC CORR with the output being the Pearson correlation coefficient (r^2) and the respective 95% confidence intervals. Further, the correlations between rectal and surface temperatures at time points 0, 0.25, 0.50, 0.75, 1, 1.25, 1.50, 2, 3, 4 and 24 h were estimated. Correlation was deemed very high if $r^2 \geq 0.90$, high if r^2 between 0.70 and 0.89, moderate if r^2 between 0.50 and 0.69, low if r^2 between 0.30 and 0.49 and negligible if $r^2 < 0.30$ (Hue et al., 2021). The level of significance for analysis was set at $p <$ 0.05.

The effects of the birth weight, time relative to birth and the interaction of birth weight and time relative to birth on the rectal and surface temperatures of piglets were estimated using a mixed model in PROC MIXED, as presented in Equation 1:

Equation 1: $temperature = birth\ weight\ category_{fr,ls,p,s} + time\ related\ to\ birth_{fr,ls,p,s} + colostrum\ intake\ category_{fr,ls,p,s} + (birth\ weight\ category * \ time\ related\ to\ birth)_{fr,ls,p,s}$

where fr = farrowing room; ls = litter size; p = sow parity and s = sow. The preliminary model also tested the effects of piglet sex, but it was found to be not significant as a confounder and was removed from the final model. The outputs of the model were least-square means, their respective standard errors, and differences between least-square means.

The effects of sow parity, room, litter size, BW and piglet sex were tested using a linear regression in PROC GLIMMIX to determine their effect on surface and rectal temperature agreeance. The model is presented in Equation 2:

Equation 2: $temperature\ agreeance = birth\ weight_{ls,p,s} + time + (birth\ weight * \ time)_{ls,p,s}$

where ls = litter size; p = sow parity; s = sow. The preliminary model also tested the effects of piglet sex, but it was found to be not significant as a confounding factor. The outputs of the model were least-square means, their respective standard errors, and their difference between least-square means and their respective 95% confidence intervals.

The effects of birth weight, time relative to birth, piglet sex, and the interaction of birth weight and time relative to birth on survival to 9 d were estimated using linear regression in PROC GLIMMIX as presented in Equation 3:

Equation 3: $survival = (birth\ weight\ category * colostrum\ intake\ category)_{fr,ls}$

where *fr* = farrowing room and *ls*= litter size. The preliminary model also tested the effects of sow and sow parity, but these were found to be not significant as confounders. The outputs of the model were the geometric means and their respective 95% confidence intervals.

The effect of the interaction of birth weight category and colostrum intake with rectal temperature category on survival to 9 d were estimated using linear regression in PROC GLIMMIX, as presented in Equation 4:

Equation 4: $survival = (RC * colostrum\ intake\ category * birth\ weight\ category)$ or

$$survival = (SC * colostrum\ intake\ category * birth\ weight\ category)$$

where RC= rectal temperature category and SC= surface temperature category. The outputs of the model were the geometric means and their respective 95% confidence intervals of the proportion that survived.

3. Results:

3.1 Relationships Between Rectal and Surface Temperature

Rectal and surface temperatures showed a moderate correlation of 68.7% (67.7 – 69.7). The correlations within BWC were all moderate: BWC1 = 71.4% (69.0 – 73.5), BWC2 = 68.8% (67.4 – 70.0) and BWC3 = 64.5% (62.2 – 66.6). The correlations within colostrum intake category were also moderate; low = 69.4 % (68.2 – 70.6) and normal = 61.8 % (59.8 – 63.7).

Surface temperatures showed a positive increase with bodyweight across time, but the pattern was more variable (Figure 1a). Heavier piglets had higher rectal temperatures from 0.25 h to 24 h (Figure 1b). Compared to piglets consuming ≤ 200 g colostrum, piglets who consumed more than 200 g of colostrum had higher rectal temperatures at 1.25 h (32.2 ± 0.51 °C vs 31.6 ± 0.51 °C; $p < 0.001$) and surface temperatures (34.5 ± 0.34 °C vs 34.5 ± 0.33 °C; $p < 0.001$).

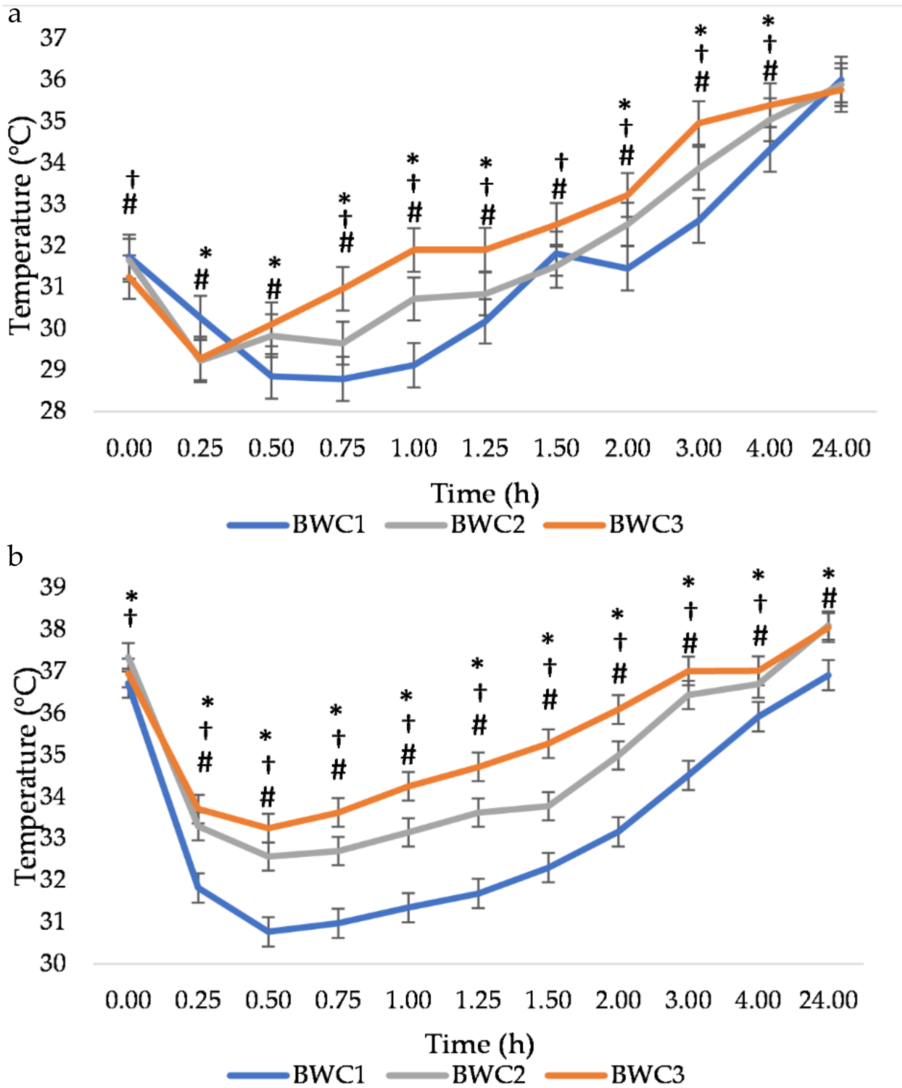

Figure 1: Mean ± Standard Error for the piglet temperature; Figure 1a: Surface temperature and Figure 1b: Rectal temperature across body weight category (BWC), adjusted for the effect of the sow, parity, litter size and farrowing room, in 11196 piglet observations. BWC1; ≤0.8kg. BWC2; between 0.81kg – 1.1kg. BWC3: between 1.11-1.2kg. Significant difference at $p < 0.05$. * Indicates difference between BWC1 and BWC2. † Indicates difference between BWC2 and BWC3. # Indicates difference between BWC1 and BWC3.

At times 0 and 0.25 h post-birth, piglet surface and rectal temperatures had a negligible correlation. From time 0.5 to 3 h after birth, correlations were moderate to high and at 4 h, low to moderate. At 24 h, the correlation of piglet rectal and surface temperatures was once again negligible (Figure 2).

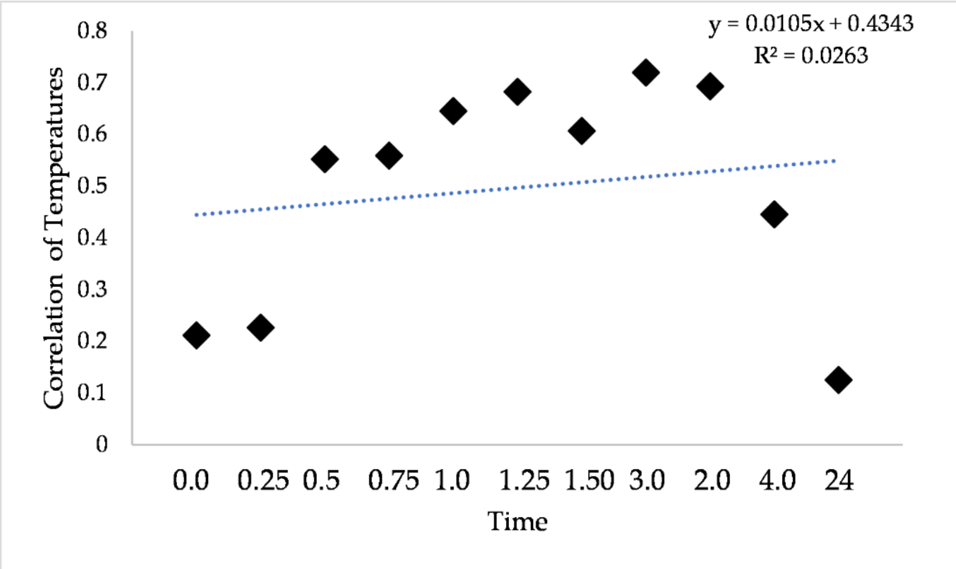

Figure 2: Pearson's correlation coefficient for the relationship between rectal and surface temperature in 11,196 piglet observations across time points.

3.2 Agreeance of Surface and Rectal Temperature

The number of piglets whose surface temperature was within 2 °C of their rectal temperature (in agreeance) was influenced by the interaction between body weight and colostrum intake ($p < 0.001$; Table 1). No piglets from BWC1 obtained > 200 g of colostrum. For BWC2 and BWC3, as colostrum intake increased the proportion of piglets with temperature agreeance increased, although not significantly.

Table 1: Proportion and 95% Confidence intervals of piglets with surface and rectal temperatures that were within 2 °C, for 11196 piglet observations. Colostrum intake; Low; ≤ 200 g colostrum. Normal > 200 g colostrum. Birth weight category BWC1 < 0.8 kg birth weight; BWC2 between 0.8 and 1.1 kg; and BWC3 between 1.1 and 1.2 kg. Corrected for litter size.

		Colostrum intake	
		Low	Normal
Body weight (kg)	1	47.0 (40.9 – 53.2)	-
	2	40.5 (34.9 – 46.4)	48.2 (42.0 – 54.3)
	3	47.4 (40.8 – 54.2)	56.7 (50.4 – 62.7)

Overall, surface and rectal temperatures were more likely to be within 2 °C of each other as piglets got older ($p < 0.001$). At time 0, piglets from all BWC had low levels of agreeance between surface and rectal temperature (Figure 3). At 0.25 h, BWC1 piglets reached a higher ($p < 0.001$) agreeance than the other BWC piglets. From 0.5 h onwards, the agreeance across BWC did not change. At 3 h, BWC1 and BWC3 piglets had higher ($p < 0.001$) agreeance than BWC2. At 24 h, the proportion of agreeance was lower ($p < 0.001$) in BWC1 piglets.

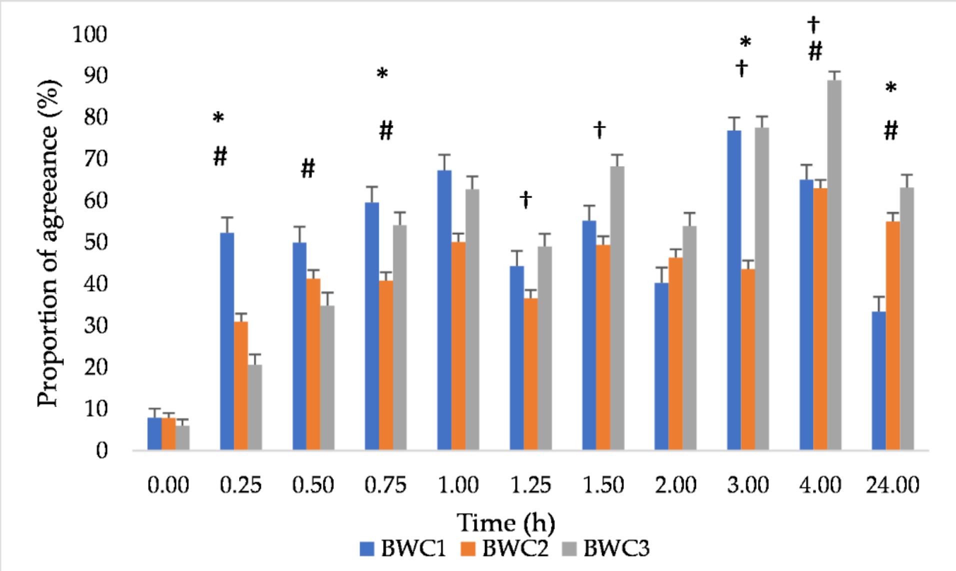

Figure 3: Proportion and 95% confidence intervals for surface and rectal temperature agreeance within 2°C for 11,196 piglet observations for the interaction of time (h) and birth weight categories (BWC). BWC1; < 0.8 kg. BWC2; 0.8 and 1.1 kg. BWC3; between 1.11 and 1.2 kg. Corrected for litter size. * Indicates difference between BWC1 and BWC2 within time point. † Indicates difference between BWC2 and BWC3 within time point. # Indicates difference between BWC1 and BWC3 within time point.

3.3 Overall Survival

No piglets from BWC1 obtained > 200g of colostrum (Table 3 and 4). Further, only 25% of BWC1 piglets survived to 9 d. In both BWC2 and BWC3, piglet survival increased with increased colostrum intake ($p < 0.001$; Table 2).

Table 2: Proportion and respective 95% confidence intervals of survival rates to 9 d for 1,029 piglet observations by birth weight category, time and the interaction between birthweight and time. BWC1 ≤ 0.80 kg; BWC2 0.81 kg to 1.10 kg; BWC3 1.11 kg to 1.2 kg. Colostrum intake; Low ≤ 200 g, Normal > 200 g. N = number of observations

Parameter			Colostrum intake	
			Low	Normal
		N	663	366
Body weight (kg)	1	187	25.0 (18.0 – 33.3)	-
	2	579	88.0 (85.0 – 91.0)	100 (95.0 – 100.0)
	3	263	79.0 (69.0 – 87.2)	82.0 (76.0 – 87.1)

3.4 Survival and Rectal and Surface Temperatures

The lightest piglets (BWC1) were only represented in low and medium rectal temperature categories (RC1 and RC2), and, within this group of piglets, as rectal temperature increased above 32°C so did their survival (Table 4). Further, within all rectal temperature categories, as colostrum intake increased so did their survival. An exception to this was BWC3 / RC2 piglets where no piglets died when colostrum intakes were less than 200 g.

Table 3: Proportion and respective 95% confidence intervals of survival rates to 9 d for 1,029 piglet observations by rectal (RC) and surface (SC) temperature categories at 1.25 h post birth. RC1 ≤ 32.0 0C; RC2 32.1 0C to 35.0 0C; RC ≥ 35.1 0C. SC1 ≤ 30.4 0C; SC2 30.6 0C to 32.5 0C; SC=3 ≥ 32.6 0C. Birthweight category (BWC)1 ≤ 0.80 kg; BWC2 0.81 kg to 1.10 kg; BWC3 1.10 to 1.2 kg. Colostrum intake: Low ≤ 200 g; Normal > 200 g. N = number of observations.

			RC1			SC1	
			Colostrum intake			Colostrum intake	
			Low	Normal		Low	Normal
		N	294	67	N	269	41
BWC	1	110	16.7 (10.4 – 25.7)	-	77	2.3 (0.8 – 7.5)	-
	2	203	91.6 (86.2 – 95.0)	100 (95.0 – 100.0)	208	93.2 (89.0 – 95.9)	100 (95.0 – 100.0)
	3	48	100 (95.0 – 100.0)	100 (95.0 – 100.0)	27	100 (95.0 – 100.0)	100 (95.0 – 100.0)
			RC2			SC2	
			Colostrum intake			Colostrum intake	
			Low	Normal		Low	Normal
			190	87		248	123
BWC	1	77	43.9 (29.1 – 59.9)	-	81	66.7 (55.1 – 76.6)	-
	2	141	87.8 (79.8 – 92.9)	100 (95.0 – 100.0)	182	100 (95.0 – 100.0)	100 (95.0 – 100.0)
	3	59	100 (95.0 – 100.0)	61.4 (45.7 – 75.0)	108	100 (95.0 – 100.0)	77.9 (67.0 – 86.0)
			RC3			SC3	
			Colostrum intake			Colostrum intake	
			Low	Normal		Low	Normal
			145	212		146	202
BWC	1	-	-	-	29	55.2 (36.7 – 72.3)	-
	2	217	80.5 (70.2 – 87.9)	100 (95.0 – 100.0)	191	67.1 (55.7 – 76.7)	100 (95.0 – 100.0)
	3	140	50.0 (32.7 – 67.3)	85.2 (77.1 – 90.8)	128	50.0 (32.9 – 67.5)	83.3 (74.4 -89.6)

4. Discussion:

From our data, Pearson's correlation analysis suggested that surface (at the base of the ear) and rectal temperature of piglets in the postpartum period are only moderately correlated. This is at odds with previous research that suggested the base of the ear is one of the best thermal windows with a high correlation between surface and rectal temperature (Tabuaciri et al., 2012; Soerensen and Pedersen, 2015). A thermal window is a skin/surface area which is well perfused by blood and as a result is a good 'window" to the core body temperature (Soerensen and Pedersen, 2015). However, previous studies using infrared thermal technology in pigs have largely focussed on older pigs that have established thermoregulation and greater fat deposits (Reviewed by Soerensen and Pedersen, 2015). Small piglets have little natural insulation, a higher surface area to volume ratio and limited energy reserves to assist in thermoregulation compared to their heavier born counterparts (Herpin et al., 2002;

Kammersgaard et al., 2011). Furthermore, piglets are born wet, moving from a temperature regulated *in utero* environment of approximately 39°C to an external environment significantly cooler (Muns et al., 2016). Therefore, previously validated methods of measuring surface temperature using infrared thermal technology for older pigs may not be as applicable to neonatal piglets

Birth weight significantly influenced the rectal and surface temperature profiles of piglets during the first 24 h of life. Further, rectal temperature, colostrum intake and birthweight interacted to influence survival. None of the smallest piglets (BWC1) obtained > 200g of colostrum and these piglets also did not have rectal temperatures above 35°C at 1.25 h. However, if they did have higher temperatures, albeit < 35 °C, their rate of survival increased. Survival was impacted by a colostrum intake and body weight interaction and, therefore, our hypothesis is supported in that small piglets need intervention to increase their colostrum intake and accelerate temperature recovery to improve their survival.

Overall, our data support previous reports which showed that smaller piglets are less likely to consume sufficient colostrum and have lower survival (Hales et al., 2013; Caldara et al., 2014; Douglas et al., 2016; Tucker et al., 2022). A relationship between temperature (and hypothermia) and birth weight has been established, as has a relationship between birth weight and colostrum intake on preweaning survival (Kammersgaard et al., 2011). However, whilst intuitive, the three-way interaction between body temperature, birth weight and colostrum intake on survival has not, to our knowledge, been documented. That the effect might have been different if temperatures were measured at a different time cannot be discounted, but we rationalised that by 1.25 h any prenatal influence of the sow should have worn off as the piglet would have dried and sucked. Also, by 1.25 h, thermoregulation should be functioning better and thus the piglets on the upwards curve of temperature recovery, as previously documented (Caldara et al., 2014; Vande Pol et al., 2020).

Piglets from BWC1 consumed insufficient colostrum and had rectal temperatures in categories RC1 and RC2. We speculate that if smaller piglets receive enough colostrum, they will have sufficient energy to better thermoregulate and thus would have been represented in RC3. Compared to BWC2 piglets, the BWC3 piglets had lower survival at 9 days post-birth, regardless of colostrum intake. Although this contrasts with previously reported data (Caldara et al., 2014), our study only used piglets having birth weights up to 1.2 kg. Accepting that classifying piglets as light or heavy can be very subjective, so our heavier pigs were simply relatively heavier but not heavy by commercial standards (e.g., 1.4 kg). The negative association with survival may have been exacerbated by these relatively heavier piglets having a higher maintenance energy requirement (Le Dividich et al., 2005).

Similar to previous research, piglet temperature had decreased by 0.25 h from birth, although the start of recovery was evident from 0.5 h, rather than 1 h as previously documented (Caldara et al., 2014). This was followed by a gradual increase to 24 h. This difference in recovery patterns presumably reflects the farrowing environments including, but not limited to, ambient temperatures, heating management and piglet drying (Caldara et al., 2014). The difference between the rectal and surface temperature recovery curves highlights the influence that external factors have on surface temperature. It is known that smaller piglets have a greater surface area to volume ratio and, therefore, presumably lose heat more rapidly and would be affected quickly by environmental changes.

Our results showed that rectal and surface temperatures measured in the first 15 min post-birth are not well correlated. It is likely that surface temperature is highly affected by the piglets being wet upon birth and the marked difference between *in utero* and environmental temperatures (Herpin et al., 2002; Vande Pol et al., 2021). This is supported by the increasing correlation as time increased to 4 h after birth. However, at 24 h the correlation was once again negligible, indeed lower than that observed at birth. The effect of the piglets being wet could be mitigated or reduced by rubbing or the use of heat lamps or collective litter body heat (Herpin et al., 2002; Vande Pol et al., 2021). These methods would all work to increase surface temperature but not necessarily core temperature, thus the correlation between rectal and surface temperatures would be questionable and therefore infrared cameras are not useful at this time for temperature measures shortly after birth.

It is established that piglets are born with only enough energy to sustain them for the first 24 h of life, thus colostrum and/or milk intake is critical (Devillers et al., 2011; Theil et al., 2011). We surmise that at 24 h there are piglets with depleted energy reserves that did not consume sufficient colostrum and/or milk and, therefore, could no longer efficiently maintain thermoregulation (Charneca et al., 2010; Villanueva-Garcíaa et al., 2021). This suggestion is strengthened by the absence of any lightweight piglets obtaining sufficient colostrum likely having a considerable influence on this low correlation. However, the lack of correlation between surface and rectal temperatures at these times raise questions as to whether surface temperature is a suitable method for predicting piglet performance.

When examined by birth weight category, BWC1 piglets showed a shorter time interval from birth to increased surface and rectal temperature agreeance. Smaller piglets have a higher surface area to volume ratio explaining how heat loss would be quicker and thus internal and external temperature are likely to be more similar than observed for larger piglets (Caldara et al., 2014). However, BWC3 piglets maintained a higher level of temperature agreeance once achieved, while the BWC1 piglets showed a decreased temperature agreeance at 24 h, further supporting the suggestion of low energy reserves mentioned above.

Our results showed that when RC and SC are compared within the survival model, RC showed greater difference in survival between BWC and colostrum intake groupings, further illustrating the limitations of surface temperature determinations.

Other studies which have focused on the use of infrared thermal technology in piglets have concluded that this technology has potential to be an effective tool, albeit not identical to rectal temperature (Kammersgaard et al., 2013). The present authors agree that the use of surface temperature readings in place of rectal temperatures would be a less invasive and disruptive to monitor thermoregulation. It is also well known that there are many factors which affect the surface texture using infrared technology, such as angle of camera, background light, ambient temperature, humidity, and stress (Magnani et al., 2011; Zhang et al., 2016). One major challenge of recording surface temperatures is the manipulation of the piglet required to obtain an accurate reading. The most effective method is to pick up the piglet and manoeuvre it so that exact and repeatable measures can be recorded. However, in doing so, the piglet is exposed to different environmental conditions within the crate and triggers stress which has been shown to have a substantial impact on thermal window temperature readings, in addition to using energy from their limited supply (Tuchscherer et al., 2000; Magnani et al., 2011; Vinkers et al., 2013). These challenges and our results suggest that the use of a hand-held infrared camera is impractical for direct application for producers. However, with increasing interest in machine learning and automation in pig production, there is potential for further research and application in this area (Lu et al., 2018).

5. Conclusions:

Surface temperature measured via infrared thermal camera technology was less effective than rectal temperature at predicting survival to day 9 but can be used to indicate relative temperature recovery over the first 24 h of a piglets' life when taken repetitively. Colostrum intake, birth weight, and temperature are all directly related to survival and should be considered together when monitoring piglets. Further research into different methods of surface temperature recording and the practicality of using surface temperature in commercial production systems which are less controlled than in research, are required.

Declaration of Interest: none

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Chapter 6:

Using a handheld infrared camera to assess potential for thermal windows to substitute for rectal thermometers in monitoring post-natal piglet temperature

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Using a handheld infrared camera to assess potential for surface temperature to substitute for rectal thermometers in monitoring piglet post-natal temperature

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Abstract:

This study examined piglet surface temperatures using an infrared thermal camera (pointer), verified by the maximum temperature extracted by an algorithm from the thermal images, at the base, tip of ear or eye locations, compared to rectal temperature. The influence of piglet bodyweight (BWC1; ≤0.80 kg, BWC2; 0.81 kg to 1.10 kg and BWC3; >1.10 kg), time post-partum (0 and 24 h), and colostrum intake (CI1; <200 g and CI2, ≥200 g) were investigated. Ear tip temperatures showed low correlations with rectal temperature ($r^2 < 0.39$). Both the ear base and eye had moderate correlations ($r^2 = 0.53$ and 0.55) to rectal temperature, and high correlation between pointer and extracted values ($r^2 = 0.73$ and 0.82, respectively). Eye pointer temperatures showed moderate correlation ($r^2 = 0.50$) at birth and negligible correlation at 24 h ($r^2 = 0.14$). Eye extracted temperatures showed low (0 h; $r^2 = 0.42$) or negligible correlations (24 h; $r^2 = 0.21$). The extracted values for eye, but not rectal or ear base, temperatures were higher ($P = 0.01$) in piglets consuming greater amounts of colostrum. Surface temperatures were only moderately comparable to rectal temperatures, thus not appropriate for commercial application.

Keywords: Birth weight, Colostrum intake, Piglet, Rectal temperature, Surface temperature, Correlation

1. Introduction:

Body temperature is an important indicator of pig welfare and performance, and an appropriate temperature is critical for neonatal piglets as they establish thermoregulation (reviewed by Tucker et al., 2021). The non-invasive use of infrared cameras to record piglet body temperature is a growing area of research and of interest across multiple production animal species (Soerensen and Pedersen, 2015). Non-contact temperature recording can potentially eliminate the stress often caused by other more invasive methods such as the measurement of rectal temperature, which may also result in the transfer of bacteria and other pathogens to the animal (Godyn and Herbut, 2017). Currently, it is necessary to restrain neonatal animals to obtain their temperature rectally, which is the gold standard for measuring body temperature of young animals (Dewulf et al., 2003). Restraint can cause stress at a critical time for the neonate which can influence the validity of the temperature recorded leading to inaccurate interpretation of temperature changes (Magnani et al., 2011; Godyn and Herbut, 2017). Further, obtaining body temperature using rectal thermometers can be stressful, potentially traumatic and interruptive to suckling, thus potentially disadvantaging the piglets. It has been suggested that infrared thermal technology could be used in pigs to detect surface temperatures (Shao and Xin, 2008; Brown-Brandl et al., 2013; Zhang et al., 2019; Jorquera-Chavez et al., 2021). If applicable, this technology could be used on farm to detect at risk, lower viability piglets early for appropriate and timely intervention. A risk threshold similar to that suggested with rectal temperature (< 32°C at 1.5 h post birth; Tucker et al., unpublished data) could be established for surface temperature and be applied across production systems. However, most studies testing infrared thermal technologies have been performed with older pigs that have established thermoregulation and under different environmental conditions (Magnani et al., 2011). Further, most experiments have been conducted under tightly controlled environmental conditions which are not comparable to those of commercial production and, therefore, further studies are required to validate the use of this technology in commercial conditions and their applicability to the pork industry.

Previously, Chung et al. (2010) suggested that infrared thermometry was a suitable alternative to rectal temperature under the conditions of a germ-free facility with no handling of experimental piglets, while others have also supported the utility of infrared thermometry but in a climate-controlled chamber (Mostaço et al., 2015). Under conditions more representative of commercial production, Schmid et al. (2021) found that infrared ear thermometry could be used to assess temperature in pigs but with surface measures at the inner thigh and abdomen being best at estimating core temperature. However, with the need for significant animal manipulation, this provided no advantage over rectal thermometry. It is known that piglet temperatures change rapidly in the first 24 h of life and can be used as an indicator of likely survival (Mount, 1959; Caldara et al., 2014; Sasaki et al., 2016; Santiago et al., 2019). Therefore, development of a non-invasive protocol to measure piglet body temperatures in this period could be used commercially to predict early survival chance and allow early intervention for at-risk piglets. Surface temperature recorded at the base of the ear has recently been shown to have a moderate correlation to rectal temperature during the first 24 h, but with the poorest correlations being at birth and 24 h (Tucker et. al., unpublished data). We hypothesized that under relatively uncontrolled commercial conditions, piglet surface temperature measured with a handheld infrared camera at birth and 24 h would not be concordant to rectal temperature and thus not appropriate as a replacement in production.

2. Methods:

This experiment was conducted between January and March 2021 in a commercial piggery in southern New South Wales and was approved by the Rivalea Animal Ethics Committee (Protocol 20R047) in accordance with the Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council, 2013).

2.1 Animals and Housing

The data set included 109 piglets (53 male and 56 female) born to 6 multiparous Large White x Landrace sows (parity 3.45 ± 1.16; 1 – 4). Total born litter sizes (14.9 ± 2.4) were recorded including born alive and stillborn but excluding mummified piglets. Sows were moved to their farrowing accommodation at 110 ± 1 d of gestation and housed in individual slatted floor farrowing crates (0.5 x 2.0 m). Each crate was equipped with a sow and piglet level nipple drinker, solid floored creep area located to the side of the crate, with a heat lamp positioned centrally over the creep area. The farrowing rooms were semi-enclosed with natural ventilation and a dripper cooling system set to automatically activate at 28 °C. Additional portable evaporative coolers were used in the first 2 weeks after farrowing to aid in temperature control.

The sows were fed a standard lactation diet formulated to provide 15 MJ DE/kg, 16.7% protein and 0.90% SID lysine at 3.8 kg/d from the entry to the farrowing house. Once farrowed, sows were fed to-appetite via hand feeding twice per day until weaning. Sows were monitored daily for general health and welfare by research and production staff throughout the study. All sows farrowed naturally without induction and no sows required manual assistance. Fostering and piglet processing occurred after the experimental period.

2.2 Experimental Design

At delivery of each piglet the time of birth was recorded, and the piglet was moved within 5 min of birth to a semi-enclosed plastic container mounted on a scale located behind the farrowing crate. Birth weight of each piglet was recorded, and thermal images were taken to measure the surface temperature at the base of the right ear, tip of the right ear and eye (Figure 1) with minimal additional manipulation (occasional repositioning of the ear was necessary to obtain access to the back of the ear and or eye when covered). The FLIR® E8 infrared thermal camera (FLIR Systems, Wilsonville, OR, USA) with an emissivity value set to 0.985 was used at a 30 cm distance from the piglet to record all surface temperatures. All images were saved for further analysis. Rectal temperature was recorded immediately after the images were obtained using a standard digital thermometer with a 32°C minimum limit. Piglets were then tagged and returned to the crate location they were picked up from. At 24 h after birth, piglets were reweighed, new thermal images obtained at all locations, and rectal temperature recorded (following the same procedures performed at birth). Any mortalities between birth and 24 h were recorded.

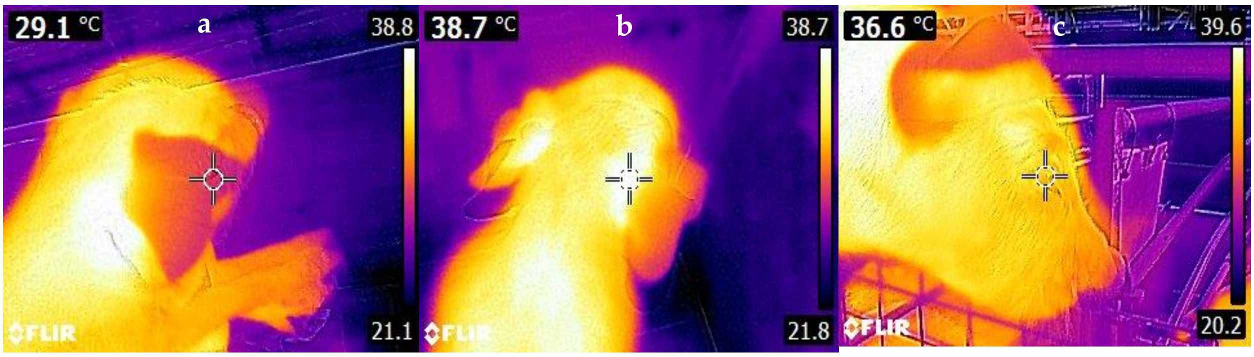

Figure 1: FLIR® E8 camera examples of thermal images of different surface locations obtained with the FLIR E8 camera, using the pointer. Figure 1a = ear tip. Figure 1b = base of ear. Figure 1c = eye.

Infrared thermal images were analysed using MATLAB® R2020 (MathWorks Inc. Natick, MA, USA) and FLIR® Atlas SDK (FLIR Systems, Wilsonville, OR, USA; Jorquera-Chavez et al., 2021). The radiometric information of each image was extracted, and the desired region of interest selected, which allowed extraction of the maximum temperature from this region. The algorithm extracted temperature will be referred to as the extracted value throughout this paper and the automatically generated value from the FLIR E8 camera will be referred to as the pointer value.

2.3 Statistical Analysis

All statistical analyses were performed with SAS version 9.4 (Statistical Analysis Software, Cary, NC, USA). Level of significance was set at P<0.05. Some data were manipulated prior to analysis:

Surface temperature difference between two temperature methods were calculated to create a new binomial variable ('temperature agreeance'); agree = within 1°C, and disagree = ± > 1°C. This rule was applied to the following combinations:

- ear base; extracted - pointer
- eye; extracted – pointer

Ear tip was not used for this comparison due to its low correlation to rectal temperature and within surface temperature methods.

Piglets were categorised into three groups based on their birth weight: BWC1: ≤ 0.80 kg; BWC2: 0.81 kg to 1.10 kg; and BWC3: > 1.10 kg. Colostrum intake for each piglet was calculated using the equation developed by Devillers et al. (2007):

$$CI = -217.4 + 0.217 \times t + 1861019 \times \frac{W}{t} + BW \times \left(\frac{54.8 - 1861{,}019}{t}\right) \times (0.9985 - 3.7 \times 10^{-7} \times t_{fs}^{2})$$

where CI = colostrum intake (g), W = piglet body weight at 24 h (kg), BW = piglet body weight at birth (kg), t = age (min), and t_{fs} = time elapsed from birth to first sucking (min); t_{fs} was assumed to be 30 min and t was 1440 min (24 h).
Piglets were also categorised into 2 groups based on their colostrum intake based on 200 g being the recommended minimum amount of colostrum needed (Quesnel et al., 2012) (CL1: < 200 g, CL2: ≥ 200 g).

The PROC CORR procedure of SAS was used to estimate the correlation between rectal and surface temperature by both the camera pointer value and extracted values and between pointer and extracted values at respective locations. Pearson correlation coefficients and the respective 95% confidence intervals were the output. Correlation was deemed very high if r^2 ≥

0.90, high if r^2 = 0.70 to 0.89, moderate if r^2 = 0.50 to 0.69, low if r^2 = 0.30 to 0.49, and negligible if r^2 < 0.30 (Hue et al., 2021).

The effect of time and colostrum intake on ear base and eye temperatures from both the extracted and pointer were estimated using a mixed model in PROC MIXED, as presented in Equation 1:

$$Surface\ temperature = Time_{ls} + \ Colostrum\ intake_{ls} \qquad (1)$$

The effect of time and colostrum intake on rectal temperatures were estimated using a mixed model in PROC MIXED, as presented in Equation 2:

$$Rectal\ temperature = Time_{ls} + \ Colostrum\ intake_{ls} \qquad (2)$$

where ls = litter size. Piglet sex, week born, sow parity, crate lamp on or off, and BWC were tested but all were non-significant as covariables or fixed effects (P > 0.10). The outputs for all PROC MIXED procedures were the means and their respective standard errors.

The effect of time on the number of piglets that agreed within 1°C of surface temperature values was estimated using a mixed model in PROC GLIMMIX as presented in Equation 3:

$$Temperature\ agreeance = Time + Colostrum\ intake \qquad (3)$$

Piglet sex, litter size, week born, sow parity, crate lamp on or off and BWC were tested but all were non-significant as covariables (P > 0.10). The outputs were proportions and their respective 95% confidence intervals represented in brackets.

3. Results:

3.1 Correlation Between Surface and Rectal Temperatures

At the base of the ear, both the pointer and extracted temperatures were moderately correlated with rectal temperature (r^2 = 0.51 and 0.53, respectively; Figure 2a). At the tip of the ear, the pointer and the extracted temperatures had a negligible correlation with rectal temperature (r^2 = 0.24 and 0.18, respectively; Figure 2b). The temperature of the eye showed a moderate correlation to rectal temperature for both the pointer and extracted values (r^2 = 0.60 and 0.55, respectively; Figure 2c).

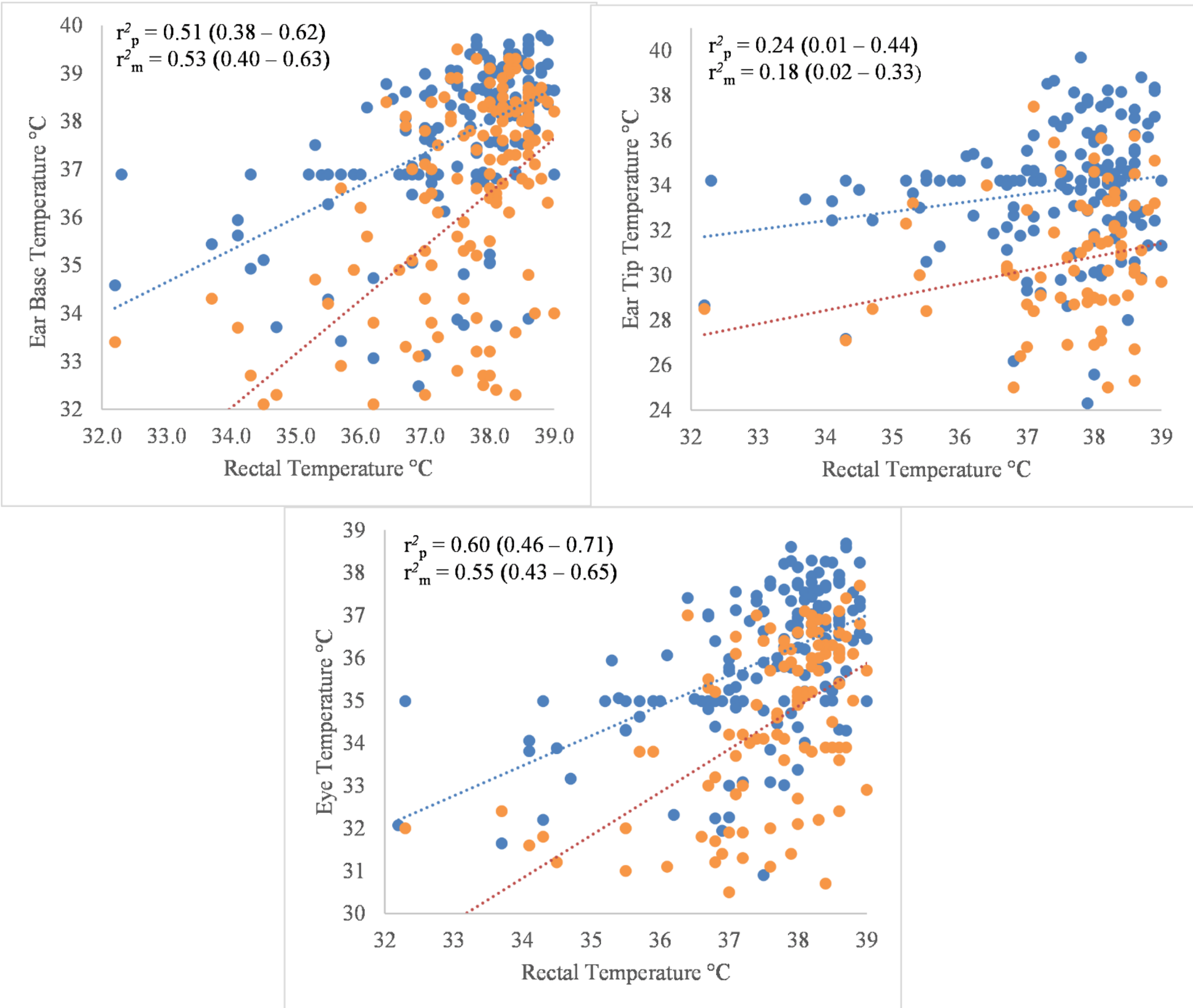

Figure 2: Pearson's correlation coefficient and respective 95% confidence intervals for Pointer (orange, r^2_p) and Extracted (blue, r^2_m) temperatures from thermal images taken using *FLIR® E8 infrared thermal camera,* between rectal temperature and locations in 109 piglets. Figure 2a presents Ear base temperature, Figure 2b presents Ear Tip temperature and Figure 2c presents Eye temperature, measured by thermal imaging camera.

When comparing 0 and 24 h, ear base temperature showed negligible correlation to rectal temperature for pointer values at 24 h and low for the extracted values and (r^2 = 0.22 and 0.30 respectively; Table 1). Ear tip temperature showed a moderate correlation to rectal temperature only for the pointer value at time 0 (r^2 = 0.36) and negligible for time 24 h (r^2 = -0.07) and extracted values at both time points (r^2 = 0.19 and 0.05 respectively). Eye temperature showed a medium correlation between pointer and rectal temperatures at time 0 and negligible correlation at time 24 h (Table 1). Similarly, the eye extracted value had low correlation at time 0 and negligible correlation at time 24 h.

Table 1: Pearson's correlation coefficient (r2; 95% confidence intervals) for correlation between rectal temperature and surface temperature locations for camera generated pointer values and algorithm extracted values across time 0 (birth) and 24 h in 109 piglets. N = number of observations for each time grouping.

		Time (relative to birth)	
		0 h	24 h
	N	48	61
Ear base	Pointer	0.38 (0.11 – 0.60)	0.22 (-0.03 – 0.45)
	Extracted	0.31 (0.03 – 0.55)	0.30 (0.05 – 0.51)
Ear tip	Pointer	0.36 (-0.11 – 0.70)	-0.07 (-0.39 – 0.26)
	Extracted	0.19 (-0.10 – 0.45)	0.05 (-0.21 – 0.29)
Eye	Pointer	0.50 (0.25 – 0.69)	0.14 (-0.12 – 0.38)
	Extracted	0.42 (0.15 – 0.53)	0.21 (-0.04 – 0.44)

3.2 Pointer vs Extracted Surface Temperatures

Ear base and eye temperatures showed a high correlation between pointer and extracted values (r^2 = 0.73 and 0.82, respectively; Figures 3a and 3c), while the ear tip showed a moderate correlation between pointer and extracted values (r^2 = 0.52; Figure 3b).

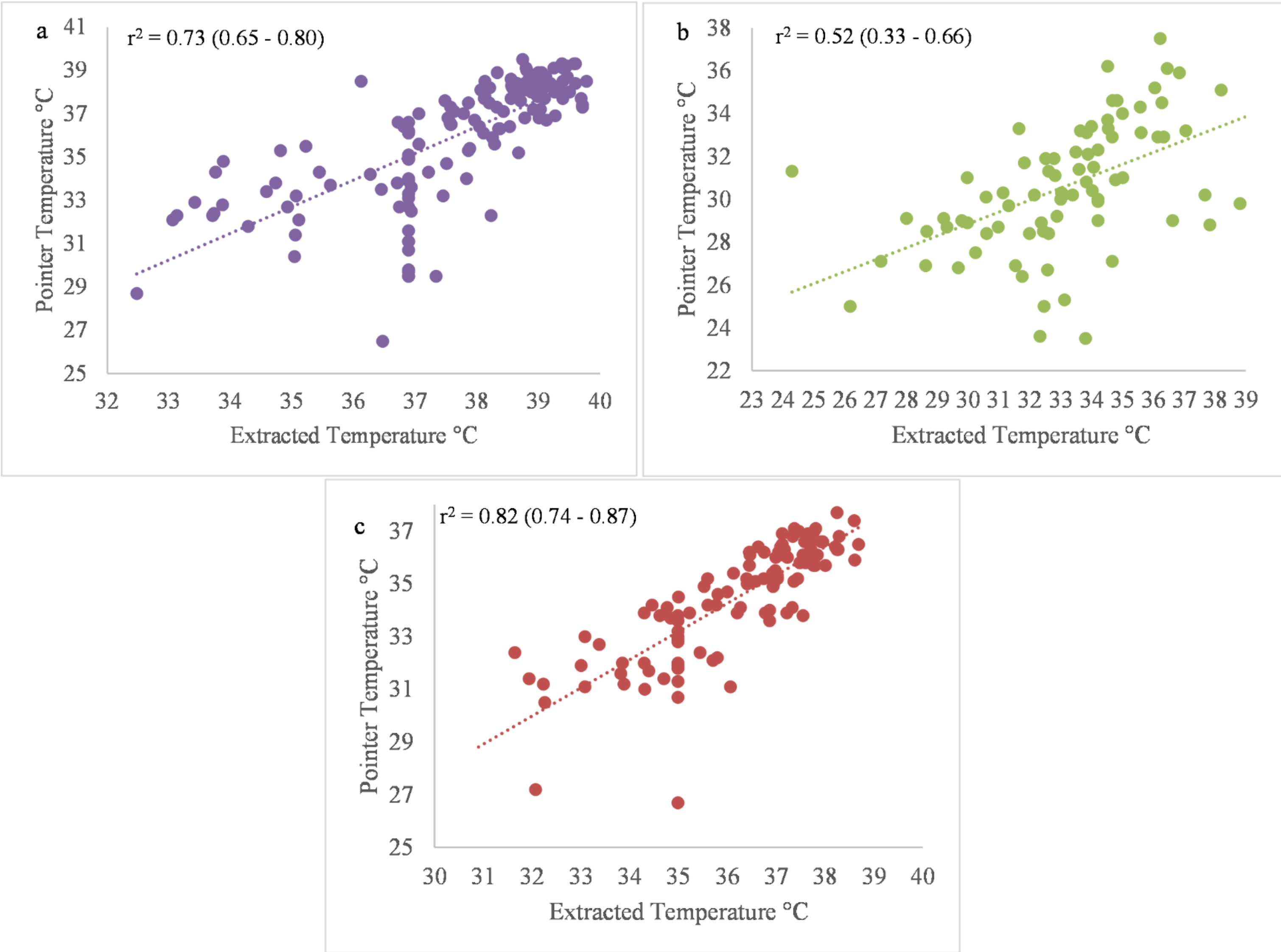

Figure 3: Pearson's correlation coefficient and respective 95% confidence intervals for the relationship between the Extracted temperature and Pointer temperature from thermal images taken using a *FLIR® E8 infrared thermal camera* at 3 locations in 109 piglets. Figure 3a presents the base of the ear (purple), Figure 3b presents the tip of the ear (green), Figure 3c presents the eye (red).

3.3 Factors Affecting Thermal Surface Temperature

Ear base temperatures were not significantly impacted by colostrum intake category (Extracted, $P = 0.27$; Pointer, $P = 0.76$) and were higher ($P < 0.001$) at 24 h than at birth (Table 2).

Table 2: Mean ± SEM for surface temperature extracted and pointer recorded values taken at the base of the ear of 109 piglets between birth (0 h) and 24 h post birth and piglets who consumed less or more than 200 g of colostrum. N = number of piglets per group. Adjusted for litter size.

			Ear base (°C)	
		N	Extracted	Pointer
Time (h)	0	48	36.4 ± 0.41 #	34.4 ± 0.58 #
	24	61	38.5 ± 0.38	37.6 ± 0.52
Colostrum (g)	< 200	38	37.2 ± 0.42	35.9 ± 0.59
	≥ 200	71	37.7 ± 0.37	36.1 ± 0.51

# Indicates $P < 0.001$ between categories within method and variable

Pointer temperature of the eye was not significantly impacted by colostrum intake category ($P = 0.48$), but the extracted temperature was significantly higher in those piglets consuming ≥ 200 g of colostrum ($P = 0.01$; Table 3). Both temperatures were higher in piglets at 24 h than at birth ($P < 0.001$).

Table 3: Mean ± SEM for surface temperature extracted and pointer recorded values taken at the eye of 109 piglets between birth (0 h) and 24 h post birth and piglets who consumed less than or greater than 200 g of colostrum. N = number of piglets per group. Adjusted for litter size.

			Eye (°C)	
		N	Extracted	Pointer
Time (h)	0	48	34.7 ± 0.24 #	32.9 ± 0.30 #
	24	61	37.4 ± 0.21	35.8 ± 0.27
Colostrum (g)	< 200	38	35.6 ± 0.26 #	34.3 ± 0.32
	≥ 200	71	36.4 ± 0.20	34.5 ± 0.24

# Indicates $P < 0.001$ between categories within method and variable

Rectal temperatures were not significantly affected by colostrum intake ($P = 0.29$) but tended ($P = 0.08$) to be higher at 24 h than at birth (Table 4).

Table 2: Mean ± SEM for rectal temperature taken via digital thermometer of 109 piglets between birth (0 h) and 24 h post birth and piglets who consumed less than or greater than 200 g of colostrum. N = number of piglets per group. Adjusted for litter size.

		N	Rectal temperature (°C)
Time (h)	0	48	37.7 ± 0.15 *
	24	61	38.2 ± 0.13
Colostrum (g)	< 200	38	37.8 ± 0.15
	≥ 200	71	38.1 ± 0.13

* Indicates *P* < 0.05 between categories within method and variable

Temperature agreeance between the pointer derived value and the extracted value was only significantly impacted by time in one model (Table 5); at 24 h, the agreeance at the ear base between extracted and pointer values tended to be lower than at birth (*P* = 0.08).

Table 5: Mean ± SEM for rectal temperature taken via digital thermometer of 109 piglets between birth (0 h) and 24 h post birth and piglets who consumed less than or greater than 200 g of colostrum. N = number of piglets per group. Adjusted for litter size.

		Time (h)		Colostrum intake (g)	
	N	0	24	< 200	≥ 200
Ear base extracted – ear base pointer	109	61.3 (37.2 – 80.9)	33.3 (17.0 – 54.9)	38.3 (17.4 – 64.7)	56.0 (36.2 – 74.1)
Eye extracted – eye pointer	109	66.6 (41.9 – 84.7)	66.0 (44.4 – 82.5)	56.3 (31.7 – 78.2)	75.0 (55.3 – 88.0)
Eye extracted – ear base max	109	68.6 (44.3 – 85.8)	56.3 (35.8 – 74.8)	63.5 (37.6 – 83.4)	61.8 (42.1 – 78.2)
Eye pointer – ear base pointer	109	78.6 (53.7 – 92.0)	75.6 (54.1 – 89.1)	75.2 (48.5 – 90.8)	78.8 (59.2 – 90.5)

4. Discussion:

Body temperature is a major indicator of a pig's health, performance, and potential for survival (Brown-Brandl et al., 2013; Jorquera-Chavez et al., 2020; Weng, 2020; Jorquera-Chavez et al., 2021), and skin or eye surface temperatures have been suggested as appropriate alternatives to rectal temperature, allowing for less manipulation of the piglet at measurement (Soerensen and Pedersen, 2015). However, this suggested relationship remained to be evaluated under commercial production conditions. Our data show that the base of the ear and the eye were the locations on the piglet that showed the best correlations between the thermal infrared camera pointer and extracted surface temperature values. However, their correlation to rectal temperature was still only moderate and thus these methods did not appear to be a good substitute for rectal temperature measurement under production conditions, supporting our hypothesis.

Unlike in previous studies where the thermal temperatures at the base of the ear and eye were reported to be highly correlated with rectal temperature (Soerensen and Pedersen, 2015), our study showed that this seems not to be always accurate under production conditions. The extracted and pointer values for the base of the ear and eye locations were moderately correlated to rectal temperature. However, thermal temperature of the ear tip was not well correlated with rectal temperature using either pointer or the extracted values. This supports the previous findings by Tabuaciri et al. (2012) who also showed that ear tip temperature had a lower correlation to rectal temperature than ear base of newborn piglets. Anecdotally, the ear tip was the easiest to consistently access each time, but it was difficult to maintain it in the camera range without piglet manipulation. Other studies using temperature loggers which were directly attached to the tip of the ear showed greater promise and may be more appropriate for this location (Garrido-Izard et al., 2019).

Rectal temperature was poorly correlated with surface temperature when considered with respect to time. In general, ear tip had the lowest correlation values followed by ear base and eye, although the confidence intervals were large for all correlations and, therefore, this variability may have affected the trend. However, the trend is supported by previous suggestions that the eye is the most sensitive to minor changes in temperature. Regardless, the lack of correlation at different time points supports our suggestion that, currently, measuring surface temperature under production conditions is not viable.

The ear base and eye are good thermal locations for surface temperature readings but obtaining clear and consistent images without piglet manipulation seems to be difficult. Our study showed a high correlation between these locations suggesting that base of ear and eye are comparable and could be used when a location e.g., the eye, is covered by an ear. However, it has been shown that stress can have a significant effect on the surface temperatures of the ear and eye (Magnani et al., 2011; Vinkers et al., 2013; Herborn et al., 2015) in pigs, among other species. When pigs were placed under a stress test, the temperature at the eye and right ear decreased after the test due to vasoconstriction (Magnani et al., 2011). This highlights that even the 'best' suggested locations for surface temperature are highly affected by environment and stressors, decreasing their validity under variable production conditions. It should be noted that the majority of pig temperature studies were primarily performed in older pigs of varying ages and reproductive stages with established energy reserves, unlike newborn piglets. In the first 24 h of life neonatal piglets are exposed to high levels of stress, like great environmental changes from in utero to the crate environment and competition for critical resources (Herpin et al., 2002; Caldara et al., 2014; Muns et al., 2016). With the known stress effect on surface temperature readings, it is reasonable to suggest that neonatal piglet surface temperature is less reliable and more effected by stress. Alternatively, it could be assumed that all neonatal piglets are exposed to high levels of stress and thus the effect on surface temperature is similar. However, it is well known that smaller piglets have lower energy reserves and are poorer thermoregulators (Herpin et al., 2002; Caldara et al., 2014; Cooper et al., 2019). Therefore, this subset of piglets are potentially under greater levels of stress and thus their temperature reading could be greatly impacted by stress. Currently, the only method of monitoring stress effects is measuring cortisol in saliva or faecal samples which, in newborn piglets, requires further handling or is impossible until colostrum is absorbed (Martínez-Miró et al., 2016; Wolf et al., 2020). Therefore, although this cannot be accounted for, it should be considered in all neonatal piglet temperature monitoring studies.

Temperature was significantly higher at 24 h for both ear base and eye extracted and pointer values than at birth. This was expected as, by 24 h, surviving piglets should have recovered from the initial post-natal temperature drop and, therefore, their internal temperature is likely to be higher and more stable. However, at 24 h, a greater number of piglet ear base extracted, and pointer values were not in agreeance than was evident at birth, although it should be noted that the confidence intervals were quite large. Some of this variation may be contributed by an increase in inaccurate location readings due to the piglets being more active at 24 h. It is also possible that some of the piglets have used up most of their energy supply and thus are conserving energy by reducing peripheral blood flow and so reducing the surface temperature (Charneca et al., 2010; Devillers et al., 2011; Tansey and Johnson, 2015; Villanueva-Garcíaa et al., 2021).

An effect of difference in amount of estimated colostrum consumed was only evident in the eye temperatures, with an effect not being identified in the ear base data, due to it being more influenced by environmental factors than the eye temperature (reviewed by Soerensen and Pedersen, 2015). Previous studies have shown that factors such as room temperature, heat source location, exposure duration and level, humidity, light exposure, hair coverage/density and distance of camera to pig, all impact the surface temperature and the cameras' ability to record it (Soerensen and Pedersen, 2015; Zhang et al., 2016; Schmid et al., 2021). This could suggest that at 24 h the piglets are affected by a greater variation in, and sources of, factors in their environment than at birth. Our results may also suggest that since, this experiment was performed in summer, less fluctuation between day conditions were likely to occur thus potentially reducing the variation between individual piglet temperatures at birth and 24 h. Additionally, within our study design the piglets were picked up and placed within a designated area to measure their temperatures, minimising disturbance to the sow and creating a consistent environment for each image (Schmid et al., 2021). The piglets were not necessarily restrained during measurement but the movement to outside of the crate to take the images would be unlikely to be replicated under production conditions. Therefore, greater environmental variation could occur, which might result in greater difficulty obtaining repeatable image readings. Under research conditions it is easier to account for and control for additional factors (Mostaço et al., 2015) but in production this is impractical. Further research is required to evaluate systems that potentially reduce variation discussed previously i.e., automatic monitoring systems to record infrared thermal surface temperature (Kammersgaard et al., 2013; Lu et al., 2018).

5. Conclusion

Infrared thermal images taken at the ear and eye in neonatal piglets at birth and 24 h did not appear to be an adequate replacement for rectal temperature (measured by conventional digital thermometer) under production conditions. However, ear base and eye infrared thermal temperatures were found to be in moderate to high agreeance at both birth and 24 h suggesting that these could be used interchangeably if one is not obtainable without piglet manipulation. The use of handheld thermal infrared technology to monitor piglet temperature change seems to be more appropriate for use in research than under production conditions. Future research and use of thermal infrared technology in production should be focused on a system that can automatically account for the changing environmental conditions.

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Chapter 7:

Neonatal piglet temperature changes: effect of intraperitoneal warm saline injection

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Contribution to the Paper	Conceptiualization, Methodology, Investigation, Formnal analysis, Writing and Editing		
Overall percentage (%)	85%		
Certification:	This paper reports on original research I conducted during the period of my Higher Degree by Research candidature and is not subject to any obligations or contractual agreements with a third party that would constrain its inclusion in this thesis. I am the primary author of this paper.		
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By signing the Statement of Authorship, each author certifies that:

i. the candidate's stated contribution to the publication is accurate (as detailed above);

ii. permission is granted for the candidate in include the publication in the thesis; and

iii. the sum of all co-author contributions is equal to 100% less the candidate's stated contribution.

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Article

Neonatal Piglet Temperature Changes: Effect of Intraperitoneal Warm Saline Injection

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Simple Summary The lighter a piglet is the worse is their ability to keep warm after birth. If they cannot recover from the reduction in temperature from in the womb to the crate they are at higher risk of hypothermia and death. A study was undertaken to investigate if providing them with a warm saline injection could improve their temperature over the first 24 h of life and their survival to weaning. Results show that lightweight piglets who received warmed saline had higher rectal temperatures at 24 h, increased colostrum intake, and greater survival at d 20.

Abstract: Piglets are poor at thermoregulation immediately following birth and take up to 24 h to recover from their initial temperature drop. The present study aimed to determine if providing piglets with a 15 mL intraperitoneal injection of warm (45 °C) saline at birth would improve their internal temperature recovery to 24 h of age, and how the treatment interacted with birth weight (BWC = 1; ≤0.80 kg, BWC = 2; 0.81 kg to 1.10 kg, and BWC = 3; >1.10 kg), rectal temperature at 1.5 h (RC = 1; ≤32.0 °C, RC = 2; 32.10 °C to 35.0 °C, and RC = 3; ≥35.10 °C), and colostrum intake (CI = 1; < 200 g and CI = 2, ≥200 g) to affect preweaning survival. Treated BWC1 piglets had improved rectal temperatures from 2 to 24 h. BWC3 piglets who consumed insufficient colostrum also had improved rectal temperature between 1 and 24 h post-birth. Colostrum intake was improved with saline injection in BWC2 piglets of RC1 and RC3 ($p < 0.001$) and BWC3-RC3 piglets ($p < 0.001$). Treated BWC1 improved survival to 20 d ($p < 0.001$). Irrespective of BWC, piglets from all RC had greater survival when injected with saline. The greatest difference was for piglets in RC1, likely due to all BWC1 piglets falling within this category. The results suggest that an intraperitoneal injection of warmed saline is an effective way to improve piglet temperature recovery to 24 h, colostrum intake, and survival in low-birth-weight piglets. These findings will be helpful for producers who have large numbers of low-birth-weight piglets born and are able to provide individual care.

Keywords: rectal temperature; warming; birth weight; thermoregulation; temperature recovery; survival; intraperitoneal

1. Introduction

Piglets are born with relatively little adipose tissue and no brown fat, meaning they have a limited energy supply to thermoregulate and for mobility to obtain colostrum [1]. They experience a sharp decline and subsequent slow recovery in body temperature over the first 24 h of life [2–4]. The temperature decline can impair their ability to move and thus access colostrum and milk, resulting in hypoglycaemia and chilling, predisposing them to death by overlay or starvation [5,6].

A piglet's initial temperature decline and its ability to thermoregulate are directly related to its weight [3]. Smaller piglets have a higher surface area to volume ratio and proportionally greater heat loss, and so are at greater risk of mortality due to hypothermia [7].

The ambient temperature in the farrowing location is usually set for the sows' thermal requirements [8,9], which are below the piglet lower critical temperature [1] and so piglets must rely on additional heat sources such as heat lamps and/or mats. However, this heated area is stationary and is located away from the udder, with the total distance depending on the sow [10]. In order to maintain body temperature as well as having to adapt to the temperature change outside of the heated area, the movement back and forth by the piglets to obtain access to colostrum/milk uses some of their energy. For piglets that have very little energy due to their size and/or missed previous milk letdowns, this can be critical to their survival.

Previous studies that have suggested intervention strategies such as supplementary nutritional products (e.g., milk from other sows or cows, or energy-rich supplements) had varying results but all reduced the available stomach capacity for colostrum consumption [11–13]. Further, studies have shown the drying of piglets to have some effect on short-term temperature improvement, but few have shown long-term benefit to survival, suggesting minimal effects on the piglet internal temperature [4,7,14,15]. Despite data from previous studies, the success seemed to be heavily dependent on the piglet's morphology, the quality of its environment, and the method of external or internal intervention.

In humans and companion animals, hypothermia is often treated with warm saline combined with warming of the skin surface [16–18]. Additionally, it is standard practice to use fluids warmed to 37–41 °C to prevent pre- and intra-operative hypothermia in patients [19]. Some safety studies in dogs have showed that intravenous (IV) fluid at both 40 °C and 65 °C was a safe and effective means of treating hypothermia [17,18]. Administration of warm IV fluids could be an alternative to providing a heat source that is not stationary and will not reduce stomach space. However, in commercial practice, the administering of IV fluids is neither practical nor economically viable. Therefore, we hypothesized that giving a bolus intraperitoneal injection of saline warmed to 45 °C, being a similar but higher temperature than their in-utero environment [20,21], into potentially compromised piglets would ameliorate body heat loss and improve preweaning piglet survival.

2. Materials and Methods

This experiment was performed in September and October 2021, at the University of Adelaide, Roseworthy piggery, SA, approved by the institutional Animal Ethics Committee (Approval number; S-2021-046).

2.1. Housing and Management

The raw data set included 104 piglets (55 male and 49 female) born to 11 multiparous sows (Large white × Landrace; parity 2 to 4; 2.95 ± 0.49) born within observation hours. Total born litter sizes were recorded, including born alive and stillborn but excluding mummified piglets.

Sows were moved into one of three farrowing rooms at about 110 d of gestation and housed in conventional individual farrowing crates (0.5 m × 2 m) equipped with sow and piglet level nipple drinkers. The farrowing house was environmentally controlled and was maintained at about 22 °C throughout lactation using an automatic thermostat system and cool cells. Farrowing crates were equipped with a heat mat on one side of the sow set on a heating curve from 31 °C at farrowing to 24 °C prior to weaning. Crates were scraped daily, and health and welfare checks performed a minimum of 2 times daily throughout the study. From entrance to the farrowing house until farrowing, sows were fed a standard wheat/barely/lupin-based lactation diet formulated to supply all necessary nutrients (14 MJ DE/kg, 17% protein, and 0.8% SID lysine) at 2.5 kg/d. Once farrowed, sows were fed to appetite via hand feeding twice per day until weaning. Sows were induced to farrow by vulva injection of 125 µg cloprostenol (Juramate®, Jurox Pty limited, Rutherford, New South Wales, Australia) at 0700 and 1300 h on d 114 of gestation [22]. Farrowing observations were conducted daily from 0630 to 1700 h and piglets received an iron injection and a Toltrazuril drench (Baycox®, Elanco Australasia Pty Ltd, Macquarie Park, New South Wales, Australia) at 4 d of age.

Piglets were assigned prenatally by their birth order to receive 15 mL intraperitoneal saline warmed to 45 °C (saline, n = 52) or to receive no treatment (control, n = 52). The saline dose was based on the author's clinical experience. Saline was warmed using bottle warmers (NUK, Zeven, Germany) and the temperatures monitored using digital meat thermometers. All piglets were held head down by their rear legs and saline piglets injected as shown in Figure 1 using a 20 mL syringe and a 20 g − ½ inch needle.

At expulsion of each piglet, the birth time and the rectal temperature of the sow were recorded as representative of the piglet birth temperature. At 0.25 h after birth, the piglets were weighed and received their pre-allocated treatment. The rectal temperatures of the piglets were recorded 2 min post saline injection or 2–4 min from picking up (control pigs) and at 1, 1.5, 2, 4, and 24 h relative to their birth time. At 4 and 20 d, piglet rectal temperatures were recorded again. Piglet weights at 24 h and at 20 d were used to calculate suckling weight gain. Colostrum intakes (*CI*) were calculated from 15 min and 24 h piglet weights using the equation developed by Devillers et al. [23]:

$$CI = -217.4 + 0.217 \times t + 1{,}861{,}019 \times \frac{W}{t} + BW \times \left(\frac{54.8 - 1{,}861{,}019}{t}\right) \times (0.9985 - 3.7 \times 10^{-7} \times t_{fs}^2) \quad (6)$$

where CI = colostrum intake (g), W = piglet body weight at 24 h (kg), BW = piglet body weight at birth (kg), t = age (min), and t_{fs} = time elapsed from birth to first sucking (min). On the basis of the research of Devillers et al. [23], t_{fs} is assumed to be 30 min and t is 1440 min.

Colostrum intake was categorized into 2 levels on the basis of 200 g being the recommended minimum amount of colostrum needed to survive: level 1 includes piglets who consumed <200 g of colostrum and level 2 includes piglets who consumed ≥200 g. Survival was recorded to 20 d of lactation.

Figure 1. Intraperitoneal injection site of piglets.

2.2. Statistics

All statistical analyses were performed with SAS version 9.4 (Statistical Analysis Software, Cary, NC, USA). For the statistical analyses, data were bootstrapped at root of 24 using PROC SURVEYSELECT resulting in a total 1589 observations at piglet level and 142 sow-level observations available for the analyses. The accuracy of the data was tested using PROC MEANS with all means of the bootstrapped data being similar to the original data to the second decimal point.

Correlations between rectal temperature and time were tested using PROC CORR with the output being the Pearson's correlation coefficient and the respective 95% confidence intervals. Correlation was considered to be very high if $r^2 \geq 0.90$, high if $r^2 = 0.7$ to 0.89, moderate if $r^2 = 0.5$ to 0.69, low if $r^2 = 0.3$ to 0.49, and negligible if $r^2 < 0.3$ [24]. Rectal temperature and body weight across time were moderately correlated ($r^2 = 0.60$), thus, prior to analysis, some data were manipulated:

Piglet birth weights were assigned to one of three categories: low (BWC = 1; ≤0.80 kg), mid (BWC = 2; 0.81 kg to 1.10 kg), and high (BWC = 3; >1.10 kg). The 0.8 kg value is based on commercial experience indicating pigs of this weight or less have minimal survival and documented evidence that piglets of 1.1 kg or heavier had good survival rates [24]. Piglet rectal temperatures at 1.5 h after birth were assigned to one of three categories (RC): low (RC = 1; ≤32.0 °C), mid (RC = 2; 32.1 °C to 35.0 °C), and high (RC = 3; ≥ 35.1 °C). The 1.5 h time was chosen, as it is a time point at which the piglets should start to show temperature recovery, thus indicating their vitality. Further, limitations from the human rectal thermometer restricted recording piglet temperatures below 32 °C, resulting in likely biased data prior to this time point. Significance was set at the $p < 0.05$ level.

The effect of the birth weight, time of measure relative to birth, treatment, parity and colostrum intake, and the interactions between birth weight, time of measure, treatment, and colostrum intake, on the rectal temperature of piglets were estimated using a Mixed model in PROC MIXED, as presented in Equation (2):

$$\begin{aligned} Temperature = [&birth\ weight\ category + time\ of\ measure\ related\ to\ birth + \ treatment\ group \\ &+ parity + colostrum\ group + (birth\ weight\ category \\ &*\ time\ of\ measure\ related\ to\ birth * treatment\ group \\ &* colostrum\ group)]_{piglet\ ID} \end{aligned} \quad (2)$$

where parity was a random factor and piglet ID was treated as a repeated measure. The preliminary model also tested the effects of litter size, farrowing room and piglet sex, but these were found to be not significant as confounders ($p > 0.1$).

The outputs of all PROC MIXED models were least-square means, their respective standard errors, and differences between least-square means.

The effect of the interaction between birth weight, treatment, and temperature category on colostrum intake was estimated using a Mixed model in PROC MIXED, as presented in Equation (3):

$$Colostrum\ intake = (birth\ weight\ category * treatment\ group * rectal\ temperature\ category) \quad (3)$$

The preliminary model also tested the effects of sow, parity, sex, litter size, and farrowing room, but these were found to be not significant as confounders ($p > 0.1$).

The effect of the interaction of body weight category, treatment, and colostrum intake grouping on piglet suckling weight gain was estimated using a Mixed model in PROC MIXED, as presented in Equation (4):

$$Suckling\ weight\ gain\ (kg) = (birth\ weight\ category * treatment\ group * colostrum\ group)_P \quad (4)$$

where p = sow parity. The preliminary model also tested the effects of sow, sex, litter size, and farrowing room, but these were found to be not significant as confounders ($p > 0.1$).

The effect of birth weight category, and interaction of sex and treatment group with birth weight category on survival to 20 d were estimated using linear regression in PROC GLIMMIX (binary distribution), as presented in Equation (5):

$$\begin{aligned} Survival = birth\ weight\ category_{fh,ls} &+ \ (birth\ weight\ category * treatment\ group)_{fh,ls} \\ &+ \ (birth\ weight\ category * sex)_{fh,ls} \\ &+ \ (birth\ weight\ category * colostrum\ group)_{fh,ls} \end{aligned} \quad (5)$$

where *fh*= farrowing room and *ls*= litter size. The preliminary model also tested the effects of sow and parity, and treatment group and sex alone, but these were found to be not significant as confounders ($p > 0.1$). The outputs of all PROC GLIMMIX models were the geometric means and their respective 95% confidence intervals.

The effect of the interaction of birth weight category, sex, and treatment group with rectal temperature category on survival to 20 d were estimated using linear regression in PROC GLIMMIX as presented in Equation (6):

$$\begin{aligned} Survival = (birth\ weight\ category * RC) &+ \ (sex * RC) + (treatment\ group * RC) \\ &+ \ (colostrum\ group * RC) \end{aligned} \quad (6)$$

where RC= rectal temperature category.

3. Results

3.1. Temperature

Intraperitoneal injection of saline warmed to 45 °C increased the rectal temperature of BWC1 piglets from 2 h ($p < 0.001$; Figure 2a). BWC2 and BWC3 piglets showed an increased rectal temperature at time points between 0.25 h and 4 h from birth (BWC2 = 1,1.5 and 4 h; $p < 0.001$; BWC3 = 0.25, 1, 1.5, 2 and 4 h; $p < 0.001$; Figure 2b, c).

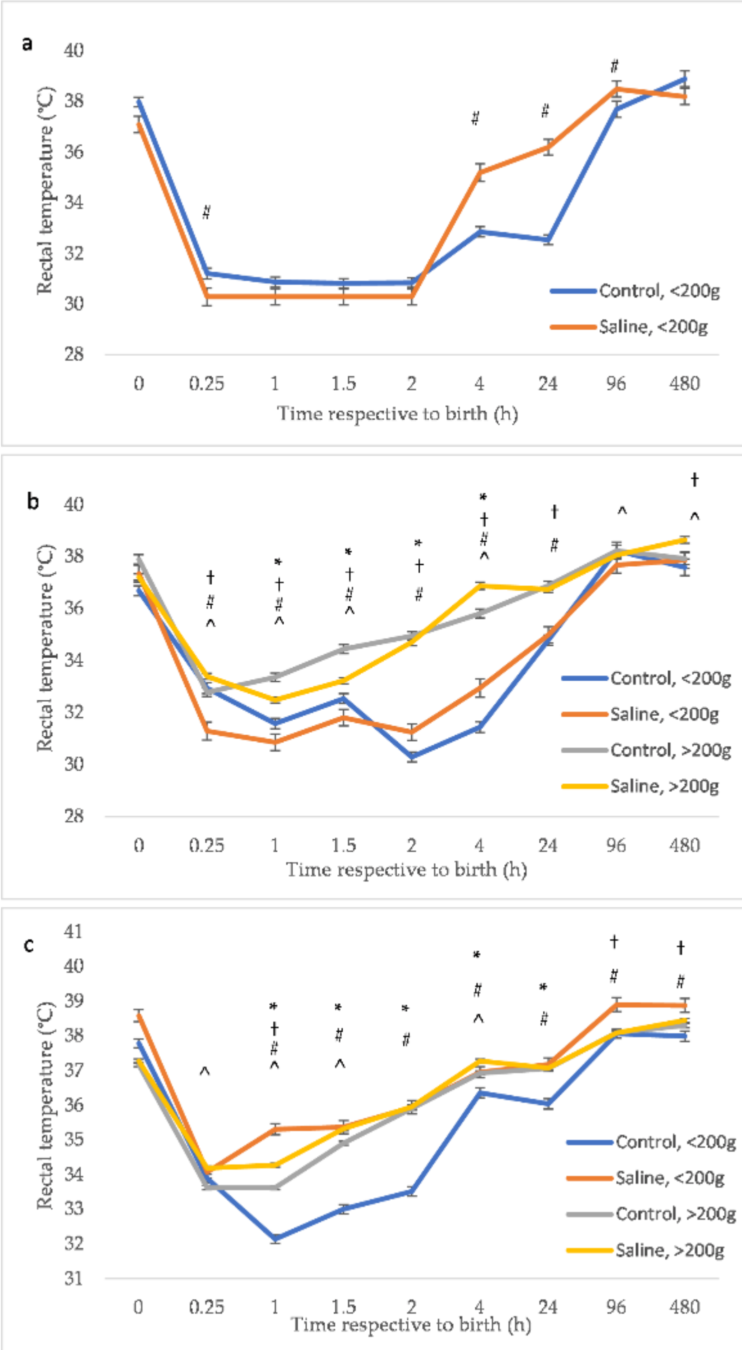

Figure 2. Mean ± standard error for the piglet rectal temperature for 13,330 piglet observations after bootstrapping at a root of 24, from birth to 20 days (480 h) within bodyweight category. (**a**) presents BWC1 (includes piglets with birth weights ≤0.8 kg). (**b**) presents BWC2 (includes piglets with birth weights 0.81–1.1 kg). (**c**) presents BWC3 (includes piglets with birth weights ≥1.2 kg). Piglets were control or received a saline injection and ingested less than or greater than 200 g of colostrum. Adjusted for parity. * Denotes a significant ($p < 0.05$) effect of colostrum consumption within control piglets control piglets. † Denotes a significant effect of colostrum intake within saline piglets. # Denotes a significant difference between treatment groups for piglets consuming < 200 g colostrum. ^ Denotes a significant treatment effect for piglets consuming >200 g colostrum.

3.2. Colostrum Intake

Medium weight piglets within RC1 and RC3 increased their colostrum intake when provided with warm saline ($p < 0.001$; Table 1). Heavier piglets showed a significant decrease in colostrum intake when in RC1 but an increase in the RC3 ($p < 0.001$). Unlike heavier piglets, lightweight piglets did not show a significant increase in colostrum intake either in the lowest ($p = 0.27$) or highest ($p = 0.77$) RC, due to large standard errors, although numerically they showed the same pattern of improvement as in the lowest rectal temperature category.

Table 1. Mean ± SE for predicted colostrum intake (g) based on piglet weight change in 1589 piglet observations after bootstrapping at a root of 24. Body weight category: BWC1; ≤ 0.80 kg, BWC2; 0.81 kg to 1.10 kg, and BWC3; >1.10 kg. Saline = intraperitoneal 45 °C saline injection. N = number of piglet observations per group.

Treatment			**RC1**		
	N	BWC1 = 37	BWC2 = 49	BWC3 = 116	**Overall**
Control	130	66.9 ± 34.2	−439.7 ± 40.1 [a]	76.86 ± 21.8 [a]	−39.2 ± 26.7
Saline	72	189.0 ± 105.0	142.3 ± 33.4 [b]	−135.9 ± 33.4 [b]	−4.04 ± 29.6
			RC2		
	N	BWC1 = 0	BWC2 = 39	BWC3 = 234	
Control	154	-	295.2 ± 52.0	175.9 ± 16.6	183.9 ± 19.9
Saline	119	-	254.1 ± 39.9	214.6 ± 20.2	217.2 ± 17.1
			RC3		
	N	BWC1 = 68	BWC2 = 174	BWC3 = 872	
Control	491	166.0 ± 57.3	−177.8 ± 28.7 [a]	237.4 ± 9.4 [a]	205.3 ± 10.05
Saline	623	189.0 ± 55.0	246.8 ± 17.2 [b]	351.0 ± 9.1 [b]	326.9 ± 4.96
Overall		119.7 ± 3.98	99.97 ± 13.0	251.1 ± 5.99	Na

[a-b] Denotes significance at $p < 0.001$ between treatments within BWC and RC.

3.3. Suckling Weight Gain

Lightweight piglets consumed less than 200 g and, if treated, had lower weight gains than control piglets ($p < 0.001$; Table 2). The opposite was evident for medium-weight piglets consuming sufficient colostrum, with treated piglets having increased weight gain ($p < 0.001$). Heavier piglets were not influenced by treatment regardless of colostrum intake ($p = 0.61$ and 0.27, respectively).

Table 2. Mean ± SE for suckling weight gain (kg) from 24 h to 20 d in 1274 piglet observations after bootstrapping at a root of 24. Body weight category: BWC1; ≤ 0.80 kg, BWC2; 0.81 kg to 1.10 kg, and BWC3; >1.10 kg. Saline = intraperitoneal 45 °C saline injection. N = number of piglets per group.

			***Colostrum Intake* < 200 g**		
	N	BWC1 = 36	BWC2 = 59	BWC3 = 115	**Overall**
Control	103	6.9 ± 0.37 [a]	-	5.5 ± 0.35	6.24 ± 0.90
Saline	107	5.3 ± 0.37 [b]	5.5 ± 0.35	5.6 ± 0.36	5.82 ± 0.05
			***Colostrum intake* ≥ 200 g**		
	N	BWC1 = 0	BWC2 = 123	BWC3 = 941	
Control	451	-	5.8 ± 0.36 [a]	4.7 ± 0.34	4.87 ± 0.03
Saline	613	-	6.5 ± 0.34	4.6 ± 0.33	5.02 ± 0.03
Overall		6.29 ± 0.07	6.13 ± 0.05	4.87 ± 0.02	

[a] Denotes significance at $p < 0.001$ between treatment within BWC and colostrum intake group.

3.4. Survival

Table 3 lists the survival of piglets to day 20 by BWC across treatment, sex, and colostrum intake. The BWC1 piglets injected with warm saline had an improved survival at 20 days from

11.7 to 100% despite none consuming more than 200 g of colostrum (p <0.001; Table 3). Sex indicated that females had lower survival than males particularly in BWC1. BWC2 piglets showed decreased survival with increased colostrum intake but BWC3 piglets showed the opposite.

Table 3. Percentages and respective 95% confidence intervals of survival rates from day 1 (24 h) to 20 days for 1589 piglet observations after bootstrapping at a root of 24. Body weight category: BWC = 1; ≤0.80 kg, BWC = 2; 0.81 kg to 1.10 kg, and BWC = 3; >1.10 kg. Saline = intraperitoneal 45 °C saline injection. N = number of piglet observations included.

<table>
<tr><th colspan="2">Parameter</th><th>N</th><th>BWC1 = 105</th><th>BWC2 = 262</th><th>BWC3 = 1222</th><th>Overall</th></tr>
<tr><td rowspan="2">Treatment</td><td>Control</td><td>753</td><td>11.7 (8.4–15.0)</td><td>74.4 (68.9–79.3)</td><td>72.5 (69.8–75.0)</td><td>73.3 (71.7–74.8)</td></tr>
<tr><td>Saline</td><td>814</td><td>100 (95.0–100.0)</td><td>78.4 (74.8–81.6)</td><td>90.6 (89.3–91.8)</td><td>88.3 (87.2–89.4)</td></tr>
<tr><td rowspan="2">Sex</td><td>F</td><td>750</td><td>50.0 (43.2–100.0)</td><td>67.4 (62.5–72.0)</td><td>82.7 (80.6–84.6)</td><td>79.8 (78.3–81.2)</td></tr>
<tr><td>M</td><td>839</td><td>100 (96.0–100.0)</td><td>83.6 (79.8–86.8)</td><td>84.2 (82.4–85.9)</td><td>81.6 (80.3–82.9)</td></tr>
<tr><td rowspan="2">Colostrum Intake</td><td>< 200 g</td><td>335</td><td>100 (96.0– 100.0)</td><td>84.7 (80.3–88.2)</td><td>78.1 (74.7–81.2)</td><td>71.5 (69.0–74.0)</td></tr>
<tr><td>≥ 200 g</td><td>1254</td><td>-</td><td>62.6 (61.5–69.6)</td><td>87.7 (86.7–88.6)</td><td>83.1 (82.0–84.1)</td></tr>
<tr><td colspan="2">Overall</td><td></td><td>100 (95.0–100.0)</td><td>76.5 (73.0–79.6)</td><td>83.5 (81.9–84.9)</td><td>NA</td></tr>
</table>

Table 4 lists the survival of piglets to day 20 by RC across BWC treatment, sex and colostrum intake category. No lightweight piglets (BWC1) had rectal temperatures within the medium (RC2) and high range (RC3) at 1.5 h relative to birth (Table 4). Piglets that were injected with saline had greater survival at 20 days than all control piglets across relative temperature groups (Table 4). Female piglets with RC 1 survived less than male piglets from the same RC.

Table 4. Percentages and respective 95% confidence intervals of survival rates at 20 d for 1589 piglet observations after bootstrapping at a root of 24. RC = 1 temperature ≤ 32.0 °C, RC = 2; temperature 32.1 °C to 35.0 °C, and C = 3; temperature ≥35.1 °C. Body weight categories; BWC1; ≤0.80 kg, BWC2; 0.81 kg to 1.10 kg, and BWC3; >1.10 kg. Saline = intraperitoneal 45 °C saline injection. N = number of piglet observations included.

<table>
<tr><th colspan="2">Parameters</th><th>N</th><th>RC1 = 347</th><th>RC2 = 398</th><th>RC3 = 844</th><th>Overall</th></tr>
<tr><td rowspan="3">Body weight category</td><td>BWC1</td><td>105</td><td>13.78 (8.96–20.6)</td><td>-</td><td>-</td><td>52.3 (45.9–58.7)</td></tr>
<tr><td>BWC2</td><td>262</td><td>39.2 (32.2–46.6)</td><td>62.6 (52.9–71.3)</td><td>80.5 (76.6–83.8)</td><td>72.1 (69.5–74.8)</td></tr>
<tr><td>BWC3</td><td>1222</td><td>36.9 (31.3–42.8)</td><td>85.5 (825.3–88.2)</td><td>92.2 (91.0–93.3)</td><td>84.1 (83.0–85.1)</td></tr>
<tr><td rowspan="2">Treatment</td><td>Control</td><td>753</td><td>9.02 (0.01–14.2)</td><td>69.9 (64.6–74.8)</td><td>63.3 (48.9–75.7)</td><td>73.3 (71.7–74.8)</td></tr>
<tr><td>Saline</td><td>814</td><td>100 (95.0–100.0)</td><td>83.8 (79.5–87.3)</td><td>92.7 (87.1–96.0)</td><td>88.3 (87.2–89.4)</td></tr>
<tr><td rowspan="2">Sex</td><td>F</td><td>750</td><td>20.8 (16.5–25.8)</td><td>75.8 (69.7–81.1)</td><td>100 (95.0–100.0)</td><td>79.8 (78.3–81.2)</td></tr>
<tr><td>M</td><td>839</td><td>36.9 (30.9–43.3)</td><td>75.9 (70.1–80.9)</td><td>100 (95.0–100.0)</td><td>81.6 (80.3–82.9)</td></tr>
<tr><td rowspan="2">Colostrum intake</td><td><200 g</td><td>335</td><td>44.2 (38.3–50.3)</td><td>71.0 (62.2–78.5)</td><td>100 (95.0–100.0)</td><td>71.5 (69.0–74.0)</td></tr>
<tr><td>≥200 g</td><td>1254</td><td>16.2 (12.3–21.2)</td><td>80.1 (76.2–83.5)</td><td>100 (95.0–100.0)</td><td>83.1 (82.0–84.1)</td></tr>
<tr><td colspan="2">Overall</td><td></td><td>30.6 (27.5–33.8)</td><td>81.3 (79.0–83.6)</td><td>90.4 (89.5–91.3)</td><td>NA</td></tr>
</table>

We also noted that when modelling colostrum intake by treatment group in BWC1 piglets, mean colostrum intake was increased with the saline injection (control = 92.9 ± 3.4 g; saline = 189.0 ± 5.7 g). This presumably influenced their relative survivals.

4. Discussion

Thermoregulation is critical for newborn piglets; however, they have little energy reserves to rely on. Current mainstream strategies can enhance energy loss, limit colostrum intake, and/or have only short-term benefits [11,15,21]. Consequently, our objective was to test a method, based on treatment of hypothermic humans and companion animals, to maintain and or improve piglet internal temperature in the critical period after birth. Our data show that when administered saline was warmed to 45 °C, rectal temperatures in all BWC piglets were improved at certain critical time points in succession. Further, piglets receiving warm saline had improved colostrum intake and preweaning survival.

Injecting warm saline resulted in an increase in rectal temperature in BWC1 piglets at 2 h to 24 h after birth despite no BWC1 piglets consuming >200 g of colostrum, which is common in production. However, the 200 g recommended minimum average colostrum intake is based on the 'average' piglet. It is reasonable to suggest that the minimum would be lower in lower birth weight piglets and the 189 g consumed by treated BWC1 pigs was entirely adequate. It should also be mentioned that this performance indicator is reliant on a calculation based off of temperature and weight, both factors in the analysis [23]. Although this method is widely accepted and referred to it has the potential to increase error in these situations. We were unable to determine if there was an improvement from 0.25 h to prior to 2 h, as piglet temperatures dropped below 32 °C which was the minimum reading for the digital thermometer. BWC2 piglets who consumed < 200 g colostrum had improved rectal temperature between 2 and 4 h when injected, whilst piglets who consumed >200 g colostrum had a lower temperature from 1 to 1.5 h but higher at 4 h and 20 d compared to the non-injected BWC2 piglets. These results show how critical colostrum consumption was and that if sufficient colostrum was consumed by medium-sized piglets, then there was less need for internal temperature intervention. However, BWC3 consistently had lower rectal temperatures in piglets who consumed <200 g colostrum and received no saline injection than all other BWC3 piglets. This suggests that if BWC3 piglets who consumed < 200 g colostrum were provided with a warm saline injection, their rectal temperature could be sustained at a similar level to heavy piglets who consumed >200 g colostrum. Overall, these results show that for the more at-risk lightweight piglets, provision of a warm saline injection can increase rectal temperatures over time, and for larger piglets there was a greater colostrum–temperature interaction, which could be manipulated by providing this internal intervention.

As rectal temperatures increased so did colostrum intakes across BWC. Further, colostrum intake was greater in BWC2 piglets when provided the saline injection, as it was also in BWC3 piglets in RC3. Treated BWC1 piglets showed a numerically increased mean colostrum intake but the standard errors were larger, particularly those in RC1. This may be due to a subset of piglets within the low BWC, with a lower potential for survival regardless of reasonable intervention, which would be identifiable by other measures suggested in previous studies but not considered in this present study design [25,26]. Therefore, injecting warmed saline had not only improved rectal temperature but serendipitously also colostrum intake and/or potential for intake. Suckling weight gain was significantly higher in BWC1 and BWC2 piglets who did not receive the saline injection; however, the mean suckling weight gain for all piglets was within reasonable production standards. Therefore, injecting warm saline did not have a negative effect on growth to d 20. It could be suggested that the stress from additional handling and injecting could have disadvantaged the piglets, contributing to this lower weight gain. However, as no sham injection treatment group was used, this cannot be confirmed or denied.

The improvements in temperature resulted in markedly increased survival for the lightest piglets at 20 d and also for BWC3 piglets. Further, treatment increased survival across all RC but especially for low temperature piglets. Since saline is an easily absorbed fluid, it could be argued that this increase may also involve a potential rehydration effect, aiding their survival. However, in a preliminary study, we tested the effect of intraperitoneal injection of saline at about 39 °C, which we assume to represent hydration alone, on survival to 9 d, which resulted in higher mortality rates with 52 of 67 non-treated piglets and 34 of 62 treated piglets surviving (Tucker et al., unpublished data). Further, in the present study, the authors noted no clinical signs of dehydration. Although we acknowledge that the effect of hydration cannot be separated within this study design, findings of the preliminary study support our theory of the effect being predominantly a result of a temperature effect on the piglets.

Other studies have documented a similar increase in rectal temperature with interventions such as drying and warming under heat lamps. However, those studies did not show the same sustained improvement in survival unless environmental temperatures were far from ideal [4,15]. Our data showed an increase in survival in piglets from all rectal temperature categories at 1.5 h when injected with warm saline. We infer that this increase across body weight and rectal temperature categories suggests a greater sustained temperature improvement, reducing the amount of energy the piglets are required to mobilize, thus maintaining their critical stores and improving the rate of survival. This was further supported by the increased colostrum intake across BWC and RC, most notably in BWC1 piglets.

Colostrum is the key to having sufficient energy for thermoregulation and survival and growth [27,28]. Providing piglets with fresh colostrum directly by collection and feeding or assisting onto the teat to suckle is a direct way of ensuring colostrum intake and thus subsequent survival [29,30]. However, both collection and assisting are time consuming and difficult. As no easy and efficient collection method of colostrum collection from sows exists, such practices are rarely applied on farm. Alternatively, energy supplements are quick and easily accessible, often provided as a drench or easily administered via pump bottle as a supplement to suckling [13,31]. However, energy supplements can increase energy available for absorption of the piglet but reduce the available stomach space for consumption of colostrum, which is the goal of providing assistance to piglets for improved survival [11,13]. Therefore, assuming appropriate training, our internal intervention with warmed saline, which is simple and straight forward, to directly improve temperature whilst indirectly improving colostrum intake, may have higher potential for application in production.

Localized environmental (heat lamp) and external interventions (warming) are still viable and important methods for thermoregulation assistance. However, in environments that are less stable and/or ideal, they do not have the same capacity to directly improve piglet temperature and induce sustained indirect effects on growth and survival. Our study supports previous findings in that the lightest piglets should be targeted for warming interventions, although benefits were seen in larger piglets.

5. Conclusions

Temperature regulation is critical for survival of piglets of all sizes, and it is important to continue working on ways to improve and assist in regulation, especially in low-birth-weight piglets. Injecting saline at 45 °C could be a useful strategy to warm piglets and indirectly increase colostrum intake; however, the temperature of the saline must be monitored closely and thus training would be required. Injecting saline and other suggested strategies such as drying piglets, in addition to measuring rectal temperature, is time sensitive and manually intensive. The priority should be on maintaining and optimizing the whole environment with specific interventions such as these, reserved for compromised and low-birth-weight piglets.

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Institutional Review Board Statement: This experiment was performed in September and October 2021, at the University of Adelaide, Roseworthy piggery, SA, approved by the institutional Animal Ethics Committee (Approval number; S-2021-046). All procedures were carried out according to The Australian Code for the Care and Use of Animals for Scientific Purposes (National Health and Medical Research Council, 2013).

Data Availability Statement: Data available from the senior author on reasonable request.

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Conflicts of Interest: The authors declare no conflict of interest.

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Chapter 8:

General Discussion

Discussion

The central issue of low viability piglets is investigated in the studies included in this thesis, focusing on identifying and managing these piglets with a production application focus. The overall aim of this thesis was to determine if there was a way to better identify low viability piglets through their morphology and body temperature and thus more effectively manage them, allowing for earlier intervention and better distribution of time and resources for optimal production outcomes. The approach taken is illustrated in Figure 2.1, with the resulting studies including investigation into 1) morphological characteristics of piglets, 2) impact of sow farrowing performance on stillborn number and mortality, 3) piglet rectal and surface temperature changes over their first 24 h, 4) the validity of surface temperatures at different times under production conditions and, finally, 5) manipulating piglet survival by warming them with a warm intraperitoneal saline bolus.

Neonatal viability is influenced by many interrelated factors which can be difficult to identify early and monitor and so effectively intervene, especially in a species which has many offspring and is managed intensively. The viability of a sow's offspring in relation to subsequent performance and survival is a common benchmark in production and research outcomes. However, there is great inconsistency in terminology and characteristics used, especially in research, making interpretation and application of management outcomes questionable. This also contributes to the inaccurate identification of piglets with a predisposition to impaired survival and raises questions as to how applicable these outcomes are. Therefore, the aim of Chapter 3 was to determine if the morphological characteristics abdominal circumference and crown to rump length, used in humans and previously suggested as performance indicators in pigs, could be used in relation to survival (Loughna et al., 2009; Hales et al., 2013; Douglas et al., 2016). This chapter reports on the relationship of these morphological characteristics individually at birth and at 24 h and suggested that when considered alone are minimal indicators for survival, but that birth abdominal circumference could predict colostrum intake, which is a critical factor for viability. Additionally, we investigated the role of individual piglet abdominal circumference and crown to rump length in proportion to each other by comparing the level disproportion a piglet presented with at 24 h on their performance and survival. This showed that in smaller piglets the more disproportionate the piglet was the better was their performance and survival. These findings showed that not all small pigs are destined to die and that some are more responsive to interventions. Therefore, morphology may have greater predictive value than current methods of just weighing piglets and categorizing them as small, medium, or large. This method could be useful to better allocate farrowing house resources, however, it is time consuming and requires a certain level of accuracy and additional data compared to that commonly collected in production. Therefore, for a producer with less resources and time, a simpler identification method would be a more applicable approach.

Chapter 4 focused on the sow's impact on her piglet's starting viability demonstrated through the standard production benchmarks of stillborn numbers, piglet weight gain and preweaning mortality (PWM). It is well established that piglets of low viability are large contributors to PWM and are increasing as a result of greater piglet variation following selection for larger litters (Quiniou et al., 2002; Arango et al., 2006; Riddersholm et al., 2021). In turn, this increases the time and energy requirements of the sow in order to expel her piglets (Manu et al., 2017; Langendijk and Fleuren, 2018; Manu et al., 2019). As farrowing duration increased so did the incidence of stillborn and the likelihood of piglets experiencing dystocia (Cowart, 2007), which could decrease their viability at birth and thus their subsequent performance and survival. Recent research has identified the impact of sow feeding frequency as she transitions from gestation to lactation on the duration of her farrowing (Feyera et al., 2018; Gourley et al., 2020). However, these two studies presented conflicting results. Although both studies had large litter sizes, one showed a low mean farrowing duration and thus little effect, whereas the other study showed a longer mean farrowing duration and yet a significant reduction in stillbirths (Feyera et al., 2018; Gourley et al., 2020). We compared a simple one vs two feeds per day regime prior to farrowing to investigate if farrowing duration could be manipulated, and thus affect subsequent piglet survival and growth, as well as the impact on subsequent sow reproductive performance. It would be pertinent to test these strategies on a variety of farms and under different constraints to fairly present to producers results which are relevant to their systems. The findings of our study supported both previous studies as increasing feeding frequency did decrease farrowing duration although not as much as in the previous study of Feyera et al., (2018). Further, Chapter 4 demonstrated that feeding frequency and farrowing duration have a critical relationship to stillborn number in some sows with high farrowing durations. However, it also demonstrated that this is not necessarily true for all sows and the benefits of applying the increased feeding frequency is constrained by the practicality of manual feeding within normal production working hours.

Body temperature is a common measure of thermoregulatory function and one of the key predictors of piglet survival. Mmost commonly rectal temperature is used across species to identify health status. Piglets are exposed to a marked temperature decrease from the in utero to external environments and have limited energy reserves to rely on to survive (Kammersgaard et al., 2011; Andersen and Pedersen, 2016). Therefore, it was determined that a temperature characteristic such as temperature recovery may be simpler albeit more labour demanding than measuring piglet morphology (Chapter 3) to identify and monitor viability in the critical first 24 h. However, it was identified that repetitive rectal temperature recording could be stressful for the piglets as well as labour intensive, therefore, Chapter 5 was designed to investigate temperature recovery comparing surface and rectal measurements. This study was conducted under production conditions with minimal additional measures taken to control for external factors, unlike many thermal surface temperature research trials including the few performed on piglets (Chung et al., 2010; Mostaço et al., 2015). The purpose of this was to test the comparability of surface and rectal temperatures as a producer would apply in commercial practice. The findings of our study showed that rectal and surface temperatures were comparable (high agreeance) at some timepoints, however, there was a notably lower agreeance at birth and 24 hours suggesting that surface temperature is not indicative of internal temperature under certain conditions. At birth, piglet temperature is changing rapidly with exposure to the cooler environment, and they are also wet (Caldara et al., 2014; Vande Pol et al., 2020; Villanueva-Garcíaa et al., 2021), whereas at 24 h we proposed that there is greater variation reflecting a difference in remaining energy to thermoregulate. Despite the lack of correlation/agreeance, both surface and rectal temperatures were able to detect a significant difference between piglets that obtained sufficient colostrum, or not. However, surface temperature was not as sensitive to differences between piglets of different birthweights, whereas rectal temperature was able to indicate an increase in survival for low birthweight piglets if rectal temperature was above 32°C at 1.25 h post birth. These results led us to question how accurate surface temperature is under different conditions and if monitoring at different locations would produce improved results. Therefore, we built on these findings and investigated the accuracy of three different surface locations, including at the two least correlated timepoints (birth and 24 h).

Chapter 6 compared a piglet's eye, ear base and ear tip surface temperatures using the handheld camera to the rectal temperature at birth and 24 h. Within the literature, the eye is reported to be a good indicator of internal temperature across species, however, stress has been shown to impact temperatures recorded at this location in particular (Magnani et al., 2011; Vinkers et al., 2013; Herborn et al., 2015). Ear base is also reported to be relatively good, however, not as good as the eye, and the ear tip is not as supported by the literature but is a location more easily captured without piglet manipulation (Tabuaciri et al., 2012). Most previous surface temperature studies have been performed with pigs of more mature reproductive status and ages (reviewed by Soerensen and Pedersen, 2015) from which we know that surface temperature is related to age and growth (Zakari et al., 2021). Neonatal piglets are physiologically different to older pigs and are under high levels of stress in the first critical 24 h, in which they must compete with litter mates for limited resources (Herpin et al., 2002; Caldara et al., 2014; Muns et al., 2016). Therefore, we reasoned that the previously established surface temperature findings were not necessarily readily applicable to piglet recording and management. To properly compare these surface temperatures to rectal temperature, the automatically produced temperature reported by the handheld thermal camera was also compared to an algorithm extracted maximum temperature produced from the thermal image. As expected, the ear tip was the least accurate surface location in all comparisons performed due to its poorer blood circulation and, contrary to our assumption, was very difficult to accurately obtain due to piglet movement. The base of the ear and eye temperatures showed good repeatability across the automatic and algorithm extracted values indicating that the handheld camera was highly repeatable but only moderately correlated to rectal temperature. Despite these conclusions the limitations of surface temperature namely the effect of piglets being wet severely impacts the usefulness of infrared cameras for use as alternatives to rectal temperature especially soon after birth. From the findings of Chapters 5 and 6, we determined that the use of a handheld infrared thermal camera to measure surface temperature at the eye and base of ear are not appropriate under commercial production conditions, unless high environmental accountability is possible.

In addition to monitoring temperature, we investigated a novel method of manipulating temperature to improve thermal recovery and survival. As highlighted in Chapter 2, it is well established that there is a critical relationship between thermoregulation and colostrum intake due to the energy status of piglets. Previous research has focused on singular approaches to managing piglets by collecting and feeding colostrum or energy supplements, or externally warming piglets through drying or providing additional heated areas (Farmer et al., 1998;

Declerck et al., 2016; Muns et al., 2017; Cooper et al., 2019; Vande Pol et al., 2021). Colostrum is difficult to collect and store although it is the best supplement that can be given. Energy supplements provide an energy boost but take up valuable stomach space which counter acts the purpose of increasing energy to improve suckling success. Manually drying is effective but requires time and does not translate to improved survival under all environmental conditions (Vande Pol et al., 2021). Stationary heat sources are effective but rely on the piglet remaining within the area heated, which is away from the udder. Therefore, Chapter 7 was designed to mimic the standard human surgery practice of warming fluids prior to introduction to the body to help maintain body temperature and prevent intra- and post-operative hypothermia (Oshvandi et al., 2014; Campbell et al., 2015). A saline bolus was warmed to 45°C and injected intraperitoneally at 15 min post birth to determine if providing warmed saline could improve the temperature recovery time and subsequent survival of piglets. The findings showed that low birth weight piglets had improved rectal temperature, colostrum intake and survival when provided with the warm saline. We surmised that it is likely that the provision of warm saline to the smaller piglets who have higher heat loss and lower energy reserves were able to use less energy on thermoregulation and thus have more successful suckling bouts, so improving their survival. Further to this, heavier piglets also showed improvement in rectal temperature at 1.5 h and colostrum intake although not as notably. Although the effect of warming and hydration could not be separated by this study design it is reasonable to suggest from these findings that warmed saline administered via intraperitoneal injection is an effective method for improving lightweight piglet viability and is useful for producers able to provide individual care.

Challenges and Limitations

As with all pig experimental work dealing with early life and farrowing measures, we were greatly limited by the litter output of the sow on trial which, unless detailed foetal measures are taken by ultrasonography, provides no way to avoid an unknown litter size. To the limit sample size constraint, the scope of this thesis was low viability piglets, the traditionally smaller last-born piglets in each litter. To lessen the effects of these limitations, older sows were employed. Despite this, all experimental work carried out as part of this thesis was limited by these factors and so sample sizes were smaller than expected and so data manipulation through bootstrapping was necessary.

The study design in Chapter 7 did not investigate hydration and temperature effects independently as we were limited by available piglet numbers, resources, skilled personnel, and practicality. Intraperitoneal injection should only be performed by someone who is competent and trained. To separate hydration and temperature effects, a saline injection at body temperature would need to be administered to reproduce the hydration effect without reducing or increasing body temperature. However, as the piglet internal temperature is rapidly decreasing, by the time it took to draw up and position the piglet to administer the saline, the piglet internal temperature would have changed. To maintain the high quality and accuracy required for the intraperitoneal injection and administer the saline without having a negative effect on the piglet, this potential control treatment was not considered within the experimental design.

Further Research

The outcomes of this thesis add to the information available about the multifaceted management necessary to identify and manage low viability piglets. Further, it highlights the limitation of individual farm resources, especially labour and time, as well as infrastructure in the applicability of new management strategies. Despite the complexity of this area, this research generates questions and areas of further investigation to expand the knowledge on, and better identify, management protocols for low viability piglets within production. Potential areas for future development are outlined in this section.

The proportionality of a piglet's morphology was relatively effective at indicating likely survival and performance, particularly in smaller piglets (Chapter 3). Still, the study did not include piglets larger than 1.2 kg and was relatively small in terms of sample size. Further, the focus was on 24 h measures because birth measures are difficult to obtain accurately. However, abdominal circumference alone could be a different avenue to monitor colostrum intake on farms as an alternative to needing to calculate an estimate. Overall, measuring morphology is a labour-intensive process which could be performed and bring great benefit to future research into the success of management strategies. However, for producers, it is unlikely that they are able to spare adequate labour to measure all piglets at appropriate times. Therefore, as smart farming and monitoring systems are becoming more popular, an investigation into measuring morphology through algorithms in fixed cameras could provide a solution to this and a new avenue for piglet management.

Research from Chapter 4 adds to the evidence of the importance of transition sow management and its effects on piglet early survival. However, due to the sample size limitation of the study, the impact on an individual piglet rather than litter level was not investigated. A further look into the relationship between sow energy prior to farrowing and the influence of her farrowing progression on piglet viability, such as time to suckle, could further explain one of the potential causes of low viability piglets. There is limited research that considered the impact of management and nutritional changes on farrowing duration as it is difficult to monitor with limited labour and staffing hours. Therefore, research into basic and advanced monitoring systems for application to the farrowing crate would be a key area to improving the quality of subsequent research into sow manipulation and potentially increase the accuracy of interventions by production staff.

The use of surface temperature in neonatal piglets has been shown by the findings of Chapters 5 and 6 to be only moderately comparable to rectal temperature, contrary to previous research in older pigs. This is likely due to the environment having a significant influence on measurements. Therefore, it may be appropriate for use as a research tool where greater control can be applied and more variables measured and accounted for, but not in commercial production. The use of smart thermal technology is an area of great potential and, therefore, is an area to further investigate. Investigating the use of fixed monitoring systems which can record temperature as well as environmental conditions such as humidity could produce a readily usable method for monitoring surface temperatures repetitively without needing to repeatedly handle the piglets, reducing labour requirements for monitoring. Furthermore, the findings from Chapter 6 highlighted that ear base and eye are potential thermal windows even at the more variable time points (birth and 24 h). However, despite these results we would also consider that other less researched methods, such as wearable temperature monitors, may be of interest for future research, allowing for a more targeted approach for group application such as small or sickly pigs.

Research concerning both temperature and energy manipulation should be undertaken as litter size continues to grow at a rate greater than of colostrum yield. The findings from Chapter 7 showed that warming by intraperitoneal saline injection can increase body temperature in neonatal piglets and thus potentially translate to better survival. However, this is considering only one aspect of the critical relationship between temperature, energy, and colostrum intake. Therefore, it is imperative that future research investigate that if warming of the energy supplement or colostrum could be of more benefit to the piglet than just providing it as available and how this compares to providing a warm intraperitoneal bolus.

Conclusions

Viability is a complicated indicator to define and monitor and so it's' use as a research and production benchmark is confusing and inconsistent. The experimental findings of this thesis provide further understanding of different methods for identifying and managing low viability piglets thus achieving the overarching aim of this thesis. These studies provide multiple avenues for future research into industry applicable ways to early identify and appropriately apply limited resources such as time.

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