Evaluation of long-term industry selection for increased carcass leanness in Duroc swine

by

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DEDICATION

I would like to dedicate this thesis to my grandfather, Charles Walsh, whose incredible enthusiasm for people and hogs was the initial spark for my interest in swine genetics. I constantly meet people within the swine industry who speak of you with a great deal of respect. You have been an outstanding role model through many of the challenges of my scholastic career. I realize that my graduate education is an endeavor you wished to undertake yourself, and I hope that I have pursued my career path in a manner that you would have perceived for yourself.
# TABLE OF CONTENTS

CHAPTER 1. GENERAL INTRODUCTION 1  
Thesis Organization 3

CHAPTER 2. LITERATURE REVIEW 5  
Marketing Changes within the Pork Industry 5  
Genetic Parameters of Growth Performance, Carcass Composition, and Meat and Eating Quality Traits 8  
Genetic and Phenotypic Trends 15  
Breed Differences 17  
Gender Differences 20  
Growth and Development of Carcass Composition and Intramuscular Fat 21  
Effects of Fat Thickness on Pork Quality Measures 25

CHAPTER 3. EVALUATION OF LONG-TERM INDUSTRY SELECTION FOR INCREASED CARCASS LEANNESS IN Duroc Swine: I. EFFECT ON CARCASS COMPOSITION, PERFORMANCE, AND GROWTH CURVES 28  
Abstract 29  
Introduction 30  
Materials and Methods 31  
Results and Discussion 34  
Implications 40  
Literature Cited 42

CHAPTER 4. EVALUATION OF LONG-TERM INDUSTRY SELECTION FOR INCREASED CARCASS LEANNESS IN Duroc Swine: II. EFFECT ON MEAT AND EATING QUALITY 51  
Abstract 52  
Introduction 53  
Materials and Methods 54  
Results and Discussion 58  
Implications 66  
Literature Cited 67

CHAPTER 5. GENERAL SUMMARY 74

CHAPTER 8. REFERENCES CITED 76

ACKNOWLEDGMENTS 82
CHAPTER 1. GENERAL INTRODUCTION

Descriptive terms such as quantity and quality have been referred to with distinctly different levels of importance when applied to economic concerns of pork production over the past quarter century. The latter of which is a more subjective characteristic and is more difficult to measure, particularly as done by consumers. However, as the live hog is converted to meat and displayed to the consumer, the measure of quality becomes a greater concern. Unfortunately due to an increasingly volatile and competitive hog market, producers constantly struggle with the issue of how to create a pork industry that is economically viable. In turn, selection schemes initiated by producers revolve solely around those traits of economic importance. The initiation of grid-based marketing systems within the past 20 years has created an opportunity for producers to increase the value of the hogs they market through increased lean percentage. Prior to 1985, 90 percent of hogs marketed were sold as traditional ‘commodity pork’ where price was determined on a live weight basis (Hayenga, 1985). The utilization of incentive-based marketing systems became increasingly important to producers seeking added value to the hogs they produce, corresponding to increased selection for lean percentage. As a result, the percentage of hogs sold on a carcass basis rose to 28 percent in 1988 and to 78 percent in 1997 (Brorsen et al., 1998).

In nearly 20 years, pork producers have made tremendous strides toward providing a leaner product to the packer, and ultimately, the consumer. However, through intensive selection for increased carcass leanness, the swine industry has allowed consumer acceptance issues to arise as a result of decreased meat quality. Quality characteristics that play an
integral role in consumer acceptance, such as intramuscular fat, have decreased as breeders have intensely selected for increased leanness (Barton-Gade, 1990; Cameron, 1990).

Berger et al. (1994) provided significant genetic correlations among composition, meat, and eating quality traits, suggesting that changes in carcass composition traits may affect meat quality characteristics. Some of the meat and eating quality traits that have significant genetic correlations with tenth-rib backfat thickness include: intramuscular fat percentage (.32), Intron tenderness (-.25), cooked moisture percentage (-.48), cooking loss percentage (.38), and juiciness score (-.19). Loin muscle area is also shown to be genetically associated with intramuscular fat percentage (-.37), Intron tenderness (.18), cooked moisture percentage (.26), and cooking loss percentage (-.16). All of these correlations are antagonistic in nature, and some are large enough to create significant problems with meat quality if they are ignored in selection schemes aimed at increased carcass leanness. These data were derived, however, from progeny of boars farrowed in 1990-91 and significant genetic improvement has been made in carcass leanness since that time. As a result, further deterioration in quality traits has also likely occurred. Evaluation of the genetic correlations among growth, composition, and quality traits in a current population will provide the opportunity to update this information and increase our understanding of these genetic relationships.

It is illustrated in Hiner et al. (1965) and Jensen et al. (1967) that quality characteristics, particularly intramuscular fat percentage, of meat were significantly better before intense selection was placed on carcass leanness. Not only was it documented that meat quality was higher, but more specifically, Duroc pigs had much greater marbling than the other breeds. Today, the Duroc breed is used extensively as a terminal sire in the
production of crossbred market hogs because of its known advantage over other breeds in terms of growth rate and meat quality characteristics.

In order to remain competitive in the future, it is important that producers develop a way to differentiate their product. Overcoming the issue of pork quality is an avenue that will enable the producer to improve consumer acceptance of pork. By quantifying the effect that long-term intensive selection for increased carcass leanness has had on meat quality characteristics, we may begin to explore opportunities for producers to add value to the products they produce.

The objectives of this study were three-fold. The primary objective was to quantify the effect that selection for decreased backfat thickness and increased loin muscle area (i.e. increased percent lean) has had on meat and eating quality traits and performance since the initiation of incentive-based hog pricing in the mid to late 1980s. The second objective of the study was to assess any changes in growth patterns of these traits that may have resulted from marketing scheme changes during this time period. The final goal of the study was to identify boars or genetic lines from the 1980s with superior meat quality that maintain adequate growth and carcass composition in today’s pork industry.

**Thesis Organization**

This thesis is presented as a general introduction, a literature review, two individual papers, and a general summary. References cited in the general introduction and literature review follow the general summary section. All reference citations are in compliance with the CBE Style Manual used by the Journal of Animal Science to which these papers will be
submitted. Each individual paper consists of an abstract and four sections: introduction, materials and methods, results and discussion, and implications. Literature cited within the papers is listed after the implication section of each individual paper.
CHAPTER 2. LITERATURE REVIEW

Marketing Changes within the Pork Industry

The 1980s and 1990s have been part of dramatic changes in swine production and marketing. As the swine industry became more highly specialized, the method by which hogs were valued began to evolve as well. Not more than two decades ago, less than 10 percent of hogs were sold with the use of a carcass merit pricing system. Today in the U.S., the price for over 75 percent of hogs marketed is dictated by a carcass merit pricing system, allowing processors to quickly notify the producer of carcass value (Schroeder et al., 2004; Brorsen et al., 1998). Within the past quarter century, producers have witnessed a wide array of marketing changes- all of which have initiated certain subsequent breeding schemes by producers seeking to increase profit margins. This section will discuss those market changes utilized by packers and processors in the procurement of hogs.

The most dated method of hog value determination was based on a per-head negotiated price driven by live weight as a pig crosses the scale (Shepherd et al., 1940). This method quickly evolved into a scheme used in Canada and many countries in Europe since the 1930s and involved the use of an estimator of leanness on the basis of carcass weight and grade. Raikes et al. (1973) reported that all hogs in Canada during the early 1970s were marketed on a grade and weight basis.

Shepherd et al. (1940) revealed a fundamental reason for the inaccuracy of hog pricing on the basis of live weight. With this method of procurement, the packer buyer was unable to accurately assess carcass value of an individual hog as well as differentiate carcass merit differences between lots of hogs. Another apparent flaw with live weight pricing of
hogs was that the variation in carcass value well exceeded the variation in price paid for individual hogs.

Traditional live pricing of hogs involved one of three methods for determining value as described by Raikes et al. (1973). The first of which was a “live sort” method where hogs were weighed and sorted into separate weight and estimated grade groups and price was determined accordingly. Secondly, with the use of a “live average” method, a packer buyer would estimate the number of hogs in each weight and grade category to negotiate an average price for the entire lot. The final “adjusted live sort” method utilized the same process as the “live sort” method; however, high and low quality hogs were sorted and priced separately.

Wiley et al. (1951) examined a more accurate method of hog procurement by determining a live value that more closely reflected carcass value. This study found that percentage of lean cuts (picnic, ham, loin, and butt) were strongly correlated with carcass weight (CW) and average backfat (BF) and concluded that a grid pricing system could be useful for more accurately determining carcass value when CW and BF are available.

Though only three percent of all hogs marketed in the United States were sold on a carcass merit or grade and weight basis (Ikerd and Cramer, 1970), further usefulness of this method was revealed when Pearson et al. (1970) determined that the same level of accuracy in terms of carcass merit determination could be achieved with only one measurement of last rib backfat. Consequently, a single backfat measure could be utilized instead of the average of three measures, and ultimately increase the practicality of the procurement system.

Interestingly, a survey conducted by Hayenga et al. (1985) revealed that though systems of hog pricing were quickly reaching high levels of practical accuracy, only 10 to 12
percent of producers actually sold hogs on a carcass merit basis. Few packers actually utilized this information in their pricing methods over the next 15 years, inhibiting industry progress toward the production of leaner hogs (Topel, 1986). This was in part due to the fact that some producers were reducing total fat in the market hogs they produced, yet didn’t feel that the price incentives were enough to merit continued improvement in carcass leanness (Hayenga, 1985).

Established marketing systems that enabled packers and processors to offer greater incentives for the production of improved carcass leanness were investigated by Grisdale et al. (1984). This work utilized 174 hog carcasses to further develop carcass pricing guidelines and found a strong correlation between carcass value and carcass weight, 10th rib backfat, and weight of the four lean cuts ($r = 0.78, -0.79, \text{ and } 0.76, \text{ respectively}$). Carcass composition differences could be more accurately assessed on line, allowing packers the added confidence to accentuate the incentives offered for increased carcass leanness.

Recently, the swine industry has witnessed a steady decrease in the marketing of hogs on the spot market from 64 percent in 1994 to only 17 percent in 2001 (Smith, 2001). Carcass weight and a measure of backfat and/or loin muscle depth has become the preferred way to procure hogs over the last decade (McKissick, 1998). With this change in procurement away from live weight pricing, packers and processors have needed fast, accurate, and reliable measures to estimate carcass composition. Today, a large majority of hogs are graded by measuring last rib backfat with a steel ruler, backfat and loin muscle depth with an optical grading probe, or with the use of an ultrasonic device to estimate carcass lean composition. These methods to estimate carcass composition also enable producers to accurately evaluate carcass leanness indicators in breeding stock (Smith, 2001).
With accurate measurement methods, genetic parameters, and a pricing system that provides economic incentives for leanness, producers could effectively select for enhanced carcass composition and ultimately increase profit margins.

**Genetic Parameters of Growth Performance, Carcass Composition, and Meat and Eating Quality Traits**

This section will illustrate that an awareness of the estimates of genetic parameters for traits that tie together growth performance, carcass composition, meat quality, and consumer acceptance are imperative for efficient simultaneous genetic improvement of traits in more than one of the above trait categories. Concurrently, it will suggest that complex selection objectives are essential to prevent degradation in meat quality and consumer acceptance while selecting to improve genetic merit of performance and/or carcass composition.

*Genetic Parameters of Growth Performance.*

The direct heritability of growth performance has been well established; however, its genetic relationship with other economically important traits (namely backfat) encompasses a relatively large range in estimates. This section will review significant, recently published estimates of the genetic parameters associated with growth performance in studies where pigs were allowed *ad libitum* intake.

Data from 5,649 Duroc X Landrace pigs by 65 different sires were used by Lo et al. (1992) to estimate genetic parameters for age to 103.6 kg (AGE) and average daily gain (ADG) from 39.5 to 103.6 kg. The reported heritability estimates and standard errors for AGE and ADG were $0.43 \pm 0.08$ and $0.36 \pm 0.07$, respectively. Age to 103.6 kg was
estimated to have a moderate unfavorable genetic correlation with carcass backfat thickness \((r_g = -0.35)\) and a favorable low genetic correlation with carcass loin muscle area \((r_g = 0.14)\). However, ADG was found to include a moderately favorable genetic correlation with carcass tenth-rib backfat \((r_g = 0.43)\) and a low and unfavorable genetic relationship with carcass loin muscle area \((r_g = -0.18)\). Similar genetic correlations between growth performance and ultrasonically measured backfat and loin muscle area were also estimated in this study.

Bryner et al. (1992) utilized data on 7,951 Yorkshire boars from 26 central boar test stations from 1984 through 1990 to estimate heritabilities and genetic correlations for backfat and growth rate. Direct heritabilities for backfat and average daily gain were estimated to be 0.56 and 0.24, respectively. The additive genetic correlation between average daily gain and backfat was approximately zero \((-0.05)\), indicating that selection for one of these traits will not inhibit progress in the other trait and that simultaneous selection for both traits can be effective.

Data representative of eight major swine seedstock populations in the United States were used to estimate genetic parameters of various economically important traits by Berger et al. (1994). The data utilized in this study encompassed 135 seedstock breeders from 20 states and 234 sire groups from 1991 to 1993. Growth performance was found to be moderately heritable \((h^2 = 0.58)\) and revealed a weak genetic antagonism with backfat measured at the tenth rib \((-0.04)\).

Sonesson et al. (1998) estimated genetic parameters of performance traits with the use of 4,356 records from a Dutch Large White population. Pigs in this study were fed *ad libitum* and growth rate was adjusted to 175 days of age while backfat was adjusted to 104 kg
of body weight. The heritability estimate (SE) of growth rate was 0.41 (0.02) and had a genetic relationship with backfat of 0.38.

Perhaps the most widely utilized publication regarding genetic parameters of performance traits is a compilation of literature found in *The Genetics of the Pig*. Clutter and Brascamp (1998) reviewed published parameter estimates for post weaning growth performance in pigs fed *ad libitum* or semi-*ad libitum* diets. Numerous studies were accumulated (including those described above) to provide average parameter estimates and associated ranges. Heritability estimates for average daily gain (ADG), daily feed intake (DFI), and feed/gain (FCR) averaged to 0.31, 0.29, and 0.30 and ranged from 0.03 to 0.49, 0.13 to 0.62, and 0.12 to 0.58, respectively.

Numerous estimates were also compiled for the genetic correlations (estimate; range) between ADG and DFI (0.65; 0.32 to 0.89) as well as the genetic relationship between ADG and FCR (-0.53; -0.24 to 0.34). Reports of the correlation between ADG and backfat thickness were quite variable, ranging from moderate and favorable (-0.26) to moderately unfavorable (0.55). Although some of the variation in estimates may be due to breed differences, many of the differences in experimental design (i.e. feeding regimen) and measurement methods may likely contribute to the wide range in parameter estimates.

*Genetic Parameters of carcass composition and meat quality traits.*

Increasing the carcass composition (i.e. lean to fat ratio) of swine has been, for several decades, a major objective of swine breeding schemes within the United States; and thus, a very large number of genetic studies have been devoted to composition traits. More recently, a greater emphasis has been put on the actual properties of muscle that affect
quality. Though not to the extent of carcass composition traits, research has increasingly been conducted on this topic and reliable genetic parameters have been well documented. Berger et al. (1994) studied carcass and meat quality data from the National Barrow Show Progeny Test from 1991 to 1993 to estimate genetic parameters and illustrate that changes in composition traits may affect meat quality characteristics. Some of the meat and eating quality traits that were found to have significant genetic correlations with tenth-rib backfat thickness include: intramuscular fat percentage (.32), Instron tenderness (-.25), cooked moisture percentage (-.48), cooking loss percentage (.38), and juiciness score (-.19). Loin muscle area was also shown to be genetically associated with intramuscular fat percentage (-.37), Instron tenderness (.18), cooked moisture percentage (.26), and cooking loss percentage (-.16). All of these correlations are antagonistic in nature, and some are large enough to create significant problems with meat quality if they are ignored in selection schemes aimed at increased carcass leanness.

The Terminal Sire Line Evaluation (NPPC, 1995) reported results from different methods of estimating genetic parameters. Heritability estimates of 0.35, 0.69, and 0.52 based on a sire model, dam model, and a sire + dam model, respectively, were reported for lean percentage. Heritability estimates for carcass tenth rib backfat and loin muscle area were derived using the same three models plus an animal model. Reported estimates of heritability using the four different models for backfat were 0.32, 0.72, 0.52, and 0.46, respectively, while estimates for loin muscle area were 0.39, 0.58, 0.48, and 0.48, respectively. Though at least moderately heritable in each case, the use of four different models further establishes the range of estimates that can arise even when the same data set is utilized.
Knapp et al. (1997) studied genetic parameters for individual meat quality traits and their relationships to lean meat content in three different breeds using a REML procedure applied to a multivariate animal model. This study utilized 5,921 Large White (LW), 3,143 Landrace (LR), and 6,533 Pietrain (PT) records to evaluate the genetic components of lean meat content, intramuscular fat percentage, color, percent drip loss, and pH. For lean meat content, heritability values ranged from 0.40 in PT to 0.53 in LW. The results for pH show relatively low heritability values for LW and LR (0.19, 0.14); however, the heritability estimate for pH of PT was considerably higher at 0.37. Estimated heritabilities for color were moderate to low with a range from 0.22 to 0.26 and are higher than the estimates for percent drip loss (0.10 to 0.21). Heritability estimates for percent intramuscular fat were higher than any other meat quality trait evaluated (0.38 to 0.67). Breed differences among heritability values were considerably smaller in magnitude for lean meat content than for the meat quality traits evaluated.

With regard to genetic correlations, significant antagonisms were noted between lean meat content and all four meat quality characteristics. Generally, all four meat quality traits contained genetic relationships in the desired direction, with the strongest association between pH and color (0.45 to 0.74) along with pH and percent drip loss (-0.52 to 0.76). These results not only confirm a negative relationship between lean meat content and meat quality, but also, individual selection for each of the traits listed as well as simultaneous selection for various indicators of meat quality can be effective.

In order to control variation in pork quality, relationships among biochemical measurements, sensory, and processing characteristics must be determined. Huff-Lonergan et al. (2002) evaluated the phenotypic associations between specific biochemical and sensory
characteristics to obtain a better understanding of how changes in certain traits may influence overall pork quality. Data from a three generation resource family that was established to map genes affecting meat and eating quality were used in this study. Many significant correlations among various meat and eating quality characteristics were reported.

In this study, subjective color, marbling, and firmness scores were all significantly correlated with most sensory traits. Marbling was also significantly correlated with firmness, drip loss, percentage cook loss, and measures of tenderness. Both marbling and percentage intramuscular fat were positively correlated with flavor scores and negatively correlated with off-flavor scores. Additionally, drip loss was significantly correlated with measures of subjective color, tenderness, and product flavor. These data indicate that darker product was typically firmer, retained more moisture, and was more tender. Concurrently, product with a high degree of drip loss would also tend to be lighter in color, be less tender, have less pork flavor, and have more off-flavor.

Further evaluation of the relationships among carcass measurements and meat quality revealed that tenth-rib backfat and loin eye area were both highly correlated with percentage intramuscular fat in an antagonistic manner. Ultimately, this study illustrates that selection for increased carcass leanness can dramatically affect various meat quality characteristics and have a detrimental impact on the palatability of fresh pork.

Three review papers have summarized literature results for the genetic parameters of some of the common carcass composition and meat quality traits. Ducos (1994) reviewed the traits of ultrasonic backfat depth, loin muscle area, and lean percentage from which an average heritability of 0.45, 0.48, and 0.54 were estimated based on 143, 35, and 77 published estimates, respectively.
Stewart and Schinkel (1989) reviewed 175 published papers involving genetic parameter estimates for carcass traits and published corresponding weighted averages for heritabilities and genetic correlations in Genetics of Swine. The traits reviewed were ultrasonic backfat, carcass backfat, loin muscle area, and lean percentage, and all showed moderate heritability (between 0.4 and 0.6). This review also illustrated consistent results of a very strong negative genetic relationship between lean percentage and backfat measured at the tenth rib ($r_g = -0.87$), as well as a strong genetic correlation between lean percentage and loin muscle area ($r_g = 0.65$).

Similarly, Sellier (1998) provided an extensive evaluation of literature published on the genetic parameters of meat quality traits in The Genetics of the Pig. Of the meat quality traits reviewed, percentage intramuscular fat obtained the highest average heritability (0.50), representing a range of published values from 0.26 to 0.86. Various other meat quality traits (average $h^2$; range) such as ultimate pH (0.21; 0.07 to 0.39), objective color (0.28; 0.15 to 0.57), and water holding capacity (0.15; 0.01 to 0.43) had considerably lower average heritability values. Much more variability was reported among the heritability estimates of sensory panel scores. Tenderness score had the highest average heritability value (0.29) with a range in published values of 0.18 to 0.70, while flavor, juiciness, and overall acceptability scores obtained heritability values of 0.09, 0.08, and 0.25 and ranges of 0.01 to 0.16, 0.00 to 0.28, and 0.16 to 0.34, respectively.

Genetic associations among meat quality traits reported by Sellier (1998) revealed many significant genetic relationships, yet considerable variation among published values. Drip loss had the strongest genetic correlation with ultimate pH (-0.71), but had much weaker associations with reflectance (0.49), and percent intramuscular fat (-0.08). Water holding
capacity was found to be genetically associated with ultimate pH (0.45), reflectance (-0.39), and percent intramuscular fat (0.12). Percent intramuscular fat was reported to have favorable, yet small, average published genetic correlations with various other meat quality traits such as cooking loss (0.07), reflectance (0.01), and tenderness (0.15). Interestingly, overall sensory panel acceptability obtains a strong positive genetic association with ultimate pH (0.59), water holding capacity (0.46), and percent intramuscular fat (0.61).

The genetic antagonisms between carcass leanness and various meat quality traits were also reviewed by Sellier (1998). Lean percentage was reported to have negative associations with ultimate pH (-0.13), intramuscular fat content (-0.34), tenderness (-0.20), juiciness (-0.18), and overall acceptability (-0.48).

Due to its economic importance as well as the significant genetic component underlying this trait, substantial genetic gains have been realized in terms of carcass leanness. It is apparent, however, that with the strong genetic antagonisms that exist between carcass leanness and numerous meat and eating quality traits, subsequent degradation in pork quality has likely occurred over time.

**Genetic and Phenotypic Trends**

Estimation of genetic progress in traits gives an important evaluation of the efficiency of applied improvement schemes. It also supplies the animal breeder with the essential information to develop more successful genetic programs in the future. This section will review the phenotypic and genetic trends realized for production and carcass traits and how they relate to subsequent changes in meat quality.
Kaplon et al. (1991) utilized performance test records on Polish Large White boars collected from 1978 to 1987 from 94 herds to estimate phenotypic, genetic, and environmental trends. A total of 114,347 performance records were analyzed with the use of an animal model for the evaluation of average daily gain (ADG), backfat thickness (BF), and days to 110 kg (DAYS). Estimated phenotypic and genetic trends were 6.80 g/day and 0.04 g/day for ADG, -0.065 mm and -0.009 mm for BF, and -2.76 d and -0.01 d for DAYS, respectively. Though phenotypic trends are relatively large and desirable, genetic trends estimated from these data suggest that selection practices have not been very effective for the genetic enhancement of performance and composition traits.

A similar study was conducted by Kovac and Groeneveld (1990) with the use of German swine herdbook populations. Records from 2,337 herds and 11 testing stations from 1979 through 1987 were evaluated with the use of multiple-trait, mixed model methodology to estimate genetic trends for daily gain (DG), feed conversion efficiency (FCE), lean-to-fat ratio (R) and meat quality score (MQS). Results of this study were reported for four different breeds heavily used in the German commercial industry (German Landrace, German Large White, Pietrain, German Landrace B). Considerable genetic gain was realized for DG between the years of 1979 and 1987, ranging from 21.7 g/day in German Landrace to 55.3 g/day in Pietrain. Cumulative genetic response (range) for R (-0.008 to -0.030) and FCE (-0.082 to -0.142) were also relatively high for all four breeds. Due to the fact that each of the breeds is used for a different purpose within the German swine industry, a larger range in estimated cumulative genetic response was reported for MQS. The German Landrace, typically used in dam lines, had the largest cumulative genetic gain in meat quality score of
3.23; however, the Pietrain, used extensively as a terminal sire, revealed a negative cumulative genetic response (-0.67) between 1979 and 1987 for MQS.

Genetic trends were recently estimated by Chen et al. (2002) with the use of National Swine Registry Swine Testing and Genetic Evaluation System (STAGES) data from the years of 1985 to 2000. Records on 361,300 Yorkshire, 154,833 Duroc, 99,311 Hampshire, and 71,097 Landrace pigs were analyzed with an animal model and REML procedures to estimate genetic trends for lean growth rate (LGR), days to 113.5 kg (DAYS), backfat (BF), and loin eye area (LEA). All estimated genetic trends for DAYS, BF, LEA, and LGR were favorable. The largest genetic gains for LGR and DAYS were realized by the Duroc breed with changes of 3.28 g/d per year and -0.54 d/yr, respectively. Additionally, Yorkshires had the largest yearly genetic gains of -0.45 mm/yr and 0.41 cm²/yr for BF and LEA, respectively. The average genetic change over the four breeds were 2.35 g/yr, -0.40 d/yr, -0.39 mm/yr, and 0.37 cm²/yr for LGR, DAYS, BF, and LEA, respectively.

Results from the above studies illustrate that significant genetic progress has been realized in moderately to highly heritable traits of economical importance. Characteristics such as these (namely carcass composition) have been the primary focus in breeding schemes across the country, certainly elevating the level of genetic progress within the last two decades.

**Breed Differences**

In order to develop effective crossbreeding systems aimed at enhancing traits that directly affect profit (i.e. growth performance and carcass composition) while avoiding degradation of product quality, knowledge of breed differences is required. This section will
briefly discuss significant literature documenting breed differences relative to their usefulness for improvement of growth performance, carcass composition, and meat and eating quality characteristics.

Lo et al. (1992) evaluated breed effects in the Duroc and Landrace Breeds for growth, real-time ultrasound, carcass, and pork quality traits. A total of 5,649 pigs and 960 carcasses were used to determine the relative differences between the Duroc and Landrace breeds as well as estimates of individual heterosis for each of the trait categories listed above. Estimates of direct genetic effects revealed significant advantages (difference between Duroc and Landrace) of the Duroc breed for backfat thickness, loin muscle area, standardized lean yield, lean gain per day of age, and percentage intramuscular fat. No breed effects were detected for eating quality traits. Favorable heterosis estimates of 27.6 g/d for average daily gain, 1.5 kg for standardized lean yield, and 14.7 g for lean gain per day of age were reported; however undesirable, yet non-significant heterosis effects were revealed for pork color and percentage intramuscular fat. Results from this study illustrate the usefulness of the Duroc breed as a terminal sire for increasing carcass composition without decreasing pork eating quality.

Results from the National Pork Producers Council Terminal Line Program report an extensive evaluation of breed and genetic line differences for numerous, growth performance, carcass composition, and pork quality traits (NPPC, 1995). Breeds that are many times used as terminal sires (i.e. Berkshire, Duroc, Hampshire, Spot, and Yorkshire) are not significantly different for growth performance traits such as lean efficiency; however, the Duroc breed had a significant advantage over all other sire breeds for days to 250 lbs and average daily gain on test when mated to crossbred females. For carcass lean percentage and
loin muscle area, the Hampshire breed was superior to all other purebreds, while Durocs and Yorkshires were not significantly different from each other. Similarly, Hampshires as well as Yorkshires had significantly less tenth-rib backfat than other purebreds evaluated.

The evaluation of pork quality characteristics such as ultimate pH, water holding capacity, and percent drip loss reveal an advantage for Berkshires when compared to Hampshires, Yorkshires, and Spots; however, they have no significant advantage over the Duroc breed. All other purebreds had a significant advantage over Hampshires for objective measures of pork color. The Duroc breed had significantly more intramuscular fat when compared to all other purebreds, while the Berkshire, Hampshire, Spot, and Yorkshire breeds were not significantly different. Sensory taste panel results revealed no significant differences between breeds for of juiciness, flavor, and off-flavor scores; however, the Berkshire, Duroc, and Hampshire breeds were reported to have more desirable chewiness scores, though not significantly different from each other, when compared to Yorkshires and Spots. Breed comparisons illustrate that depending on breeding objectives, each breed has its own relative usefulness. Specifically, the Duroc, Hampshire, and Yorkshire breeds appear to be advantageous for breeding schemes aimed at enhancing carcass composition, while the Duroc breed is the most useful for increasing growth performance. Additionally, the Berkshire and Duroc breeds should generally have the greatest impact on pork quality.

Goodwin (2004) reported growth, carcass, and meat quality differences of pure breeds included in the National Barrow (NBS) Sire Progeny test between March, 1991 and August, 2004. This included fifteen test groups, including eight breeds and 6,024 records. Mixed linear models were used to determine fixed effects of contemporary group, sex, and breed. In the evaluation of growth performance, Duroc, Landrace, Poland China, and
Yorkshire had the fastest rate of gain and were not significantly different from each other. Least squares means for loin muscle area revealed that Hampshire pigs had the most loin muscle area and the least backfat, while the Berkshire breed had less loin muscle area and more backfat than all breeds tested. In the evaluation of meat quality, Duroc pigs had the greatest percentage of intramuscular fat, while Berkshire and Chester White pigs had the highest pH values. Additionally, Berkshire pigs excelled all other breeds for the evaluation of cooking loss, Instron tenderness, juiciness score, and tenderness score.

**Gender Differences**

For many operations throughout the U.S., not only are gender differences important in many nutrition and management practices, but they also play an important role in how producers utilize niche marketing systems. The following section will outline the gender differences reported by two extensive projects.

Results from the Terminal Line Program conducted by the National Pork Producers Council (NPPC, 1995) outline many gender differences for growth performance, carcass composition, and meat quality. This study utilized records from 3,261 crossbred progeny of 675 sires representing 10 different breeds/genetic lines. In this study, barrows required significantly fewer days to reach 113 kg and had significantly greater average daily gains. However, gilts excelled barrows in carcass composition measures of loin muscle area, tenth-rib backfat, last-rib backfat, and last lumbar backfat. Collectively, gilts had higher lean percentages, but were not significantly different from barrows for lean gain on test. Barrows and gilts were not significantly different from each other for evaluations of loin firmness, ultimate pH, drip loss, or objective color measures of Minolta reflectance and Hunter L.
values. For evaluations of meat quality traits such as marbling score, loin lipid content, and Instron tenderness, barrows had a significant advantage when compared to gilts. Similarly, barrows had higher sensory taste panel scores for tenderness and flavor.

As mentioned previously, Goodwin (2004) reported results of fifteen test periods from the National Barrow Show (NBS) Sire Progeny test. Results of this study showed no changes in the sex rank among the eight breeds evaluated. Barrows in this study had significantly higher average daily gains, greater percentages of intramuscular fat, lower pH values, lower Instron tenderness values, and higher juiciness scores from taste panelists when compared to gilts. Significantly more loin muscle area and less backfat at the tenth-rib, last-rib, and last lumbar locations were found in gilts when compared to barrows. Additionally, gilts of this study had significantly lower values for Minolta reflectance and Hunter L values.

Outside of objective measures of color, gender differences are consistent across both studies and should provide strong insight to relative sex advantages for growth performance, carcass composition, and meat quality characteristics.

**Growth and Development of Carcass Composition and Intramuscular Fat**

*Rates and patterns of backfat and loin muscle area deposition.*

As discussed earlier, pricing of hogs on the basis of grade and yield has occurred for many decades. For this reason, the economic importance lean percentage and growth rate have led to extensive evaluation of the growth and development of the specific components of lean gain in swine. This section will review major publications specifically dealing with the deposition rates and patterns of loin muscle area and backfat.
In an early study evaluating the deposition rate of backfat, Hetzer et al. (1956) found a significant linear increase in fat depth for barrows, gilts, and boars. A metal probe was used to determine rates of deposition in hogs from 68 to 102 kg. In this population, backfat increased linearly at a rate of 0.066 mm/kg in barrows, 0.048 mm/kg in gilts, and 0.051 mm/kg in boars.

Noffsinger et al. (1959) evaluated fat deposition in four inbred lines of swine. Backfat was measured at 11 kg increments starting at 45 kg until slaughter at weights ranging from 73 to 86 kg. A Lean Meter was used to measure backfat along the midline of the animal at the shoulder, mid-lumbar, and over the ham. Regression analysis procedures indicated that across the four lines, 75% of the variation in backfat was attributable to body weight. They determined deposition of backfat was nearly linear over the weight range evaluated.

Quijandra and Robison (1971) conducted a study to examine body weight and backfat deposition rates in purebred Duroc and Yorkshire swine. Weights and backfat measurements were taken every seven days from 119 to 154 days of age. Linear regression of backfat on weight revealed slightly different curves for each breed, sex, and breed-sex subgroups. However, they concluded that correction factors pooled across breeds and sexes were sufficient in adjusting backfat to a weight constant basis.

Ultrasound techniques were used to assess swine fat and muscle deposition in a study reported by Mersmann (1982). Swine were sequentially scanned at 40, 78, and 93 kg of body weight and deposition rates were calculated using linear regression analysis. Growth rates were approximately linear for backfat ranging from 0.17 mm/kg to 0.27 mm/kg. A mean loin muscle area deposition rate of 0.27 cm²/kg was reported.
Moeller (1990) utilized serial ultrasonic measurements of loin muscle area, fifth-rib backfat, tenth-rib backfat, last-rib backfat, and last lumbar backfat to assess deposition rates. In this population, loin muscle area deposition rate was 0.286 cm$^2$.kg. The analysis of backfat measurement revealed deposition rates of 0.250 mm/kg at the fifth rib, 0.241 mm/kg at the tenth rib, 0.167 mm/kg at the last rib, and 0.162 mm/kg at the last lumbar location.

The fixed effect of sex was significant in the evaluation of all backfat measures, with barrows depositing fat at a faster rate than gilts at all locations. No difference was detected in loin muscle deposition rates between barrows and gilts.

In a study evaluating performance differences associated with the use of electronic versus commercial feeders, Casey (2003) evaluated deposition rates and growth patterns of body weight and ultrasonically measured backfat and loin muscle area. Yorkshire boars and gilts ($n = 475$) were weighed on-test at a mean weight of 39.4 kg and were weighed and scanned at two week intervals. Mean body weight at off-test was 115.8 kg. Traits were analyzed with the use of a random regression model. Analysis of serially measured traits revealed that gilts on the electronic feeders ate less, grew slower, and deposited less backfat and loin muscle area throughout most of the test period when compared to boars. The effect of feeder type was not significant for the evaluation of boar growth performance. Gilts revealed a curvilinear pattern of body weight, loin muscle area, and backfat accretion throughout the test period when averaged across feeder type. Boars also had a curvilinear pattern of body weight and loin muscle area accretion; however, revealed a linear pattern of backfat deposition throughout the test period.
Rates and patterns of intramuscular fat deposition.

Though growth and deposition of traits dealing with lean percentage of swine (backfat and loin muscle area) have been well studied and documented, such resources are not available in swine for the study of growth and development of intramuscular fat. However, due to a market that emphasizes carcass quality, along with earlier availability of technology, recent studies to evaluate deposition rates and patterns of marbling and percent intramuscular fat have been conducted in beef cattle.

Ultrasound measures were used in a study by Brethour (2000) to evaluate marbling and backfat changes in feedlot cattle. Serial ultrasound estimates were obtained from two genetically diverse groups of cattle fed high-energy rations for averages of 166 and 148 d. These measurements were utilized to develop mathematical models to describe changes in backfat and marbling as a function of days on feed. A modified power function was used to evaluate changes in marbling through the feeding period. This study reported that marbling scores progress at a very slow rate through much of the finishing period, while backfat thickness increases exponentially.

Similar results were reported by Rouse et al. (2003) in a study that evaluated deposition rates of rib eye area, backfat, and percent intramuscular fat. This study utilized serial scan measurements of 315 Angus bulls at 28 d intervals. They concluded that while rib eye area and backfat deposition patterns can be sufficiently explained as a function of body weight gain, percent intramuscular fat is best described as a function of age. When evaluated on an age basis, percent intramuscular fat increases at a relatively constant rate from 220 to 400 days of age.
Bruns et al., (2004) evaluated relationships among body weight, body composition, and intramuscular fat content in steers with the use of a serial slaughter experiment involving two groups (yr 1, n = 40; yr 2, n = 45) of Angus steers of known age and parentage. Steers were allotted to five slaughter groups based on hot carcass weight. Regression analysis was utilized to evaluate the change in carcass characteristics and composition as a function of carcass weight. In this study, degree of marbling increased linearly in relation to hot carcass weight. They concluded that marbling is not a late-developing tissue, however, develops at a constant rate through the feeding period.

**Effects of Fat Thickness on Pork Carcass Quality Measures**

One hundred thirty-three pork carcasses with varying levels of leanness and muscling were selected from four packers in the United States to investigate pork meat quality in relation to carcass composition (Pringle and Williams, 2001). In this study, correlation and regression analysis were used to determine relationships among traits as well as pork quality differences between varying levels of carcass composition. In terms of fat thickness, it was reported that carcasses with less than 2.03 cm of backfat had significantly less marbling as well as softer and more watery lean than carcasses in fatter categories. Also, fat thickness showed no effect on visual color scores and Instron tenderness. The effects of increased muscling were similar to those of leanness as carcasses with more loin eye area had significantly lower marbling scores, decreased firmness, and more drip loss; however, no significant difference in Instron tenderness was reported when compared across muscle groups. Though enhanced carcass composition (i.e. leaner and more muscular carcasses) appeared to have no effect on product tenderness in this study, it is obvious that overall pork quality is negatively impacted by selection for reduced fatness and increased muscling.
In a study reported by Lonergan et al. (2001), a unique line of Duroc pigs was established by intensive selection for increased lean growth to ultimately determine the correlated response in fresh pork quality. Intense selection pressure on lean growth over five generations produced significant genetic gain in lean growth, carcass lean, and loin eye area. In relation to the control line, the line intensely selected for lean growth had significantly lower subjective firmness scores, and greater amounts of moisture lost as measurable drip in the longissimus. There were no differences between the lines, however, for subjective color scores, glycolytic potential, or ultimate pH. Therefore, it appears in this study that intense selection for lean growth, much like that done by the industry over the past 25 years, will compromise pork quality.

Though a smaller number of records were utilized, similar general conclusions were reported from a study conducted by Fabian et al. (2000) where six generations of intense selection on lean growth efficiency were performed on Duroc pigs. Eight select line pigs and eight control line pigs were used to determine response to selection for growth performance as well as the ultimate correlated response in fresh pork quality. Six generations of selection proved to be effective for the enhancement of growth performance in terms of average daily gain and the ratio of feed to gain. Unfortunately, this genetic gain realized was at the expense of meat quality as the select line had significantly lower subjective meat color scores (2.02 vs. 2.29), firmness scores (2.45 vs. 3.23), and marbling scores (2.82 vs. 3.55) when compared to the control line.

Brocks et al. (2000) studied two separate selection lines of Dutch Large White pigs divergently selected for either low backfat thickness (L-line) or fast growth (F-line) to evaluate correlated responses in various histochemical characteristics in different muscles.
Samples from second and fourth generation pigs from each of the two lines were analyzed for differences in fiber type composition, fiber area, and capillary density in the longissimus lumborum (LL) and biceps femoris (BF) muscles.

Results of this study illustrated that selection for either decreased backfat thickness or increased growth rate will affect different muscle fiber properties associated with pork quality. Specifically, significant differences in muscle fiber characteristics were shown between F- and L-line pigs, where pigs of the low backfat selection line had a lower percentage of oxidative and a higher percentage of glycolytic myofibers. Biceps femoris muscles, involved in posture and locomotion, became more glycolytic through selection for increased growth rate or decreased backfat, whereas LL muscles became more oxidative. Results of this study show that intensive selection for lean muscle growth changes more oxidative muscles into muscles with a higher glycolytic capacity. Future breeding programs could use different muscle fiber traits, such as increased oxidative potential, to aid in selection for increased pork quality while preserving growth performance.

During the last two decades pig breeding programs have been focused on selection for rapid production of lean meat. However, because this is influenced by several interacting genes, unfavorable correlated responses, typically in the form of decreased meat quality, have also resulted.
CHAPTER 3. EVALUATION OF LONG-TERM INDUSTRY SELECTION FOR INCREASED CARCASS LEANNESS IN DUROC SWINE: I. EFFECT ON CARCASS COMPOSITION, PERFORMANCE, AND GROWTH CURVES

A paper to be published in the Journal of Animal Science

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Abstract: A study was conducted to evaluate differences in performance, carcass composition, and growth patterns of pigs sired by purebred Duroc boars currently available and pigs sired by purebred Duroc boars from the mid 1980s. Two lines were developed by randomly allocating littermate and ½ sib pairs of females to matings by current (CTP) or old (OTP) time period boars. Boar, barrow, and gilt progeny from two replications were weighed on test at a group mean live weight of 63.5 kg. Serial ultrasonic measurements of 10th rib loin muscle area (LMA), off-midline backfat (BF10), and intramuscular fat percentage (IMF) from the first replication were collected every two weeks and used to assess deposition rate and growth pattern differences. Off-test ultrasonic LMA, BF10, and IMF measurements were collected on 789 pigs in both replications at a mean live weight of 109 kg. Records on pigs sired by CTP boars, from both replications (n = 557), represented 23 sires while pigs sired by OTP boars (n = 232) were from 15 sire groups. All available barrows and randomly selected gilts (n = 277) were sent to a commercial abattoir and measurements of tenth-rib backfat (CBF10), last rib backfat (CLRBF), last lumbar backfat (CLLBF), and loin muscle area (CLMA) were collected. Pigs sired by CTP boars had more (P < 0.05) LMA and less BF10, while pigs sired by OTP boars had significantly more IMF. Carcass evaluation revealed more CLMA, and significantly less CBF10, CLRBF, and CLLBF for pigs sired by CTP boars. No significant difference (P > 0.05) was revealed in average daily gain measured over the entire test period between the two time periods. Analysis of serial backfat measurements revealed a linear pattern of backfat deposition between 73 and 118 kg. Pigs sired by OTP boars deposited more backfat (P < 0.05) at a significantly faster rate than pigs sired by CTP boars throughout the entire test period. A curvilinear cumulative tissue deposition pattern was revealed for LMA and IMF within both
time periods. Significant linear and quadratic regression coefficient differences between lines indicated that pigs sired by CTP boars deposited more LMA and less IMF per kg of live weight gain than pigs sired by OTP boars. Results from this study illustrate that significant progress toward the enhancement of carcass composition has been realized within the Duroc breed since the mid 1980s. Long term selection response in carcass leanness has also resulted in alterations in deposition patterns and accretion rates of correlated traits such as LMA and IMF.

Key Words: Swine, Growth curves, Carcass composition

**Introduction**

Due to an increasingly volatile and competitive hog market, producers constantly struggle with the issue of how to create a pork industry that is economically viable. The increase in the use of grid-based marketing systems within the past 20 years has created an opportunity for producers to enhance the value of the hogs they market through improved lean percentage. Prior to 1985, 90 percent of hogs marketed were sold as traditional ‘commodity pork’ where price was determined on a live weight basis (Hayenga et al., 1985). The utilization of incentive-based marketing systems became increasingly important to producers seeking to add value to the hogs they produced, corresponding to increased selection for lean percentage. As a result, the percentage of hogs sold on a carcass basis rose to 28 percent in 1988 and to 78 percent in 1997 (Brorsen et al., 1998). In nearly 20 years, pork producers have made tremendous strides toward providing a leaner product to the packer, and ultimately, the consumer (Chen et al., 2002). However, as a result of intensive selection for increased carcass leanness, consumer acceptance issues such as decreased meat
quality have arisen. Quality characteristics that play an integral role in consumer acceptance, such as intramuscular fat, have subsequently decreased as breeders have intensely selected for increased leanness (Barton-Gade, 1990; Cameron, 1990). The objectives of this study were two-fold. The primary objective was to compare the growth performance and carcass composition of pigs sired by boars from the time period at which grid-based marketing systems were introduced to the industry’s current position where virtually all hogs are sold on a percent lean basis. A second objective of the study was to assess potential changes in growth patterns of these traits that may have resulted due to marketing scheme changes since the mid 1980s.

**Materials and Methods**

*Derivation of Lines*

Two lines were formed by randomly allocating littermate and $\frac{1}{2}$ sib pairs of Duroc females to matings by current (CTP) or old (OTP) time period Duroc boars. Boars utilized were randomly selected from two commercially oriented regional boar studs. All boars and females utilized in the study were stress tested to ensure the absence of the recessive mutant HAL1843 allele. Matings to CTP boars were made using fresh semen while matings to OTP boars were made utilizing frozen semen. Six matings per boar from the OTP and five matings per boar from the CTP were made in order to obtain a minimum of three litters per sire and account for potential conception rate differences. Matings were performed across two subsequent breeding seasons. Females mated to CTP boars in the first parity were then mated to OTP boars in the second parity and vice versa to reduce the effect of dam on pig performance.
**Progeny Test**

The total number of pigs evaluated within each line and gender for each trait category are presented in Table 1. In the first replication, boars, gilts, and barrows in each line were weighed and ultrasonically evaluated for tenth-rib loin muscle area (LMA), backfat (BF10), and intramuscular fat percentage (IMF) every two weeks beginning at a group mean live weight of 63.5 kg. Off-test ultrasonic measurements were collected in both replications at a mean live weight of 109 kg. Ultrasonic images were collected with an Aloka 500V SSD ultrasound machine fitted with a 3.5 MHz, 12.5 cm linear-array transducer by a National Swine Improvement Federation certified technician. Off-midline BF10 and LMA were measured from a cross-sectional image taken at the 10th rib. A sound transmitting guide conforming to the pig’s back was attached to the ultrasound probe and vegetable oil was used as conducting material between the probe and skin. A minimum of four longitudinal images were collected seven cm off-midline across the 10th to 13th ribs. Texture analysis software (Amin et al., 1997) was used to estimate final IMF parameters and IMF was predicted by the method of Newcom et al. (2002). Upon completion of the test, all available barrows and randomly selected gilts were sent to a commercial abattoir for carcass evaluation. Carcass measurements were obtained by Iowa State University personnel 24 h post-mortem. Standard carcass collection procedures, as outlined in Pork Composition and Quality Assessment Procedures (NPPC, 2000), were followed to obtain measurements of tenth-rib backfat (CBF10), last rib backfat (CLRBF), last lumbar backfat (CLLBF), and loin muscle area (CLMA). Kilograms of lean at market weight and at trial entry were estimated using the following fat-free lean equation developed by the National Pork Producers Council (NPPC, 2000):
Market weight lean (kg) = 0.3782 × sex (barrow and boar = 1; gilt = 2) – 2.9488 × (BF10, cm) + 0.3817 × (LMA, cm²) + 0.291 × (off-test weight, kg) – 0.2424

Trial entry lean (kg) = 0.188 × (on-test weight, kg) – 1.644

Lean gain on test (LGOT) was calculated by subtracting the estimate of trial entry lean from market weight lean and dividing by days on test.

Statistical Analysis

To evaluate the effect of time period on growth performance, carcass composition, and deposition rates, two types of analyses were utilized: phenotypic analysis of traits measured over the entire test period, and phenotypic analysis of traits measured serially.

Whole test period traits. Traits measured through the entire test period such as average daily gain (ADG) and lean gain on test (LGOT), as well as traits evaluated upon completion of the test period, were analyzed with the following linear mixed model using SAS (SAS Inst. Inc., Cary, NC):

\[ y_{ijklmnp} = TP_i + S_j + CG_k + b_1OD_1 + b_2OFFWT_m + SR(TP)_{ni} + DM_p + \epsilon_{ijklmnp} \]

where

- \( y_{ijklmnp} \) = trait measured on the \( m \)th pig of the \( j \)th sex in the \( i \)th time period and in the \( k \)th contemporary group
- \( TP_i \) = fixed effect of the \( i \)th time period
- \( S_j \) = fixed effect of the \( j \)th sex
- \( CG_k \) = fixed effect of the \( k \)th contemporary group (based on on-test date)
- \( OD_1 \) = fixed effect of the \( 1 \)th off-test date
- \( OFFWT_m \) = linear effect of the off-test body weight of the \( m \)th pig
SR(TP)_{ni} = \text{effect of the } n^{\text{th}} \text{ sire nested within the } i^{\text{th}} \text{ time period, assumed random with } SR(TP)_{ni} \sim N(0, \sigma_{SR}^2) \\
DM_p = \text{effect of the } p^{\text{th}} \text{ dam, assumed random with } DM_p \sim N(0, \sigma_{DM}^2) \\
\epsilon_{ijklmnp} = \text{residual with } \epsilon_{ijklmnp} \sim N(0, \sigma_{\epsilon}^2) \\

The above model is the result of a stepwise process of fitting all two-way interactions between fixed effects along with second and third order polynomial effects of the covariate OFFWT and subsequently removing non-significant (P > 0.05) individual effects sequentially.

*Serially measured traits.* Traits measured serially were body weight (BW), BF10, LMA, and IMF. A random regression model was fit to the serial data using SAS (SAS Inst. Inc., Cary, NC) to model covariances between repeated records. Fixed and random curves were added to the previous model to evaluate growth patterns of serially measured traits. Interactions of second order polynomial terms with \(TP_i\) were also fit for the evaluations of BW, LMA, and IMF, while the interaction of a first order polynomial term with \(TP_i\) was fit for BF10. A first order polynomial was fit for the random curves of BW, BF10, LMA, and IMF. An unstructured covariance structure was fit for the random terms and an auto-regressive covariance structure was fit for the residuals. Fixed effects were dropped from the model sequentially by backward elimination.

**Results and Discussion**

Least squares means for the effect of time period on growth performance measured over the entire test period, ultrasonically measured traits, and in-plant measures of carcass composition are presented in Table 2.
Growth Performance

Average daily gain. No significant difference (P > .05) between time periods was found for average daily gain measured over the entire test period. Significant differences (P < .05) were detected between sexes in both time periods, and a significant interaction between sex and time period was also found. Within pigs sired by OTP boars, LS means for ADG of boars (0.90 ± 0.018), barrows (0.83 ± 0.015), and gilts (0.80 ± 0.013) were all significantly different. However, LS means for ADG between boars and barrows sired by CTP boars were not different (P > 0.05), while gilts were significantly different from boars and barrows. The uneven distribution of gender records (Table 1) between time periods (particularly barrows) may explain the significant (P < 0.05) effect of sex x time period in the evaluation of ADG. The relative growth performance differences between sexes has been well documented (NPPC, 1995) and is similar to the findings of this study. Genetic and phenotypic trends reported by Chen et al. (2002) and Kaplon et al. (1991) indicate that a significant difference should be expected in ADG between time periods, and thus, contrast the finding of this study. However, these results may emphasize the industry’s strong selection pressure placed on lean percentage relative to that of growth performance since the mid to late 1980s.

Lean gain on test. Pigs sired by CTP boars had more LGOT (P < 0.05) than pigs sired by OTP boars. Differences in LGOT can be substantially affected by marginal differences in carcass composition, particularly loin muscle area. Due to the fact that there were no significant differences found for ADG in this study, this difference in LGOT is consistent with time period differences of in-plant and ultrasonic measurements of carcass composition found in the current study.
In-Plant Measures of Carcass Composition

The effect of time period was significant \( (P < .05) \) for all three measures of carcass backfat. Carcass evaluation revealed significantly less CBF10, CLRBF, and CLLBF for pigs sired by CTP boars when compared to pigs sired by OTP boars. Additionally, pigs sired by CTP boars had significantly more CLMA. Significant differences were detected between sexes (Table 2) for all measures of carcass composition, consistent with findings of NPPC (1995) and Stewart and Schinkel (1989). Findings of this study confirm the success of industry-wide selection for carcass leanness and coincide with genetic and phenotypic trends reported by Chen et al. (2002) and Kaplon et al. (1991).

Ultrasonically Measured Traits

Off-test measures. Differences for traits measured ultrasonically were similar to those measured on the carcass. Ultrasonic evaluation revealed more \( (P < 0.05) \) LMA and significantly less BF10 for pigs sired by CTP boars. Similar gender differences in ultrasonically measured compositional traits were found when compared to the in-plant carcass evaluation in this study (Table 2). Pigs sired by OTP boars, however, had significantly greater \( (P < 0.05) \) ultrasonic measurements of IMF when compared to pigs sired by CTP boars (4.53% vs. 4.10%).

Serially Measured Traits

Cumulative tissue deposition patterns as well as daily accretion curves for each time period are plotted in Figures 1 to 4 for BW, BF10, LMA, and IMF, respectively. Mean deposition rates for BF10, LMA, and IMF are listed by time period and gender in Table 3.

The analysis of serially measured BW revealed no significant difference in daily weight gain between time periods. A curvilinear pattern of daily weight gain (Figure 1) was
detected for pigs sired by boars from both time periods. Similar daily body weight accretion rates were reported by Casey (2003) and Moeller (1994). As previously mentioned, the results of this study for daily weight accretion are contrary to what would be expected from the genetic and phenotypic trends reported by Chen et al. (2002) and Kaplon et al. (1991), and may be explained by the unequal distribution of records among genders in this study (Table 1).

The analysis of serial backfat measurements revealed a linear pattern of cumulative backfat deposition between 73 and 118 kg. Daily accretion of BF10, however, followed a curvilinear pattern (Figure 2) when evaluated per kg of BW gain. Pigs sired by OTP boars deposited more backfat (P < 0.05) at a significantly faster rate per kg of BW gain than pigs sired by CTP boars throughout the entire test period (Table 3). The daily accretion rate difference for backfat between time periods explains the greater difference in BF10 at the conclusion of the test when compared to the onset of the test. Barrows deposited BF10 at a faster rate (P < 0.05) than boars while gilts had the lowest daily BF10 accretion rate (Table 3), a finding supported by Moeller (1994), who reported an average BF10 deposition rate of 0.271 ± 0.008 mm/kg measured over a similar weight range. Smith et al. (1992) reported a curvilinear BF10 deposition pattern over a weight range of 20 to 118 kg BW estimated from serial ultrasonic measurements of backfat. Gu et al. (1992), in a serial slaughter study involving five distinct genotypes, reported BF10 increased linearly with weight between 59 and 127 kg. These studies represent plausible ranges of daily backfat accretion and deposition patterns representative of the genetics of pigs sired by CTP boars evaluated in this study. It is also reported in previous studies (Hetzer et al., 1956; Noffsinger et al., 1959; and Quijandria and Robinson, 1971) that deposition of backfat is essentially linear during the
finishing phase of production. These early reports coincide with deposition patterns found for OTP-sired pigs in the present study.

A curvilinear pattern of loin muscle accumulation, similar for each time period, was detected for serially measured LMA (Figure 3). Plotted fixed curves of daily LMA accretion per kg of BW were significantly different between time periods. Pigs sired by CTP boars deposited LMA at a faster ($P < 0.05$) and relatively constant rate through the course of the test. OTP-sired pigs, however, accelerated the rate at which they deposited LMA (in a linear fashion) to a point where there was no significant difference in daily LMA accretion rates between lines at the conclusion of the test. A significant time period x sex interaction was detected for the evaluation of LMA accretion rate. Within both time periods, gilts deposited LMA at the fastest rate (Table 3), a result supported by the findings of Moeller (1994). However, boars sired by CTP boars revealed the lowest rate of LMA deposition relative to that of gilts and barrows. Among pigs sired by OTP boars, barrows had the lowest rate of LMA deposition when compared to the other two sexes. Casey (2003) reported curvilinear daily LMA accretion curves in a study evaluating boars and gilts on commercial and electronic feeders. Regardless of feeder type, gilts deposited LMA at a faster rate than boars through the course of the test period. Gu et al. (1992) suggested that cumulative LMA accretion followed a relatively linear pattern of deposition from 55 to 135 kg of BW, similar to the findings for pigs sired by boars from both time periods in this study.

The analysis of serially measured IMF revealed a curvilinear cumulative deposition pattern for both time periods in which pigs sired by OTP boars deposited greater amounts of IMF from 73 to 118 kg of BW (Figure 4). Daily IMF accretion patterns illustrate that OTP-sired pigs had more IMF at 118 kg due to a significantly faster rate of accretion early in the
test period. In contrast, pigs sired by CTP boars increased the rate at which they deposited IMF in a linear fashion through the test period and concluded the test with a daily deposition rate not significantly different (P > 0.05) from pigs sired by OTP boars. The effects of sex and time period x sex were not significant for IMF deposition rates within each time period.

Due to only recent developments in ultrasound technology to estimate IMF in the live animal, the evaluation of serial slaughter experiments is the only useful method to compare results found in this study. Such studies to evaluate IMF deposition patterns have only been conducted in beef cattle. In a serial slaughter experiment in beef cattle (Bruns et al., 2003), linear changes in marbling score relative to hot carcass weight were reported. In this study, steers revealed higher marbling scores as they increased in carcass weight and decreased the rate at which they deposited IMF from 200 to 400 kg of hot carcass weight. They concluded that IMF is not necessarily a late-developing tissue, but is a tissue that has the opportunity to develop early in growth if nutritional management permits. Others (May et al., 1992; Van Koeevering et al., 1995) have reported increases in marbling when the feeding time was extended and indicated that marbling developed quadratically as time on feed increased, before reaching a plateau at approximately 112 to 119 d. As days on feed increase, growth slows; however, our research in swine indicates that cumulative IMF deposition as a component of growth (not time) increased through the duration of the test period for both lines evaluated. Cumulative IMF deposition patterns for both lines presented in the current study are consistent with the findings of marbling deposition patterns as a component of growth in beef cattle.

Weis et al. (2004) explored the relationship of energy intake and body weight on body composition in growing pigs. This study emphasized that energy intake may limit the
expression of lean tissue growth for much of the growing-finishing period in modern pig genotypes with high lean tissue growth potential. This result, confirmed by Schinckel and de Lange (1996), may explain the difference in IMF accretion rates observed between lines in the current study. Pigs in this study, regardless of sire time period, were fed the same finishing diet formulated to meet NRC (1998) requirements. Differences in IMF deposition rates observed between time periods may be partially due to a distinctly different genetic potential for lean tissue growth inherent between lines, in combination with corresponding energy requirements needed to reach maximum lean growth. Ultimate IMF content at slaughter appears to be a function of a pig’s genetic propensity to deposit IMF, in combination with nutritional management throughout the finishing period.

Implications

Results from this study illustrate that significant progress toward the enhancement of carcass composition, whether measured in-plant or via ultrasound, has been realized within the Duroc breed since the mid 1980s. Long term selection response in carcass leanness has also yielded similar alterations in deposition patterns and accretion rates of correlated traits such as LMA and IMF. Unfortunately, this increased carcass leanness through time has evolved without equivalent progress in growth performance and has been at the expense of meat quality traits, namely intramuscular fat percentage. Hog procurement systems will likely contain emphasis on parameters of lean percentage in the future; however, it is important for producers to use a balanced approach to selection objectives that include traits such as meat quality. Ultimately, findings of this study should enable packers and processors
to further understand the long-term ramifications of grid-based pricing of hogs when little or no emphasis on meat quality is applied.
Literature Cited


Table 1. Distribution of records from a study comparing purebred Duroc pigs sired by boars from two different time periods

<table>
<thead>
<tr>
<th>Trait Category</th>
<th>Number of Observations</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Total</td>
</tr>
<tr>
<td>Growth &amp; ultrasonically meas.(^3)</td>
<td>789</td>
</tr>
<tr>
<td>Carcass composition(^4)</td>
<td>277</td>
</tr>
<tr>
<td><strong>Gender</strong></td>
<td></td>
</tr>
<tr>
<td>Boar</td>
<td>101</td>
</tr>
<tr>
<td>Gilt</td>
<td>368</td>
</tr>
<tr>
<td>Barrow</td>
<td>320</td>
</tr>
</tbody>
</table>

\(^1\) CTP = Current Time Period.
\(^2\) OTP = Old Time Period.
\(^3\) Average daily gain; lean gain on test; ultrasonically measured off-test loin muscle area, backfat, and intramuscular fat percentage.
\(^4\) In-plant carcass measures of 10\(^{th}\) rib backfat, last rib backfat, last lumbar backfat, and loin muscle area.
Table 2. Least squares means (±SE) for average daily gain and carcass composition from a study comparing purebred Duroc pigs sired by boars from two different time periods

<table>
<thead>
<tr>
<th>Item</th>
<th>Current</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Growth performance</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Average daily gain, kg/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boar</td>
<td>0.88 ± 0.01</td>
<td>0.90 ± 0.02</td>
</tr>
<tr>
<td>Gilt</td>
<td>0.81 ± 0.01</td>
<td>0.80 ± 0.01</td>
</tr>
<tr>
<td>Barrow</td>
<td>0.87 ± 0.01</td>
<td>0.83 ± 0.01</td>
</tr>
<tr>
<td>Lean gain on test, kg/d</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Boar</td>
<td>0.34 ± 0.01a</td>
<td>0.29 ± 0.01b</td>
</tr>
<tr>
<td>Gilt</td>
<td>0.36 ± 0.01a</td>
<td>0.32 ± 0.01b</td>
</tr>
<tr>
<td>Barrow</td>
<td>0.34 ± 0.00a</td>
<td>0.30 ± 0.01b</td>
</tr>
<tr>
<td><strong>In-plant measurements</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenth-rib backfat, cm</td>
<td>2.03 ± 0.05a</td>
<td>2.82 ± 0.08b</td>
</tr>
<tr>
<td>Gilt</td>
<td>1.86 ± 0.10a</td>
<td>2.57 ± 0.09b</td>
</tr>
<tr>
<td>Barrow</td>
<td>2.25 ± 0.06a</td>
<td>3.03 ± 0.08b</td>
</tr>
<tr>
<td>Last rib backfat, cm</td>
<td>2.39 ± 0.05a</td>
<td>2.77 ± 0.05b</td>
</tr>
<tr>
<td>Gilt</td>
<td>2.34 ± 0.08a</td>
<td>2.69 ± 0.07b</td>
</tr>
<tr>
<td>Barrow</td>
<td>2.45 ± 0.05a</td>
<td>2.83 ± 0.07b</td>
</tr>
<tr>
<td>Last lumbar backfat, cm</td>
<td>1.93 ± 0.05a</td>
<td>2.41 ± 0.05b</td>
</tr>
<tr>
<td>Gilt</td>
<td>1.81 ± 0.07a</td>
<td>2.36 ± 0.07b</td>
</tr>
<tr>
<td>Barrow</td>
<td>2.03 ± 0.05a</td>
<td>2.49 ± 0.06b</td>
</tr>
<tr>
<td>Loin muscle area, cm²</td>
<td>41.73 ± 0.58a</td>
<td>34.83 ± 0.71b</td>
</tr>
<tr>
<td>Gilt</td>
<td>43.22 ± 0.86a</td>
<td>36.80 ± 0.82b</td>
</tr>
<tr>
<td>Barrow</td>
<td>40.08 ± 0.59a</td>
<td>32.92 ± 0.81b</td>
</tr>
<tr>
<td><strong>Ultrasonically measured</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tenth-rib backfat, cm</td>
<td>1.88 ± 0.04a</td>
<td>2.41 ± 0.05b</td>
</tr>
<tr>
<td>Boar</td>
<td>1.69 ± 0.06a</td>
<td>2.13 ± 0.07b</td>
</tr>
<tr>
<td>Gilt</td>
<td>1.79 ± 0.04a</td>
<td>2.32 ± 0.05b</td>
</tr>
<tr>
<td>Barrow</td>
<td>2.16 ± 0.04a</td>
<td>2.79 ± 0.06b</td>
</tr>
<tr>
<td>Loin muscle area, cm²</td>
<td>39.77 ± 0.53a</td>
<td>34.97 ± 0.69b</td>
</tr>
<tr>
<td>Boar</td>
<td>39.03 ± 0.66a</td>
<td>33.82 ± 0.83b</td>
</tr>
<tr>
<td>Gilt</td>
<td>41.38 ± 0.54a</td>
<td>36.80 ± 0.72b</td>
</tr>
<tr>
<td>Barrow</td>
<td>39.04 ± 0.54a</td>
<td>34.09 ± 0.77b</td>
</tr>
<tr>
<td>Intramuscular fat, %</td>
<td>4.00 ± 0.08a</td>
<td>4.43 ± 0.10b</td>
</tr>
<tr>
<td>Boar</td>
<td>3.67 ± 0.13a</td>
<td>3.76 ± 0.15b</td>
</tr>
<tr>
<td>Gilt</td>
<td>3.86 ± 0.08a</td>
<td>4.47 ± 0.11b</td>
</tr>
<tr>
<td>Barrow</td>
<td>4.48 ± 0.08a</td>
<td>5.06 ± 0.13b</td>
</tr>
</tbody>
</table>

aGLS means with different superscripts within a row are significantly different (P<0.05).
Table 3. Least squares means (±SE) for deposition rates of tenth-rib backfat, loin muscle area, and percent intramuscular fat averaged over the entire test period from a study comparing purebred Duroc pigs sired by boars from two different time periods

<table>
<thead>
<tr>
<th>Item</th>
<th>Time Period</th>
<th>Current</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Overall</td>
<td></td>
<td></td>
</tr>
<tr>
<td>BF10, mm/kg</td>
<td></td>
<td>0.163 ± 0.006&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.230 ± 0.009&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Boar</td>
<td></td>
<td>0.151 ± 0.015&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.220 ± 0.021&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Gilt</td>
<td></td>
<td>0.146 ± 0.008&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.201 ± 0.011&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Barrow</td>
<td></td>
<td>0.193 ± 0.008&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.267 ± 0.015&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Overall</td>
<td>0.011 ± 0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.021 ± 0.003&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Boar</td>
<td>0.014 ± 0.004</td>
<td>0.016 ± 0.006</td>
</tr>
<tr>
<td></td>
<td>Gilt</td>
<td>0.006 ± 0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.024 ± 0.003&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>Barrow</td>
<td>0.012 ± 0.002&lt;sup&gt;a&lt;/sup&gt;</td>
<td>0.023 ± 0.004&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
</tbody>
</table>

BF10 = Tenth-rib backfat; LMA = Loin muscle area; IMF = Intramuscular fat.

<sup>ab</sup> LS means with different superscripts within each row are significantly different (P< 0.05).
Figure 1. Daily body weight gain from a study comparing purebred Duroc pigs sired by boars from two different time periods.
Figure 2. Daily and cumulative backfat accretion from a study comparing purebred Duroc pigs sired by boars from two different time periods
Figure 3. Daily and cumulative loin muscle area accretion from a study comparing purebred Duroc pigs sired by boars from two different time periods.
Figure 4. Daily and cumulative intramuscular fat accretion from a study comparing purebred Duroc pigs sired by boars from two different time periods
CHAPTER 4. EVALUATION OF LONG-TERM INDUSTRY SELECTION FOR INCREASED CARCASS LEANNESS IN Duroc Swine: II. EFFECT ON MEAT AND EATING QUALITY

A paper to be published in the *Journal of Animal Science*

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Abstract: A study was conducted to evaluate differences in meat and eating quality traits between purebred Duroc pigs sired by boars currently available and pigs sired by boars from the mid 1980s. Two lines were developed by randomly allocating littermate and ½ sib pairs of females to matings by current (CTP) or old (OTP) time period boars. Matings by CTP boars were made using fresh semen and matings by OTP boars were via frozen semen. Boar, barrow, and gilt progeny from two replications were weighed off test at a mean pen weight of 109 kg. All available barrows and randomly selected gilts were sent to a commercial abattoir and used for meat and eating quality evaluation. Records on pigs sired by CTP boars (n = 178) represented 23 sires while pigs sired by OTP boars (n = 99) consisted of 15 sire groups. Chemical intramuscular fat percentage was determined by lab analysis of a slice from the loin at the 10th rib. Additional meat and eating quality traits measured were: Minolta reflectance and Hunter L color (24 and 48 h); pH (24 h and 7 d); water holding capacity; subjective visual scores for color, marbling, and firmness (48 h); Instron tenderness; cooking loss; and trained sensory panel evaluations (7 d). Time period differences were assessed by the use of a mixed model that included fixed effects of time period, replication, sex, contemporary group, and the interaction of sex by time period. The random effect of dam and the random effect of sire nested within time period were also included. Pigs sired by OTP boars had a higher intramuscular fat percentage, lower Instron tenderness values, and higher subjective marbling and color scores than pigs sired by CTP boars (P < 0.05). There were no significant differences between time periods for Minolta reflectance, Hunter L (24 and 48 h), water holding capacity, pH (24 h and 7 d), and subjective firmness scores. Trained sensory evaluations revealed higher flavor scores and lower off-flavor scores (P < 0.05) for OTP sired pigs; however, no significant differences in tenderness score, juiciness
score, chewiness score, and cooking loss were found between lines. Long-term selection response in carcass composition has been at the expense of meat and eating quality traits. 

Key Words: Swine, Meat Quality, Eating Quality

**Introduction**

Descriptive terms such as quantity and quality have been referred to with distinctly different levels of importance in the swine industry when applied to economic concerns over the past quarter century. Quality is a more subjective characteristic and is more difficult to measure, particularly as done by consumers. As the live hog is converted to meat and displayed to the consumer, evaluation of quality becomes a greater concern. Unfortunately, due to an increasingly volatile and competitive hog market, producers constantly struggle with the issue of how to create a pork industry that is economically viable. In turn, selection schemes initiated by producers revolve solely around those traits of economic importance. The initiation of grid-based marketing systems within the past 20 years has created an opportunity for producers to increase the value of the hogs they market through increased lean percentage. Prior to 1985, 90 percent of hogs marketed were sold as traditional 'commodity pork' where price was determined on a live weight basis (Hayenga, 1985). The utilization of incentive-based marketing systems became increasingly important to producers seeking added value to the hogs they produce, corresponding to increased selection for lean percentage. As a result, the percentage of hogs sold on a carcass basis rose to 28 percent in 1988 and to 78 percent in 1997 (Brorsen et al., 1998).

In nearly 20 years, pork producers have made tremendous strides toward providing a leaner product to the packer, and ultimately, the consumer. However, through intensive
selection for increased carcass leanness, the swine industry has allowed consumer acceptance issues to arise as a result of decreased meat quality. Quality characteristics that play an integral role in consumer acceptance, such as intramuscular fat, have decreased as breeders have intensely selected for increased leanness (Barton-Gade, 1990; Cameron, 1990).

Hiner et al. (1965) and Jensen et al. (1967) illustrate that quality characteristics, particularly intramuscular fat percentage, of meat were significantly better before intense selection was placed on carcass leanness. Not only was it documented that meat quality was higher, but more specifically, Duroc pigs had much greater marbling than the other breeds. Today, the Duroc breed is used extensively as a terminal sire in the production of crossbred market hogs because of its known advantage over other breeds in terms of growth rate and meat quality characteristics. The primary objective of this study was to quantify the effect that selection for decreased backfat thickness and increased loin muscle area (i.e. increased percent lean) has had on meat and eating quality traits since the initiation of incentive-based hog pricing in the mid to late 1980s.

**Materials and Methods**

*Derivation of Lines*

Two lines were formed by randomly allocating littermate and ½ sib pairs of females to matings by current (CTP) or old (OTP) time period boars. Boars from each time period were randomly selected from available resources from two commercially oriented regional boar studs. All boars and females utilized in the study were stress tested to ensure the absence of the recessive mutant HAL1843 allele. Matings by CTP boars were made using fresh semen while matings by OTP boars were made utilizing frozen semen. Six matings per
boar from the OTP and five matings per boar from the CTP were made in order to obtain a minimum of three litters per sire and to account for potential conception rate differences. Matings were performed across two subsequent breeding seasons. Females mated to CTP boars in the first parity were then mated to OTP boars in the second parity and vice versa to assist in reducing the effect of dam on pig performance across both lines.

*Carcass Evaluation*

Upon completion of the progeny test described in Schwab et al. (2005), all available barrows and randomly selected gilts were slaughtered at a commercial abattoir. Records on pigs sired by CTP boars (n = 178) represented 23 sires while pigs sired by OTP boars (n = 99) consisted of 15 sire groups. Following slaughter and a 24 h chill, ultimate pH was measured on the 10th rib face of the longissimus muscle using a pH star probe (SFK Ltd, Hvidovre, Denmark). Hunter L (L24) score and Minolta Reflectance (a measure of light reflectance where lower values indicate darker and more desirable color) were measured on the 10th rib face of the loin using a Minolta CR-310 (Minolta Camera Co., Ltd., Japan) with a 50-mm-diameter aperture, D65 illuminant, and calibrated to the white calibration plate. A section of bone-in loin containing the 10th rib was removed from the carcass and transported to the Iowa State University Meat Laboratory, Ames. At 48 h post-mortem, Hunter L scores (L48) and Minolta Reflectance were again obtained using the Minolta-CR 310 on the 10th rib loin face. A 3.2 mm slice from the 10th rib face was then removed and utilized for intramuscular fat determination (Bligh and Dyer, 1959).

The 11th and 12th rib sections were cut into 2.54 cm chops and set freshly cut side up for 10 min to allow the sample to bloom. Subjective measures of color (1-6), marbling (1-10), and firmness (1-3) were evaluated on the 11th rib face according to NPPC (2000).
Water holding capacity was measured on the 11th rib face by the filter paper method of Kauffman et al. (1986) and is reported in mg of water absorbed by the filter paper, indicating that lower values are more desirable.

**Sensory Evaluation**

The 11th and 12th rib chops were vacuum packaged and taken to the Iowa State University Food Science Laboratory where they were refrigerated at 0° C for seven d. A trained sensory panel with three members evaluated cooked loin quality attributes (Huff-Lonergan et al., 2002). Chops were cooked to 71° C in an electric broiler (Amana model ARE 640, Amana, IA), with sample temperature monitored by Chromega/Alomega thermocouples (0.02 diameter, 1.8m length) attached to an Omega digital thermometer (DSS-650, Omega Engineering, Inc., Stamford, CT). Weights prior to and immediately after cooking were used to calculate percent cooking loss. Three 1.3 cm³ cubes were removed from the center of the 11th rib sample and evaluated by a trained sensory panel for juiciness (1 = dry and 10 = juicy), tenderness (1 = tough and 10 = tender), chewiness (1 = not chewy and 10 = very chewy), flavor (1 = little pork flavor, bland and 10 = extremely flavorful, abundant pork flavor), and off-flavor (1 = no off-flavor and 10 = abundant non-pork flavor) using an end-anchored, 10-point scoring system (AMSA, 1995). Individual booths with red overhead lighting were provided for each panelist. Room temperature, deionized, distilled water and unsalted crackers were served between samples to cleanse the palette. Sample evaluations were averaged across panelists for analysis. The 12th rib section was evaluated for tenderness using an Instron Universal Testing Machine (model 1122; Instron Corp., Canton, MA) fitted with a circular, five-pointed star probe (nine mm diameter with six mm between points) (Oltrogge-Hammernick and Prusa, 1987).
Statistical Analysis

Time period differences for meat and eating quality traits were assessed with the use of the PROC MIXED procedure in SAS (SAS Inst. Inc., Cary, NC). Least squares means and corresponding standard errors were computed with the use of the following mixed model:

\[ Y_{ijklmnp} = TP_i + S_j + CG_k + b_1 OD_l + b_2 CWT_m + SR(TP)_ni + DM_p + \epsilon_{ijklmnp} \]

where

\[ Y_{ijklmnp} = \text{trait measured on the } m^{th} \text{ pig of the } j^{th} \text{ sex in the } i^{th} \text{ time period and in the } k^{th} \text{ contemporary group} \]

\[ TP_i = \text{fixed effect of the } i^{th} \text{ time period} \]

\[ S_j = \text{fixed effect of the } j^{th} \text{ sex} \]

\[ CG_k = \text{fixed effect of the } k^{th} \text{ contemporary group (based on on-test date)} \]

\[ OD_l = \text{fixed effect of the } l^{th} \text{ off-test date} \]

\[ CWT_m = \text{linear effect of the carcass weight of the } m^{th} \text{ pig} \]

\[ SR(TP)_ni = \text{effect of the } n^{th} \text{ sire nested within the } i^{th} \text{ time period, assumed random} \]

\[ \text{with } SR(TP)_ni \sim N(0, \sigma_{SR}^2) \]

\[ DM_p = \text{effect of the } p^{th} \text{ dam, assumed random with } DM_p \sim N(0, \sigma_{DM}^2) \]

\[ \epsilon_{ijklmnp} = \text{residual with } \epsilon_{ijklmnp} \sim N(0, \sigma_{\epsilon}^2) \]

The above model is the result of a stepwise process of fitting all two-way interactions between fixed effects along with second and third order polynomial effects of the covariate CWT and subsequently removing non-significant (P > .05) individual effects sequentially.
Associations between traits were determined by calculating phenotypic correlations with the use of the PROC CORR procedure in SAS.

**Results and Discussion**

*Meat Quality Characteristics*

Least squares means and corresponding standard errors for meat quality traits are presented by time period in Table 1.

*Intramuscular fat.* Loins from pigs sired by OTP boars had greater amounts of intramuscular fat when compared to pigs sired by CTP boars ($P < 0.05$). Likewise, the OTP line had significantly higher subjective marbling scores than the CTP line. Line differences for the two aforementioned traits are consistent in amplitude and illustrate that a significant difference has arisen through long-term selection for carcass leanness as a result of antagonistic genetic relationships documented by Berger et al., (1994) and Knapp et al., (1997).

*Pork color.* Loins from pigs sired by OTP boars received significantly higher subjective color scores than loins from pigs sired by CTP boars. There were no significant differences between lines for Minolta reflectance and Hunter L values measured at 24 and 48 hours post-mortem. It is important to note that the inconsistency between the above results may be influenced by the greater amounts of intramuscular fat in pigs sired by OTP boars. Objective measures of percent reflectance are evaluated on a section of the exposed lean tissue, a portion of which is intramuscular fat. Thus, samples from the OTP line may have higher and less desirable reflectance values on consistent samples of lean color due to elevated levels of intramuscular fat.
Loin pH and water retention properties. This study revealed a trend for slightly higher pH measurements at 48 hours post-mortem for pigs sired by OTP boars; however, they were not significantly different ($P > .05$) from pigs sired by CTP boars. No significant difference was detected for pH measured at seven days post-mortem. The evaluation of water-holding capacity, percent cooking loss, and subjective firmness scores revealed no significant difference between time periods in this study. Huff-Lonergan et al. (2002) provided significant correlations between marbling and meat quality measures of firmness (0.37), percent drip loss (-0.12), and 48 hour pH (0.15) to suggest that an increase in intramuscular fat should result in enhancements of such carcass quality measures. The genetic correlations between intramuscular fat percentage and quality measures such as pH and various water retention properties (Sellier, 1998), though in the desired direction, are small enough to require a larger sample of carcass measures to detect a difference not attributable to randomness.

Tenderness. Sire time period significantly affected Instron tenderness values among pigs evaluated in this study as pigs sired by OTP boars had significantly lower Instron tenderness values when compared to pigs sired by CTP boars. When intense selection is based on enhanced carcass leanness, an antagonistic genetic relationship between tenth-rib backfat and tenderness ($r_g = 0.12$), documented by Berger et al. (1994), was also evident in this study.

Sensory Panel Characteristics

Least squares means and corresponding standard errors for eating quality traits are presented by time period in Table 2. Palatability of pork is generally described and measured using a combination of sensory and objective measurements. Previous studies in beef cattle
have evaluated in-plant measures of meat quality and their relationship with sensory evaluations of palatability. As illustrated by Thompson (2004), consumer panels are effective when used to estimate sensory attributes, but have the disadvantage that the correlations between the different attributes are generally high within a given panelist. This complicates the interpretation of relationships among sensory evaluations and carcass traits. Elevated levels of intramuscular fat percentage in pork have been reported to be associated with greater juiciness, more desirable flavor, greater tenderness, and overall palatability (Murray et. al, 2004). However, as illustrated by Van Oeckel et al. (1999), intramuscular fat has a higher association with flavor (r = .31) and tenderness (r = .31) than with juiciness (r = .15).

**Tenderness.** Though significant differences in objective tenderness values were detected between time periods in this study, sensory panel evaluation revealed no significant difference in tenderness scores between pigs sired by boars from the two different time periods. Pigs sired by OTP boars tended to have lower and more desirable tenderness scores; however, the sample of pigs utilized in the sensory evaluation was not large enough to detect a difference outside of possible random chance. As described by Thompson (2004), sensory evaluations of tenderness in beef tend to have a strong relationship with objective tenderness measures such as peak force. However, they are rather simplistic in nature and do not take into account the complex interactions that occur with flavor and juiciness during the eating process. Shakelford et al. (1995) examined the relationship between shear force and trained sensory panel tenderness ratings in beef cattle and reported that shear force did not accurately reflect differences in overall tenderness and that overall tenderness varies much more than juiciness or flavor.
Juiciness and chewiness. Sensory panel scores for juiciness and chewiness of loins from pigs sired by OTP boars were not statistically different (P > .05) from loins from pigs sired by CTP boars. Indirectly, these results are inconsistent with differences detected in intramuscular fat percentage between lines in this study. It has been reported that higher levels of intramuscular fat in beef are associated with elevated juiciness as detected by taste panelists (Thompson, 2004). The lubrication effect of marbling, as stated by Thompson (2004), stimulates salivation and leads to the perception of increased juiciness.

Flavor and off-flavor. Significant differences were detected between time periods by sensory taste panelists for the evaluation of flavor and off-flavor. Pigs sired by OTP boars had significantly higher (P < .05) flavor scores and lower off-flavor scores, indicating more desirable pork flavor and less incidence of off-flavor than pigs sired by CTP boars. These results are consistent with documented relationships among various meat and eating quality traits. As aforementioned, flavor has a relatively strong relationship with intramuscular fat content (Van Oeckel et al., 1999) as species-specific flavors are contained in fat and can impact taste panel evaluations of flavor.

Lean composition is a complicated trait influenced by several interacting genes. Unfavorable correlated responses, typically in the form of decreased meat quality, have resulted when strong selection emphasis is placed on this trait. This study illustrated that long-term selection response in terms of increased carcass leanness has been at the expense of meat quality traits, namely intramuscular fat percentage, tenderness, and color, as well as eating quality traits such as flavor and off-flavor scores.

Phenotypic Correlations
The unique population under study provides an opportunity to evaluate any changes in correlations that may have resulted from drastic changes in lean percentage over time. Relationships among measures of carcass composition, meat quality traits, and eating quality traits are presented by time period in Tables 3 and 4. In most cases, correlation coefficients among meat quality traits and sensory evaluations for pigs sired by both time periods were in the same direction and low in magnitude. However, relationships between measures of carcass composition and meat quality yielded contrasting results between lines.

**Correlations among carcass composition and measures of meat quality.** Correlation coefficients among carcass composition and meat quality characteristics are presented in Table 3. Within both time periods, tenth-rib backfat (BF10) was negatively correlated ($P < 0.05$) with loin muscle area, and had a significant positive association with subjective marbling and IMF. These data are consistent with previous research (Huff-Lonergan et al., 2002), and indicate that fatter carcasses will have less loin muscle area and greater amounts of intramuscular fat. Within the CTP line, BF10 was significantly associated with Minolta reflectance and Hunter L values. However, no significant correlation was detected between BF10 and either objective measure of loin color in the OTP line. Huff-Lonergan et al. (2002) reported a correlation of 0.19 between tenth-rib backfat and Hunter L color, which is comparable to the findings for the CTP line in the present study. The difference between lines for this relationship may be explained by greater amounts of intramuscular fat found in pigs sired by OTP boars. The positive association between IMF and both objective measures of color illustrates that the greater percentage of IMF found in the OTP line may result in less desirable measurements of loin color, depleting the relationship between these traits within this line.
Loin muscle area was more highly correlated with 24 h pH and subjective measures of color and firmness within the OTP line than in the CTP line. In all three cases, this correlation coefficient was not significant for pigs sired by CTP boars. Within the OTP line, the correlation between 24 h pH and measures of carcass composition (LMA and BF10) is significant and low to moderate in magnitude. However, these two correlation coefficients are not significant within the CTP line, illustrating that the correlation between pH and measures of carcass composition has eroded as a result of long-term selection for carcass leanness. Relationships among these traits within the CTP line correspond favorably to previous reports (Hamilton et al., 2003; Huff-Lonergan et al., 2002). Many technological advancements in the methods by which carcasses are slaughtered and processed have occurred along with the selection response realized in carcass composition since the mid to late 1980s. These changes may provide some insight to the differences in relationships among traits found between time periods in this study.

**Correlations between carcass composition, meat quality, and sensory attributes.**

Correlation coefficients among carcass composition, meat quality, and sensory attributes are presented in Table 4. Relationships among measures of carcass composition and sensory attributes were comparable between time periods in this study. Within the CTP line, BF10 was significantly correlated with juiciness score and tenderness score, indicating that loins from pigs with more subcutaneous fat were perceived to be juicier and more tender by panelists. Loin muscle area had a significant negative correlation with flavor score and a significant positive correlation with off-flavor score in pigs sired by CTP boars. These data indicate that loins from CTP-sired pigs with larger loin muscle area measurements had less pork flavor and more off-flavor. Correlation coefficients between BF10 and sensory
evaluations of juiciness score and flavor score were significant within the OTP line. This is as expected, because subcutaneous fat is typically associated with a greater amount of intramuscular fat, a contributor to product juiciness. No significant correlations were detected between LMA and sensory attributes within the OTP line. Huff-Lonergan et al. (2002) reported comparable significant correlations between tenth-rib backfat and tenderness score (0.19), flavor score (0.24), and off-flavor score (-0.21). Similarly, significant correlations were also reported between loin muscle area and tenderness score (-0.18), flavor score (-0.16), and off-flavor score (0.10). In general, it appears that these same relationships were found in the CTP-sired population used in this study. However, genetic relationships noted by NPPC (1995), show little or no consistent association among measures of carcass composition and sensory attributes, similar to phenotypic relationships within the OTP line in the present study. Although the relationships between carcass composition and measures of palatability found in the CTP line are significant and supported by previous research, the magnitude of the correlations are small enough to indicate that other factors (outside of carcass composition) have a greater influence on sensory evaluations of pork.

Correlations among meat and eating quality traits. Typically, pH measurements are used to predict several meat quality characteristics. Correlations of pH measured at 24 h postmortem with other quality traits were consistent across time periods. Due to the greater number of observations and smaller standard errors for correlations within the CTP line (data not shown), more correlations among meat and eating quality characteristics were significant in this line. However, minimal differences in the magnitude of correlation coefficients among time periods were detected between pH and other measures of pork quality. Within the CTP line, water holding capacity and all measures of color were more highly associated
with 24 h pH (Table 3), in a manner that indicated that higher loin pH values correspond to
darker color and greater water retention. These correlations, though similar in direction,
were not significant within the OTP line, and this result is likely due to the lower number of
observations utilized in this line. The moderate associations between pH and measures of
color found within the CTP line of this population are in agreement with several studies
showing that elevated pH values are related to darker loin color (De Vol et al., 1988;
Hovenier et al., 1992; NPPC, 1995). A significant relationship, supported by reports of Huff-
Lonergan (2002), was found between subjective measures of marbling and firmness within
the OTP line. The same relationship, however, was not significant within the CTP line. It is
possible that the greater amounts of IMF found in OTP-sired pigs may aid in the firmness of
loins within this line.

Numerous important relationships between various meat quality traits were detected
across both time periods. Highly significant associations between water holding capacity and
all measures of color were found for both lines, and are supported by genetic correlations
reported by NPPC (1995). The significant association between percent intramuscular fat and
Instron tenderness detected in both lines in this population is also supported by several
studies involving percent lipid and shear force evaluations of tenderness, illustrating that
greater percentages of intramuscular fat are correlated to enhanced tenderness of pork (De
Vol et al, 1988; Huff-Lonergan et al., 2002). Additionally, a moderate significant correlation
was detected between subjective firmness and all measures of color. Percent cooking loss
had a significant relationship, moderate in magnitude, with sensory attributes of juiciness
score, tenderness score, and chewiness score (Table 4). Huff-Lonergan (2002) also reported
similar values for subjective firmness and Hunter L values, as well as the association
between percent cooking loss and sensory evaluations of juiciness score and tenderness score.

**Implications**

Due to sizeable economic incentives at the packer level initiated during the mid 1980s, breeding programs have been focused on selection for rapid production of lean pork during the last two decades. As markets are ultimately dictated by consumer preference, selection practices should include emphasis on quality traits (in addition to lean percentage) in breeding programs. The fact that meat quality characteristics are influenced by many factors makes the prediction and genetic improvement of such traits extremely complicated. Understanding the relationships among many measures of pork quality is important if variation is to be controlled and progress in such traits is to be made. By quantifying the effect that long-term intensive selection for increased carcass leanness has had on meat quality characteristics and consumer acceptance, we may begin to identify opportunities for producers to add value to the pork products they produce.
Literature Cited


Table 1. Least squares means (±SE) for meat quality traits in purebred Duroc pigs sired by boars from two different time periods

<table>
<thead>
<tr>
<th>Item</th>
<th>Current</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intramuscular fat percentage, %</td>
<td>3.09 ± 0.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.48 ± 0.15&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Instron tenderness, kg</td>
<td>5.98 ± 0.12&lt;sup&gt;a&lt;/sup&gt;</td>
<td>5.31 ± 0.13&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Subjective color score (1-6)</td>
<td>3.87 ± 0.08&lt;sup&gt;a&lt;/sup&gt;</td>
<td>4.09 ± 0.08&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>Subjective firmness score (1-3)</td>
<td>2.08 ± 0.04</td>
<td>2.14 ± 0.04</td>
</tr>
<tr>
<td>Subjective marbling score (1-10)</td>
<td>3.07 ± 0.13&lt;sup&gt;a&lt;/sup&gt;</td>
<td>3.54 ± 0.15&lt;sup&gt;b&lt;/sup&gt;</td>
</tr>
<tr>
<td>24 hr. Minolta reflectance, %</td>
<td>22.70 ± 0.31</td>
<td>23.25 ± 0.34</td>
</tr>
<tr>
<td>48 hr. Minolta reflectance, %</td>
<td>21.40 ± 0.28</td>
<td>21.78 ± 0.32</td>
</tr>
<tr>
<td>24 hr. Hunter L value, %</td>
<td>47.67 ± 0.32</td>
<td>48.10 ± 0.35</td>
</tr>
<tr>
<td>48 hr. Hunter L value, %</td>
<td>46.20 ± 0.30</td>
<td>46.60 ± 0.33</td>
</tr>
<tr>
<td>48 hr. pH</td>
<td>5.77 ± 0.02</td>
<td>5.80 ± 0.02</td>
</tr>
<tr>
<td>7 day pH</td>
<td>5.65 ± 0.01</td>
<td>5.65 ± 0.01</td>
</tr>
<tr>
<td>Water holding capacity, mg</td>
<td>47.33 ± 2.31</td>
<td>47.75 ± 2.46</td>
</tr>
<tr>
<td>Percent cooking loss, %</td>
<td>19.09 ± 0.38</td>
<td>18.96 ± 0.42</td>
</tr>
</tbody>
</table>

<sup>ab</sup>Means with different superscripts within each row differ (P < 0.05).
Table 2. Least squares means (±SE) for sensory panel evaluation of eating quality traits in purebred Duroc pigs sired by boars from two different time periods

<table>
<thead>
<tr>
<th>Item</th>
<th>Time Period</th>
<th>Current</th>
<th>Old</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tenderness score (1-10)</td>
<td></td>
<td>6.67 ± 0.19</td>
<td>7.19 ± 0.22</td>
</tr>
<tr>
<td>Flavor score (1-10)</td>
<td></td>
<td>1.98 ± 0.10^a</td>
<td>2.35 ± 0.11^b</td>
</tr>
<tr>
<td>Off-flavor score (1-10)</td>
<td></td>
<td>3.08 ± 0.14^a</td>
<td>2.63 ± 0.14^b</td>
</tr>
<tr>
<td>Juiciness score (1-10)</td>
<td></td>
<td>6.12 ± 0.15</td>
<td>6.18 ± 0.16</td>
</tr>
<tr>
<td>Chewiness score (1-10)</td>
<td></td>
<td>2.52 ± 0.13</td>
<td>2.23 ± 0.15</td>
</tr>
</tbody>
</table>

^a^Means with different superscripts within a row differ (P < 0.05).
Table 3. Phenotypic correlations by time period among carcass composition and measures of meat quality in purebred Duroc pigs sired by boars from two different time periods*

<table>
<thead>
<tr>
<th>Item</th>
<th>BF10</th>
<th>LMA</th>
<th>pH</th>
<th>MIN</th>
<th>HUNT</th>
<th>C</th>
<th>M</th>
<th>F</th>
<th>WHC</th>
<th>IMF</th>
<th>CL</th>
<th>INST</th>
</tr>
</thead>
<tbody>
<tr>
<td>BF10</td>
<td></td>
<td></td>
<td>0.01</td>
<td>0.16</td>
<td>0.16</td>
<td>0.10</td>
<td>0.45</td>
<td>-0.02</td>
<td>0.02</td>
<td>0.39</td>
<td>-0.14</td>
<td>-0.28</td>
</tr>
<tr>
<td>LMA</td>
<td>-0.39</td>
<td></td>
<td></td>
<td>-0.07</td>
<td>-0.07</td>
<td>0.07</td>
<td>-0.19</td>
<td>0.05</td>
<td>-0.15</td>
<td>-0.23</td>
<td>-0.04</td>
<td>0.00</td>
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<tr>
<td>pH</td>
<td>0.25</td>
<td></td>
<td>-0.34</td>
<td>-0.34</td>
<td>0.39</td>
<td>0.15</td>
<td>0.36</td>
<td>-0.41</td>
<td>0.09</td>
<td>-0.08</td>
<td>-0.26</td>
<td></td>
</tr>
<tr>
<td>MIN</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.15</td>
<td>0.99</td>
<td>-0.61</td>
<td>0.03</td>
<td>-0.37</td>
<td>0.55</td>
<td>0.21</td>
<td>0.14</td>
<td>0.13</td>
<td></td>
</tr>
<tr>
<td>HUNT</td>
<td>-0.03</td>
<td>0.00</td>
<td>-0.15</td>
<td>0.99</td>
<td>-0.61</td>
<td>0.03</td>
<td>-0.38</td>
<td>0.55</td>
<td>0.21</td>
<td>0.14</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>0.16</td>
<td></td>
<td>-0.22</td>
<td>0.21</td>
<td>-0.66</td>
<td>-0.67</td>
<td>0.24</td>
<td>0.41</td>
<td>-0.49</td>
<td>0.00</td>
<td>-0.11</td>
<td>-0.24</td>
</tr>
<tr>
<td>M</td>
<td>0.50</td>
<td>-0.46</td>
<td>0.23</td>
<td>-0.05</td>
<td>-0.06</td>
<td>0.29</td>
<td>0.41</td>
<td>-0.07</td>
<td>0.68</td>
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<tr>
<td>F</td>
<td>0.18</td>
<td></td>
<td>-0.28</td>
<td>0.18</td>
<td>-0.42</td>
<td>-0.42</td>
<td>0.54</td>
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<td>-0.21</td>
<td>0.06</td>
<td>-0.16</td>
<td>-0.19</td>
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<td>WHC</td>
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<td>0.44</td>
<td>0.45</td>
<td>-0.39</td>
<td>-0.20</td>
<td>-0.40</td>
<td>0.07</td>
<td>0.14</td>
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<tr>
<td>IMF</td>
<td>0.49</td>
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<td>0.13</td>
<td>0.25</td>
<td>0.24</td>
<td>0.03</td>
<td>0.65</td>
<td>0.13</td>
<td>-0.08</td>
<td>0.00</td>
<td>-0.24</td>
<td></td>
</tr>
<tr>
<td>CL</td>
<td>-0.11</td>
<td>0.11</td>
<td>-0.12</td>
<td>0.25</td>
<td>0.26</td>
<td>-0.34</td>
<td>-0.21</td>
<td>-0.27</td>
<td>0.33</td>
<td>-0.06</td>
<td>0.37</td>
<td></td>
</tr>
<tr>
<td>INST</td>
<td>-0.21</td>
<td>0.19</td>
<td>-0.08</td>
<td>-0.21</td>
<td>-0.22</td>
<td>-0.09</td>
<td>-0.16</td>
<td>-0.07</td>
<td>0.05</td>
<td>-0.33</td>
<td>0.28</td>
<td></td>
</tr>
</tbody>
</table>

*Correlations for current time period are above diagonal; correlations for old time period are below diagonal; bold values indicate significant correlations (P < 0.05).

1BF10 = tenth-rib backfat; LMA = loin muscle area; pH = 24 h pH; MIN = Minolta reflectance; HUNT = Hunter L value; C = subjective color; M = subjective marbling; F = subjective firmness; WHC = water holding capacity; IMF = percent intramuscular fat; CL = percent cooking loss; INST = Instron tenderness.
Table 4. Phenotypic correlations by time period among carcass composition, meat quality, and sensory attributes in purebred Duroc pigs sired by boars from two different time periods*

<table>
<thead>
<tr>
<th>Item</th>
<th>Current time period</th>
<th></th>
<th></th>
<th>Old time period</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Trait^1</td>
<td>JS</td>
<td>TS</td>
<td>CS</td>
<td>FS</td>
<td>OFS</td>
</tr>
<tr>
<td>Tenth-rib backfat</td>
<td>0.25</td>
<td>0.20</td>
<td>-0.14</td>
<td>0.13</td>
<td>-0.10</td>
<td></td>
</tr>
<tr>
<td>Loin muscle area</td>
<td>-0.01</td>
<td>0.03</td>
<td>0.04</td>
<td>-0.022</td>
<td>0.16</td>
<td></td>
</tr>
<tr>
<td>24 hr. pH</td>
<td>0.24</td>
<td>0.19</td>
<td>-0.18</td>
<td>0.36</td>
<td>-0.23</td>
<td></td>
</tr>
<tr>
<td>Minolta</td>
<td>-0.28</td>
<td>-0.15</td>
<td>0.07</td>
<td>-0.16</td>
<td>0.15</td>
<td></td>
</tr>
<tr>
<td>Hunter</td>
<td>-0.28</td>
<td>-0.15</td>
<td>0.07</td>
<td>-0.16</td>
<td>0.14</td>
<td></td>
</tr>
<tr>
<td>Subjective color</td>
<td>0.29</td>
<td>0.19</td>
<td>-0.09</td>
<td>0.13</td>
<td>-0.15</td>
<td></td>
</tr>
<tr>
<td>Subjective marbling</td>
<td>0.19</td>
<td>0.19</td>
<td>-0.12</td>
<td>0.27</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>Subjective firmness</td>
<td>0.25</td>
<td>0.23</td>
<td>-0.17</td>
<td>0.19</td>
<td>-0.29</td>
<td></td>
</tr>
<tr>
<td>Water holding capacity</td>
<td>-0.28</td>
<td>-0.13</td>
<td>0.05</td>
<td>-0.28</td>
<td>0.18</td>
<td></td>
</tr>
<tr>
<td>% Intramuscular fat</td>
<td>0.16</td>
<td>0.14</td>
<td>-0.08</td>
<td>0.28</td>
<td>-0.20</td>
<td></td>
</tr>
<tr>
<td>% Cooking loss</td>
<td>-0.46</td>
<td>-0.38</td>
<td>0.35</td>
<td>-0.01</td>
<td>0.00</td>
<td></td>
</tr>
<tr>
<td>Instron tenderness</td>
<td>-0.39</td>
<td>-0.65</td>
<td>0.62</td>
<td>-0.25</td>
<td>-0.01</td>
<td></td>
</tr>
</tbody>
</table>

*Bold values indicate significant correlations (P < 0.05).
^1JS = juiciness score; TS = tenderness score; CS = chewiness score; FS = flavor score; OFS = off-flavor score.
**GENERAL SUMMARY**

Producers constantly struggle with the issue of how to create a pork industry that is economically viable. In turn, breeding programs within the last two decades have been focused solely around those traits of economic importance. Due to sizeable economic incentives at the packer level initiated during the mid 1980s, selection schemes have intensely emphasized lean growth since that time. However, though markets are ultimately dictated by consumer preference, little emphasis has been placed on characteristics dealing with consistency and quality of pork displayed at the retail counter.

The underlying objective of this thesis was to evaluate the long-term changes that have occurred in the Duroc breed as a result of the industry's selection emphasis on carcass leanness. This objective involved four specific goals: 1.) determine the selection response in terms of enhanced carcass leanness achieved since the mid 1980s; 2.) investigate the correlated response in various measures of meat and eating quality due to the industry's long-term selection for leanness; 3.) evaluate the alterations in tissue deposition rates and growth patterns of measures of carcass composition and meat quality; and 4.) establish a better understanding of the relationships among many measures of meat quality, eating quality, and carcass composition.

Results from this study illustrate that significant progress toward the enhancement of carcass composition, whether measured in-plant or via ultrasound, has been realized within the Duroc breed since the mid 1980s. Unfortunately, this increased carcass leanness through time has evolved without equivalent progress in growth performance and has been at the expense of meat quality traits such as intramuscular fat, tenderness, and color, as well as
eating quality traits such as flavor and off-flavor scores. Additionally, long-term selection response in carcass leanness has also yielded similar alterations in deposition rates and patterns of correlated traits such as loin muscle area and intramuscular fat. Relationships between various meat quality characteristics and measures of carcass composition were found in this study to have been slightly altered within the last two decades; however, the correlations among many measures of meat quality and sensory attributes have remained constant.

Though hog procurement systems will likely maintain an economic emphasis on lean percentage in the near future, a balanced approach to breeding objectives that include indicators of meat quality is important to prevent further deterioration of pork quality. Findings of this study should not only enable packers and processors to further understand the long-term ramifications of lean-based marketing of hogs with little or no emphasis on meat quality, but may also begin to identify opportunities for producers to add value to the pork products they produce.
REFERENCES CITED


First of all, I would like to express my sincere appreciation for those who provided me with so much guidance throughout my graduate career. My committee members, Dr. John Mabry and Dr. Dan Nettleton, have offered a great deal of assistance towards my understanding of quantitative genetics and statistical analysis, and have provided extensive guidance toward the completion of my degree. I greatly appreciate both of their contributions. Certainly the greatest contribution towards numerous aspects of my graduate education thus far has been from my major professor, Dr. Tom Baas. Your major professor has such an influence on not only what you take away from your education, but also determines how much you enjoy your graduate experience. I have to say that I could not imagine a more rewarding experience. You have provided me with the opportunity to travel the world while attaining a tremendous exposure to the industry, while at the same time, you have been a great friend and role model. Needless to say, I look forward to the remainder of my time under your instruction.

The list of fellow graduate students that have helped me along the way is an extensive one. Throughout the long-term details of my graduate program, fellow graduate students such as Bryce Martin and Mark Knauer have donated a big portion of their time and I owe them a great deal. My special thanks go to Jeremy Burkett and Nick Berry who are also always willing to set aside whatever it is that they are working on to help in data collection or even lend an ear for frustration. Doug Newcom has also played an integral part of my education from the time I began my master’s degree. He has been a great teacher and I think of him as a member of my graduate committee. Additionally, I owe a great deal of thanks to
Jay Lampe who has taught me the details of ultrasound technology, a portion of my graduate project that I could not have tackled without his expertise. I will always value his friendship. His understanding of hogs and the swine industry in general is something I truly admire.

To echo that of my dedication, it is the contributions of my family that I owe for instilling in me a sense of drive, confidence, curiosity, and a passion for the livestock industry early in life. It is these contributions along with their constant love and support that lead to the many opportunities of my education. I have the greatest set of parents. I love them both very dearly. Finally, perhaps the greatest sacrifice for my education within the recent past has come from Sarah Gregory. Her constant support and understanding are contributions that I hope to someday find a way to repay. She is deserving of an honorary degree for all that she has done for me along the way.