

THE USE OF PULMONARY ARTERIAL PRESSURE FOR IMPROVED BEEF CATTLE
MANAGEMENT BY MODELING RELATIONSHIPS WITH PULMONARY ARTERIAL
PRESSURE AND PERFORMANCE, MATERNAL, AND CARCASS TRAITS

by

Kaylen Ann Stearns

A thesis submitted in partial fulfillment
of the requirements for the degree

of

Master of Science

in

Animal and Range Science

MONTANA STATE UNIVERSITY
Bozeman, Montana

August 2025

©COPYRIGHT

by

Kaylen Ann Stearns

2025

All Rights Reserved

DEDICATION

To my late Grandpa Dewane Stearns, a hardworking cattleman who loved his family, ranch, and cattle. He was a true example of grit, determination, and resilience.

ACKNOWLEDGEMENTS

First and foremost, thank you to my advisor, Dr. Tim DelCurto. I am so grateful for the opportunity to learn from you these past two years. You have provided me with knowledge and wisdom that I will take with me for the rest of my life. Dr. Hannah DelCurto-Wyffels, thank you for being one of my most important mentors, providing me with opportunities that push me out of my comfort zone, and allowing me to discover how much I truly enjoy teaching students. I appreciate all your advice, ideas, and daily office chats more than you'll ever know. Dr. Sam Wyffels, thank you for providing great advice on not only animal science and research, but also life. My project wouldn't have been possible without your wealth of knowledge, especially in statistics. Dr. Megan Van Emon, thank you for all the help with publishing papers, edits, and popping into the grad office to provide us with a good laugh whenever you're in town.

A special thank you to Sitz Angus for the opportunity to use their bull data to research heart-lung function. It was a dream come true to work with a premier seedstock operation. Thank you to Taylre and the rest of Sitz crew for entrusting me with such an exciting project.

To Amanda Grude, Caroline Gatschet, Jack Nance, Blaire Westby, and Tucker Lytton, thank you each for the support, encouragement, and help that you each provided. I am so thankful that I got to experience MSU with all of you. Blaire and Tucker, thank you for every minute you spent helping at the feedlot, I appreciate all your dedication and sacrifices.

To Mom and Dad, thank you for allowing me to chase my dreams, showing me the value of hard work, and immersing me within animal agriculture. To Jared and Jana, two of the funniest people I know, thank you for the constants laughs and reminders to never take life too seriously. I am so grateful for the support of everyone who has helped me get to this point.

TABLE OF CONTENTS

1. GENERAL INTRODUCTION	1
2. THE USE OF PULMONARY ARTERIAL PRESSURE (PAP) FOR IMPROVED BEEF CATTLE MANAGEMENT	4
Contribution of Authors and Co-Authors	4
Manuscript Information.....	5
Simple Summary	6
Abstract	6
Introduction	7
History	8
Economic Impact.....	9
Increased Susceptibility of HAD in Bovine	10
Measuring Pulmonary Arterial Pressure.....	11
Interpreting PAP Scores.....	12
Factors Impacting PAP Score Variations	13
Concerns at Moderate Elevations	16
Alternative Methods of Measuring PAP.....	17
Inheritance of PAP	18
PAP Scores as an EPD.....	19
Relationship between PAP Scores and Economically Relevant Traits.....	20
PAP Scores and Gestation Length.....	20
PAP Scores and Birth Weight.....	21
PAP Scores and Weaning Weight.....	23
PAP Scores and Yearling Weight	23
PAP Scores and Carcass Traits.....	24
Future Research	25
Conclusions	26
References	27
3. EVALUATING PULMONARY ARTERIAL PRESSURE IN ANGUS YEARLING BULLS AT HIGH ELEVATION: ASSOCIATIONS WITH BIRTH TRAITS AND GROWTH PERFORMANCE.....	32
Contribution of Authors and Co-Authors	32
Manuscript Information.....	34
Simple Summary	35
Abstract	35
Introduction	36
Materials and Methods	38
Results	43
Modeling Analysis	43

Sire Line Progeny Analysis.....	48
Dam Sire Line Progeny Analysis.....	52
Discussion	55
Conclusions	57
References	59
 4. RELATIONSHIP OF YEARLING ANGUS BULL PULMONARY ARTERIAL PRESSURE SCORES WITH PRODUCTION, MATERNAL, AND CARCASS EXPECTED PROGENY DIFFERENCES	 63
Contribution of Authors and Co-Authors	63
Manuscript Information.....	65
Simple Summary	66
Abstract	66
Introduction	67
Materials and Methods	69
Operation A.....	69
Operation B.....	70
Pulmonary Arterial Pressure Test.....	70
Data Collected.....	70
Statistical Analysis	71
Results	74
Discussion	79
Conclusions	82
References	83
 5. CONCLUSION	 86
Conclusion and Summary	86
Future Research Directions	88
REFERENCES CITED	89

LIST OF TABLES

Table	Page
1. Table 2.1. Risk Categories for HAD based on PAP score.	12
2. Table 3.2. Model selection for evaluating the nature (linear, asymptotic, or quadratic) of the relationship between PAP and performance metrics, gestation length, and birth weight on 12 to 18-month-old purebred Angus bull PAP scores.	41
3. Table 3.3. Model selection for evaluating the effects of performance metrics, gestation length, birth weight, fall versus spring sale, and associated interactions on 12 to 18-month-old purebred Angus bull PAP scores.	42
4. Table 3.4. Influence of five registered Angus dam sire lines on mean grand progeny PAP scores, the range of PAP scores, and the coefficient of variation for 1135 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA.	53
5. Table 4.1. Expected Progeny Differences evaluated within this study. Groups and abbreviations are according to the American Angus Association.	71
6. Table 4.2. Model selection for evaluating the nature (linear, asymptotic, or quadratic) of the relationship between PAP and production, maternal, and carcass EPDs on 12–18-month-old Angus bulls.	72
7. Table 4.3. Model selection for evaluating the effects of production, maternal, and carcass EPDS, fall versus spring sale, and associated interactions on 12 to 18-month-old purebred Angus bull PAP scores.	73

LIST OF FIGURES

Figure	Page
1. Figure 2.1. This heifer has High Altitude Disease. The noticeable edema begins at her head and continues down through her brisket—Photo Courtesy of Dr. Tim Holt, Colorado State University.	8
2. Figure 2.2. Factors that might influence beef cattle Pulmonary Arterial Pressure (PAP) estimates (adapted from Holt and Callan, 2007).	16
3. Figure 3.1. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and gestation lengths for 485 eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. This relationship was best described by an asymptotic model ($P < 0.01$; $\beta = 33.74 \pm 11.25$).	43
4. Figure 3.2. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and birth weight for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P > 0.01$; $\beta_{\text{Fall Sale}} = 3.04 \pm 0.82$, $\beta_{\text{Spring Sale}} = 2.91 \pm 0.81$) The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B.	44
5. Figure 3.3. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and birth to weaning growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P=0.05$; $\beta = -1.29 \pm 0.65$).	46
6. Figure 3.4. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and weaning to yearling growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P = 0.02$; $\beta = -1.21 \pm 0.54$).	47
7. Figure 3.5. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and weaning to yearling growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P < 0.01$; $\beta = -2.48 \pm 0.90$).	48

8. Figure 3.7. Mean PAP scores of sires with >100 progeny within the data set. Compact letter displays indicate the differences between mean PAP scores of progeny ($P < 0.01$)..... 51
9. Figure 3.8. Mean PAP scores of dam sires (progeny's maternal grandsire) with >100 progeny within the data set. Statistically mean PAP scores of progeny tended to be different ($P = 0.09$). 54
10. Figure 4.1. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and CED EPD. This relationship was best represented by a log transformed model. Calving Ease Direct is expressed as a difference percentage of unassisted births, with a higher value indicating greater calving ease in first-calf heifers. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B..... 75
11. Figure 4.2. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and BW EPD. This relationship was best represented by a log transformed model. The BW EPD is expressed in pounds and predicts the sire's ability to transmit birth weight to his progeny. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B..... 76
12. Figure 4.3. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and WW EPD. This relationship was best represented by a log transformed model. The WW EPD is expressed in pounds and predicts the sire's ability to transmit weaning weight to his progeny. There was no difference between the two sales..... 77
13. Figure 4.4. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and YW EPD. This relationship was best represented by a log transformed model. The YW EPD is expressed in pounds and predicts the sire's ability to transmit yearling weight to his progeny. There was no difference between the two sales..... 78
14. Figure 4.5. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and CW EPD. This relationship was best represented by a log transformed model. The CW EPD is expressed in pounds and the difference in hot carcass weight of a sire's progeny compared to the progeny of other sires. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B..... 79

ABSTRACT

Pulmonary arterial pressure (PAP) determines an animal's susceptibility to High Altitude Disease (HAD) which causes pulmonary hypertension due to hypoxia. It is estimated that 1.5 million head of cattle are raised in high altitude environments (above 1500 m) and HAD accounts for 3-5% of calf death loss yearly. Study 1 modeled the relationship of PAP estimates with gestation length, birth weight, and grow traits of developing bulls. Additionally, it compared mean PAP scores of the most common sire and grandsire lines from progeny within the data set. Study 2 modeled the relationship of PAP estimates with production, maternal, and carcass expected progeny differences (EPDs). For both studies, bull PAP estimates were collected from Angus yearling bulls ranging in age from 5400 12–18-month-old bulls from 2016-2023 from a Montana-based Angus operation. In study 1, increased gestation lengths showed increased PAP scores ($P < 0.01$). Bulls with greater birth weight had greater PAP scores ($P < 0.01$). There was no observed relationship between bull PAP and weaning weight ($P = 0.26$). Additionally, PAP was negatively correlated to yearling weight ($P = 0.04$). Bulls with greater birth-to-weaning gains had decreased PAP scores ($P = 0.05$). Increased weaning-to-yearling gains had lower PAP scores ($P = 0.02$). Greater birth-to-yearling growth had lower PAP scores ($P < 0.01$). Sire lines influenced offspring PAP scores ($P < 0.01$), and dam sire lines tended to have an effect on offspring PAP scores ($P = 0.09$). In study 2, bulls with greater calving ease direct had lower PAP scores ($P < 0.01$). Bulls with greater birth weight EPDs had increased PAP scores ($P < 0.01$). The weaning weight EPD was positively correlated to PAP scores ($P < 0.01$). Increased yearling weight EPDs had greater PAP scores ($P < 0.01$). Bulls with greater PAP had increased carcass weight EPDs ($P = 0.03$). There were no observed relationships ($P \geq 0.17$) between bull PAP and scrotal circumference, maternal milk, ribeye area, or marbling EPDs. In summary, PAP was related to many performance traits and production EPDs, however these relationships explain very little of the variation in PAP estimates.

CHAPTER ONE

GENERAL INTRODUCTION

High Altitude Disease (HAD) is a noninfectious disease that impacts cattle, mainly in elevations above 1500 m.(Holt 2019) This disease goes by a variety of names including Brisket Disease, High Mountain Disease (HMD), and Right-sided Heart Failure (RHF) (Holt and Callan 2007). The stress from the lack of oxygen and hypoxic conditions causes pulmonary vasoconstriction and hypertension (Markel 2023). Eventually, cattle will be sent into cardiac failure due to reduced heart-lung function (Markel 2023). There is no treatment or cure and the only recommendation is to move effected cattle to lower elevations (Glover and Newsom 1914).

Approximately, 1.5 million head of cattle reside in high elevation environments in the United States (Williams, Bertrand et al. 2012). It is estimated that there is a 3-5% calf death loss, annually which translates to 75,000 head and USD 60 million lost, annually due to HAD (Holt and Callan 2007, Williams, Bertrand et al. 2012). However, there continues to be a growing concern of this disease in elevations below 1500 m especially in feedlot cattle (Neary, Garry et al. 2015). Those cases of this disease below 1500 m are considered RHF (Neary, Garry et al. 2015). Feedlots have reported that cases of RHF have nearly doubled since 2000 with a high frequency reported in Angus cattle (Neary, Garry et al. 2015). Mortality is estimated to be 11 out of every 10,000 head (Heaton, Bassett et al. 2019). It is important to note that this also comes at a time when carcass weights have reached an all-time high (Thomas, Krafur et al. 2017)

Cattle are at an increased risk for HAD for several reasons. The lack of oxygen causes pulmonary vascular shunting (Heath, Castillo et al. 1969). Pulmonary vascular shunting moves blood flow in the body from areas of low oxygen concentration to areas of higher concentration

(Alexander and Jensen 1963). Additionally, the bovine lung has a small lobulated anatomical pattern and is considered small compared to its body weight ratio (Veit and Farrell 1978). All of these factors make cattle more likely to experience pulmonary hypertension which causes the hypertrophy and dilation of the right ventricle (Alexander 1962, Holt and Callan 2007).

To help mitigate the risk of an animal developing HAD, pulmonary arterial pressure (PAP) scores are used to determine an animal's susceptibility to HAD (Holt and Callan 2007). Through a right-heart catheterization process, a PAP test measures the resistance of blood flow through the lungs (Shirley, et al. 2008). Scores will range from 34 millimeters of mercury (mmHg) to greater than 50 mmHg, and lower scores are more desirable (Holt and Callan 2007). Seedstock producers use PAP scores as a way to market their cattle to those who put an increased emphasis on heart-lung function within their cattle herd (Stearns, 2024)

For the past four decades, selection for growth and performance in Angus cattle has continually trended upward (Pauling, Speidel et al. 2023). There have been concerns that increasing growth and performance has also caused an increase in PAP scores. It is crucial to determine relationships between PAP and these traits because these are economically relevant traits that producers rely on for profit. Several studies have been conducted between PAP and these economically relevant traits; however, these studies have yielded conflicting results.

The objective of this research was to model the relationship of PAP estimates with Angus bull maternal, growth, and carcass traits using both actual performance data and expected progeny differences (EPDs) as calculated by the American Angus Association (AAA). The results of this research will provide beef cattle producers with a practical understanding of the

relationship between PAP estimates and economically important traits to allow producers to make informed breeding decisions.

CHAPTER TWO

THE USE OF PULMONARY ARTERIAL PRESSURE (PAP) FOR IMPROVED BEEF CATTLE MANAGEMENT

Contribution of Authors and Co-Authors

Author: K. Stearns

Contributions: Conceptualization, Methodology, Investigation, Writing-original draft preparation, Writing- review and editing, Supervision, and Visualization Creation

Co-Author: H. DelCurto-Wyffels

Contributions: Conceptualization, Methodology, Investigation, Writing-review and editing, Supervision, and Project Administration

Co-Author: S. Wyffels

Contributions: Conceptualization, Methodology, Investigation, and Writing- reviewing and editing

Co-Author: M. Van Emon

Contributions: Investigation and Writing- review and editing

Co-Author: T. DelCurto

Contributions: Conceptualization, Methodology, Investigation, Writing- reviewing and editing, Resource Curation, Visualization Creation, Supervision, and Funding Acquisition

Manuscript Information

Kaylen Stearns, Hannah DelCurto-Wyffels, Sam Wyffels, Megan Van Emon, and Tim DelCurto

Animals

- ☐ Prepared for submission to a peer-reviewed journal
- ☐ Officially submitted to a peer-reviewed journal
- ☐ Accepted by a peer-reviewed journal
- ☒ Published in a peer-reviewed journal

Multidisciplinary Digital Publishing Institute

Published: August 22, 2024

Animals 2024, 14(16), 2430

DOI: 10.3390/ani14162430

Simple Summary

An estimated USD 60 million is lost annually due to High Altitude Disease in the cow–calf industry, and there continues to be a growing concern about heart–lung function in feedlot cattle located at moderate elevations. As the cattle industry puts more emphasis on and focuses on heart–lung function, it is valuable to provide a review of past research and information gaps regarding pulmonary arterial pressure (PAP) and its use in the beef cattle industry.

Abstract

Pulmonary arterial pressure (PAP) determines cattle’s susceptibility to High Altitude Disease (HAD), also known as Brisket Disease, High Mountain Disease, and right-sided heart failure (RHF). This non-infectious disease causes pulmonary hypertension due to hypoxia. PAP measures the resistance of blood flow through the lungs. It is estimated that 1.5 million head of cattle are raised in high-altitude environments (above 1500 m) and HAD accounts for 3–5% of calf death loss yearly. In addition, there have been increasing concerns about feedlot cattle succumbing to RHF at moderate elevations. This review focuses on the historical background, explanation of PAP measurement and scores, genetic implications, and the relationship between PAP and economically relevant traits. Specifically, traits such as gestation length, birth weight, weaning weight, and yearling weight may impact PAP scores. In addition, environmental effects and other factors impacting PAP score variations are discussed. Information gaps and research needs are addressed to determine where missing information could improve the understanding of PAP while also benefiting beef cattle producers in high-elevation production systems.

Introduction

High Altitude Disease (HAD) is a non-transmissible, non-infectious disease that impacts beef cattle production at elevations above 1500 m due to low oxygen saturation in the atmosphere (Holt, 2019). High Altitude Disease is also known as Brisket Disease, right-sided heart failure (RHF), and High Mountain Disease (HMD) (Holt & Callan, 2007). The stress from the lack of oxygen can cause the animal to develop HAD (Holt, 2019). High Altitude Disease causes hypoxic pulmonary vasoconstriction, and eventually, the animal will be sent into cardiac failure due to reduced heart–lung function (Markel, 2023). The progression of this disease begins with alveolar hypoxia, then pulmonary vasoconstriction, which leads to pulmonary remodeling and eventually turns into pulmonary hypertension (Holt, 2019). Eventually, hypertrophy of the right ventricle will occur, which causes dilation of the right ventricle, and this leads to right-sided heart failure (Holt, 2019). Clinical signs of HAD include brisket edema, lethargy, jugular vein distention, diarrhea, poor appetite, and death (Figure 1) (Glover & Newsom, 1914). While RHF is most common among cattle, left-sided heart failure can also occur. Left-sided heart failure presents clinical signs of respiratory stress, such as dyspnea and cough, due to the overload of the pulmonary circulation system (De Morais HA, 2005). However, the cardiovascular system is a closed circuit, so no matter which side of the heart fails first, eventually, it becomes bilateral heart failure (Ivany & Illanes, 1999). Pulmonary arterial pressure (PAP) scores were developed to determine an animal's susceptibility to HAD (Holt & Callan, 2007). Pulmonary arterial pressure scores measure the resistance of blood flow through the lungs (Shirley et al., 2008). Beef cattle producers in high-elevation production systems have used PAP scores for several

decades as a guide to make management decisions and determine an animal's survivability in high-elevation environments (Cockrum et al., 2014; Enns et al., 1992; Shirley et al., 2008).



Figure 2.1. This heifer has High Altitude Disease. The noticeable edema begins at her head and continues down through her brisket—Photo Courtesy of Dr. Tim Holt, Colorado State University.

History

Cattle exhibiting clinical signs of what is now known as HAD were first reported in 1914 by Glover and Newsom (Glover & Newsom, 1914) in Colorado. In 1913, Glover and Newsom were chosen by cattle ranchers in Colorado to explore what ranchers called Dropsy, or HMD (Rhodes, 2005). These cattle resided in areas of high elevation (2743–3048 m) in Colorado (Glover & Newsom, 1914). The cattle displayed the same clinical signs of edema, poor appetite,

dull appearance, lethargy, and death that are used to describe HAD currently (Glover & Newsom, 1914).

Following two years of research, Glover and Newsom reached several conclusions about this physiological disease that are still held today (Rhodes, 2005). The first conclusion was that altitude was the main cause of HAD (Glover & Newsom, 1914). Secondly, cattle who were transported from low elevations to high elevations were more susceptible, and these cattle should be gradually introduced to higher altitudes (Glover & Newsom, 1914). From a physiological standpoint, Glover and Newsom concluded that the hearts of cattle who were diagnosed with HAD were overworked (Glover & Newsom, 1914). Thus, Glover and Newsom (1914), recommended that cattle experiencing these symptoms be moved to lower elevations. The same recommendation still exists for cattle exhibiting similar symptoms today (Markel, 2023). Glover and Newsom (1914) recommended using native bulls who were suited for the high elevations as herd sires to improve the “hardiness of the herd.” From these observations, Glover and Newsom made the assumption that an animal’s susceptibility to HAD was heritable (Glover & Newsom, 1914).

Economic Impact

In 2012, it was estimated that 1.5 million head of cattle were raised in high-altitude environments (Williams et al., 2012). High Altitude Disease accounts for 3–5% of calf death loss in high-elevation production systems yearly (Holt & Callan, 2007). Given these figures, it is reported that HAD costs the cattle industry approximately USD 60 million each year, with an estimated loss of 75,000 head of cattle (Williams et al., 2012). Research has shown that by evaluating PAP scores when selecting and retaining breeding stock, producers can help mitigate

the risk of cattle developing HAD by selecting animals that are better suited for production systems at high elevations (Shirley et al., 2008).

Increased Susceptibility of HAD in Bovine

Pulmonary vascular shunting occurs as a response in all animals to hypoxic conditions (Holt & Callan, 2007) and is described as persistent exposure of the pulmonary vasculature to increased pressure, which will result in severe pulmonary vascular disease (Heath et al., 1969). Pulmonary vascular shunting acts to move pulmonary blood flow away from poorly oxygenated tissues in the lung to tissues with a higher oxygen content (Alexander & Jensen, 1963). Comparing pulmonary vascular shunting across species revealed that cattle experienced the greatest shunting across the tested species of llamas, dogs, and cats (Heath et al., 1969).

The bovine pulmonary system is relatively small compared to its body weight and has a smaller lobulated anatomical pattern, which makes it more likely to suffer from severe pulmonary hypertension and loss of function (Veit & Farrell, 1978). The increase in pulmonary vascular shunting, combined with the anatomical features of the bovine lung, makes cattle much more susceptible to pulmonary hypertension caused by hypoxia (Alexander & Jensen, 1963; Holt & Callan, 2007). Pulmonary vascular shunting will eventually lead to the remodeling of pulmonary arteries caused by hypertrophy and muscularization (Alexander, 1962; Alexander & Jensen, 1963). The increased resistance will cause a loss of function within the peripheral pulmonary arteries (Alexander & Jensen, 1963). These changes within the pulmonary system cause hypertrophy and dilation of the right ventricle, which is followed by RHF (Alexander, 1962; Holt & Callan, 2007).

Measuring Pulmonary Arterial Pressure

A pulmonary arterial pressure (PAP) score measures the resistance of blood flow through the lungs (Shirley et al., 2008). Similar to human blood pressure, PAP is measured in millimeters of mercury (mmHg) (Holt & Callan, 2007). Scores will range from 30 mmHg to >50 mmHg, with lower scores being more desirable (30–40 mmHg) (Holt & Callan, 2007). For accurate measurements, PAP scores should be taken at elevations of at least 1500 m and after cattle have spent at least three weeks residing at 1500 m to induce hypoxic conditions (Holt & Callan, 2007; Speidel et al., 2020). The accuracy of the test can be improved by residing at elevations greater than 1500 m for longer than 3 weeks (Holt & Callan, 2007). Cattle should be greater than 12 months of age when tested to reduce variation, as it has been shown PAP scores will increase as an animal matures (Holt & Callan, 2007; Neary et al., 2015; Will et al., 1975). Therefore, the scores of animals who are tested at younger than 12 months of age are an inaccurate representation of the animal's true PAP score (Holt & Callan, 2007).

Pulmonary arterial pressure measurements are performed through a chute-side, right-sided heart catheterization procedure by inserting a flexible catheter into the jugular vein (Ahola et al., 2006). The animal should be properly restrained within a squeeze chute, and the head should also be restrained (Holt & Callan, 2007). It is important to note that the chute should not be squeezed too tight to ensure accurate results (Holt & Callan, 2007). The pressure within the jugular vein is first measured (Holt & Callan, 2007). For normal animals at 1500 m and above, the pressure within the jugular vein should be within 6–12 mmHg (Holt & Callan, 2007). The catheter is passed through the right atrium and into the right ventricle (Holt & Callan, 2007). Another measurement is taken with the right ventricle (RV), known as the RV measurement

(Holt & Callan, 2007). In healthy animals at 1500 m and above, the RV measurement should range from 18–30 mmHg (Holt & Callan, 2007). Finally, the catheter reaches the pulmonary artery, where the PAP measurement is taken (Holt & Callan, 2007). The mean PAP (mPAP) score is then measured from the pressure transducer connected to the end of the catheter in the pulmonary artery by measuring and taking the average of both the diastolic and systolic pressures (Ahola et al., 2006).

Interpreting PAP Scores

Based on PAP scores and the elevation of the operation, some animals may be better suited for higher-elevation production systems compared to others. The mean PAP score can be used to determine the animal's risk for developing HAD (Table 1). Holt and Callan (2007) recommend that animals who have a PAP score of less than 41 mmHg at greater than 12 months of age can be retained as breeding stock (Holt & Callan, 2007). Animals with a PAP score of greater than 49 mmHg at any age should not be retained in high-elevation production systems (Holt & Callan, 2007). Cattle with PAP scores between 41 mmHg and 49 mmHg should be closely observed and used with caution in high-elevation operations (Holt & Callan, 2007). Cattle at risk of developing HAD residing in high elevations will have PAP scores between 48 and 213 mmHg (Holt & Callan, 2007).

Table 2.1. Risk Categories for HAD based on PAP score.

Mean PAP Score	Low Elevations (<1219m)	Moderate Elevations (1219-1524 m)	High Elevations (1524-2286 m)	Extreme Elevations (> 2286 m)
34-45 mmHg	Low Risk	Low Risk	Low Risk	Low Risk
46-49 mmHg	Moderate Risk	Moderate Risk	Moderate Risk	Moderate Risk
>50 mmHg	Moderate Risk	Moderate Risk	High Risk	High Risk

Markel, 2023, Adapted from Holt and Callan, 2007.

Factors Impacting PAP Score Variations

Several factors can influence PAP scores (Figure 2). When selecting and retaining breeding stock, Holt and Callan recommend considering several factors. While it has been shown that all breeds have cattle that vary greatly in PAP scores and all have animals with high PAP scores (>50 mmHg), some genetic lines within breeds perform better in high-elevation environments and have more desirable PAP scores (Holt & Callan, 2007). A case study at the San Juan Basin Research Center 4 Corners Bull Test evaluated the factors influencing PAP across ten different breeds (Crawford et al., 2017). It was shown that breed ($P < 0.001$) was an important factor for considering variations in PAP scores (Crawford et al., 2017). Simmental bulls were shown to have the highest mPAP scores (53.1 ± 2.1) (Crawford et al., 2017). The authors attribute this result to the uniqueness of the Simmental bulls consigned to the bull test (Crawford et al., 2017). In addition, the authors also found this result surprising due to the fact that Simmental cattle originate from Switzerland, and it would be expected that this breed would be adapted to high-elevation environments (American Simmental Association, 2014). Hereford Bulls and Polled Hereford Bulls had the lowest mPAP scores at 42.3 ± 0.4 and 42.3 ± 0.8 , respectively (Crawford et al., 2017). However, another study conducted in 2020 showed that a cross between Angus and Red Angus cattle had the highest mPAP (González-Murray et al., 2020). A comparison study between Angus and Salers cattle showed there are specific single nucleotide genomic polymorphisms (SNP) responsible for the genetic diversity that increases resilience to HAD (Krehbiel et al., 2017). Angus cattle in this study were sorted into a low PAP group (<41 mmHg) and a high PAP group (>41 mmHg), and even between the two groups of Angus cattle, it was revealed that there were differences in genetic frequencies (Krehbiel et al.,

2017). Evidence suggests that an animal's susceptibility to HAD is inherited (Holt & Callan, 2007)

A study by Moore et al. (Moore et al., 1979) showed that pregnant females who are susceptible to HAD had an increase in both PAP and blood flow resistance compared to pregnant females who are resistant to HAD. Females that were shown to be resistant to HAD had no change in their PAP scores (Moore et al., 1979). Females with an already high PAP score will have an increased score when pregnant, which will put a greater strain on heart and lung function (Moore et al., 1979). Animals experiencing a concurrent or past respiratory illness, parasites, or lung abscess may test with a higher PAP score, as these conditions can induce hypoxia and increase the risk of pulmonary hypertension (Holt & Callan, 2007).

When performing PAP tests, environmental factors can influence the outcomes. As mentioned previously, PAP scores should be taken at an elevation of 1500 m or higher to ensure accurate results (Holt & Callan, 2007; Speidel et al., 2020). Those who are measuring the PAP scores of cattle that are expected to be used as breeding stock in high-elevation production systems should pay special attention to the elevation at which the PAP scores are taken (Holt & Callan, 2007; Speidel et al., 2020). Cold environmental temperatures below 0 degrees Celsius can cause pulmonary hypertension and increase vascular resistance in cattle, which increases PAP scores (Will et al., 1978).

Certain feedstuffs, such as ionophores and a certain alkaloid found in locoweed, can increase PAP scores. Cattle that are fed ionophores are shown to have greater PAP scores (Holt & Callan, 2007). A small pilot study conducted at a feedyard in Colorado above 1500 m showed that 44% of calves had a PAP score of greater than 50 mmHg, and 71% had a PAP score of

greater than 45 mmHg after being fed ionophores for 6 weeks per label recommendation (Holt & Callan, 2007). After the removal of the ionophores from the diet, PAP scores decreased by a mean of 6 mmHg (Holt & Callan, 2007).

Swainsonine, an alkaloid found in locoweed, specifically species in the *Astragalus* and *Oxytropis* genus, has been shown to induce HAD following consumption in high-elevation environments (James et al., 1991). Swainsonine was fed in the milk to a group of young Holstein bull calves at an elevation of 3090 m and compared to another group of bull calves that did not receive swainsonine in the milk (James et al., 1991). All five calves that were fed swainsonine displayed clinical signs of HAD, including edema in the brisket and right ventricular hypertrophy (James et al., 1991). Only one calf out of five in the control group displayed signs of HAD (James et al., 1991). Holt and Callan (2007) have reasoned that the increased instances of HAD are due to the cardiotoxic effects of swainsonine combined with hypoxia-induced pulmonary hypertension.

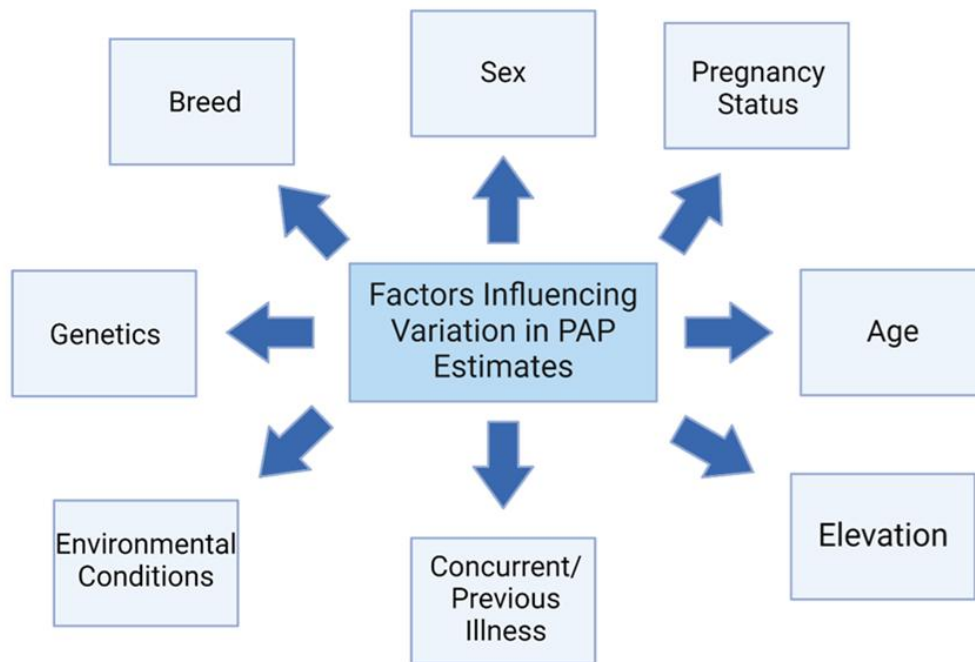


Figure 2.2. Factors that might influence beef cattle Pulmonary Arterial Pressure (PAP) estimates (adapted from Holt and Callan, 2007).

Concerns at Moderate Elevations

Recently, there has been an increase in RHF at moderate elevations considered to be below 1500 m (Neary et al., 2015). From 2000 to 2012, the cases of RHF in feedyards across the United States and Canada have nearly doubled, making RHF the second leading cause of death in feedyards behind pneumonia (Neary et al., 2015). The increase in RHF deaths comes as carcass weights in the United States have reached an all-time high (Thomas et al., 2017). Grain-fed cattle are shown to have the highest PAP scores (Thomas et al., 2018). Pulmonary arterial pressure scores of fattening feedlot cattle ranged from 42 to 143 mmHg (Thomas et al., 2018). Comparing the PAP scores of feedlot cattle to other classes of cattle showed that the mean PAP

score of Angus feedlot cattle was 8.3 mmHg greater than yearling Angus bulls and 13 mmHg higher than grazing Angus heifers (Thomas et al., 2018).

A case study conducted by Moxley and coworkers (2019) discussed the reasons for the increase in RHF deaths in a feedlot located in western Nebraska. Cattle with pulmonary vascular lesions supported the idea that RHF is caused by hypoxia-induced pulmonary hypertension (Moxley et al., 2019). Furthermore, these cattle were kept at moderate elevations, which led researchers to believe that they were genetically predisposed to pulmonary hypertension because of hypoxia (Moxley et al., 2019). There was also an increase in intimal hyperplasia in pulmonary elastic arteries, which is consistent with HAD (Ahola et al., 2006; Moxley et al., 2019).

Alternative Methods of Measuring PAP

Measuring PAP scores can be seen as a possibly dangerous, invasive, and expensive procedure (Ahola et al., 2006). Due to the risks associated with the procedure, seedstock producers have been slow to adopt the practice (Ahola et al., 2006). Ahola and coworkers (2006) conducted a study exploring alternative measurements for PAP scores using hemogram values, pulse oximetry, and a portable clinical analyzer. Hemogram values were shown to be the most reliable and accurate (Ahola et al., 2006). A blood sample was taken following the removal of the catheter after the PAP score measurement (Ahola et al., 2006). The morphology of red blood cells was evaluated (Ahola et al., 2006). Changes in red blood cell morphology and red blood cell distribution width can indicate increased erythropoiesis and vasoconstriction of the pulmonary vessels (Ganong, 2001). Past evidence has shown that cattle will modify their red blood cell characteristics to compensate for hypoxia (Cueva, 1967). In addition, previous research has shown cattle with increased PAP scores will have premature ventricular

contractions, increased hemoglobin levels, red blood cell mass, and erythropoietin, a hormone responsible for signaling the need for more red blood cells (Card, 1977). Hemoglobin levels and red blood cell distribution proved to show the most promising results when evaluating blood samples compared to PAP scores (Ahola et al., 2006). More research should be evaluated to establish a definite correlation between red blood cell characteristics and PAP.

The use of pulse oximetry was also evaluated and was a poor predictor of PAP scores (Ahola et al., 2006). Previous research conducted by Cueva (1967) suggested that as hemoglobin levels were altered, it may also cause a change in blood oxygen saturation (SpO_2). SpO_2 values were collected at two locations on the cattle, and neither proved to be an accurate predictor of PAP. However, the researchers believe that the inability to refrain cattle from movement and the black hide color of the cattle may have impacted the accuracy of the pulse oximeter (Ahola et al., 2006).

The portable clinical analyzer was also found to be a poor predictor of PAP scores (Ahola et al., 2006). Blood samples were taken from the cattle and immediately evaluated by the portable clinical analyzer (Ahola et al., 2006). Several blood samples were incorrectly evaluated due to immediate clotting, and no results were gathered from those samples (Ahola et al., 2006). The portable clinical analyzer evaluated 11 blood components, and no correlation was detected between blood components and PAP scores (Ahola et al., 2006).

Inheritance of PAP

Several studies have estimated the heritability of PAP in beef cattle and range from 0.20 to 0.46, respectively (Cockrum et al., 2014; Crawford et al., 2016; Enns et al., 1992; Shirley et al., 2008). Variations have been reportedly caused by differences in age, sex, and breed type

(Crawford et al., 2016). Bulls have a reported heritability for PAP of 0.31, and heifers reported a heritability of 0.20 (Cockrum et al., 2014). In spring-born registered Angus cattle, PAP was found to be moderately heritable at 0.34 (Shirley et al., 2008). Environmental influences have also been shown to affect the heritability levels of certain traits due to changes in the phenotype of the animal (DeNise et al., 1988).

Neary (2014) conducted a genome-wide association study (GWAS) on PAP phenotype and genotype. The results showed that PAP is a polygenic trait, meaning that PAP is influenced by an estimated one thousand genes (Neary, 2014). These genes were associated with a variety of pathways, including immune function, tissue remodeling, and metabolism (Neary, 2014). Since PAP is a polygenic trait, an SNP-based predictor is required to predict performance, accurately calculate estimated progeny differences (EPD), and make genetic advancements (Thomas et al., 2018).

PAP Scores as an EPD

In 2019, the American Angus Association (AAA), Angus Genetics Inc. (AGI), and Colorado State University (CSU) released an EPD for PAP scores for producers to follow and make informed genetic decisions (Ryans, 2019). International Genetic Solutions (IGS) and CSU also partnered together to create a multi-breed PAP EPD using Simmental, Red Angus, and commercial cattle (Geiss & Culbertson, 2020). The PAP EPD is used to determine an animal's "survivability" in high-elevation environments (Thomas et al., 2018) and is expressed in mmHg (Geiss & Culbertson, 2020; Ryans, 2019). A lower score is more favorable and should indicate that a sire should produce offspring with a lower PAP score (Geiss & Culbertson, 2020; Ryans, 2019). IGS reports that in 2020, the PAP EPD ranged in sires from -7.4 to 24.1 with a reported

accuracy of 0.20 (Geiss & Culbertson, 2020). It is reported that 90% of cattle will have a PAP EPD ranging from -4 to +4 (Thomas et al., 2018).

Both the AAA and IGS stress the point that a PAP EPD does not replace a PAP test for an animal's survivability at high elevations due to the environmental factors that can impact an animal's heart-lung function, such as illness, body condition, and other factors that can impact high-elevation beef cattle production (Geiss & Culbertson, 2020). The PAP EPD should be used to select parents of the next generation while mitigating risks for producers at high elevations (Ryans, 2019). Additionally, producers located at high elevations can select sires for artificial insemination (AI) and have background knowledge on how the expected offspring should handle the added stress of a high-elevation production setting (Geiss & Culbertson, 2020).

Relationship between PAP Scores and Economically Relevant Traits

Seedstock producers use PAP scores as a marketing tool to sell seedstock animals to those producers who have cattle operations in high elevations and prevent RHF. As RHF continues to be a persistent issue in both moderate and high-elevation environments and the cattle industry pushes to better understand cattle heart health, it is necessary to determine how PAP estimates can impact traits that producers rely on for profit. Several studies have been conducted attempting to understand the relationship between PAP and economically relevant traits. To date, these studies have yielded conflicting results.

PAP Scores and Gestation Length

Selection for low birth weight sires and/or calving ease sires has been shown to directly decrease gestation length (Burfening et al., 1978). In contrast, as gestation length increases, it is

estimated that birth weight increases by 0.25 kg/day (Burfening et al., 1978). The lungs are not used in utero and are some of the last tissues to develop (Funston et al., 2010). Lung maturity at birth is directly correlated to fetal maturity and surfactant production (Eigenmann et al., 1984), which supports the claim that shortened gestation lengths can directly impact lung function. Surfactant production helps promote a healthy pulmonary system by reducing surface tension and preventing the collapse of alveoli (Rebello et al., 1996). An immature pulmonary system can put a calf at greater risk for respiratory stress disease (Benesi, 1993). Furthermore, research has suggested that respiratory stress disease may put an animal at an increased risk of developing pulmonary hypertension (Thomas et al., 2018).

A study by Foxworthy and coworkers (2018) investigated the possible influence of a 286-day gestation length on yearling PAP scores. Foxworthy et al. (2018) hypothesized that since lung development occurs in utero, gestation lengths may be a cause for variation in yearling PAP scores. Gestation lengths were measured from the point of artificial insemination to the calving date (Foxworthy et al., 2018). The relationship between gestation lengths and yearling PAP scores was then evaluated using the Pearson correlation coefficient and a simple linear regression model (Foxworthy et al., 2018). The study showed that a 286-day gestation length was a weak, negative predictor (-0.005) of yearling PAP scores and an animal's susceptibility to HAD (Foxworthy et al., 2018).

PAP Scores and Birth Weight

According to the AAA, the birth weight of the calf should be measured within 24 h of calving and should be measured in lbs./kgs. Putting an increased selection pressure on low birth weights to prevent dystocia has decreased birth weights and gestation lengths (Burfening et al.,

1978). Similar to the gestation length discussion above, the health of the pulmonary system seems to be directly correlated to the size of the calf at birth (Shoup et al., 2015). Lighter birth-weight calves have been shown to have a compromised respiratory system, while heavier birth-weight calves are shown to be healthier and more resilient to stressors put on their respiratory system (Shoup et al., 2015). However, it should be noted that dystocia in high-birth-weight calves can compromise the animal's viability and survivability due to a host of reasons, such as hypoxia, injury, inflammation, and others (Murray & Leslie, 2013). Dystocia has the ability to impact an animal's health and performance throughout its lifespan (Murray & Leslie, 2013). Dystocia has the ability to impact an animal's health and performance throughout its lifespan (Murray & Leslie, 2013).

Two conflicting studies have been reported defining a relationship between PAP scores and birth weights. Crawford et al. (2016) used cattle that were owned by the Colorado State University—Beef Improvement Center (CSU-BIC) located near Encampment, Wyoming, for the research project, which aggressively culls for PAP scores above 42 mmHg. Cattle resided at an average elevation ranging from 2149 to 2410 m. Pulmonary arterial pressure scores were collected at an average of 356 days of age (Crawford et al., 2016). Data records from 1993 to 2014 were analyzed for this study. Crawford et al. reported a weak, positive genetic correlation (0.15 ± 0.09) between PAP scores and birth weights (Crawford et al., 2016). Crawford et al. (2016) also suggested that selecting for lower PAP scores may decrease birth weights.

Similarly, Shirley et al. (2008) used a database of PAP scores and body weights from a ranch in Colorado that resides at an average elevation of 1980 m. Pulmonary arterial pressure measurements were taken during weaning, and the average age was approximately 277 days

(Shirley et al., 2008). Records were used from 1984 to 2003, with approximately 115 animals being PAP tested every year (Shirley et al., 2008). Shirley et al. (2008) reported that PAP scores and birth weights were moderately and positively genetically correlated (0.49 ± 0.12). Unlike the study discussed above (Crawford et al., 2016), it was concluded that selection for performance and growth at low altitudes may increase PAP scores and susceptibility to HAD if moved to high elevations (Shirley et al., 2008). Additionally, those who select for performance in high-elevation production systems should consider PAP scores when selecting for economically relevant traits (Crawford et al., 2016; Shirley et al., 2008).

PAP Scores and Weaning Weight

Previous work has also evaluated the relationship between PAP scores and weaning weights (Crawford et al., 2016; Shirley et al., 2008). Crawford et al. (2016) observed a weak to modest relationship (0.22 ± 0.08) between PAP scores and weaning weights. Particularly for weaning weight, it was suggested that the selection for higher weaning weights could contradict the selection for lower PAP scores (Crawford et al., 2016). Shirley et al. (2008) observed a moderate, positive genotypic correlation (0.50 ± 0.18) between PAP scores and weaning weights. Phenotypic correlations between PAP and weights were determined to be positive but low (0.02 ± 0.03) (Shirley et al., 2008). Both studies argued for caution when putting selection pressure on weaning weight for cattle residing in high-elevation environments and production systems (Crawford et al., 2016; Shirley et al., 2008).

PAP Scores and Yearling Weight

Crawford et al. (2016) evaluated the relationship between PAP scores and yearling weights while also looking into the relationship between PAP scores and postweaning gain.

There was found to be a weak genetic correlation (0.12 ± 0.08) between PAP scores and yearling weights, as well as postweaning gain (Crawford et al., 2016). An earlier study conducted by Schimmel (1980) used records from multiple different breeds using a sire model analysis and showed there was a strong negative relationship (-0.75 ± 0.65) between PAP scores and yearling weights.

Pauling et al. (2023) also researched the relationship between PAP scores and yearling weights. A preexisting data set, including growth, carcass ultrasound records, and PAP scores from replacement heifers and bulls born between 1992 and 2015, was obtained from the AAA (Pauling et al., 2023). Cattle were separated into contemporary groups, and a 6-trait analysis was performed, resulting in a low genetic correlation (<0.20) between PAP scores and yearling weights (Pauling et al., 2023).

PAP Scores and Carcass Traits

Pauling et al. (2023) also evaluated the relationship between PAP scores and carcass traits using a previous data set made available by the AAA. It was hypothesized that increased selection pressure for increased muscle mass and fat deposition would cause an increase in PAP (Jensen et al., 1976; Neary et al., 2015; Pauling et al., 2023). The data set included ultrasound values for backfat, ribeye area, rump fat, and intramuscular fat (Pauling et al., 2023). The traits were compared through a 6-trait analysis (Pauling et al., 2023). The results showed a low genetic correlation (<0.20) between PAP scores and ultrasound values for backfat, rump fat, and intramuscular fat (Pauling et al., 2023). There was a moderate, positive genetic correlation (0.25 ± 0.12) between PAP scores and ribeye area, which indicates that an increase in muscle mass and single trait selection for the ribeye area can cause an increase in PAP (Pauling et al., 2023).

Pauling et al. (2023) suggest that breeders recognize the unfavorable relationship between the two traits.

Future Research

For over 100 years, HAD has been impacting the beef cattle industry (Rhodes, 2005). In 2012, 5% of the beef cattle herd in the United States ran at high elevations (Williams et al., 2012). With an estimated loss of USD 60 million annually (Williams et al., 2012) and a growing concern for feedlot cattle located at moderate elevations, the US beef cattle industry has been paying close attention to heart–lung function in cattle production. An increase in mean PAP scores has occurred, especially in feedlot cattle, as we put increased selection pressure on performance, and finished carcass weights have reached an all-time high (Williams et al., 2012).

There have been limited studies regarding the relationship between PAP and other traits. To date, these studies have yielded conflicting results. As the cattle industry continues to pay more attention to and learn more about PAP, it is important to have a practical application that producers can use and understand to make breeding decisions. Research to further understand the relationship between PAP and economically relevant traits would be beneficial to the beef industry. A better understanding of PAP could help decrease congestive heart failure and pulmonary hypertension in beef cattle while also decreasing economic losses. Additionally, current measurements of PAP are an invasive and expensive procedure performed by a licensed veterinarian. Alternative, less invasive procedures are needed to increase the use and application of PAP in beef production systems.

Conclusions

For over 100 years, HAD has been impacting the beef cattle industry (Rhodes, 2005). In 2012, 5% of the beef cattle herd in the United States ran at high elevations (Williams et al., 2012). With an estimated loss of USD 60 million annually (Williams et al., 2012) and a growing concern for feedlot cattle located at moderate elevations, the US beef cattle industry has been paying close attention to heart–lung function in cattle production. An increase in mean PAP scores has occurred, especially in feedlot cattle, as we put increased selection pressure on performance, and finished carcass weights have reached an all-time high (Williams et al., 2012).

There have been limited studies regarding the relationship between PAP and other traits. To date, these studies have yielded conflicting results. As the cattle industry continues to pay more attention to and learn more about PAP, it is important to have a practical application that producers can use and understand to make breeding decisions. Research to further understand the relationship between PAP and economically relevant traits would be beneficial to the beef industry. A better understanding of PAP could help decrease congestive heart failure and pulmonary hypertension in beef cattle while also decreasing economic losses. Additionally, current measurements of PAP are an invasive and expensive procedure performed by a licensed veterinarian. Alternative, less invasive procedures are needed to increase the use and application of PAP in beef production systems.

References

- Ahola, J., Enns, R., & Holt, T. (2006). Examination of potential methods to predict pulmonary arterial pressure score in yearling beef cattle. *Journal of Animal Science*, 84(5), 1259-1264. <https://doi.org/10.2527/2006.8451259x>
- Alexander, A. (1962). The bovine lung: normal vascular histology and vascular lesions in high mountain disease. *Respiration*, 19(6), 528-542. <https://doi.org/10.1159/000192262>
- Alexander, A., & Jensen, R. (1963). PULMONARY VASCULAR PATHOLOGY OF BOVINE HIGH MOUNTAIN DISEASE. *American Journal of Veterinary Research*, 24, 1098-1111.
- American Simmental Association. (2014). *Beef Briefs: History of the Simmental Breed*. https://www.pasimmental.com/files/wpcontent/uploads/2014/03/Simmental_history.pdf
- Benesi, F. J. (1993). Neonatal calf asphyxia syndrome. Importance and critical evaluation. *Journal title: Archives of the School of Veterinary Medicine of the Federal University of Bahia*, 16(1), 38-48.
- Burfening, P. J., Kress, D. D., Friedrich, R. L., & Vaniman, D. D. (1978). Phenotypic and Genetic Relationships between Calving Ease, Gestation Length, Birth Weight and Prewaning Growth. *Journal of Animal Science*, 47(3), 595-600. <https://doi.org/10.2527/jas1978.473595x>
- Card, C. S. (1977). *The bovine erythron during hypoxic stress*. PhD Dissertation Colorado State Univ. Fort Collins, CO.
- Cockrum, R., Zeng, X., Berge, N., Neary, J., Garry, F., Holt, T., Blackburn, H., Thomas, S., Speidel, S., & Garrick, D. (2014). Angus cattle at high altitude: Genetic relationships and initial genome-wide association analysis of pulmonary arterial pressure. Proc. World Congress Appl. Livestock Prod,
- Crawford, N., Enns, R., Speidel, S., LaShell, B., Holt, T., & Thomas, M. (2017). CASE STUDY: factors influencing pulmonary arterial pressure in cattle of the San Juan Basin Research Center 4-Corners Bull Test data. *The Professional Animal Scientist*, 33(3), 387-392. <https://doi.org/10.15232/pas.2016-01587>
- Crawford, N. F., Thomas, M. G., Holt, T. N., Speidel, S. E., & Enns, R. M. (2016). Heritabilities and genetic correlations of pulmonary arterial pressure and performance traits in Angus cattle at high altitude1. *Journal of Animal Science*, 94(11), 4483-4490. <https://doi.org/10.2527/jas.2016-0703>
- Cueva, S. M. (1967). *Blood oxygen transport in cattle "susceptible" and "resistant" to High Mountain (Brisket) Disease* [Colorado State University].

- De Morais HA, S. D. (2005). Pathophysiology of heart failure. In F. E. Ettinger SJ (Ed.), *Textbook of Veterinary Internal Medicine. 6th ed* (pp. 914-940). Saunders Elsevier.
- DeNise, S., Torabi, M., Ray, D., & Rice, R. (1988). Genetic parameter estimates for preweaning traits of beef cattle in a stressful environment. *Journal of Animal Science*, 66(8), 1899-1906. <https://doi.org/10.2527/jas1988.6681899x>
- Eigenmann, U., Schoon, H., Jahn, D., & Grunert, E. (1984). Neonatal respiratory distress syndrome in the calf. *The Veterinary Record*, 114(6), 141-144. <https://doi.org/10.1136/vr.114.6.141>
- Enns, R., Brinks, J., Bourdon, R., & Field, T. (1992). Heritability of pulmonary arterial pressure in Angus cattle. *Proc. West. Sect. Am. Soc. Anim. Sci*,
- Foxworthy, H., Enns, R., Speidel, S., Thomas, M., & Holt, T. (2018). 286 Gestation length as a weak predictor of yearling pulmonary arterial pressure and risk of developing high altitude disease in Angus cattle at high elevation. *Journal of Animal Science*, 96(suppl_3), 106-107. <https://doi.org/10.1093/jas/sky404.235>
- Funston, R. N., Larson, D. M., & Vonnahme, K. A. (2010). Effects of maternal nutrition on conceptus growth and offspring performance: Implications for beef cattle production1. *Journal of Animal Science*, 88(suppl_13), E205-E215. <https://doi.org/10.2527/jas.2009-2351>
- Ganong, W. F. (2001). In *Review of Medical Physiology* (20th ed.). McGraw-Hill Book Co.
- Geiss, L., & Culbertson, R. (2020). *Multibreed PAP EPD Released* <https://herdbook.org/staticfiles/fileCMS/Index/Multibreed%20PAP%20EPD%20Released.pdf>
- Glover, G. H., & Newsom, I. E. (1914). *Brisket disease: dropsy of high altitudes* (Vol. 204). Agricultural Experiment Station of the Agricultural College of Colorado.
- González-Murray, R. A., Sánchez-Castro, M. A., Thomas, M. G., Speidel, S. E., & Enns, R. M. (2020). Heterosis and its potential influence on pulmonary arterial pressure in beef cattle. *Translational Animal Science*, 4(Supplement_1), S118-S121. <https://doi.org/10.1093/tas/txaa117>
- Heath, D., Castillo, Y., Arias-Stella, J., & Harris, P. (1969). The small pulmonary arteries of the llama and other domestic animals native to high altitudes. *Cardiovascular Research*, 3(1), 75-78. <https://doi.org/10.1093/cvr/3.1.75>
- Holt, T. (2019). *Bovine High-mountain Disease*. Merck Manual: Veterinary Manual <https://www.merckvetmanual.com/circulatory-system/bovine-high-mountain-disease/bovine-high-mountain-disease>

- Holt, T. N., & Callan, R. J. (2007). Pulmonary arterial pressure testing for high mountain disease in cattle. *Veterinary Clinics of North America: Food Animal Practice*, 23(3), 575-596. <https://doi.org/10.1016/j.cvfa.2007.08.001>
- Ivany, J. M., & Illanes, O. G. (1999). Congestive heart failure due to epicardial lymphosarcoma in a Holstein cow. *Can Vet J*, 40(11), 819-820.
- James, L. F., Panter, K. E., Broquist, H. P., & Hartley, W. J. (1991). Swainsonine-induced high mountain disease in calves. *Vet Hum Toxicol*, 33(3), 217-219.
- Jensen, R., Pierson, R., Braddy, P., Saari, D., Benitez, A., Horton, D., Lauerman, L., McChesney, A., Alexander, A., & Will, D. (1976). Brisket disease in yearling feedlot cattle. *Journal of the American Veterinary Medical Association*, 169(5), 515-517.
- Krehbiel, B. C., Thomas, M. G., Speidel, S. E., Enns, R. M., & Blackburn, H. D. (2017). Genetic structure of Angus and Salers in relation to SNP associated with pulmonary arterial pressure. *Journal of Animal Science, suppl. supplement 4*, 95, 87-88. <https://www.proquest.com/scholarly-journals/genetic-structure-angus-salers-relation-snp/docview/1947371029/se-2?accountid=28148>
- Markel, C. D. (2023). *Characterizing Effects of Management Strategy and Degree of Pulmonary Hypertension on Live Growth Performance, Carcass Quality, and Respiratory Microbiome of Finishing Beef Cattle* (Publication Number 30634728) [M.S., University of Wyoming]. ProQuest One Academic. United States -- Wyoming. <https://www.proquest.com/dissertations-theses/characterizing-effects-management-strategy-degree/docview/2854315038/se-2?accountid=28148>
- Moore, L. G., Reeves, J. T., Will, D. H., & Grover, R. F. (1979). Pregnancy-induced pulmonary hypertension in cows susceptible to high mountain disease. *Journal of Applied Physiology*, 46(1), 184-188. <https://doi.org/10.1152/jappl.1979.46.1.184>
- Moxley, R. A., Smith, D. R., Grotelueschen, D. M., Edwards, T., & Steffen, D. J. (2019). Investigation of congestive heart failure in beef cattle in a feedyard at a moderate altitude in western Nebraska. *Journal of Veterinary Diagnostic Investigation*, 31(4), 509-522. <https://doi.org/10.1177/1040638719855108>
- Murray, C. F., & Leslie, K. E. (2013). Newborn calf vitality: Risk factors, characteristics, assessment, resulting outcomes and strategies for improvement. *The Veterinary Journal*, 198(2), 322-328. <https://doi.org/10.1016/j.tvjl.2013.06.007>
- Neary, J. M. (2014). *Epidemiological, physiological and genetic risk factors associated with congestive heart failure and mean pulmonary arterial pressure in cattle* (Publication Number 3635657) [Ph.D., Colorado State University]. Agricultural & Environmental Science Collection; ProQuest One Academic. United States -- Colorado. <https://www.proquest.com/dissertations-theses/epidemiological-physiological-genetic-risk/docview/1615100266/se-2?accountid=28148>

- Neary, J. M., Garry, F. B., Holt, T. N., Thomas, M. G., & Enns, R. M. (2015). Mean pulmonary arterial pressures in Angus steers increase from cow–calf to feedlot–finishing phases1. *Journal of Animal Science*, 93(8), 3854-3861. <https://doi.org/10.2527/jas.2015-9048>
- Pauling, R. C., Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2023). Genetic parameters for pulmonary arterial pressure, yearling performance, and carcass ultrasound traits in Angus cattle. *Journal of Animal Science*, 101. <https://doi.org/10.1093/jas/skad288>
- Rebello, C. M., Ikegami, M., Polk, D., & Jobe, A. (1996). Postnatal lung responses and surfactant function after fetal or maternal corticosteroid treatment. *Journal of Applied Physiology*, 80(5), 1674-1680. <https://doi.org/10.1152/jappl.1996.80.5.1674>
- Rhodes, J. (2005). Comparative physiology of hypoxic pulmonary hypertension: historical clues from brisket disease. *Journal of Applied Physiology*, 98(3), 1092-1100. <https://doi.org/10.1152/japplphysiol.01017.2004>
- Ryans, K. (2019, February 1 2019). *Research PAP EPD Launched by Angus Genetics Inc.* <https://www.angus.org/pub/newsroom/releases/020119-pap-epd-launch.html>
- Schimmel, J., Brinks, J., Russell, B., Mangus, W., & Denham, A. (1980). Genetic aspects of High Mountain [Brisket] disease in beef cattle. Proceedings of the Annual Meeting. American Society for Animal Science Western Section (USA),
- Shirley, K. L., Beckman, D. W., & Garrick, D. J. (2008). Inheritance of pulmonary arterial pressure in Angus cattle and its correlation with growth1. *Journal of Animal Science*, 86(4), 815-819. <https://doi.org/10.2527/jas.2007-0270>
- Shoup, L. M., Wilson, T. B., González-Peña, D., Ireland, F. A., Rodriguez-Zas, S., Felix, T. L., & Shike, D. W. (2015). Beef cow prepartum supplement level and age at weaning: II. Effects of developmental programming on performance and carcass composition of steer progeny1. *Journal of Animal Science*, 93(10), 4936-4947. <https://doi.org/10.2527/jas.2014-8565>
- Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2020). Evaluation of the sensitivity of pulmonary arterial pressure to elevation using a reaction norm model in Angus Cattle. *Journal of Animal Science*, 98(5). <https://doi.org/10.1093/jas/skaa129>
- Thomas, M. G., Krafur, G. M., Holt, T. N., Enns, R. M., Speidel, S. E., Garry, F. B., Cánovas, Á., Medrano, J., Brown, R. D., Stenmark, K. R., & Neary, J. M. (2017). GENETICS OF BRISKET DISEASE IN BEEF CATTLE : A NOT SO HIGH ALTITUDE PROBLEM.
- Thomas, M. G., Neary, J. M., Krafur, G. M., Holt, T. N., Enns, R. M., Speidel, S. E., F. B., Garry, Cánovas, Á., Medrano, J. F., Brown, R. D., & Stenmark, K. R. (2018). Pulmonary Hypertension (PH) in Beef Cattle : Complicated Threat to Health and Productivity in Multiple Beef Industry Segments.

- Veit, H., & Farrell, R. (1978). The anatomy and physiology of the bovine respiratory system relating to pulmonary disease. *The Cornell Veterinarian*, 68(4), 555-581.
- Will, D., Horrell, J., Reeves, J., & Alexander, A. (1975). Influence of altitude and age on pulmonary arterial pressure in cattle. *Proceedings of the Society for Experimental Biology and Medicine*, 150(3), 564-567. <https://doi.org/10.3181/00379727-150-39>
- Will, D., McMurtry, I., Reeves, J., & Grover, R. (1978). Cold-induced pulmonary hypertension in cattle. *Journal of Applied Physiology*, 45(3), 469-473. <https://doi.org/10.1152/jappl.1978.45.3.469>
- Williams, J. L., Bertrand, J. K., Misztal, I., & Łukaszewicz, M. (2012). Genotype by environment interaction for growth due to altitude in United States Angus cattle1. *Journal of Animal Science*, 90(7), 2152-2158. <https://doi.org/10.2527/jas.2011-4365>

CHAPTER THREE

EVALUATING PULMONARY ARTERIAL PRESSURE IN
ANGUS YEARLING BULLS AT HIGH ELEVATION:
ASSOCIATIONS WITH BIRTH TRAITS AND GROWTH
PERFORMANCE

Contribution of Authors and Co-Authors

Author: K. Stearns

Contributions: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation,
Writing-original draft preparation, Writing-review and editing, Visualization Creation, and
Supervision

Co-Author: H. DelCurto-Wyffels

Contributions: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation,
Writing- review and editing, Supervision, and Project Administration

Co-Author: S. Wyffels

Contributions: Conceptualization, Methodology, Formal Analysis, Investigation, Data Curation,
Writing-review and editing, Visualization Creation, and Supervision

Co-Author: M. Van Emon

Contribution: Investigation, Writing- review and editing, and Supervision

Co-Author: N. G. Davis

Contributions: Writing- review and editing and Visualization Creation

Co-Author: T. Sitz

Contribution: Data Curation and Writing- review and editing

Co-Author: T. DelCurto

Contribution: Conceptualization, Methodology, Formal Analysis, Investigation, Resource
Curation, Data Curation, Writing-review and editing, Supervision, and Funding Acquisition

Manuscript Information

Kaylen Stearns, Hannah DelCurto-Wyffels, Sam Wyffels, Megan Van Emon, Noah G. Davis,
Taylre Sitz, and Tim DelCurto

Animals

- ☐ Prepared for submission to a peer-reviewed journal
- ☐ Officially submitted to a peer-reviewed journal
- ☐ Accepted by a peer-reviewed journal
- ☒ Published in a peer-reviewed journal

Multidisciplinary Digital Publishing Institute

Published: April 30, 2025

Animals 2025, 15(9), 1302

DOI: 10.3390/ani15091302

Simple Summary

As the cattle sector puts more emphasis and focus on heart–lung function, it is important to understand the relationship between pulmonary arterial pressure (PAP) scores and performance measurements. This study characterized the relationship between PAP scores and gestation length, birth weight, and growth traits. The results showed that as gestation length and birth weight increased, PAP scores also increased. In comparison, bulls with increased yearling weights and birth to yearling gains had decreased PAP scores. No relationship was observed between PAP scores and weaning weight. By evaluating these relationships, beef cattle producers can gain better insights and tools for selecting cattle for high-elevation production systems.

Abstract

The objectives of this study were to model the relationship between pulmonary arterial pressure (PAP) estimates and birth weight, gestation length, and growth traits of developing bulls. Pulmonary arterial pressure estimates were collected from Angus yearling bulls ranging in age from 12 to 18 months from a Montana-based Angus operation (>1600 m elevation, 5406 yearlings/18-month-old bulls from 2016–2023). Pulmonary arterial pressure was positively correlated with birth weight ($p < 0.01$) and gestation length ($p < 0.01$). No relationship was observed between bull PAP and weaning weight ($p = 0.26$). Pulmonary arterial pressure scores were negatively correlated with yearling weight ($p = 0.04$). Additionally, PAP estimates were negatively correlated with birth-to-weaning gains ($p < 0.01$) and weaning-to-yearling gains ($p = 0.02$). Lastly, PAP scores were negatively correlated with birth to yearling growth ($p < 0.01$). Sire lines influenced offspring PAP scores ($p < 0.01$), and dam–sire lines tended to have an effect on offspring PAP scores ($p = 0.09$). In summary, PAP scores were related to birth weight, gestation length, yearling weight, and growth from birth to yearling age. Our findings suggest that selection for higher growth should also emphasize selecting for lower PAP scores.

Introduction

Pulmonary arterial pressure (PAP) determines an animal's susceptibility to High Altitude Disease (HAD), also known as Brisket Disease, High Mountain Disease (HMD), and right-sided heart failure (RHF)(Holt & Callan, 2007). This is a non-infectious disease that causes pulmonary vasoconstriction due to hypoxia(Markel, 2023). High Altitude Disease impacts beef cattle production at elevations above 1500 m due to decreased oxygen saturation in the atmosphere (Holt & Callan, 2007). Clinical signs of HAD include brisket edema, lethargy, jugular vein distention, diarrhea, poor appetite, and death (Glover & Newsom, 1914). There is currently no treatment or cure for HAD (Glover & Newsom, 1914). The only recommendation is to move affected animals to lower elevations with more tolerable oxygen conditions(Glover & Newsom, 1914). In 2012, it was estimated that 1.5 million head of cattle resided in high elevation production systems(Williams et al., 2012). High Altitude Disease accounts for 3-5% of the annual calf death loss at altitude (Holt & Callan, 2007) and result in an economic loss of approximately \$60 million, annually (Williams et al., 2012).

There is an increased susceptibility of HAD in bovids because of their pulmonary system (Alexander & Jensen, 1963; Holt & Callan, 2007). Pulmonary vascular shunting is a mechanism that moves pulmonary blood flow away from poorly oxygenated tissues in the lung to areas of higher oxygen concentration (Alexander & Jensen, 1963). Shunting occurs in all animals during times of hypoxia (Holt & Callan, 2007) and causes persistent exposure of pulmonary vasculature to increased pressure (Heath et al., 1969). This constant increased exposure and pressure will lead to remodeling of the pulmonary arteries caused by hypertrophy and muscularization (Alexander, 1962; Alexander & Jensen, 1963). Eventually, this will lead to loss of function

within the peripheral pulmonary arteries and cause dilation of the right ventricle, followed by heart failure (Alexander, 1962; Alexander & Jensen, 1963; Holt & Callan, 2007). The bovine pulmonary system experiences the greatest amount of pulmonary vascular shunting across the tested species of llamas, dogs, and cats (Heath et al., 1969). In addition, the bovine lung is relatively small compared to its body weight and has a smaller lobulated anatomical pattern which increases the likelihood of cattle to suffer from severe pulmonary hypertension and loss of function (Veit & Farrell, 1978).

Seedstock producers use PAP scores as a tool to market their cattle to producers who operate at high elevations or those who use heart lung-function as a selection criteria (Stearns et al., 2024). Additionally, selection for growth and performance has continually trended upward for the past four decades in Angus cattle (Pauling et al., 2023). Consequently, the cattle sector is putting more emphasis on heart-lung function as there continues to be an increase in RHF at moderate elevations which comes when carcass weights have drastically increased (Heaton et al., 2019; Neary, 2014; Thomas et al., 2018).

There is minimal research conducted relating PAP measurements to cattle performance and previous research that has been performed has yielded conflicting results. The objectives of this study were to model the relationship of PAP with gestation length, birth weight, and growth traits of developing Angus bulls. In addition, this study compares mean PAP scores of the most common sire and grandsire lines from progeny within the data set. Increased knowledge of PAP scores and the relationship between performance traits and PAP estimates can allow for a better understanding of selection goals in beef cattle.

Materials and Methods

We collaborated with a Montana-based Angus operation to gather data on 5,406 head of 12 to 18-month-old purebred Angus bulls who were sold in their annual production sales from 2016-2023. Bulls were raised and resided in elevations greater than 1600 m. It is important to note that this operation has two separate locations that function as two separate ranches. Bulls from Operation A are sold in the December production sale (Fall sale) and are PAP tested at 18 months of age. Bulls are weaned in a pasture setting in the fall, then sent to the ranch feedlot for the winter. In the spring, bulls are turned out on forest allotments ($\approx$ 2590 m elevation) to graze. They return back to the feedlot in the fall where they are PAP tested following their return from elevation. While at the feedlot, they receive a light growing ration until sale. Bulls from Operation B are sold in the March production sale (Spring sale) and are PAP tested at 12 months of age. Bulls from operation B are weaned into a feedlot ($\approx$ 1600 m elevation) in early September. The bulls are sorted into groups by weight and started on a high roughage diet. From there, concentrates of corn and dried distillers grains are gradually added to the ration. Bulls are PAP tested the middle of December. Through a right-heart catheterization procedure (Ahola et al., 2006), a PAP test measures the resistance of blood flow through the lungs (Shirley et al., 2008). Measurement of PAP is performed routinely by a licensed veterinarian at beef cattle operations in high elevations since the 1980s. In 2019, the American Angus Association (AAA) established a PAP expected progeny difference (EPD). Therefore, an AACUC was not obtained for the study. Similar to human blood pressure, PAP scores are measured in millimeters of mercury (mmHg) (Holt & Callan, 2007). Scores will range from 30 mmHg to greater than 50 mmHg, with lower scores being more desirable (30-40 mmHg) (Holt & Callan, 2007). Pulmonary arterial pressure

scores are influenced by several factors, including age, sex, genetics, and environmental conditions (Holt & Callan, 2007; Neary et al., 2015; Speidel et al., 2020; Will et al., 1975, Will et al., 1978).

Data gathered included individual bull identification number, sale, sale year, birthdate, birth weight, weaning weight, yearling weight, PAP score, sire's AAA registration number, dam's AAA registration number, and progeny's AAA registration number. For a subset of the data, 485 bulls from two years of the fall sale, artificial insemination dates were obtained. Gestation length was calculated as the difference between birthdate and artificial insemination date. DNA tests were used to confirm parentage of the calf for all bulls.

Phenotypic correlations were used to determine the relationship between PAP estimates with gestation length, birth weight, and growth traits. It was hypothesized that the relationship between PAP and performance traits could be described as linear, asymptotic, or quadratic in nature (Franklin et al., 2000). Candidate models were developed reflecting the nature of each response variable to PAP using generalized linear mixed models with a fixed effect of the variable of interest as either linear, asymptotic, or quadratic in nature, and year as a random intercept. Akaike's Information Criterion adjusted for small sample sizes (AICc) was used to evaluate support for competing models (Table 1; "AICcmodavg" package for R) (Burnham, 1998). Once the nature of the relationship was determined for each variable of interest, candidate model sets using generalized linear mixed models were then developed reflecting multiple hypotheses on the relationship between each of the performance metrics, gestation length, and birth weight including the fall versus spring sale and its associated interaction each of the variables of interest on bull PAP scores using the packages "lme4" and "lmerTest"(packages for

R) (Bates et al., 2015; Kuznetsova et al., 2017). Year was treated as a random intercept. Akaike's Information Criterion adjusted for small sample sizes (AICc) was used to evaluate support for competing models reflecting hypotheses about the effects of sale (age at time of testing) and performance traits (Table 2; "AICcmodavg" package for R) (Burnham, 1998). We excluded models with $\Delta\text{AICc} \leq 2$ that differed from the top model by a single parameter if confidence intervals of parameter estimates overlapped 0 (ie., were non-informative) (Arnold, 2010). Model averaged estimates of beta-coefficients were used when multiple models were supported ("MuMin" package for R) (Bartoń, 2022). Model fit was evaluated by using marginal and conditional r^2 (Nakagawa & Schielzeth, 2013). All models and relationships were performed and evaluated in R (Team., 2022).

Table 3.2. Model selection for evaluating the nature (linear, asymptotic, or quadratic) of the relationship between PAP and performance metrics, gestation length, and birth weight on 12 to 18-month-old purebred Angus bull PAP scores.

Model ¹	K ²	AICc ³	Δ AICc ⁴	W _i ⁵	P-Value
Gestation Length					
ln(Gestation Length)	4	2783.65	0	1	<0.01
Gestation Length	4	2784.86	11.20	0	<0.01
(Gestation Length) ²	5	2806.20	22.55	0	0.85
Birth Weight					
ln(Birth Weight)	4	33627.32	0	0.97	<0.01
Birth Weight	4	33363.42	7.29	0.03	<0.01
(Birth Weight) ²	5	33374.95	18.18	0	0.82
Weaning Weight					
ln(Weaning Weight)	4	33627.32	0	1	0.24
Weaning Weight	4	33638.66	11.35	0	0.26
(Weaning Weight) ²	5	33658.47	31.15	0	0.72
Yearling Weight					
ln(Yearling Weight)	4	33612.76	0	1	0.04
Yearling Weight	4	33625.17	12.58	0	0.04
(Yearling Weight) ²	5	33646.23	33.47	0	0.64
Growth from Birth to Weaning					
ln(Growth from Birth to Weaning)	4	33215.41	0	0.99	0.03
Growth from Birth to Weaning	4	33225.35	9.94	0.01	0.05
(Growth from Birth to Weaning) ²	5	33243.76	28.35	0	0.23
Growth from Weaning to Yearling					
ln(Growth from Weaning to Yearling)	4	33413.33	0	1	0.06
Growth from Weaning to Yearling	4	33425.17	11.84	0	0.02
(Growth from Weaning to Yearling) ²	5	33646.26	33.47	0	0.07
Growth from Birth to Yearling					
ln(Growth from Birth to Yearling)	4	33131.04	0	1	<0.01
Growth from Birth to Yearling	4	33143.26	12.21	0	<0.01
(Growth from Birth to Yearling) ²	5	33164.16	33.12	0	0.81

¹Year is used as a random variable in all models. ²K= number of parameters. ³Akaike's information criterion adjusted for small sample size. ⁴Difference in Akaike's information criterion adjusted for small sample size compared to the best model. ⁵Akaike weight.

Table 3.3. Model selection for evaluating the effects of performance metrics, gestation length, birth weight, fall versus spring sale, and associated interactions on 12 to 18-month-old purebred Angus bull PAP scores.

Model ¹	K ²	AICc ³	Δ AICc ⁴	W _i ⁵	r ² m ⁶	r ² c ⁷	P-Value
Gestation Length							
ln(Gestation Length)	4	2783.85	0	1	1.40%	27.37%	<0.01
null	3	33858.87	31075.22	0	0%	0.50%	
Birth Weight							
ln(Birth Weight)	4	33356.14	0	0.66	0.25%	0.77%	<0.01
ln(Birth Weight)*sale	5	33357.46	1.33	0.34	0.35%	0.83%	<0.01
null	3	33858.87	502.74	0	0%	0.50%	
Weaning Weight							
ln(Weaning Weight)	4	33627.32	0	0.86	0.03%	0.47%	0.26
ln(Weaning Weight)*sale	5	33630.91	3.59	0.14	0.09%	0.52%	0.67
null	3	33858.87	246.11	0	0%	0.50%	
Yearling Weight							
ln(Yearling Weight)	4	33612.76	0	0.93	0.09%	0.65%	0.04
ln(Yearling Weight)*sale	5	33618.03	5.27	0.07	0.11%	0.62%	0.24
null	3	33858.87	246.11	0	0%	0.50%	
Growth from Birth to Weaning							
ln(Growth from Birth to Weaning)	4	33215.41	0	0.91	0.08%	0.48%	0.05
ln(Growth from Birth to Weaning)*sale	5	33220.15	4.74	0.09	0.12%	0.51%	0.15
null	3	33858.87	643.46	0	0%	0.50%	
Growth from Weaning to Yearling							
ln(Growth from Weaning to Yearling)	4	33413.33	0	0.93	0.12%	0.79%	0.02
ln(Growth from Weaning to Yearling)*sale	5	33418.36	5.03	0.07	0.13%	0.72%	0.07
null	3	33858.87	445.55	0	0%	0.50%	
Growth from Birth to Yearling							
ln(Growth from Birth to Yearling)	4	33131.04	0	0.96	0.16%	0.74%	<0.01
ln(Growth from Birth to Yearling)*sale	5	33137.19	6.15	0.04	0.16%	0.71%	0.04
null	3	33858.87	727.83	0	0%	0.50%	

¹Year is used as a random variable in all models. ²K= number of parameters. ³Akaike's information criterion adjusted for small sample size. ⁴Difference in Akaike's information criterion adjusted for small sample size compared to the best model.

⁵Akaike weight.

Results

Modeling Analysis

There were no significant relationships ($P=0.26$) between PAP and weaning weight. All other variables displayed asymptotic relationships with PAP (Table 1).

Gestation length displayed an asymptotic relationship ($P < 0.01$) to PAP and a single top model received 100% of the support among candidate models when determining the effects of gestation length on PAP (Table 2). A model containing only gestation length ($\beta = 33.74 \pm 11.25$; Figure 1), where PAP increased with increasing gestation length. The top model containing all supported variables had a conditional r^2 of 27.37% and a marginal r^2 of 1.40% suggesting gestation length accounts for 1.40% of the variation among PAP scores. However, it should be noted that gestation lengths were only collected for two Fall sales.

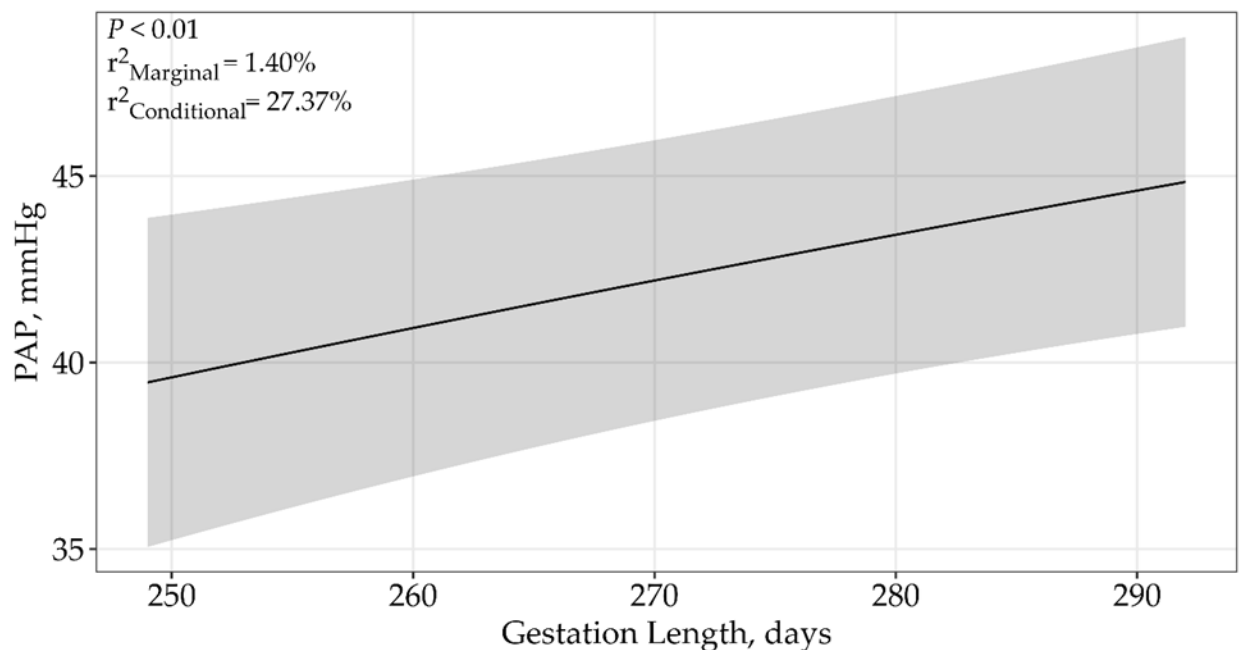


Figure 3.1. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and gestation lengths for 485 eighteen-month-old bulls raised and tested above 1600m in

southwestern, Montana, USA. This relationship was best described by an asymptotic model ($P < 0.01$; $\beta = 33.74 \pm 11.25$).

Models containing birth weight and sale accounted for 100% of the support among candidate models (Table 2). Pulmonary arterial pressure was asymptotically related to a birth weight by sale interaction ($P > 0.01$; $\beta_{\text{Fall Sale}} = 3.04 \pm 0.82$, $\beta_{\text{Spring Sale}} = 2.91 \pm 0.81$; Figure 2), where PAP increased with increasing birth weight across both sales. The top model containing all supported variables had a conditional $r^2 = 0.83\%$ and a marginal r^2 of 0.35% suggesting birth weight and sale only account for 0.35% of the variation associated with PAP.

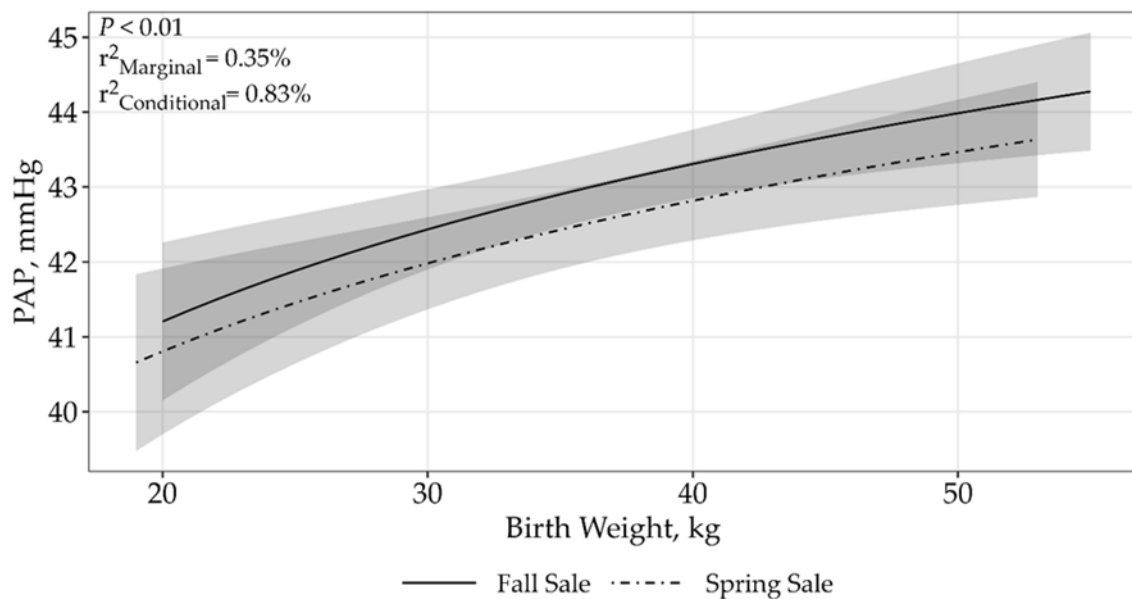


Figure 3.2. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and birth weight for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P > 0.01$; $\beta_{\text{Fall Sale}} = 3.04 \pm 0.82$, $\beta_{\text{Spring Sale}} = 2.91 \pm 0.81$) The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B.

A single top model containing weaning weight received 86% of the relative support of data when determining the effects of weaning weight on PAP ($\beta = -0.96 \pm 0.86$; $P = 0.26$), however this model may be noninformative as confidence intervals of the effect overlap 0.

A single top model containing yearling weight received 93% of the support among candidate models (Table 2; $P = 0.04$; $\beta = -2.16 \pm 1.05$; Figure 3), where PAP decreased while yearling weight increased. The top model containing all supported variables had a conditional r^2 of 0.65% and a marginal r^2 of 0.09%. Therefore, suggesting yearling weight only accounts for 0.09% of the variation associated with PAP.

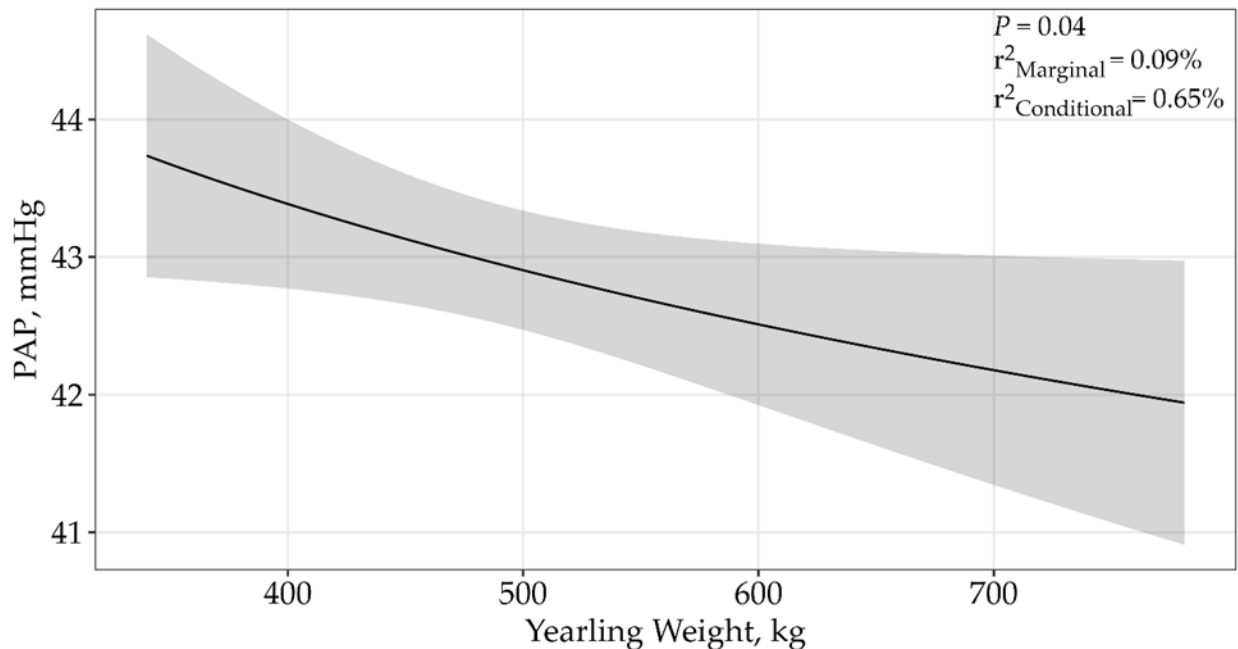


Figure 3.3. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and yearling weight for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P = 0.04$; $\beta = -2.16 \pm 1.05$).

Birth to weaning growth displayed an asymptotic relationship ($P=0.05$) and single top model received 91% of the relative support of data when determining the effects of birth to weaning gains on PAP (Table 2; $\beta = -1.29 \pm 0.65$; Figure 4), where PAP decreased with increasing birth to weaning weight growth. The top model containing all supported variables has a conditional $r^2 = 0.48\%$ and a marginal r^2 of 0.08%.

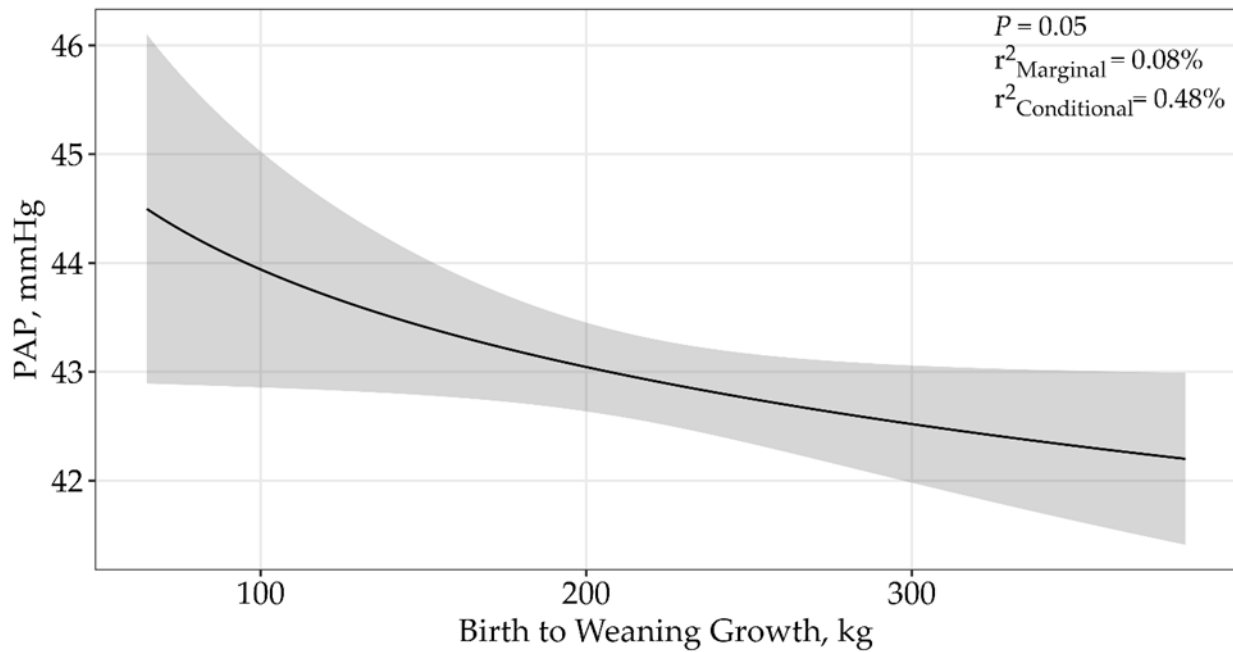


Figure 3.4. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and birth to weaning growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P=0.05$; $\beta = -1.29 \pm 0.65$).

A model containing weaning to yearling growth received 93% of support among candidate models (Table 2; $P = 0.02$; $\beta = -1.21 \pm 0.54$; Figure 5), where PAP decreased as weaning to yearling growth increased. The top model had a conditional r^2 of 0.79% and a marginal r^2 of 0.12% suggesting weaning to yearling growth only accounts for 0.12% of the variation associated with PAP.

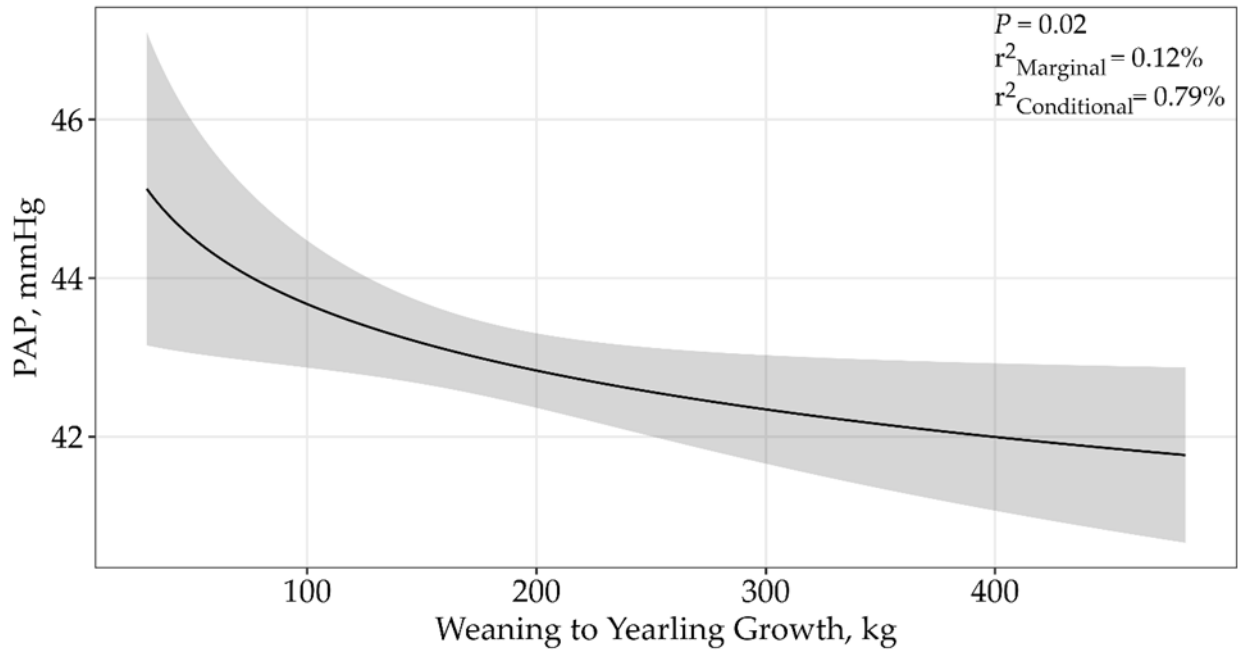


Figure 3.5. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and weaning to yearling growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P = 0.02$; $\beta = -1.21 \pm 0.54$).

An asymptotic relationship was displayed by a single top model containing birth to yearling weight ($P < 0.01$) and received 96% of the relative support of data when determining the effects of birth to yearling growth on PAP (Table 2). A model containing only birth to yearling gains ($\beta = -2.48 \pm 0.90$; Figure 6) was supported, where PAP decreased with increasing birth to yearling growth. The top model containing all supported variables had a conditional $r^2 = 0.74\%$ and a marginal r^2 of 0.16%. Based on our study this suggests birth to yearling weight only account for 0.16% of the variation associated with PAP.

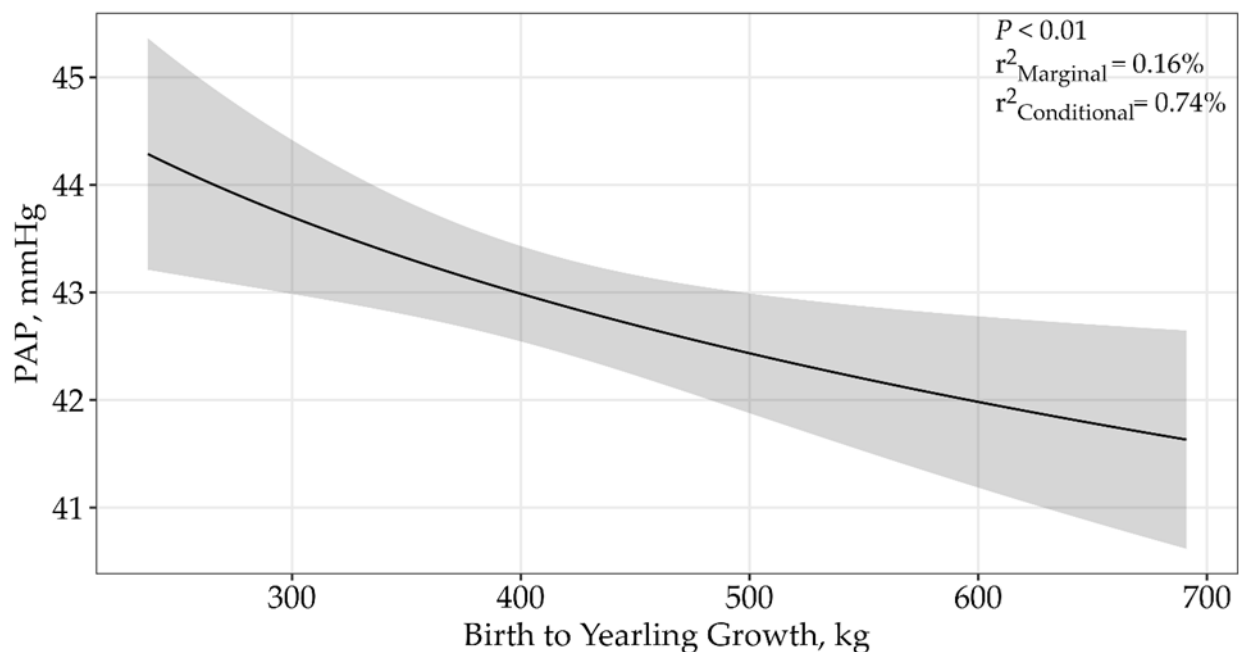


Figure 3.6. Predicted relationship ($\pm 95\%$ CI represented in the shaded areas) between PAP scores and weaning to yearling growth for 5,406 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA. The relationship was best described by an asymptotic model ($P < 0.01$; $\beta = -2.48 \pm 0.90$).

Sire Line Progeny Analysis

We identified the 10 sires with at least 100 offspring for a total of 1532 offspring. Mean PAP scores, the range of PAP scores, and the coefficient of variation for each sire are presented in Table 3. The range between the progeny of the sire line with the greatest PAP score and that of the least was 5.92 mmHg. Mean PAP scores of offspring differed by sire line ($P < 0.01$; Table 3; Figure 7). Offspring from sire 6 had the greatest mean PAP (46.56 mm Hg), which was greater than that of offspring from the eight other sires ($P < 0.01$). Offspring from sire 5 had the lowest mean PAP (40.64 mm Hg) but was only lower than that of offspring from sires 4 and 6 ($P <$

0.01). Actual sire EPDs and coefficient of variation of PAP scores are listed in Table 3 for reference.

Table 3.3. Influence of 10 registered Angus bull sire lines on mean progeny PAP scores, the range of PAP scores, and the coefficient of variation for 1532 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA.

	Sires											
	1	2	3	4	5	6	7	8	9	10	SE	P-Value
Number of offspring	125	217	110	124	238	109	112	256	139	102		
Average offspring PAP score	41.57 ^{ab}	41.84 ^{ab}	42.56 ^{ab}	43.55 ^{ac}	40.64 ^b	46.56 ^c	41.05 ^{ab}	41.36 ^{ab}	41.84 ^{ab}	42.34 ^{ab}	0.674	<0.01
CV of offspring PAP score¹	11.50	19.55	17.67	18.03	13.00	18.52	15.07	9.93	14.87	8.38		
Sire PAP EPD²	-0.62	-1.10	+2.85	+0.41	-2.29	+2.22	-0.71	-1.94	-1.34	-0.51		
EPD accuracy	0.56	0.70	0.67	0.45	0.67	0.36	0.59	0.75	0.59	0.63		

¹ coefficient of variation for PAP score expressed as a percent of the mean

² expressed in millimeters of Mercury (mmHg), with a lower EPD being more favorable

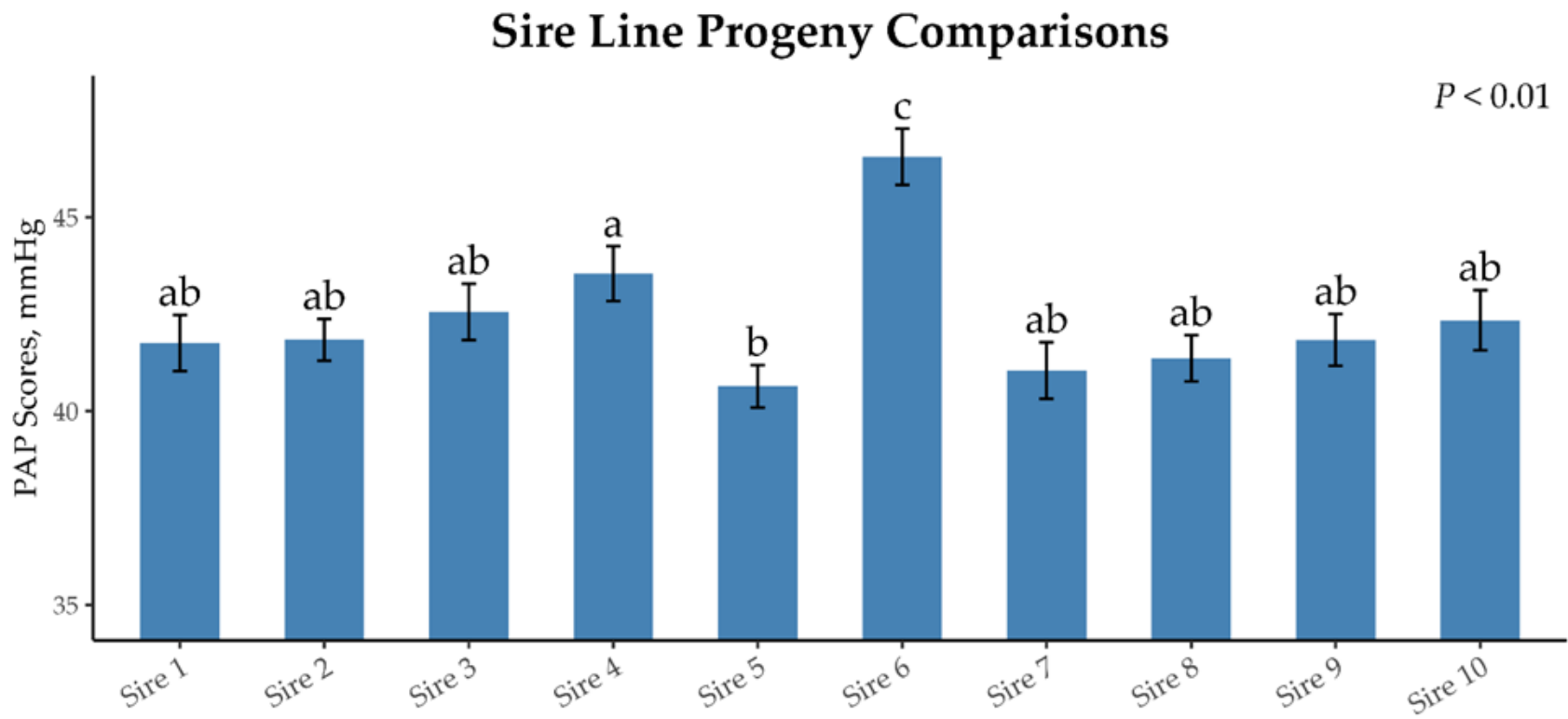


Figure 3.7. Mean PAP scores of sires with >100 progeny within the data set. Compact letter displays indicate the differences between mean PAP scores of progeny ($P < 0.01$).

Dam Sire Line Progeny Analysis

Five dam sires with at least 100 grand progeny for a total of 1135 offspring (Table 4) were identified. Mean PAP score, the range of PAP scores, and the coefficient of variation for each sire was calculated. The range between the grand progeny of the sire line with the greatest PAP score and that of the least was 2.11 mmHg. There tended to be a difference among the average mean offspring PAP score ($P = 0.09$; Table 4; Figure 8) as sire 3 reported the lowest mean PAP scores in his grand progeny, while sire 1 reported the greatest mean PAP scores. Actual dam sire EPDs and coefficient of variation of PAP scores are listed in Table 4 for reference.

Table 3.4. Influence of five registered Angus dam sire lines on mean grand progeny PAP scores, the range of PAP scores, and the coefficient of variation for 1135 twelve to eighteen-month-old bulls raised and tested above 1600m in southwestern, Montana, USA.

	Dam Sires						
	1	2	3	4	5	SE	P-Value
Number of offspring	523	144	115	246	107		
Average Offspring PAP score	43.30 ^a	42.84 ^a	41.19 ^a	42.59 ^a	42.94 ^a	0.814	0.09
CV of offspring PAP score¹	17.88	18.15	13.47	15.47	16.31		
Sire PAP EPD²	+1.96	+1.99	-0.29	-0.77	+3.38		
EPD accuracy	0.78	0.64	0.51	0.59	0.50		

¹coefficient of variation for PAP score expressed as a percent of the mean

²expressed in millimeters of Mercury (mmHg), with a lower EPD being more favorable

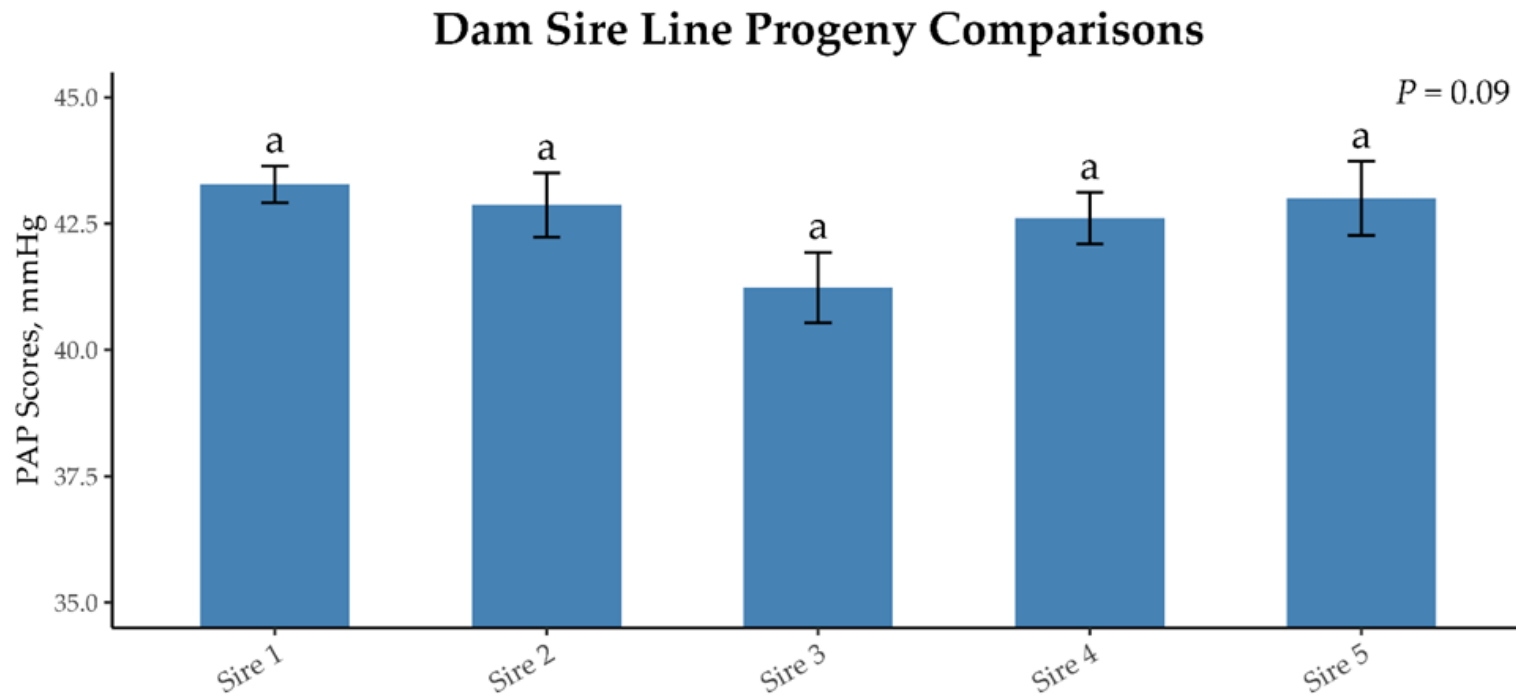


Figure 3.8. Mean PAP scores of dam sires (progeny's maternal grandsire) with >100 progeny within the data set. Statistically mean PAP scores of progeny tended to be different ($P=0.09$).

Discussion

The use of performance driven Angus seedstock cattle to define the relationship between PAP scores and gestation length, birth weight, and performance traits provided a research model that uses real world application. The candidate models showed there is a relationship between PAP and gestation length, birth weight, yearling weight. Additionally, candidate models suggested relationships between birth to weaning growth, weaning to yearling gains, and birth to yearling growth with PAP. First, looking into the relationship between PAP scores and gestation length revealed that as length of gestation increases, PAP estimates also increase. It was hypothesized that shortened gestation lengths may increase PAP scores because previous research suggests that shortened gestation lengths can decrease lung maturity which in turn may put a calf at greater risks for respiratory distress (Eigenmann et al., 1984) (Benesi, 1993). Our findings contradict a previous study by Foxworthy et al. (Foxworthy et al., 2018) that showed gestation length as a weak, negative predictor of PAP scores. In our study gestation length only explained 1.40% of the variation of PAP measurements.

The relationship between PAP scores and birth weight showed that as birth weight increased there was also an increase in PAP estimates. There were two previous studies conducted by Colorado State University which investigated the same relationship. In 2008, Shirley et al. (Shirley et al., 2008) reported that PAP scores were moderately and positively genetically correlated to birth weight. Shirley et al. (Shirley et al., 2008) concluded that selection for growth and performance may increase PAP scores. In 2016, Crawford et al. (Crawford et al., 2016) reported a weak, positive genetic correlation between PAP scores and birth weight. Based on the study, Crawford et al. (Crawford et al., 2016) suggested that selecting for lower PAP

scores may decrease birth weights. The results of these studies closely follow the results of our study. Our study indicated that birth weight accounted for 0.25% of the variation of PAP measurements.

The relationship between PAP scores and yearling weight suggested that as performance and gains increased, PAP estimates decreased. In addition, our analysis showed that bulls with increased gains from birth to weaning, weaning to yearling, and birth to yearling showed decreased PAP scores. Based on the inverse relationship our study found, we concluded that bulls with an improved heart-lung function will experience increased gains. From a biological standpoint, those bulls with improved heart-lung function are better set to achieve greater performance compared to those with decreased heart-lung function. Previous work has yielded conflicting results. In a study conducted by Schimmel et al. (Schimmel et al., 1980) in 1981, showed there was a strong, negative genetic relationship (-0.75 ± 0.65) between PAP scores and yearling weights. Contrastingly, Crawford et al. (Crawford et al., 2016) found a weak, positive genetic relationship (0.12 ± 0.08) for yearling weight. A more recent study by Pauling et al. (Pauling et al., 2023), suggested a low genetic correlation between yearling weight and PAP (0.01 ± 0.11). Although in our study, yearling weight only explained 0.09% of the variation of PAP measurements. Previous genetic correlations of post-weaning gains, have indicated similar results (-0.10 ± 0.10)(Crawford et al., 2016) and (-0.11 ± 0.12)(Pauling et al., 2023). Our phenotypic correlations suggested similar findings, as bulls with increased gains had decreased PAP scores. The growth from birth to weaning explained 0.08% of the variation of PAP estimates and the growth from weaning to yearling explained 0.12% of the variation in PAP scores.

Additionally, growth from birth to yearling explained 0.16% of the variation in PAP measurements.

The characterization of mean PAP scores of progeny from sire lines and maternal grand sire lines with more than 100 offspring within the data set showed that there is a relationship between a sire and an offspring's PAP score, reinforcing the trait's heritability. Pulmonary arterial pressure heritability estimates have ranged from 0.20 to 0.46 (Cockrum et al., 2014; Crawford et al., 2016; Enns et al., 1992; Shirley et al., 2008). There were differences observed across sire lines among mean PAP scores of progeny. The coefficient of variation (CV) provides predictability of that sire's progeny's PAP scores. Sires with a smaller CV for PAP score will generally produce offspring that have less variability.

The findings from this study could help enhance beef cattle production in high elevation systems. By better understanding how PAP scores are related to performance, beef cattle producers can make conscious bull selection decisions to achieve production goals based on their operation. Sire progeny showed consistency and little variability of PAP scores. This illustrates that sire selection for PAP does make a difference and has an impact within an operation.

Conclusions

As HAD continues to be a threat in the beef sector, it is important to understand the relationship between economically relevant traits and PAP scores. This research provides insight to producers as to how these relationships can impact beef production in high elevation systems. This research showed a significant relationship between PAP and gestation length, birth weight, yearling weight, and weaning to yearling gain. However, these relationships explain very little of the variation in PAP estimates. The sire line summary demonstrates that sire selection does

impact heart-lung function in offspring. Our results suggest there is an effect between sire and offspring's PAP scores. Based on these findings, it is crucial to continue placing emphasis on heart-lung function in all production systems and thus give cattle the ability to thrive in varied production environments. Our results suggest that selection for higher growth should also emphasize selecting for lower PAP scores. Therefore, additional research is warranted regarding beef cattle growth and performance and heart-lung function.

References

- Ahola, J., Enns, R., & Holt, T. (2006). Examination of potential methods to predict pulmonary arterial pressure score in yearling beef cattle. *Journal of Animal Science*, 84(5), 1259-1264. <https://doi.org/10.2527/2006.8451259x>
- Alexander, A. (1962). The bovine lung: normal vascular histology and vascular lesions in high mountain disease. *Respiration*, 19(6), 528-542.
- Alexander, A., & Jensen, R. (1963). PULMONARY VASCULAR PATHOLOGY OF BOVINE HIGH MOUNTAIN DISEASE. *American Journal of Veterinary Research*, 24, 1098-1111.
- Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's Information Criterion. *The Journal of wildlife management*, 74(6), 1175-1178. <https://doi.org/10.1111/j.1937-2817.2010.tb01236.x>
- Bartoń, K. (2022). MuMIn: multi-model inference. *R package version 1.46. 0*.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of statistical software*, 67, 1-48. <https://doi.org/10.18637/jss.v067.i01>
- Benesi, F. J. (1993). Neonatal calf asphyxia syndrome. Importance and critical evaluation. *Journal title: Archives of the School of Veterinary Medicine of the Federal University of Bahia*, 16(1), 38-48.
- Burnham, K.P. (1998). Model selection and multimodel inference. *A practical information-theoretic approach*.
- Cockrum, R., Zeng, X., Berge, N., Neary, J., Garry, F., Holt, T., Blackburn, H., Thomas, S., Speidel, S., & Garrick, D. (2014). Angus cattle at high altitude: Genetic relationships and initial genome-wide association analysis of pulmonary arterial pressure. Proc. World Congress Appl. Livestock Prod,
- Crawford, N. F., Thomas, M. G., Holt, T. N., Speidel, S. E., & Enns, R. M. (2016). Heritabilities and genetic correlations of pulmonary arterial pressure and performance traits in Angus cattle at high altitude1. *Journal of Animal Science*, 94(11), 4483-4490. <https://doi.org/10.2527/jas.2016-0703>
- Eigenmann, U., Schoon, H., Jahn, D., & Grunert, E. (1984). Neonatal respiratory distress syndrome in the calf. *The Veterinary Record*, 114(6), 141-144. <https://doi.org/10.1136/vr.114.6.141>
- Enns, R., Brinks, J., Bourdon, R., & Field, T. (1992). Heritability of pulmonary arterial pressure in Angus cattle. Proc. West. Sect. Am. Soc. Anim. Sci,

- Fox, J., & Weisberg, S. (2018). *An R companion to applied regression*. Sage publications.
- Foxworthy, H., Enns, R., Speidel, S., Thomas, M., & Holt, T. (2018). 286 Gestation length as a weak predictor of yearling pulmonary arterial pressure and risk of developing high altitude disease in Angus cattle at high elevation. *Journal of Animal Science*, 96(suppl_3), 106-107. <https://doi.org/10.1093/jas/sky404.235>
- Franklin, A. B., Anderson, D. R., Gutiérrez, R. J., & Burnham, K. P. (2000). CLIMATE, HABITAT QUALITY, AND FITNESS IN NORTHERN SPOTTED OWL POPULATIONS IN NORTHWESTERN CALIFORNIA. *Ecological Monographs*, 70(4), 539-590. [https://doi.org/10.1890/0012-9615\(2000\)070\[0539:CHQAFI\]2.0.CO;2](https://doi.org/10.1890/0012-9615(2000)070[0539:CHQAFI]2.0.CO;2)
- Glover, G. H., & Newsom, I. E. (1914). *Brisket disease: dropsy of high altitudes* (Vol. 204). Agricultural Experiment Station of the Agricultural College of Colorado.
- Heath, D., Castillo, Y., Arias-Stella, J., & Harris, P. (1969). The small pulmonary arteries of the llama and other domestic animals native to high altitudes. *Cardiovascular Research*, 3(1), 75-78. <https://doi.org/10.1093/cvr/3.1.75>
- Heaton, M. P., Bassett, A. S., Whitman, K. J., Krafur, G. M., Lee, S. I., Carlson, J. M., Clark, H. J., Smith, H. R., Pelster, M. C., Basnayake, V., Grotelueschen, D. M., & Vander Ley, B. L. (2019). Evaluation of EPAS1 variants for association with bovine congestive heart failure. *F1000Res*, 8, 1189. <https://doi.org/10.12688/f1000research.19951.1>
- Holt, T. N., & Callan, R. J. (2007). Pulmonary arterial pressure testing for high mountain disease in cattle. *Veterinary Clinics of North America: Food Animal Practice*, 23(3), 575-596. <https://doi.org/10.1016/j.cvfa.2007.08.001>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. *Journal of statistical software*, 82, 1-26. <https://doi.org/10.18637/jss.v082.i13>
- Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means. R package version 1.7. 2. In.
- Markel, C. D. (2023). *Characterizing Effects of Management Strategy and Degree of Pulmonary Hypertension on Live Growth Performance, Carcass Quality, and Respiratory Microbiome of Finishing Beef Cattle* (Publication Number 30634728) [M.S., University of Wyoming]. ProQuest One Academic. United States -- Wyoming. <https://www.proquest.com/dissertations-theses/characterizing-effects-management-strategy-degree/docview/2854315038/se-2?accountid=28148>
- Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R² from generalized linear mixed-effects models. *Methods in ecology and evolution*, 4(2), 133-142. <https://doi.org/10.1111/j.2041-210x.2012.00261.x>

- Neary, J. M. (2014). *Epidemiological, physiological and genetic risk factors associated with congestive heart failure and mean pulmonary arterial pressure in cattle* (Publication Number 3635657) [Ph.D., Colorado State University]. Agricultural & Environmental Science Collection; ProQuest One Academic. United States -- Colorado.
<https://www.proquest.com/dissertations-theses/epidemiological-physiological-genetic-risk/docview/1615100266/se-2?accountid=28148>
- Neary, J. M., Garry, F. B., Holt, T. N., Thomas, M. G., & Enns, R. M. (2015). Mean pulmonary arterial pressures in Angus steers increase from cow–calf to feedlot–finishing phases 1. *Journal of Animal Science*, 93(8), 3854-3861. <https://doi.org/10.2527/jas.2015-9048>
- Pauling, R. C., Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2023). Genetic parameters for pulmonary arterial pressure, yearling performance, and carcass ultrasound traits in Angus cattle. *Journal of Animal Science*, 101. <https://doi.org/10.1093/jas/skad288>
- Schimmel, J., Brinks, J., Russell, B., Mangus, W., & Denham, A. (1980). Genetic aspects of High Mountain [Brisket] disease in beef cattle. Proceedings of the Annual Meeting. American Society for Animal Science Western Section (USA),
- Shirley, K. L., Beckman, D. W., & Garrick, D. J. (2008). Inheritance of pulmonary arterial pressure in Angus cattle and its correlation with growth 1. *Journal of Animal Science*, 86(4), 815-819. <https://doi.org/10.2527/jas.2007-0270>
- Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2020). Evaluation of the sensitivity of pulmonary arterial pressure to elevation using a reaction norm model in Angus Cattle. *Journal of Animal Science*, 98(5). <https://doi.org/10.1093/jas/skaa129>
- Stearns, K., DelCurto-Wyffels, H., Wyffels, S., Van Emon, M., & DelCurto, T. (2024). The Use of Pulmonary Arterial Pressure (PAP) for Improved Beef Cattle Management. *Animals*, 14(16), 2430. <https://doi.org/10.3390/ani14162430>
- Team., R. C. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.
- Thomas, M., Neary, J., Krafur, G., Holt, T., Enns, R., Speidel, S., Garry, F., Canovas, A., Medrano, J., & Brown, R. (2018). Pulmonary hypertension (PH) in beef cattle: complicated threat to health and productivity in multiple beef industry segments. *Certified Angus Beef (CAB) White Paper*.
- Veit, H., & Farrell, R. (1978). The anatomy and physiology of the bovine respiratory system relating to pulmonary disease. *The Cornell Veterinarian*, 68(4), 555-581.
- Will, D., Horrell, J., Reeves, J., & Alexander, A. (1975). Influence of altitude and age on pulmonary arterial pressure in cattle. *Proceedings of the Society for Experimental Biology and Medicine*, 150(3), 564-567. <https://doi.org/10.3181/00379727-150-390>

- Will, D., McMurtry, I., Reeves, J., & Grover, R. (1978). Cold-induced pulmonary hypertension in cattle. *Journal of Applied Physiology*, 45(3), 469-473. <https://doi.org/10.1152/jappl.1978.45.3.469>
- Williams, J. L., Bertrand, J. K., Misztal, I., & Łukaszewicz, M. (2012). Genotype by environment interaction for growth due to altitude in United States Angus cattle1. *Journal of Animal Science*, 90(7), 2152-2158. <https://doi.org/10.2527/jas.2011-4365>

CHAPTER FOUR

RELATIONSHIP OF YEARLING ANGUS BULL PULMONARY ARTERIAL PRESSURE SCORES WITH PRODUCTION, MATERNAL, AND CARCASS EXPECTED PROGENY DIFFERENCES

Contribution of Authors and Co-Authors

Author: K. Stearns

Contributions: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis.

Writing- original draft preparation, Writing- review and editing, Visualization Creation, and
Supervision

Co-Author: H. DelCurto-Wyffels

Contributions: Conceptualization, Methodology, Investigation, Data Curation, Formal Analysis,
Writing- review and editing, Supervision, and Project Administration

Co-Author: S. Wyffels

Contributions: Conceptualization. Methodology, Investigation, Data Curation, Formal Analysis,
and Writing- review and editing

Co-Author: M. Van Emon

Contributions: Investigation and Writing- review and editing

Co-Author: N. G. Davis

Contributions: Writing- review and editing and visualization creation

Co-Author: T. Sitz

Contributions: Conceptualization, Methodology, Investigation, and Data Curation

Co-Author: T. DelCurto

Contributions: Conceptualization, Methodology, Investigation, Resource Curation, Data Curation, Writing-review and editing, Visualization Creation, Supervision, and Fund Acquisition

Manuscript Information

Kaylen Stearns, Hannah DelCurto-Wyffels, Sam Wyffels, Megan Van Emon, Noah G. Davis,
Taylre Sitz, and Tim DelCurto

- ☐ Prepared for submission to a peer-reviewed journal
- ☒ Officially submitted to a peer-reviewed journal
- ☐ Accepted by a peer-reviewed journal
- ☐ Published in a peer-reviewed journal

Submitted: June 25, 2025

Simple Summary

As the cattle industry puts more emphasis and focus on heart-lung function, it is important to understand the relationship between pulmonary arterial pressure (PAP) scores with performance estimates. This study characterized the relationship of PAP scores with production, maternal, and carcass expected progeny differences (EPDs). Results showed that as the calving ease direct EPD increased, PAP scores decreased. In contrast, bulls with increased birth weight, weaning weight, yearling weight, and carcass weight EPDs had increased PAP scores. No relationship was observed between PAP scores and scrotal circumference, maternal milk, ribeye area, and marbling EPDs. By defining these relationships, beef cattle producers are provided with better insight and tools for selecting cattle for high elevation production systems.

Abstract

The objectives of this study were to model the relationship of PAP scores with production, maternal, and carcass (EPDs). Bull PAP scores were collected from 12 – 18-month-old Angus bull from a Montana-based Angus operation ($> 1,600$ m elevation, 5,400 yearlings/18-month-old bulls from 2016 – 2023). Bulls with greater calving ease direct had lower PAP scores ($P < 0.01$; conditional $r^2 = 1.06\%$; marginal $r^2 = 0.62\%$). Bulls with greater birth weight EPDs had greater PAP scores ($P < 0.01$; conditional $r^2 = 1.15\%$; marginal $r^2 = 0.73\%$). Pulmonary arterial pressure was greater for bulls that had greater weaning weight EPDs ($P < 0.01$; conditional $r^2 = 0.82\%$; marginal $r^2 = 0.16\%$) and for bulls that had greater yearling weight EPDs ($P < 0.01$; conditional $r^2 = 0.93\%$; marginal $r^2 = 0.24\%$). Bulls with greater PAP had greater carcass weight EPDs ($P = 0.03$; conditional $r^2 = 0.69\%$; marginal $r^2 = 0.18\%$). There were no observed relationships ($P \geq 0.17$) between bull PAP and scrotal circumference, maternal milk, ribeye area, or marbling EPDs. In summary, PAP was related to calving ease direct, birth weight, weaning weight, yearling weight, and carcass weight EPDs. However, these relationships explain very little of the variation of PAP scores.

Introduction

An animal's susceptibility to High Altitude Disease (HAD), also known as Brisket Disease, High Mountain Disease (HMD), and right-sided heart failure (RHF) is determined by its pulmonary arterial pressure (PAP) score (Holt & Callan, 2007). High altitude disease is described as a non-infectious disease that causes pulmonary vasoconstriction due to hypoxia (Markel, 2023). This disease is characterized by clinical signs of brisket edema, lethargy, jugular vein distention, diarrhea, poor appetite, and death (Glover & Newsom, 1914). The only recommendation given for affected animals is to move them to lower elevation, as no treatment or cure currently exists (Glover & Newsom, 1914). Beef cattle located in production systems above 1500 m elevation are most impacted by HAD due to low oxygen saturations in the atmosphere (Holt, 2019). In 2012, it was estimated that 1.5 million head of cattle resided in high elevation production systems in the United States (Williams et al., 2012). High Altitude Disease accounts for 3-5% of calf death loss in the United States, annually (Holt & Callan, 2007) and results in economic losses of approximately USD \$60 million, yearly (Williams et al., 2012).

Bovines have an increased susceptibility to HAD because of their pulmonary system (Alexander & Jensen, 1963; Holt & Callan, 2007). During times of hypoxia, all animals will experience pulmonary vascular shunting (Holt & Callan, 2007) which causes persistent exposure of pulmonary vasculature to increased pressure (Heath et al., 1969). Eventually, this increased pressure will lead to the remodeling of the pulmonary arteries caused by hypertrophy and muscularization (Alexander, 1962; Alexander & Jensen, 1963). The hypertrophy and muscularization of the pulmonary arteries will cause loss of function in the peripheral pulmonary arteries and dilation of the right ventricle, followed by heart failure (Alexander, 1962; Alexander

& Jensen, 1963; Holt & Callan, 2007). Additionally, the small, lobulated anatomical pattern of the bovine lung increases the likelihood of cattle to suffer from severe pulmonary distress and hypertension leading to loss of function (Veit & Farrell, 1978).

Expected Progeny Differences (EPDs) are predictors of how future progeny are expected to perform compared to others within the data set. (Association, 2025). The American Angus Association (AAA) has four different grouping of EPDs, Production, Maternal, Management, and Carcass. Beef cattle producers use bull EPDs to evaluate how bulls will fit within their operation and align with their production goals. The selection of bulls based on EPDs is a crucial part of bull selection and decision making and seedstock producers will use EPDs to market their bulls to other beef cattle producers. Selection for growth and performance within the Angus breed has trended upward for the last four decades (Pauling et al., 2023). Additionally, PAP scores are also used as a marketing tool by seedstock producers to market their cattle particularly in high elevation systems to those beef cattle operations who put an emphasis on heart-lung function in their selection criteria (Stearns et al., 2024).

The AAA PAP EPD was developed and released in 2019 by the AAA, Angus Genetics Inc. (AGI), and Colorado State University (Ryans, 2019). This EPD assists in estimating an animal's "survivability" in high elevation environments (Thomas et al., 2018). Just as the PAP score, the EPD is also expressed in mmHg and a lower score is more favorable (Ryans, 2019). However, the AAA emphasizes that the PAP EPD does not replace a PAP test and there are several other environmental factors that may impact an animal's survivability in high elevation beef cattle production (Geiss & Culbertson, 2020; Ryans, 2019). However, producers are able to use this EPD as a guide to make informed decisions when selecting and have an increased

knowledge on how expected progeny should perform in high elevation environments (Geiss & Culbertson, 2020). Increased recognition of the importance of heart-lung function led to the establishment of the PAP EPD, as well as increased interest in PAP measurements.

There is limited research conducted relating PAP measurements to production, maternal, and carcass EPDs. The objectives of this study were to model the relationship of PAP with production, maternal, and carcass EPDs. Increased knowledge of PAP scores and the relationship between EPDs and PAP scores can allow for a better understanding of selection goals in beef cattle.

Materials and Methods

We collaborated with a Montana-based Angus operation to gather data on 5406 head of 12- to 18-month-old purebred Angus bulls which were sold in their annual production sales from 2016-2023. Bulls continuously resided in elevations greater than 1600 m. It is important to note that this operation has two separate locations that function as two separate ranches.

Operation A

Bulls from operation A are sold in the December production sale which will be referred to as the Fall sale and are PAP tested at 18 months of age. Bulls from operation A are weaned in a pasture setting in the fall, then sent to the ranch feedlot for the winter. In the spring, bulls are turned out on forest allotments (≈ 2590 m elevation) to graze. They return back to the feedlot (≈ 1600 m) in the fall where they are PAP tested following their return from elevation. While at the feedlot, they receive a light growing ration until sale

Operation B

Bulls from operation B are sold in the March production sale which will be referred to as the Spring sale and are PAP tested at 12 months of age. Bulls from operation B are weaned into a feedlot (≈ 1600 m elevation) in early September. The bulls are sorted into groups by weight and started on a high roughage diet. From there, concentrates of corn and dried distillers grains are gradually added into the ration. Bulls are PAP tested in the middle of December.

Pulmonary Arterial Pressure Test

Through a right-heart catheterization procedure, a PAP test measures the resistance of blood flow through the lungs (Shirley et al., 2008). Measurement of PAP has been routinely performed by a licensed veterinarian at beef cattle operations at high elevations since the 1980s. Similar to human blood pressure, PAP scores are measured in millimeters of mercury (mmHg) (Holt & Callan, 2007). Scores range from 30 mmHg to greater than 50 mmHg (Holt & Callan, 2007) and are influenced by a variety of factors, including age, sex, genetics, and environmental conditions (Holt & Callan, 2007; Neary et al., 2015; Speidel et al., 2020; Will et al., 1975; Will et al., 1978). Higher scores indicate high susceptibility to HAD, therefore lower scores are more desirable (Holt & Callan, 2007).

Data Collected

Data gathered included identification number, sale, sale year, birthdate, PAP score, along with EPDs for calving ease direct (CED), birth weight (BW), weaning weight (WW), yearling weight (YW), scrotal circumference (SC), maternal milk (Milk), carcass weight (CW), marbling (Marb), and ribeye area (RE). The provided EPDs are reflective of bulls' calculated estimates assigned by the AAA at time of sale and as published in the producer's bull sale catalogs. This is

the second paper in a two paper series through a collaboration with Sitz Angus who uses PAP testing as a standard operation procedure for all bulls marketed through their annual production sales (Stearns et al., 2025).

Table 4.1. Expected Progeny Differences evaluated within this study. Groups and abbreviations are according to the American Angus Association.¹

Production EPDs	Maternal EPDs	Carcass EPDs
Calving Ease Direct (CED)	Maternal Milk (Milk)	Carcass Weight (CW)
Birth Weight (BW)		Marbling (Marb)
Weaning Weight (WW)		Ribeye Area (RE)
Yearling Weight (YW)		
Scrotal Circumference (SC)		

¹American Angus Association

Statistical Analysis

Phenotypic correlations were used to determine the relationship between PAP scores with production, maternal, and carcass EPDs. Candidate models were developed reflecting hypothesized relationships between PAP and the maternal, production, and carcass EPDs as either linear, asymptotic, or quadratic in nature, [22] and year as a random intercept. Akaike's Information Criterion adjusted for small sample sizes (AICc) was used to evaluate support for competing models (Table 2; "AICcmodavg" package for R) [23]. Once the nature of the relationship was determined for each EPD of interest, candidate model sets using generalized linear mixed models were then developed reflecting multiple hypotheses on the relationship between each of the EPDs including fall versus spring sale and its associated interactions with each EPD of interest on bull PAP scores using the packages "lme4" and "lmerTest" (packages for

R) [24, 25]. Year was treated as a random intercept. Akaike's Information Criterion adjusted for small sample sizes (AICc) was used to evaluate support for competing (Table 3; "AICcmodavg" package for R) [23]. We excluded models with $\Delta\text{AICc} \leq 2$ that differed from the top model by a single parameter if confidence intervals of a parameter estimates overlapped 0 (ie., were non-informative)[26]. Model averaged estimates of beta-coefficients were used when multiple models were supported("MuMin" package for R) [27]. Model fit was evaluated by using marginal and conditional r^2 [28]. All models and relationships were performed and evaluated in R [29]. Significance was determined at an alpha of <0.05 with a tendency discussed at an alpha >0.05 and <0.10 .

Table 4.2. Model selection for evaluating the nature (linear, asymptotic, or quadratic) of the relationship between PAP and production, maternal, and carcass EPDs on 12–18-month-old Angus bulls.

Model ¹	K ²	AICc ³	ΔAICc^4	W _i ⁵
Calving Ease Direct				
ln(Calving East Direct)	4	33842.86	0	0.52
Calving Ease Direct	4	33843.01	0.18	0.48
(Calving Ease Direct) ²	5	33852.78	9.92	0
Birth Weight				
ln(Birth Weight)	4	33791.67	0	0.76
Birth Weight	4	33794.01	2.36	0.23
(Birth Weight) ²	5	33801.02	9.35	0.01
Weaning Weight				
ln(Weaning Weight)	4	33817.08	0	0.99
Weaning Weight	4	33825.98	8.91	0.01
(Weaning Weight) ²	5	33839.94	22.86	0
Yearling Weight				
ln(Yearling Weight)	4	33776.60	0	0.99
Yearling Weight	4	33786.75	10.16	0.01
(Yearling Weight) ²	5	33839.94	22.86	0
Maternal Milk				
ln(Maternal Milk)	4	33787.26	0	0.97
Maternal Milk	4	33793.92	6.67	0.03
(Maternal Milk) ²	5	33895.85	18.60	0

Table 4.2 Continued.

Model ¹	K ²	AICc ³	ΔAICc ⁴	W _i ⁵
Scrotal Circumference				
ln(Scrotal Circumference)	4	22413.49	0	0.63
Scrotal Circumference	4	22415.05	1.56	0.29
(Scrotal Circumference) ²	5	22417.43	3.94	0
Ribeye Area				
ln(Ribeye Area)	4	33800.94	0	0.91
Ribeye Area	4	33805.60	4.66	0.09
(Ribeye Area) ²	5	33814.41	13.46	0
Marbling				
ln(Marbling)	4	33808.49	0	0.77
Marbling	4	33810.94	2.45	0.23
(Marbling) ²	5	33819.91	11.42	0
Carcass Weight				
ln(Carcass Weight)	4	33805.00	0	0.97
Carcass Weight	4	33812.30	7.31	0.03

¹Year is used as a random variable in all models. ²K is the number of parameters. ³Akaike's Information Criterion adjust for small sample size. ⁴Difference in Akaike's Information Criterion adjusted for small sample size compared to the best model. ⁵Akaike weight.

Table 4.3. Model selection for evaluating the effects of production, maternal, and carcass EPDS, fall versus spring sale, and associated interactions on 12 to 18-month-old purebred Angus bull PAP scores.

Model ¹	K ²	AICc ³	ΔAICc ⁴	W _i ⁵	r ² m ⁶	r ² c ⁷
Calving Ease Direct						
ln(Calving Ease Direct)*sale	5	33838.18	0	0.92	0.62%	1.06%
ln(Calving Ease Direct)	4	33843.04	4.86	0.08	0.36%	0.81%
null	3	33858.87	20.69	0	0%	0.50%
Birth Weight						
ln(Birth Weight)	4	33791.67	0	0.73	0.67%	1.10%
ln(Birth Weight)*sale	5	33793.65	1.98	0.27	0.73%	1.15%
null	3	33858.87	67.21	0	0%	0.50%
Weaning Weight						
ln>Weaning Weight)	4	33817.08	0	0.78	0.16%	0.82%
ln>Weaning Weight)*sale	5	33819.66	2.59	0.22	0.21%	0.80%
null	3	33858.87	41.80	0	0%	0.50%
Yearling Weight						
ln(Yearling Weight)	4	33776.60	0	0.77	0.24%	0.92%
ln(Yearling Weight)*sale	5	33778.96	2.36	0.23	0.30%	0.92%
null	3	33858.87	82.28	0	0%	0.50%
Maternal Milk						
ln(Maternal Milk)	4	33787.26	0	0.64	0.008%	0.49%
ln(Maternal Milk)*sale	5	33788.44	1.18	0.36	0.10%	0.56%
null	3	33858.87	71.62	0	0%	0.50%
Scrotal Circumference						

Table 4.3 Continued

Model ¹	K ²	AICc ³	Δ AICc ⁴	W _i ⁵	r ² m ⁶	r ² c ⁷
ln(Scrotal Circumference)	5	22415.05	0.03	0.50	0.04%	1.30%
null	3	33858.87	11443.86	0	0%	0.50%
Ribeye Area						
ln(Ribeye Area)*sale	5	33800.85	0	0.51	0.05%	0.53%
ln(Ribeye Area)	5	33800.94	0.10	0.49	0.04%	0.53%
null	3	33858.87	58.03	0	0%	0.50%
Marbling						
ln(Marbling)	4	33808.49	0	0.53	0.02%	0.51%
ln(Marbling)*sale	5	33808.71	0.23	0.47	0.04	0.51%
null	3	33858.97	50.39	0	0%	0.50%
Carcass Weight						
ln(Carcass Weight)	4	33805.00	0	0.72	0.10%	0.68%
ln(Carcass Weight)*sale	5	33806.88	1.89	0.28	0.17%	0.69%
null	3	33858.87	53.88	0	0%	0.50%

¹Year is used as a random variable in all models. ² K is the number of parameters. ³ Akaike's Information Criterion adjusted for small sample size. ⁴ Difference in Akaike's Information Criterion adjusted for small sample size compared to the best model. ⁵ Akaike weight. ⁶ Marginal r². ⁷ Conditional r²

Results

There were no significant relationships between bull PAP and SC EPD (Table 3; P= 0.28; Fall Sale: $\beta = -0.20 \pm 0.24$; Spring Sale: $\beta = -0.77 \pm 0.42$), Milk EPD (P = 0.51; $\beta = 0.28 \pm 0.45$), RE EPD (P = 0.17; Fall Sale: $\beta = -0.47 \pm 0.58$; Spring Sale: $\beta = -1.07 \pm 0.77$), and Marb EPD (P = 0.21; Fall Sale: $\beta = -0.17 \pm 0.41$; Spring Sale: $\beta = -0.74 \pm 0.59$). These models may be noninformative as the confidence intervals of the effect overlap 0.

The CED EPD displayed an asymptotic relationship (P < 0.01) to PAP. Candidate models containing CED EPD and sale received 100% of the relative support among candidate models. (Table 3; P < 0.01, Fall Sale: $\beta = -0.06 \pm 0.02$; Spring Sale: $\beta = -0.15 \pm 0.03$; Figure 1). These findings suggest bulls with greater CED had lower PAP scores. The top model containing all the supported variables had a conditional r² = 1.06% and a marginal r² = 0.62%, suggesting that the CED EPD and sale only accounted for 0.62% of the variation associated with PAP.

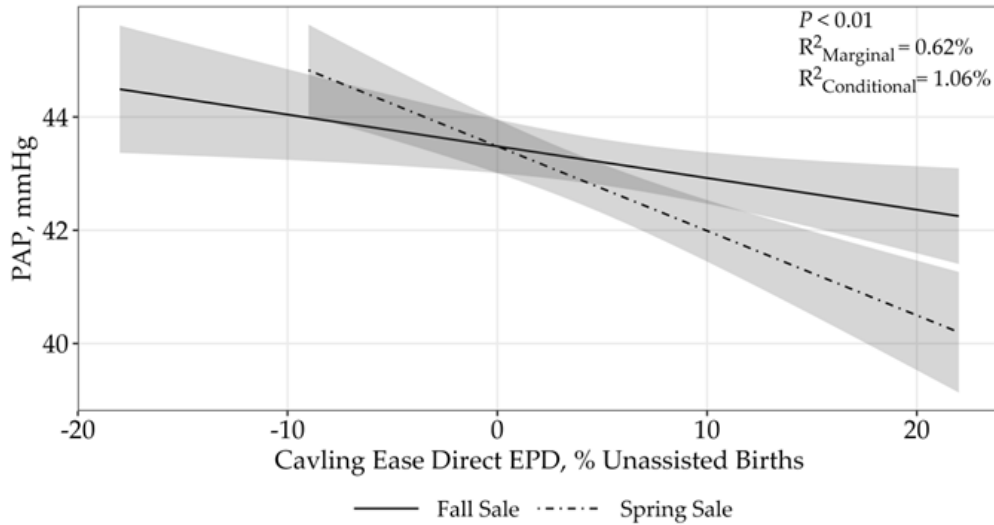


Figure 4.1. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and CED EPD. This relationship was best represented by a log transformed model. Calving Ease Direct is expressed as a difference percentage of unassisted births, with a higher value indicating greater calving ease in first-calf heifers. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B.

Candidate models containing the BW EPD and sale accounted for 100% of the support among candidate models (Table 3). The BW EPD by sale interaction displayed an asymptotic relationship to PAP scores ($P < 0.01$; Fall Sale: $\beta = 1.87 \pm 0.32$; Spring Sale: $\beta = 1.68 \pm 0.32$; Figure 2). Bulls with higher BW EPDs had higher PAP scores. The top model containing all supported variables had a conditional r^2 of 1.15% and a marginal r^2 of 0.73%, suggesting that birth weight and sale only accounted for 0.35% of the variation associated with PAP.

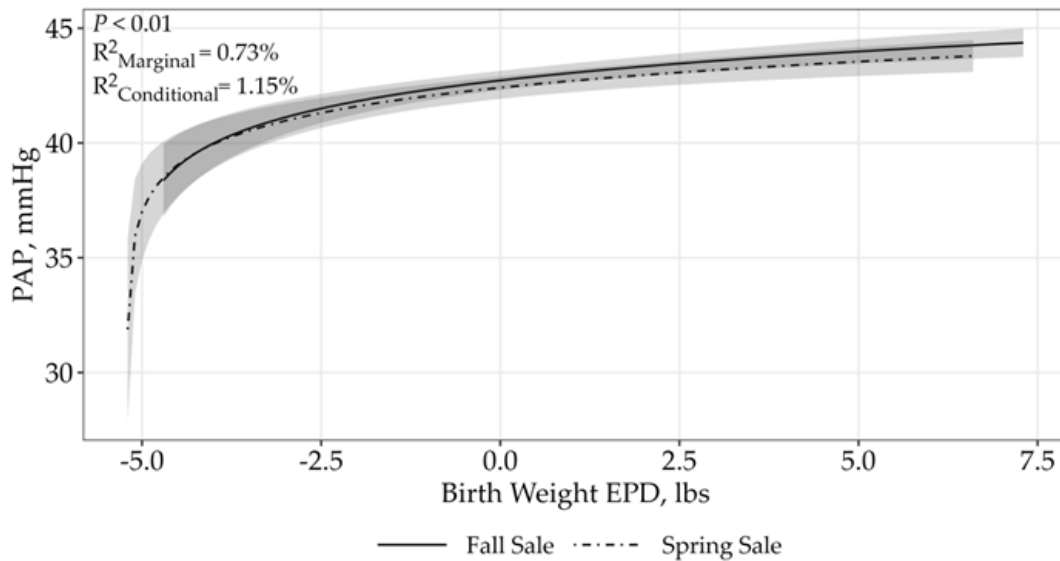


Figure 4.2. Predicted relationship ($\pm$ 95% CI represented in the shaded area) between PAP scores and BW EPD. This relationship was best represented by a log transformed model. The BW EPD is expressed in pounds and predicts the sire's ability to transmit birth weight to his progeny. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B.

A single top model containing the WW EPD received 78% of support among candidate models indicating there was no difference between sales (Table 3; $P = 0.01$; $\beta = 1.71 \pm 0.67$; Figure 2). Pulmonary arterial pressure scores increased as the WW EPD increased. The top model containing all the supported variables had a conditional r^2 of 0.82% and a marginal r^2 of 0.16%. Therefore, suggesting that the WW EPD only accounts for 0.16% of the variation in PAP scores.

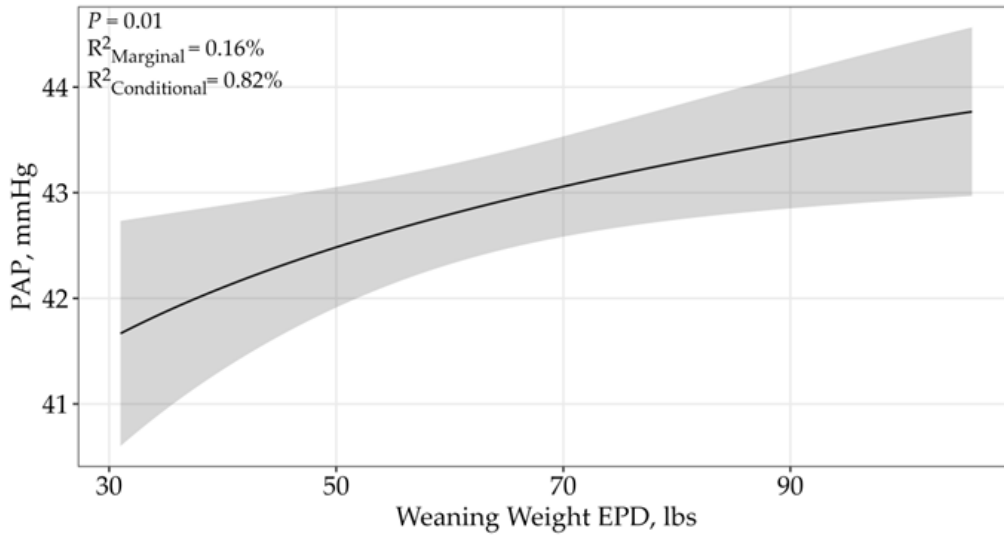


Figure 4.3. Predicted relationship ($\pm$ 95% CI represented in the shaded area) between PAP scores and WW EPD. This relationship was best represented by a log transformed model. The WW EPD is expressed in pounds and predicts the sire's ability to transmit weaning weight to his progeny. There was no difference between the two sales.

The YW EPD displayed an asymptotic relationship ($P < 0.01$) with bull PAP, and the single top model received 77% of the support among candidate model suggesting there was no difference between sales. Pulmonary arterial pressure scores increased as YW EPDs increased (Table 3; $\beta = 2.29 \pm 0.71$; Figure 4). The top model containing all supported variables had a conditional r^2 of 0.93% and a marginal r^2 of 0.24%.

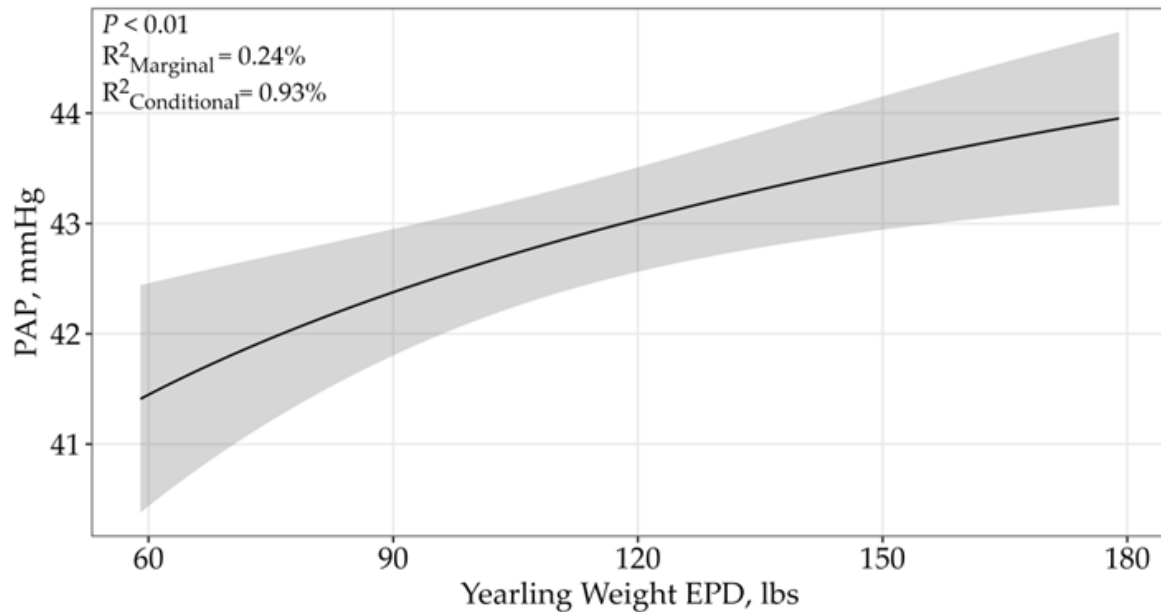


Figure 4.4. Predicted relationship ($\pm 95\%$ CI represented in the shaded area) between PAP scores and YW EPD. This relationship was best represented by a log transformed model. The YW EPD is expressed in pounds and predicts the sire's ability to transmit yearling weight to his progeny. There was no difference between the two sales.

Models containing the CW EPD and sale accounted for 100% of the support among the candidate models (Table 2). An asymptotic relationship best described the relationship between PAP and the CW EPD ($P = 0.03$; Fall Sale: $\beta = 0.77 \pm 0.35$; Spring Sale: $\beta = 0.65 \pm 0.35$; Figure 5), where PAP increased as the CW EPD increased. The top model containing all supported variables had conditional r^2 of 0.69% and marginal r^2 of 0.18 %.

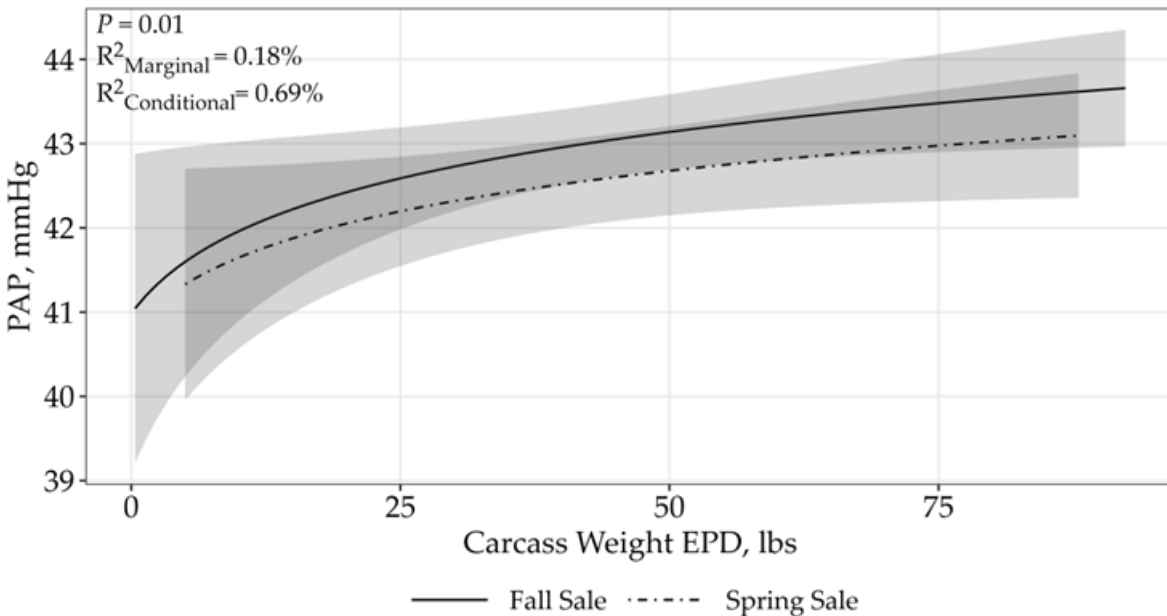


Figure 4.5. Predicted relationship ($\pm$ 95% CI represented in the shaded area) between PAP scores and CW EPD. This relationship was best represented by a log transformed model. The CW EPD is expressed in pounds and the difference in hot carcass weight of a sire's progeny compared to the progeny of other sires. The solid line represents the Fall sale hosted by operation A, while the dashed line represents the Spring sale hosted by operation B.

Discussion

Our study uses Angus seedstock performance driven bulls to assess the relationship between production, maternal, and carcass EPDs with PAP scores. While there have been studies establishing a relationship between PAP scores with actual performance, such as birth weight and yearling weight, the results have been conflicting (Crawford et al., 2016; Shirley et al., 2008; Stearns et al., 2025). In addition, there has not been a study evaluating the relationship of EPDs with PAP scores. Therefore, in this study, we chose to evaluate PAP's relationship to specific production, maternal, and carcass EPDs.

Calving Ease Direct is expressed as a difference in percentage of unassisted births, with a higher value indicating greater calving ease in first-calf heifers (Association, 2025) It predicts the

average difference in ease with which a sire's calves will be born when he is bred to first-calf heifers (Association, 2025). Looking into the relationship between CED and PAP scores, the current study found that as CED increases, the PAP measurements decreases. The BW EPD is expressed in pounds and predicts the sire's ability to transmit birth weight to his progeny compared to that of other sires (Association, 2025). Similarly, our candidate model indicated that as the BW EPD increased, PAP measurements also increased. Previous research demonstrated that birth weight was positively and moderately genetically correlated to PAP (Shirley et al., 2008). When comparing the relationship of PAP scores with actual birth weight, it showed that as birth weight increased, PAP scores did as well (Stearns et al., 2025) (Shirley et al., 2008).

The WW EPD is expressed in pounds and predicts the sire's ability to transmit weaning growth to his progeny compared to that of other sires (Association, 2025). The relationship between WW EPD and PAP scores suggested that as the WW EPD increased so did PAP scores. There have been conflicting results in previous research analyzing the relationship of PAP to WW. One study observed no significant phenotypic correlation between actual weaning weight and PAP measurements (Stearns et al., 2025), while a different study indicated that the phenotypic correlation showed to be positive but low (0.02 ± 0.03) (Shirley et al., 2008). Genotypic correlations were weak to moderate relationships between PAP scores and weaning weights (0.22 ± 0.08 ; 0.50 ± 0.18) (Crawford et al., 2016; Shirley et al., 2008).

The YW EPD is expressed in pounds and predicts the sire's ability to transmit yearling growth to his progeny compared to that of other sires (Association, 2025). Our study suggested that as YW EPD increased, PAP scores decreased. This result conflicted with phenotypic correlations which investigated the relationship between PAP scores and actual yearling weight,

and showed that as actual yearling weight increased, PAP measurements decreased (Stearns et al., 2025). Previous genotypic correlations have yielded conflicting results. Two previous genotypic correlations indicated that there is a weak genetic correlation between PAP and YW (Crawford et al., 2016; Pauling et al., 2023). However, an earlier study concluded there was a strong, negative relationship between actual yearling weights and PAP measurements (Schimmel et al., 1980).

Finally, the CW EPD, expressed in pounds, is a predictor of the difference in hot carcass weight of a sire's progeny compared to the progeny of other sires. Our results concluded that as the CW EPD increased, PAP also increased. A previous regression analysis of actual hot carcass weight and PAP, suggested there was a negative relationship (Thomas et al., 2018). This indicated that on average high PAP steers (> 49 mmHg) had a 15 kg decrease in carcass weight compared to those steers who were grouped into low and moderate PAP categories (Thomas et al., 2018).

While PAP was found to be associated with several performance, maternal, and carcass EPDs, the amount of variation explained by these relationship is less than 1%, individually. Pulmonary arterial pressure is a means to estimate heart-lung function, and, in turn, heart-lung function is dependent on many factors, both genetic and environmental. This can be illustrated in our study by evaluating the difference between conditional and marginal r^2 , which represents the amount of variation explained by the year of testing, one environmental variable that often explains as much or more of the variation of PAP scores as the EPDs.

However, our results suggest selecting for greater growth and performance using EPDs can result in greater PAP, whereas those bulls that experience greater actual growth and

performance have lower PAP scores (Stearns et al., 2025). This demonstrates the importance of keeping heart-lung function in mind when selecting cattle as results indicate those cattle with improved heart-lung function will capitalize on their genetic potential for growth and performance.

Conclusions

Heart-lung function continues to be a point of emphasis in the beef cattle sector. By determining relationships between PAP scores and EPDs that are points of selection for producers, we can better understand how these relationships can impact beef production in high elevation systems. It is important to keep heart-lung function in mind when selecting for growth and performance. This research showed significant relationships between PAP and the CED, BW, WW, YW, and CW EPDs. However, these relationships explain very little of the variation in PAP scores. Still, findings from this study can help better understand the importance of PAP in relation to growth and performance in high elevation production systems when determining an operation's goals for management. This research provides insight on the importance of selecting for heart-lung function to maximize growth and performance of beef cattle which is critical as we move toward selecting for increased growth and carcass weights.

References

- Alexander, A. (1962). The bovine lung: normal vascular histology and vascular lesions in high mountain disease. *Respiration*, 19(6), 528-542.
- Alexander, A., & Jensen, R. (1963). PULMONARY VASCULAR PATHOLOGY OF BOVINE HIGH MOUNTAIN DISEASE. *American Journal of Veterinary Research*, 24, 1098-1111.
- Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's Information Criterion. *The Journal of wildlife management*, 74(6), 1175-1178.
<https://doi.org/10.1111/j.1937-2817.2010.tb01236.x>
- American Angus Association (2025). *EPD & \$Value Definitions*. American Angus Association Retrieved March 2nd from <https://www.angus.org/tools-resources/national-cattle-evaluation/epd-value-definitions>
- Bartoń, K. (2022). MuMIn: multi-model inference. *R package version 1.46. 0*.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of statistical software*, 67, 1-48. <https://doi.org/10.18637/jss.v067.i01>
- Burnham, K.P. (1998). Model selection and multimodel inference. *A practical information-theoretic approach*.
- Crawford, N. F., Thomas, M. G., Holt, T. N., Speidel, S. E., & Enns, R. M. (2016). Heritabilities and genetic correlations of pulmonary arterial pressure and performance traits in Angus cattle at high altitude1. *Journal of Animal Science*, 94(11), 4483-4490.
<https://doi.org/10.2527/jas.2016-0703>
- Franklin, A. B., Anderson, D. R., Gutiérrez, R. J., & Burnham, K. P. (2000). CLIMATE, HABITAT QUALITY, AND FITNESS IN NORTHERN SPOTTED OWL POPULATIONS IN NORTHWESTERN CALIFORNIA. *Ecological Monographs*, 70(4), 539-590. [https://doi.org/https://doi.org/10.1890/0012-9615\(2000\)070\[0539:CHQAFI\]2.0.CO;2](https://doi.org/https://doi.org/10.1890/0012-9615(2000)070[0539:CHQAFI]2.0.CO;2)
- Geiss, L., & Culbertson, R. (2020). *Multibreed PAP EPD Released*
<https://herdbook.org/staticfiles/fileCMS/Index/Multibreed%20PAP%20EPD%20Released.pdf>
- Glover, G. H., & Newsom, I. E. (1914). *Brisket disease: dropsy of high altitudes* (Vol. 204). Agricultural Experiment Station of the Agricultural College of Colorado.

- Heath, D., Castillo, Y., Arias-Stella, J., & Harris, P. (1969). The small pulmonary arteries of the llama and other domestic animals native to high altitudes. *Cardiovascular Research*, 3(1), 75-78 <https://doi.org/10.1093/cvr/3.1.75>.
- Holt, T. (2019). *Bovine High-mountain Disease*. Merck Manual: Veterinary Manual <https://www.merckvetmanual.com/circulatory-system/bovine-high-mountain-disease/bovine-high-mountain-disease>
- Holt, T. N., & Callan, R. J. (2007). Pulmonary arterial pressure testing for high mountain disease in cattle. *Veterinary Clinics of North America: Food Animal Practice*, 23(3), 575-596. <https://doi.org/10.1016/j.cvfa.2007.08.001>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. *Journal of statistical software*, 82, 1-26. <https://doi.org/10.18637/jss.v082.i13>
- Markel, C. D. (2023). *Characterizing Effects of Management Strategy and Degree of Pulmonary Hypertension on Live Growth Performance, Carcass Quality, and Respiratory Microbiome of Finishing Beef Cattle* (Publication Number 30634728) [M.S., University of Wyoming]. ProQuest One Academic. United States -- Wyoming. <https://www.proquest.com/dissertations-theses/characterizing-effects-management-strategy-degree/docview/2854315038/se-2?accountid=28148>
- Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R² from generalized linear mixed-effects models. *Methods in ecology and evolution*, 4(2), 133-142. <https://doi.org/10.1111/j.2041-210x.2012.00261.x>
- Neary, J. M., Garry, F. B., Holt, T. N., Thomas, M. G., & Enns, R. M. (2015). Mean pulmonary arterial pressures in Angus steers increase from cow–calf to feedlot–finishing phases1. *Journal of Animal Science*, 93(8), 3854-3861. <https://doi.org/10.2527/jas.2015-9048>
- Pauling, R. C., Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2023). Genetic parameters for pulmonary arterial pressure, yearling performance, and carcass ultrasound traits in Angus cattle. *Journal of Animal Science*, 101. <https://doi.org/10.1093/jas/skad288>
- Ryans, K. (2019, Febuary 1 2019). *Research PAP EPD Launched by Angus Genetics Inc.* <https://www.angus.org/pub/newsroom/releases/020119-pap-epd-launch.html>
- Schimmel, J., Brinks, J., Russell, B., Mangus, W., & Denham, A. (1980). Genetic aspects of High Mountain [Brisket] disease in beef cattle. Proceedings of the Annual Meeting. American Society for Animal Science Western Section (USA),
- Shirley, K. L., Beckman, D. W., & Garrick, D. J. (2008). Inheritance of pulmonary arterial pressure in Angus cattle and its correlation with growth1. *Journal of Animal Science*, 86(4), 815-819. <https://doi.org/10.2527/jas.2007-0270>

- Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2020). Evaluation of the sensitivity of pulmonary arterial pressure to elevation using a reaction norm model in Angus Cattle. *Journal of Animal Science*, 98(5). <https://doi.org/10.1093/jas/skaa129>
- Stearns, K., DelCurto-Wyffels, H., Wyffels, S., Van Emon, M., Davis, N. G., Sitz, T., & DelCurto, T. (2025). Evaluating Pulmonary Arterial Pressure in Angus Yearling Bulls at High Elevation: Associations with Birth Traits and Growth Performance. *Animals*, 15(9), 1302. <https://doi.org/10.3390/ani15091302>
- Stearns, K., DelCurto-Wyffels, H., Wyffels, S., Van Emon, M., & DelCurto, T. (2024). The Use of Pulmonary Arterial Pressure (PAP) for Improved Beef Cattle Management. *Animals*, 14(16), 2430. <https://doi.org/10.3390/ani14162430>
- Team., R. C. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing. Retrieved 16 November from <https://www.R-project.org/>
- Thomas, M. G., Neary, J. M., Krafus, G. M., Holt, T. N., Enns, R. M., Speidel, S. E., F. B., Garry, C., Cánovas, Á., Medrano, J. F., Brown, R. D., & Stenmark, K. R. (2018). Pulmonary Hypertension (PH) in Beef Cattle : Complicated Threat to Health and Productivity in Multiple Beef Industry Segments.
- Veit, H., & Farrell, R. (1978). The anatomy and physiology of the bovine respiratory system relating to pulmonary disease. *The Cornell Veterinarian*, 68(4), 555-581.
- Will, D., Horrell, J., Reeves, J., & Alexander, A. (1975). Influence of altitude and age on pulmonary arterial pressure in cattle. *Proceedings of the Society for Experimental Biology and Medicine*, 150(3), 564-567. <https://doi.org/10.3181/00379727-150-390>
- Will, D., McMurtry, I., Reeves, J., & Grover, R. (1978). Cold-induced pulmonary hypertension in cattle. *Journal of Applied Physiology*, 45(3), 469-473. <https://doi.org/10.1152/jappl.1978.45.3.469>
- Williams, J. L., Bertrand, J. K., Misztal, I., & Łukaszewicz, M. (2012). Genotype by environment interaction for growth due to altitude in United States Angus cattle1. *Journal of Animal Science*, 90(7), 2152-2158. <https://doi.org/10.2527/jas.2011-4365>

CHAPTER FIVE

CONCLUSION

Conclusion and Summary

The importance of heart-lung function in beef cattle production cannot be understated, especially in high elevation production systems where calf death loss 3-5% from High Altitude Disease (HAD) and economic losses mount up to \$60 million, annually. Additionally, there continues to be a concern in moderate elevations as more cattle in feedlots experience right-sided heart failure (RHF). As the Angus breed continues to trend upward with selection for growth and performance, this study illustrates the importance of keeping heart-lung function in mind when selecting for increased growth and performance.

Our study offers a unique perspective on this issue. We worked directly with a premier Montana based seedstock operation that focuses on selling bulls that will be profitable and productive to their fellow seedstock producers and commercial cattlemen. Additionally, the size and scope of this data set is very distinct. We were able to gather data on 5,400 head of 12-to-18-month-old yearling Angus Bulls. The American Angus Association reported a combined 36,331 records of PAP measurements in 2025. Our data set accounts for 14.9% of all PAP records recorded with the American Angus Association.

This study achieved its objective of modeling relationships with PAP and gestation length, birth weight, and performance traits. Based on these relationships, it shows that bulls with increased gestation lengths and birth weights had greater PAP scores. Those bulls with increased performance (i.e. yearling weight and birth to yearling growth) showed decreased PAP scores. From these results, we concluded that bulls with improved heart-lung function experienced

increased gains and performance which from a biological perspective suggests cattle with ideal heart lung function perform better than cattle with less ideal PAP. These findings highlight the importance of keeping heart-lung function in mind when selecting cattle.

Additionally, we modeled the relationships with PAP and production, maternal, and carcass EPDs. As we look at industry trends, we see that selection for growth and performance within the Angus breed has trended upward for the past four years. Most often producers use EPDs as a method to select for added growth within their cattle herd. The results from this portion of the study indicated that bulls with greater performance EPDs had an increase in PAP scores. This suggests that while a bull may have genetic potential for greater growth and performance because of his EPDs, he may not have the potential to reach this increased performance due to decreased heart-lung function.

As we select cattle, these two studies illustrate the importance of heart-lung function. Bulls with greater actual performance are shown to have decreased PAP scores when compared to their contemporaries who have increased PAP scores. However, when selecting for growth and performance using EPDs, PAP scores increase. Based on these results, we conclude that beef cattle producers should keep heart-lung function in mind when making selection decisions to better allow for an animal's genetic potential for growth and performance to be reached.

A comparison of sire and grandsire lines of progeny within the data set indicated that sire selection does impact heart-lung function. Conscious sire selection with an emphasis on PAP and heart-lung function can be used to optimize potential within a beef herd. While we understand our research only describes a small amount of the variation within PAP estimates, this research provides practical application for beef cattle producers on the relationship between PAP and

growth and performance by recommending selection goals for those producers who want to place an increased emphasis on heart-lung function within their operation.

Future Research Directions

There continues to be a concern surrounding heart-lung function and PAP within the beef industry. This warrants additional heart-lung function and PAP research. Currently, PAP testing only provides accurate results for cattle that reside above 1500 m for at least three weeks and requires a right heart catheterization procedure that is performed by a licensed veterinarian. Finding a test that is more accessible for all beef cattle producers could help increase the accuracy of the EPD by increasing the number of records within the databases.

An animal's PAP score is impacted by both environmental and genetic components. Therefore, additional research to understand genetic and environmental variations within PAP scores is warranted to make both recommendations in management strategies and genetic selection for improved heart-lung function within beef cattle. Additionally, understanding how PAP scores affect cattle grazing patterns and behaviors in high elevation beef production systems would provide insight into animal behavior. Finally, additional research is needed to identify RHF early in feedlots to mitigate losses.

Ultimately, there is a need for additional research to assist in understanding the complex topic of heart-lung function in beef cattle.

REFERENCES CITED

- Ahola, J., Enns, R., & Holt, T. (2006). Examination of potential methods to predict pulmonary arterial pressure score in yearling beef cattle. *Journal of Animal Science*, 84(5), 1259-1264. <https://doi.org/10.2527/2006.8451259x>
- Alexander, A. (1962). The bovine lung: normal vascular histology and vascular lesions in high mountain disease. *Respiration*, 19(6), 528-542. <https://doi.org/10.1159/000192262>
- Alexander, A., & Jensen, R. (1963). PULMONARY VASCULAR PATHOLOGY OF BOVINE HIGH MOUNTAIN DISEASE. *American Journal of Veterinary Research*, 24, 1098-1111.
- American Angus Association (2025). *EPD & \$Value Definitions*. American Angus Association Retrieved March 2nd from <https://www.angus.org/tools-resources/national-cattle-evaluation/epd-value-definitions>
- American Simmental Association. (2014). *Beef Briefs: History of the Simmental Breed*. https://www.pasimmental.com/files/wpcontent/uploads/2014/03/Simmental_history.pdf
- Arnold, T. W. (2010). Uninformative parameters and model selection using Akaike's Information Criterion. *The Journal of wildlife management*, 74(6), 1175-1178. <https://doi.org/10.1111/j.1937-2817.2010.tb01236.x>
- Bartoń, K. (2022). MuMIn: multi-model inference. *R package version 1.46. 0*.
- Bates, D., Mächler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of statistical software*, 67, 1-48. <https://doi.org/10.18637/jss.v067.i01>
- Benesi, F. J. (1993). Neonatal calf asphyxia syndrome. Importance and critical evaluation. *Journal title: Archives of the School of Veterinary Medicine of the Federal University of Bahia*, 16(1), 38-48.
- Burfening, P. J., Kress, D. D., Friedrich, R. L., & Vaniman, D. D. (1978). Phenotypic and Genetic Relationships between Calving Ease, Gestation Length, Birth Weight and Preweaning Growth. *Journal of Animal Science*, 47(3), 595-600. <https://doi.org/10.2527/jas1978.473595x>
- Burnham, K.P. (1998). Model selection and multimodel inference. *A practical information-theoretic approach*.
- Card, C. S. (1977). *The bovine erythron during hypoxic stress*. PhD Dissertation Colorado State Univ. Fort Collins, CO.

- Cockrum, R., Zeng, X., Berge, N., Neary, J., Garry, F., Holt, T., Blackburn, H., Thomas, S., Speidel, S., & Garrick, D. (2014). Angus cattle at high altitude: Genetic relationships and initial genome-wide association analysis of pulmonary arterial pressure. *Proc. World Congress Appl. Livestock Prod.*
- Crawford, N. F., Thomas, M. G., Holt, T. N., Speidel, S. E., & Enns, R. M. (2016). Heritabilities and genetic correlations of pulmonary arterial pressure and performance traits in Angus cattle at high altitude¹. *Journal of Animal Science*, 94(11), 4483-4490. <https://doi.org/10.2527/jas.2016-0703>
- Crawford, N., Enns, R., Speidel, S., LaShell, B., Holt, T., & Thomas, M. (2017). CASE STUDY: factors influencing pulmonary arterial pressure in cattle of the San Juan Basin Research Center 4-Corners Bull Test data. *The Professional Animal Scientist*, 33(3), 387-392. <https://doi.org/10.15232/pas.2016-01587>
- Cueva, S. M. (1967). *Blood oxygen transport in cattle "susceptible" and "resistant" to High Mountain (Brisket) Disease* [Colorado State University].
- De Moraes HA, S. D. (2005). Pathophysiology of heart failure. In F. E. Ettinger SJ (Ed.), *Textbook of Veterinary Internal Medicine. 6th ed* (pp. 914-940). Saunders Elsevier.
- DeNise, S., Torabi, M., Ray, D., & Rice, R. (1988). Genetic parameter estimates for preweaning traits of beef cattle in a stressful environment. *Journal of Animal Science*, 66(8), 1899-1906. <https://doi.org/10.2527/jas1988.6681899x>
- Eigenmann, U., Schoon, H., Jahn, D., & Grunert, E. (1984). Neonatal respiratory distress syndrome in the calf. *The Veterinary Record*, 114(6), 141-144. <https://doi.org/10.1136/vr.114.6.141>
- Enns, R., Brinks, J., Bourdon, R., & Field, T. (1992). Heritability of pulmonary arterial pressure in Angus cattle. *Proc. West. Sect. Am. Soc. Anim. Sci.*
- Fox, J., & Weisberg, S. (2018). *An R companion to applied regression*. Sage publications.
- Foxworthy, H., Enns, R., Speidel, S., Thomas, M., & Holt, T. (2018). 286 Gestation length as a weak predictor of yearling pulmonary arterial pressure and risk of developing high altitude disease in Angus cattle at high elevation. *Journal of Animal Science*, 96(suppl_3), 106-107. <https://doi.org/10.1093/jas/sky404.235>
- Franklin, A. B., Anderson, D. R., Gutiérrez, R. J., & Burnham, K. P. (2000). CLIMATE, HABITAT QUALITY, AND FITNESS IN NORTHERN SPOTTED OWL POPULATIONS IN NORTHWESTERN CALIFORNIA. *Ecological Monographs*, 70(4), 539-590. [https://doi.org/10.1890/0012-9615\(2000\)070\[0539:CHQAFI\]2.0.CO;2](https://doi.org/10.1890/0012-9615(2000)070[0539:CHQAFI]2.0.CO;2)
- Funston, R. N., Larson, D. M., & Vonnahme, K. A. (2010). Effects of maternal nutrition on conceptus growth and offspring performance: Implications for beef cattle production¹.

- Journal of Animal Science*, 88(suppl_13), E205-E215. <https://doi.org/10.2527/jas.2009-2351>
- Ganong, W. F. (2001). In *Review of Medical Physiology* (20th ed.). McGraw-Hill Book Co.
- Geiss, L., & Culbertson, R. (2020). *Multibreed PAP EPD Released*
<https://herdbook.org/staticfiles/fileCMS/Index/Multibreed%20PAP%20EPD%20Released.pdf>
- Glover, G. H., & Newsom, I. E. (1914). *Brisket disease: dropsy of high altitudes* (Vol. 204). Agricultural Experiment Station of the Agricultural College of Colorado.
- González-Murray, R. A., Sánchez-Castro, M. A., Thomas, M. G., Speidel, S. E., & Enns, R. M. (2020). Heterosis and its potential influence on pulmonary arterial pressure in beef cattle. *Translational Animal Science*, 4(Supplement_1), S118-S121.
<https://doi.org/10.1093/tas/txaa117>
- Heath, D., Castillo, Y., Arias-Stella, J., & Harris, P. (1969). The small pulmonary arteries of the llama and other domestic animals native to high altitudes. *Cardiovascular Research*, 3(1), 75-78. <https://doi.org/10.1093/cvr/3.1.75>
- Heaton, M. P., Bassett, A. S., Whitman, K. J., Krafur, G. M., Lee, S. I., Carlson, J. M., Clark, H. J., Smith, H. R., Pelster, M. C., Basnayake, V., Grotelueschen, D. M., & Vander Ley, B. L. (2019). Evaluation of EPAS1 variants for association with bovine congestive heart failure. *F1000Res*, 8, 1189. <https://doi.org/10.12688/f1000research.19951.1>
- Holt, T. (2019). *Bovine High-mountain Disease*. Merck Manual: Veterinary Manual
<https://www.merckvetmanual.com/circulatory-system/bovine-high-mountain-disease/bovine-high-mountain-disease>
- Holt, T. N., & Callan, R. J. (2007). Pulmonary arterial pressure testing for high mountain disease in cattle. *Veterinary Clinics of North America: Food Animal Practice*, 23(3), 575-596.
<https://doi.org/10.1016/j.cvfa.2007.08.001>
- Ivany, J. M., & Illanes, O. G. (1999). Congestive heart failure due to epicardial lymphosarcoma in a Holstein cow. *Can Vet J*, 40(11), 819-820.
- James, L. F., Panter, K. E., Broquist, H. P., & Hartley, W. J. (1991). Swainsonine-induced high mountain disease in calves. *Vet Hum Toxicol*, 33(3), 217-219.
- Jensen, R., Pierson, R., Braddy, P., Saari, D., Benitez, A., Horton, D., Lauerman, L., McChesney, A., Alexander, A., & Will, D. (1976). Brisket disease in yearling feedlot cattle. *Journal of the American Veterinary Medical Association*, 169(5), 515-517.
- Krehbiel, B. C., Thomas, M. G., Speidel, S. E., Enns, R. M., & Blackburn, H. D. (2017). Genetic structure of Angus and Salers in relation to SNP associated with pulmonary arterial

- pressure. *Journal of Animal Science, suppl. supplement 4*, 95, 87-88.
<https://www.proquest.com/scholarly-journals/genetic-structure-angus-salers-relation-snp/docview/1947371029/se-2?accountid=28148>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. *Journal of statistical software*, 82, 1-26. <https://doi.org/10.18637/jss.v082.i13>
- Kuznetsova, A., Brockhoff, P. B., & Christensen, R. H. (2017). lmerTest package: tests in linear mixed effects models. *Journal of statistical software*, 82, 1-26.
- Lenth, R. (2022). emmeans: Estimated marginal means, aka least-squares means. R package version 1.7. 2. In.
- Markel, C. D. (2023). *Characterizing Effects of Management Strategy and Degree of Pulmonary Hypertension on Live Growth Performance, Carcass Quality, and Respiratory Microbiome of Finishing Beef Cattle* (Publication Number 30634728) [M.S., University of Wyoming]. ProQuest One Academic. United States -- Wyoming.
<https://www.proquest.com/dissertations-theses/characterizing-effects-management-strategy-degree/docview/2854315038/se-2?accountid=28148>
- Moore, L. G., Reeves, J. T., Will, D. H., & Grover, R. F. (1979). Pregnancy-induced pulmonary hypertension in cows susceptible to high mountain disease. *Journal of Applied Physiology*, 46(1), 184-188. <https://doi.org/10.1152/jappl.1979.46.1.184>
- Moxley, R. A., Smith, D. R., Grotelueschen, D. M., Edwards, T., & Steffen, D. J. (2019). Investigation of congestive heart failure in beef cattle in a feedyard at a moderate altitude in western Nebraska. *Journal of Veterinary Diagnostic Investigation*, 31(4), 509-522. <https://doi.org/10.1177/1040638719855108>
- Murray, C. F., & Leslie, K. E. (2013). Newborn calf vitality: Risk factors, characteristics, assessment, resulting outcomes and strategies for improvement. *The Veterinary Journal*, 198(2), 322-328. <https://doi.org/10.1016/j.tvjl.2013.06.007>
- Nakagawa, S., & Schielzeth, H. (2013). A general and simple method for obtaining R² from generalized linear mixed-effects models. *Methods in ecology and evolution*, 4(2), 133-142. <https://doi.org/10.1111/j.2041-210x.2012.00261.x>
- Neary, J. M. (2014). *Epidemiological, physiological and genetic risk factors associated with congestive heart failure and mean pulmonary arterial pressure in cattle* (Publication Number 3635657) [Ph.D., Colorado State University]. Agricultural & Environmental Science Collection; ProQuest One Academic. United States -- Colorado.
<https://www.proquest.com/dissertations-theses/epidemiological-physiological-genetic-risk/docview/1615100266/se-2?accountid=28148>

- Neary, J. M., Garry, F. B., Holt, T. N., Thomas, M. G., & Enns, R. M. (2015). Mean pulmonary arterial pressures in Angus steers increase from cow–calf to feedlot–finishing phases1. *Journal of Animal Science*, 93(8), 3854-3861. <https://doi.org/10.2527/jas.2015-9048>
- Pauling, R. C., Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2023). Genetic parameters for pulmonary arterial pressure, yearling performance, and carcass ultrasound traits in Angus cattle. *Journal of Animal Science*, 101. <https://doi.org/10.1093/jas/skad288>
- Rebello, C. M., Ikegami, M., Polk, D., & Jobe, A. (1996). Postnatal lung responses and surfactant function after fetal or maternal corticosteroid treatment. *Journal of Applied Physiology*, 80(5), 1674-1680. <https://doi.org/10.1152/jappl.1996.80.5.1674>
- Rhodes, J. (2005). Comparative physiology of hypoxic pulmonary hypertension: historical clues from brisket disease. *Journal of Applied Physiology*, 98(3), 1092-1100. <https://doi.org/10.1152/japplphysiol.01017.2004>
- Ryans, K. (2019, February 1 2019). *Research PAP EPD Launched by Angus Genetics Inc.* <https://www.angus.org/pub/newsroom/releases/020119-pap-epd-launch.html>
- Schimmel, J., Brinks, J., Russell, B., Mangus, W., & Denham, A. (1980). Genetic aspects of High Mountain [Brisket] disease in beef cattle. Proceedings of the Annual Meeting. American Society for Animal Science Western Section (USA),
- Shirley, K. L., Beckman, D. W., & Garrick, D. J. (2008). Inheritance of pulmonary arterial pressure in Angus cattle and its correlation with growth1. *Journal of Animal Science*, 86(4), 815-819. <https://doi.org/10.2527/jas.2007-0270>
- Shoup, L. M., Wilson, T. B., González-Peña, D., Ireland, F. A., Rodriguez-Zas, S., Felix, T. L., & Shike, D. W. (2015). Beef cow prepartum supplement level and age at weaning: II. Effects of developmental programming on performance and carcass composition of steer progeny1. *Journal of Animal Science*, 93(10), 4936-4947. <https://doi.org/10.2527/jas.2014-8565>
- Speidel, S. E., Thomas, M. G., Holt, T. N., & Enns, R. M. (2020). Evaluation of the sensitivity of pulmonary arterial pressure to elevation using a reaction norm model in Angus Cattle. *Journal of Animal Science*, 98(5). <https://doi.org/10.1093/jas/skaa129>
- Stearns, K., DelCurto-Wyffels, H., Wyffels, S., Van Emon, M., & DelCurto, T. (2024). The Use of Pulmonary Arterial Pressure (PAP) for Improved Beef Cattle Management. *Animals*, 14(16), 2430. <https://doi.org/10.3390/ani14162430>
- Stearns, K., DelCurto-Wyffels, H., Wyffels, S., Van Emon, M., Davis, N. G., Sitz, T., & DelCurto, T. (2025). Evaluating Pulmonary Arterial Pressure in Angus Yearling Bulls at High Elevation: Associations with Birth Traits and Growth Performance. *Animals*, 15(9), 1302. <https://doi.org/10.3390/ani15091302>

- Team., R. C. (2022). *R: A Language and Environment for Statistical Computing*. R Foundation for Statistical Computing.
- Thomas, M. G., Krafur, G. M., Holt, T. N., Enns, R. M., Speidel, S. E., Garry, F. B., Cánovas, Á., Medrano, J., Brown, R. D., Stenmark, K. R., & Neary, J. M. (2017). GENETICS OF BRISKET DISEASE IN BEEF CATTLE : A NOT SO HIGH ALTITUDE PROBLEM.
- Thomas, M. G., Neary, J. M., Krafur, G. M., Holt, T. N., Enns, R. M., Speidel, S. E., F. B., Garry, Cánovas, Á., Medrano, J. F., Brown, R. D., & Stenmark, K. R. (2018). Pulmonary Hypertension (PH) in Beef Cattle : Complicated Threat to Health and Productivity in Multiple Beef Industry Segments.
- Veit, H., & Farrell, R. (1978). The anatomy and physiology of the bovine respiratory system relating to pulmonary disease. *The Cornell Veterinarian*, 68(4), 555-581.
- Will, D., Horrell, J., Reeves, J., & Alexander, A. (1975). Influence of altitude and age on pulmonary arterial pressure in cattle. *Proceedings of the Society for Experimental Biology and Medicine*, 150(3), 564-567. <https://doi.org/10.3181/00379727-150-39>
- Will, D., McMurtry, I., Reeves, J., & Grover, R. (1978). Cold-induced pulmonary hypertension in cattle. *Journal of Applied Physiology*, 45(3), 469-473. <https://doi.org/10.1152/jappl.1978.45.3.469>
- Williams, J. L., Bertrand, J. K., Misztal, I., & Łukaszewicz, M. (2012). Genotype by environment interaction for growth due to altitude in United States Angus cattle1. *Journal of Animal Science*, 90(7), 2152-2158. <https://doi.org/10.2527/jas.2011-4365>