Factors to Consider in Regards to Pork Quality

Introduction

Defining pork quality can be a difficult task for a multitude of reasons. First, the definition of quality can differ greatly depending on the context. In general, quality can be defined as meeting a set of specifications with less variation around the mean. The challenge becomes establishing the parameters of interest and then determining the appropriate targets for those parameters. In other words, it can be challenging determining which traits should be used to define pork quality and what specific ranges should be considered “high” quality. As an example, nearly every meat quality conversation includes the ultimate pH of the loin. This makes logical sense because pH of the loin has the strongest correlation with other meat quality traits associated with the loin (Boler et al., 2010). Additionally, increasing ultimate pH improved sensory tenderness and juiciness of loin chops cooked to 71°C (160°F; Huff-Lonergan et al., 2002). However, pH is a trait that may not be understood by consumers and is not one often cited as influencing purchasing decisions. Rather, consumers routinely rate tenderness and juiciness as primary factors that influence eating experience (Moeller et al., 2010a) and use color and marbling as indicators for tenderness and juiciness when making purchasing decisions (Brewer et al., 2001a). Other meat quality traits like water-holding capacity, muscle firmness, and pH are simply proxies for traits that consumers use to rate satisfaction of meat products. The challenge with traits like water-holding capacity, firmness, and pH is that they can be dependent on a host of production traits that can sometimes antagonize meat quality. Things like seasonality (i.e. heat stress), feeding a pelletized diet, castration decisions, transportation, lairage time, and chill rate can all affect eating experience. Ultimately, it is providing a positive eating experience for the consumer that drives product satisfaction and repeat purchasing decisions. Therefore, the objective of this review was to highlight production factors that are potential influencers on lean and fat quality.

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Production Site

Immunological Castration

Immunological castration provides an alternative to surgical castration of male pigs as a means to reduce boar odor to a level indictable by consumers. Immunological castration requires pigs to receive 2 injections to effectively reduce boar odor. The U.S. Food and Drug Administration require no less than 3 weeks and no more than 10 weeks after the second injection before pigs can be slaughtered. Because of the flexibility with the timing of the second injection relative to the time of slaughter, interval between second dose and slaughter (Boler et al., 2012a), diet (Tavarez et al., 2014), marketing strategy (Lowe et al., 2014), and use with other growth promoting ingredients (Lowe et al., 2016a,b) can all affect carcass composition, meat quality, and bacon characteristics.

Harsh et al. (2017a) recently published a meta-analysis summarizing meat quality, carcass composition, and cutablity differences among immunologically castrated barrows, surgically castrated barrows, and gilts. Immunological castration does not impact instrumental color compared to castrates or gilts. There were no differences in visual marbling between immunologically castrated barrows or gilts, but both were less than surgically castrated barrows and there were no differences in instrumental tenderness between immunologically castrated and surgically castrated barrows (Harsh et al., 2017a). Immunological castration also does not impact consumer sensory perceptions compared to physically castrated males and gilts (Fonti Furnols et al., 2008). The greatest impact of immunological castration is on belly thickness. Bellies from gilt carcasses were the thinnest among all pigs. Bellies from immunologically castrated barrows were thicker than bellies from gilts, but thinner than bellies from surgically castrated barrows (Harsh et al., 2017a). Even so, carcass cutability of immunologically castrated barrow carcasses were 0.44 percentage units greater in the Boston butt and 0.39 percentage units greater in the picnic, but did not statistically differ in the ham or loin. Still, this increase resulted in a 1.52 percentage unit increase in boneless lean meat yield and an average increase of $2.44 U.S. in carcass value of immunologically castrated barrow carcasses compared with physically castrated barrow carcasses (Harsh et al., 2017a).

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Differences in belly thickness appears to be due to HCW. Bellies from immunologically castrated barrows that weighed at least 97.7 kg (215.4 lbs) were 14% thicker than bellies from carcasses that weighed less than 97.7 kg. Even though belly thickness can differ between immunologically castrated barrows and surgically castrated barrows, bacon processing characteristics such as brine uptake percentage and cooked yield did not differ (Harsh et al., 2017a). Still, commercial bacon slicing yields were 3.42 percentage units less in immunologically castrated barrows compared with surgically castrated barrows. Despite reductions in some cases of bacon slicing yields, sensory characteristics of food service style bacon (packaged without an oxygen barrier) did not differ among immunologically castrated barrows, physically castrated barrows, or gilts for oxidized odor, oxidized flavor, or overall off flavor (Herrick et al., 2016).

Diet

This document will address several new research reports addressing feedstuffs and pork quality. For a more comprehensive and classical review of nutritional influence on pig growth and quality, see the Nutrient Requirements of Swine (National Research Council, 2012).

Pelletizing

Pelleting swine diets is a technology used by the feed milling industry where a meal diet is subjected to heat and (or) moisture and then pressed through a die to agglomerate smaller particles into a larger composite (Hancock and Behnke, 2001). Feeding pelleted diets improved nutrient digestibility (Wondra et al., 1995a; Rojas et al., 2015), feed efficiency (Wondra et al., 1995a; Nemechek et al., 2015), and in some cases, increased average daily gain (Wondra et al., 1995a,b; Myers et al., 2013; Nemechek et al., 2015). Several indications are that there is no effect of diet form on carcass characteristics (Wondra et al., 1995a,b; Myers et al., 2013; Nemechek et al., 2015). However, increased carcass yield (Fry et al., 2012), back fat, and belly fat (Matthews et al., 2014) of pigs fed pelleted diets have been reported.

Specifically, there was no effect of diet form on average daily gain, average daily feed intake, or final body weight. Pigs fed pelleted diets had 3.2% greater feed efficiency compared with meal-fed pigs (Overholt et al., 2016a). Similar to previous reports, loin muscle area was not affected by pelleting diets, but 10th rib fat thickness was nearly 10% less in pigs fed a meal diet compared with those fed a pelleted diet. Interestingly, pigs fed a pelleted diet tended to have stomachs that comprised a lesser percentage of ending live weight compared with pigs fed a meal diet. Further gastric lesion scores were 0.52 percentage units greater in pigs fed a pelleted diet compared with pigs fed a meal diet. This could have economic implications in a market where by-product value drives profit.

Feeding a pelleted diet did not change visual marbling, subjective firmness, instrumental color, ultimate pH, cook loss, or instrumental tenderness. Even though meat quality was largely not affected by feeding pelleted diets compared with meal diets, fat quality and bacon characteristics were impacted (Overholt et al., 2016b).

Feeding a pelleted diet did not result in differences in belly firmness, but iodine value was increased by 4.3% compared with pigs fed a meal diet. This was directly a result of an increase in linoleic and linolenic acid of the adipose tissue from pigs fed a pelleted diet compared with adipose tissue of pigs fed a meal diet. This increase in calculated iodine value of the pellet fed pigs led to 8 less center-slices of bacon from each belly and/or a 1.2 less slices of bacon per kg (0.55 slices/lb) when compared with bacon from meal fed pigs (Overholt et al., 2016b).

DHA Supplementation

Consumption of long chain n-3 unsaturated fatty acids such as docosahexaenoic acid (DHA) and eicosapentaenoic acid (EPA) have been associated with decreased risk of cardiovascular disease, reduction in blood triglyceride levels and blood pressure, reduction in inflammation and potentially an increase in brain function (Daley et al., 2010). These fatty acids are readily available in fish and marine algae. This has led to a more recent interest in supplementing finishing swine diets with feed ingredients that contain high levels of n-3 fatty acids. Supplementation of DHA and EPA work well in swine diets because the fatty acid profile of pig adipose tissue can be altered through dietary supplementation. This provides humans an option to consume DHA and EPA without the need to increase fish and algae consumption. Fish are the best dietary source of DHA and EPA to ensure humans are meeting their dietary requirements, but some have concerns with the long-term supply of fish products (Moran et al., 2018). Therefore, interests have shifted to understanding the effects of supplementing swine diets with marine algae like Aurantiochytrium limacinum (AURA).

Barrows and gilts (144 total) were fed 1% AURA for the last 28 d of finishing before slaughter. Overall, the algae supplementation did not affect ending body weight, average daily gain, average daily feed or water intake, or feed efficiency. Additionally, no carcass traits were altered due to the inclusion of AURA. On the other hand, fatty acid profile was greatly altered. The beneficial n-3 fatty acid concentration was increased by 32.1 units, but total n-6 fatty acids were also increased. Even so, the n-6: n-3 ratio was 9.59 in adipose tissue of control fed pigs and 8.79 in adipose tissue of pigs fed 1% AURA. Daley et al., (2010) reports that consumers should keep consumption to 1 to 4 times more n-6 compared with n-3. Even though the n-6: n-3 ratio was improved (Moran et al., 2018), the differences were likely not great enough to have an overall impact on heart health due to consumption of pork products from pigs fed 1% AURA. Another thing to consider is that both n-3 and n-6 fatty acids are long chain polyunsaturated fatty acids. That means there are potential negative implications on shelf-life and color stability of products derived from pigs fed greater concentrations of these fatty acids due to the possibility of rancidity. Additionally, belly softness is likely to increase which could negatively affect the sliceability of bacon and further reducing the overall value of the carcass.

Peroxidized lipids

Increased use of corn co-products such as distillers' dried grains with solubles and oils in swine diets have increased concerns over the effects of dietary lipid composition on the quality and shelf-life of fresh and processed pork products. Feeding peroxidized lipids directly to pigs reduces lipid digestibility (Liu et al., 2014a , Lindblom et al., 2018), growth performance (Rosero et al., 2015), as well as decreases HCW and fat depth (Boler et al., 2012b) in growing-finishing pigs. In addition to the ramifications of dietary oxidized lipids on pig performance, there are potential implications for the quality and shelf-life of pork products. In recent years, a growing body of evidence has indicated that the oxidative status of lipid sources should be considered (Shurson et al., 2015). This is of particular importance to the swine industry as rendered fats and unsaturated vegetable oils are routinely used in swine diets (Overholt et al., 2018a). Even with quality control protocols, the rendering, recycling, handling, and storage of lipid sources can further exacerbate their oxidative deterioration. Furthermore, used frying oils may be recycled and added directly to diets. Discarded frying oils are typically extremely oxidized (Sebastian et al., 2014) and are likely to represent the most extreme lipid deterioration of lipid sources used in livestock feeding. The process of lipid peroxidation changes the chemical composition of the lipid through the consumption of polyunsaturated fatty acids, yielding a lipid with a greater concentration of monounsaturated and saturated fatty acids. Lipid peroxidation and the development of rancidity occurs throughout the shelf-life of meat products, even at refrigerated and frozen temperatures. The susceptibility of meat products to lipid oxidation is largely dependent on the fatty acid profile of the lipids, with oxidative susceptibility increasing with increasing polyunsaturated fatty acids in the lipid profile. Lipid oxidation is typically accompanied with deterioration of meat color from a desirable red to an undesirable brown color, due to the oxidation of oxymyoglobin to metmyoglobin (Faustman et al., 2010). Myoglobin is the major pigment protein found in muscle and is responsible for its red color.

In an experiment using 160 finishing barrows fed either oxidized or fresh corn oil, HCW of pigs fed severely oxidized oils were 4.3% lighter than carcasses from barrows fed fresh corn oil (Boler et al., 2012b). Additionally, barrows fed the oxidized corn oil were 3.7% leaner at the 10th rib. On the other hand, color, marbling, firmness, ultimate pH and drip loss did not differ between barrows fed the oxidized corn oil and barrows fed fresh corn oil (Boler et al., 2012b). In a different study, also using barrows, but instead fed either 10% fresh soybean oil (22.5°C; 72.5°F) or soybean oil that was thermally processed at 45°C (113°F) for 288 h, 90°C (194°F) for 72 h, or 180°C (356°F) for 6 h (Overholt et al., 2018a). There were no differences in loin quality traits or loin composition among any of the treatment groups. During the course of the simulated retail display period, there were no differences among any of the soybean oil treatments for cooking loss, Warner-Bratzler shear force (instrumental tenderness), instrumental color, discoloration or lipid oxidation as determined by the TBARS assay throughout a simulated retail display period.

In the United States, bacon is the most valuable pork product (U.S. Bureau of Labor Statistics, 2017) and bacon quality is dependent on fat quality of the pigs from which the bellies were derived. Therefore, the effect of feeding peroxidized feedstuffs on the quality of bellies and the shelf life is also important. Bacon was commercially manufactured from the bellies of the barrows described above where 10% soybean oil was thermally processed at either 45°C (113°F) for 288 h, 90°C (194°F) for 72 h, or 180°C (356°F) for 6 h (Overholt et al., 2018b). There were no differences among soybean oil treatments on fresh belly weight, length, width, or thickness. However, because the barrows in this experiment were fed 10% soybean oil throughout the finishing period, the calculated iodine value of the belly adipose tissue, regardless of treatment was especially high. The mean iodine value of this population was 88.82 and a maximum of 98.56. Therefore, all bellies, regardless of treatment were remarkably poor. Even so, adipose tissue consisting of all 3 fat layers of barrows fed 90°C (194°F) was the least saturated among all treatments, but would still would be considered high (IV = 79.66). Despite the abnormally high iodine values, there were no differences among soybean oil treatments for the cooked weight, cooked yield, or sliced weight of the bacon generated from those bellies. Although there were economically meaningful differences (nearly 12 percentage units) in slicing yield among soybean oil treatments, the variability in slicing yield was greater than anticipated, likely due to the excessively high iodine values. There were no interactions among soybean oil treatments and storage time for any bacon shelf life trait. There were also no differences in lipid oxidation as measured via TBARS. Similarly, there was no effect of soybean oil treatment on either sensory oxidized odor or sensory oxidized flavor.

Feeding a peroxidized grain oil results in reduced growth performance of growing and finishing pigs and appears to induce oxidative stress, but that does not appear to manifest itself in reduced pork quality traits. Most of the literature reports few or no differences in color, pH, or water-holding capacity of loin chops from pigs fed an oxidized oil compared with chops from pigs fed a fresh oil. Further, feeding an oil regardless of its peroxidation status increases the iodine value of adipose tissue, but does not appear to reduce the shelf life of bacon from those pigs.

Genetics

The first step to growing an efficient, high quality pork product is selecting genetics to fit the objective of the finished product. That objective may change depending upon the consumers' preference within the target market. For example, 2 of the

United States' most prominent export markets, Japan and Mexico, have different expectations for their imported pork. Japanese importers choose dark, heavily marbled pork, while Mexican importers are more interested in a leaner product (Lowell, 2019). Meanwhile, American consumers prefer more intensely pink pork (Brewer and McKeith, 1999) with lean fat coverage (Ngapo et al., 2007). In the past, the pursuit of lean growth in different purebred herds lead to some genetic complications. Pigs that were over-selected for lean growth developed halothane sensitivity, indicating greater stress susceptibility (Leach et al., 1996). This elevated reaction to stress lead to defects in meat quality, namely pale, soft, and exudative (PSE) pork. Another detrimental gene found in lean growth lines was the Rendement Napole (RN) gene. Pigs with the RN gene have greater stored glycogen levels in the muscle, leading to a much lower ultimate pH, thus affecting meat quality (Miller et al., 2000). Through marker-assisted selection, both the halothane and RN gene have essentially been removed from the modern genetic pool, giving producers peace of mind in choosing their breeding stock. The goal of lean and high quality pork lines is still at the forefront of the industry today. Different breeds have been used for crossbreeding programs to fit each of these purposes in U.S. pork production systems. Classic examples include the Pietrain breed, developed for highly efficient, lean growth (Edwards et al. 2003), and the Duroc breed, used for darker, more heavily marbled product (Miar, et al. 2014). The Berkshire breed has been used for their superior quality; however, their reduced reproductive performance and inefficient growth has prevented them from being widely utilized in the commercial market (Bohrer, 2013). Select Berkshire herds are still grown in the United States for niche quality markets, but are not widely used for commodity pork. Hampshire-sired pigs are also popular as a lean-growth oriented genetic line. In a study comparing purebred Duroc carcasses to purebred Hampshire carcasses, Aaslyng et al. (2003) reported that Hampshires had a greater percentage of lean meat. Hampshire carcasses also had a lesser pH, lesser percentage of intramuscular fat, and a substantially greater drip loss compared with Durocs. In a study that evaluated quality characteristics between Pietrain- and Duroc-sired market pigs, Lowell et al. (2019) reported that Duroc-sired pigs were fatter and had a greater dressing percentage compared with Pietrain-sired pigs. However, Pietrains had a greater percent standardized fat-free lean. Duroc loins were darker, more heavily marbled, and had a greater ultimate pH. Aged chops from Duroc pigs had greater extractable lipid. While these results may not be indicative of differences among all breeds used in the U.S., they provide some insight into what differences may be expected when using a quality versus a lean growth sire line.

Transport

Transport losses (categorized as dead and non-ambulatory pigs) are estimated to cost the U.S. swine industry approximately $46 million (Ritter et al. 2009). In a review of 23 field studies (6,660,569 pigs) the occurrence of dead, non-ambulatory, and total losses observed at the plant were 0.25, 0.44, and 0.69%, respectively. The incidence of dead pigs peaked from 1998-2001, then fell in 2002 and has remained constant until it was last evaluated (Ritter et al. 2009). This peak may be due in part to increased slaughter weight as well as increased slaughter throughput at plants at the start of the millennia (Ritter et al. 2009). Coincidentally, Pork Checkoff launched the Transport Quality Assurance Program (TQA), which allows transporters, producers and handlers the ability to become certified in humane pig handling in 2002. Part of humane handling includes desensitizing pigs to human handling prior to loading out. Animals that are used to contact and handling by people are less stressed by restraint than those not accustomed to people (Grandin, 1996). Rough handling by farm personnel can cause pigs to associate humans with bad experiences, leading to an increased stress response during loading and unloading (D'Souza, 1998). Thus, it is important to practice desensitizing pigs to people as well as consistently using calm, careful handling. The TQA program also provides updated guidelines in trailer recommendations (Schulz et al., 2015). It is likely that increased knowledge on low-stress handling aided in the reduction of dead pigs upon arrival at the plant. Heavier pigs are more susceptible to temperature stress and fatigue, a problem both transporters and packers alike must face as HCW has increased 0.6 kg/year (1.3 lbs/year) since 1995 (Harsh et al., 2017b). The reduction and stabilization of the incidence of dead pigs may be the effect of greater awareness of the consequences of economic loss.

In 18 of the reviewed studies, non-ambulatory pigs were further categorized as either fatigued or injured. Fatigued pigs accounted for 0.37% of total pigs, and injured accounted for 0.05% of total pigs. Fatigued pigs were defined as pigs showing signs of severe stress such as panting and lethargy. Fatigued pigs are more likely to recover; however, they still experience the repercussions of acute stress such as low blood pH and high blood lactate. Lairage time may affect the meat quality of these pigs, as acute stress immediately prior to slaughter may contribute to PSE (Barbut et al., 2008). Dead and non-ambulatory pigs are not only a welfare concern, but represent a significant economic loss for both producers and packers. This loss may be minimized through proper management in each aspect of transport (Ritter et al., 2009).

Stocking density, weather, and temperature during transport

As of 2004, the National Institute of Animal Agriculture recommends a space allowance during transit of 0.33-0.35m^2 per 100 kg (3.55-3.77 ft^2/220.5 lb) of body weight for successful transportation of pigs. Overstocking of pigs during transportation results in a greater incidence of fatigue/stress, and overheating during the summer months, while understocking trailers results in pigs being thrown about the trailer, cold stress during winter months, and economic loss due to a greater number of required trips (Tarrant, 1989). The driver can manipulate stocking density by changing the number of pigs loaded into each compartment. Body weight should also be considered when deciding how many pigs should be loaded in a compartment, such that space requirements are still met. Ritter et al. (2006) compared losses between loads of pigs stocked at 0.30 and 0.37m²/100 kg BW (3.23-3.98 ft²/220.5 lb), classifying loss as non-ambulatory and injured, non-ambulatory and non-injured, or dead pigs. Increased floor space reduced non-ambulatory, non-injured and dead pigs, thereby reducing total loss by 0.52%. However, reduced stocking density also resulted in lighter load size when applied to an entire load. Trailers loaded at 0.30 m²/100 kg (3.23 ft²/220.5 lb) BW had a capacity of 192 pigs, while those loaded at 0.37 m²/100 kg (3.98 ft²/220.5 lb) BW had a capacity of 154 pigs.

Trailer design can have considerable impact on stress during transportation. Pigs transported using a potbelly trailer exhibited a greater frequency of open-mouth breathing and skin discoloration during spring, summer, and winter compared to cohorts travelling on a straight-deck trailer (Ritter et al., 2008). Pigs on a pot-belly trailer also required greater encouragement to unload, resulting in a longer period of time on the truck at the plant and a greater usage of an electric goad (Ritter et al., 2008).

When historical data were analyzed, seasonality had an effect on total transport losses, with a greater percentage of loss occurring in August and July compared with spring and fall. Less intuitively, a greater percentage of death loss was also observed during the winter months (1.16%) compared to spring (0.79%), summer (1.13%) and fall (0.85%; Ritter and Ellis, 2006). Pigs stressed from transport exhibit an increased metabolic rate, and thus, an increase in body temperature and decrease in blood pH. Lowered blood pH indicates metabolic acidosis and thus, a greater likelihood of mortality (Wu et al., 2013). Environmental heat in the summer exacerbates this, resulting in a greater incidence of non-ambulatory, non-injured pigs. Reciprocally, pigs suddenly introduced to extreme cold temperatures are subject to cold stress, also indicated by a low blood pH and high metabolic rate as an attempt to maintain body temperature. This stress can also induce the development of a non-ambulatory, non-injured pig (Ellis and Ritter, 2006). It is because of these correlations it is so important to control trailer temperature as much as possible. In the summer, slats should be opened to allow airflow through the compartments. Sand should be used for bedding to prevent excess heat absorption (Ritter et al., 2009). Spraying pigs during transport is a commonly used method of cooling, but high humidity levels on the trailer (90-100%) may render this practice less useful (Ellis and Ritter, 2006). In winter, slats should be closed to protect pigs from cold air. Straw or hay are good beddings to help hold heat (Ritter et al., 2009). Stocking density is highly dependent upon the ambient temperature, and may need to be adjusted each season to allow the pigs to be as comfortable as possible during transport.

Length of Transit

The conversion of muscle to meat begins immediately post-stunning, and has a substantial effect on pork quality (Henckel et al., 2002). The lack of oxygen generated by slaughter produces an anaerobic environment for the muscle to continue to metabolize creatine phosphate and glycogen. This anaerobic environment results in the accumulation of lactate which, as an acidic compound, lowers the pH in the muscle. This pH decline is directly related to the amount of glycogen and creatine phosphate in the muscle at the time of stunning. Henckel et al. (2002) demonstrated that lower glycogen levels in the muscle at stunning resulted in a greater ultimate pH. This is presumably due to the lower amount of metabolite, thus resulting in a lesser amount of lactic acid produced during the conversion of muscle to meat. Lower ultimate pH is associated with lighter fresh lean color and a reduced water holding capacity (Huff-Lonergan et al., 2002). In modern pork production, a common cause of a reduction in glycogen levels is exercise during transportation and total time off of feed before slaughter.

Leheska et al. (2003) conducted a study where pigs from quality and lean growth genetic lines were either fasted or not fasted and then transported either 0.5, 2.5, or 8 hours to a packing plant. All pigs were held in lairage for approximately 2 hours prior to slaughter. Transport occurred on a mild day (19.3°C; 66.74°F) to avoid confounding the effects travel time and fasting with heat or cold stress. Loins were collected at the packing plant and allowed to age for 7d before chops were collected for glycolytic potential, drip loss, cook loss, and Warner-Bratzler shear force. Transport time had no effect on firmness or marbling scores. However, pigs transported 8.0 hours had a lesser glycolytic potential and lactate content, greater longissimus dorsi and semimembranosus ultimate pH, darker color scores, reduced 7d purge, 24h drip, and cooking loss, and were more tender when compared to those transported 0.5 hours. Pigs transported 2.5 hours had a greater longissimus dorsi and semimembranosus ultimate pH, darker color, and less 7d purge, 24h drip, and cooking loss than those transported 0.5 hours. Increasing transport time reduced the frequency of pale-colored cuts, while increasing the frequency of dark-colored cuts, indicating higher quality meat. These results indicate a depletion of glycogen in pigs travelling for longer periods of time, causing a less extreme pH decline and thus a retention of quality.

Lairage

Lairage time is a balance between efficiency of throughput and animal welfare. Packers want to move carcasses into the cooler as quickly as possible, and allow pigs ample time to rest (Aaslyng et al., 2001). Increasing lairage time from an average 1.36 hours to 17 hours decreased drip loss, improved color, and reduced incidences of PSE in the loin (Dokmanovic et al., 2014). Time in lairage may not be the only factor affecting muscle metabolism. In a carefully controlled study during the spring (3-11°C; 37.4-51.8°F) using gentle handling, it was found that lairage time did not have an effect on postmortem temperature, pH, or 1d meat quality (Aaslyng et al., 2001). However, when a second experiment was conducted during warmer temperatures (15-20°C; 59-68°F), temperature of the loin muscle at 2 min postmortem was elevated in pigs with a shorter lairage time (<30 min) compared to those with a long lairage time (>130 min). In fact, the 2 min postmortem loin temperature of long-lairaged pigs in the warmer temperatures was equal to that of pigs slaughtered in spring. Part of this cooling in long-lairage pigs may be due in part to more exposure to water sprinklers (Aaslyng et al., 2001). However, the differences in loin temperature did not affect ultimate pH or meat quality. This may be due to the use of low-stress handling. When pigs are handled quietly and according to TQA guidelines, meat quality due to handling should be optimized leaving differences attributed only to seasonality and lairage time as the effects on meat quality.

Murray et al. (2001) indicated that pigs fasted overnight did not affect carcass lean yield, but did increase skin blemishes attributed to increased aggression in the lairage pen. However, Murray et al. (2001) did observe a greater carcass yield in fasted pigs, with pigs fasted at the abattoir having a slightly greater yield than those fasted on the farm, likely due to reduced gut fill. The reduction in the gastrointestinal tract weight has a practicality during evisceration. With a smaller (more emptied) tract, evisceration is more manageable, thus reducing the risk of carcass contamination due to nicks or punctures of the viscera. The feed withdrawal period can influence other carcass characteristics as well. Frobose et al. (2014) reported that increasing the feed withdrawal time up to 48 hours decreased ending live weight and hot carcass weight. This effect was most prominent at withdrawal periods of upwards of 24 hours. Increased feed withdrawal time from 8 to 24 h also increased carcass yield. Withholding feed for longer than 24 hours did not increase carcass yield substantially. Fat depth also decreased as feed withdrawal time increased (Frobose et al., 2014).

Immobilization

The Humane Methods of Slaughter Act (HMSA) requires that the slaughtering of any animal be carried out in a manner that prevents needless suffering and increases safety for workers (FSIS, 2013). In 1978, Congress declared the authority to inspect slaughterhouses to ensure application of HMSA and created penalties for those not compliant. From this came the Federal Meat Inspection Act (FMIA), in which the government employed inspectors at every slaughterhouse across the country to oversee handling methods daily. Finally, in 2004 and again in 2011, FSIS released a notice containing a systematic approach to appropriate livestock handling to ensure compliance (FSIS, 2013). Great care has been taken in United States' slaughterhouses to follow such directives, and set standards for humane slaughter of livestock. The pursuit of the most effective and humane method of immobilization and death coupled with optimized meat quality has led many packing plants to switch to carbon dioxide (CO_2) stunning.

Rendering the animal insensible

It is required by law that the animal be instantaneously rendered insensible prior to exsanguination. The two most popular methods used to accomplish this in pigs are electrical and carbon dioxide stunning (Velarde et al., 2000). Carbon dioxide stunning has increased in popularity over the past two decades due to its positive effects on meat quality (Rodriguez et al., 2008) and is used almost exclusively in large-scale commercial facilities. The use of CO_2 stunning allows pigs to move in groups to the stunner, reducing pre-slaughter handling stress (Channon et al., 2002). Immobilization with CO_2 also reduces the need for individual pig restraint, as most elevators are designed for group loads (Rodriguez et al., 2008). Stunning with CO_2 also eliminates kicking, thereby improving worker safety during shackling, and reduces the occurrence of ecchymosis (blood splash) (Channon et al., 2002). Electrical stunning induces massive muscular contraction, resulting in greater frequencies of bone fractures, increasing the difficulty of fabrication and increased trim loss.

Different methods of electrical stunning may produce different insensibility results. Vogel et al. (2011) reported that the head-to-heart method reduced the occurrence of nose twitches when compared to the head-only method, and eliminated incidence of rhythmic breathing, natural blinking, eye tracking, and righting reflex. Head-to-heart stunning also eliminated the presence of a detectable heartbeat after stunning. Although not as aesthetically pleasing, head-to-heart stunning reduces the incidence of pigs returning to sensibility, compared to head-only stunning. Captive bolt may also be used to immobilize pigs. Due to the amount of head restraint required and the difficulty locating the correct anatomical location, this method is largely used for emergency situations, such as a fatigued pig in lairage or a pig regaining consciousness just prior to exsanguination.

Stunning and meat quality

In an effort to understand meat quality implications of electrical and CO_2 stunning, Velarde et al. (2000) conducted a study comparing 4 different abattoirs, 2 using electrical stunning and 2 using CO_2. Loin quality was measured at 2 or 7 hours postmortem, and hemorrhages and bone fractures were counted. Electrical stunning resulted in lighter loin color (greater L^* values) at 2 and 7 h postmortem. Incidence of petechial hemorrhaging in the loin and ham was increased in electrically stunned pigs compared with CO_2 stunned (Velarde et al., 2000). During electrical stunning, the hind limbs and back experience the most intense convulsion during the clonic phase. This is exacerbated by the placement of the electrodes. Head-to-back stunning increases the electrical stimulation of the muscles, while head to chest stunning reduces the intensity of muscle contraction and limits the increase in blood pressure (Velarde et al., 2000). The only muscles in a circuit when head-heart stunning is used are intercostal, which are less likely to cause petechial hemorrhaging (Vogel et al., 2011). Channon et al. (2002) reported that the use of CO_2 stunning reduced the occurrence of ecchymosis compared to electrical stunning. Pigs stunned with CO_2 will require less trimming, thus reducing labor costs and improve customer satisfaction.

Electrical stunning regardless of method also accelerates post-mortem pH decline (Channon et al., 2002). In a study comparing stun and chilling methods, Shackelford et al. (2012) reported the greatest purge loss, lowest ultimate pH, and palest color in pigs stunned using electricity compared with those stunned using CO_2. Regardless of chilling method, this study indicated CO_2 stunned pork has a darker loin color and greater water-holding capacity than the electrically stunned counterparts. It is for these reasons that the majority of U.S. packing plants have switched from electrical stunning to CO_2 stunning (Shackelford et al., 2012). Largely, CO_2 is used to induce death in swine, eliminating welfare issues associated with returning to sensibilities (FSIS, 2009).

It is advantageous for pork plants to maximize the blood collected after sticking, with an average value of $1.66 per pig. Gardner et al. (2006) found that 99.43% of blood can be collected from an exsanguinated carcass within the first 3 minutes after stick. This short dwell time also allows heat associated with blood to dissipate quicker, as well as shortening the time from exsanguination to cooler. Although high postmortem muscle temperature can negatively affect meat quality, Gardner et al. (2006) also found no difference in loin temperature by increasing time in the scald tank from 5 to 8 minutes. This suggests that any supplemental heat absorbed by soaking in a scald tank is easily dissipated once the carcass is removed. Ham temperature was the warmest in carcasses with longer scald time, but only up until 2h postmortem. Overall, dwell and scald time minimally affected pork quality, with the greater implication being that shortening the time from stun to the cooler has the bigger impact on muscle quality.

Postmortem pH and Temperature Decline

Perhaps two of the most important factors contributing to pork quality are postmortem pH decline and muscle temperature decline. Time off feed, transport duration, time in lairage and roughness of handling can all impact the postmortem muscle pH decline. For processors, pre-slaughter handling and post-slaughter chilling are extremely important factors in controlling the rate of pH and temperature decline. In living animals, muscles rely upon both aerobic and anaerobic metabolism to support muscle function. Mitochondrial oxidative metabolism is the most efficient means of producing ATP, but when the muscle is undergoing strenuous or rapid contraction, alternative, oxygen independent methods must be employed (Scheffler et al., 2007). Exsanguination (removal of the blood) at time of slaughter eliminates the oxygen supply to the muscle, making postmortem anaerobic metabolism of interest in regards to meat quality. The high rate of ATP turnover in postmortem muscle results in the rapid depletion of ATP stores. Once ATP stores are depleted, muscle will utilize its glycogen stores to make more ATP via anaerobic glycolysis. This glycolysis produces lactic acid and heat, which due to the lack of blood, cannot be removed. The build-up of these waste products drives pH decline, thus directly tying the amount of glycogen in the muscle to the extent of the pH decline (Scheffler et al., 2007). In a typical decline, muscle will reach a pH of about 5.3 to 5.7 at 24 h postmortem. In muscle with accelerated glycolysis, the pH decline is much more drastic, and more heat is produced. These carcasses typically reach an ultimate pH of 5.3 to 5.7, but will decline below 6.0 within the first hour after slaughter. The acceleration of the pH decline leads to an accelerated depletion of substrates used to make ATP. The formation of ATP is necessary to break actomyosin bonds, allowing the muscle to contract. The quicker depletion of ATP in the muscle triggers the onset of rigor mortis at a warmer temperature, leading to increased denaturation of sarcoplasmic and myofibrillar proteins (Scheffler et al., 2007). This denaturation results in reduced water-holding capacity, a key quality trait.

This cascade of events starts antemortem. Hambrect et al. (2005) reported that pigs handled roughly had a decreased muscle glycogen content, with increased lactate. Pigs that experienced stressful handling also had a lower pH and greater muscle temperature at 0.5 and 3 hours postmortem, creating a greater potential for protein denaturation. Within the pigs handled roughly, those with a long lairage time (2h) had twice the temperature increase compared to those with a short lairage time (0.5-0.75 h; Hambrect et al., 2005). Calm, careful handling is the processors best tool in reducing the incidence of pale, exudative pork due to rapid pH decline.

Carcass Chilling

In a study analyzing the effects of stunning and chilling method, Shackelford et al. (2012) reported that carcasses were >10°C (>18.9°F) warmer when chilled using a spray chill versus a blast chill system beginning at 40 min postmortem, and remained warmer for up to 6.33 hours postmortem in the loin. For this reason, many packing plants have moved from spray chilling to blast chilling in an effort to control the incidence of PSE. However, loins cooled using blast chilling have greater purge loss and can be tougher than those cooled using a spray system (Shackelford et al., 2012). Koohmaraie et al. (1996) suggested the three primary factors that influence tenderness are sarcomere length, proteolytic enzyme activity, and collagen content. Neither desmin degradation nor sarcomere length were different between chilling methods and collagen was not evaluated but not likely to differ, therefore, the cause of this toughening was unclear (Shackelford et al., 2012). Conversely, Rybarczyk et al. (2015) and Springer et al. (2003) reported that blast-chilled loins had darker color. Blakely (2015) conducted a study where alternating sides of 40 pork carcasses were subjected to either a blast chill or spray chill system. Blast-chilled loins had a cooler temperature at 2, 4, 22, and 30 h postmortem, indicating a more rapid temperature decline. Chilling method did not have an effect on measured proteolysis, but blast chilled loins were instrumentally less tender. This may be attributed to the degradation of other proteins not measured in the described analysis, such as vinculin, titin, and nebulin. It is hypothesized that the more rapid pH decline found in spray chilled loins increases calpain activity on these proteins early postmortem, leading to increased tenderness (Blakely, 2015).

Muscle anatomical location is an important factor to consider in a blast chill system. In a commercial pork quality study using nearly 1,000 carcasses, Arkfeld et al. (2016) observed a 1.76°C (3.17°F) difference in temperature from the semimembranosus to the *longissimus dorsi* at 22 h postmortem. The correlation between the two muscles began to weaken at 35 min postmortem, and was the poorest at 2 h postmortem. The correlation between loin and semimembranosus temperature was strongest at 15 hours postmortem, one hour after the loins reached ambient temperature. This is likely because loins chilled quicker than hams, causing them to reach ambient temperature sooner. Once loins equilibrated with ambient temperature, the correlation between ham and loin temperature weakened. As hams continued to chill and loin temperature did not change, the correlation slightly strengthened. Loin temperature, once equilibrated, was no longer a function of hot carcass weight. Conversely, ham temperature remained dependent on carcass weight as it continued to decline. Loins equilibrated to ambient temperature at 14 h postmortem, while even at 22 h hams had still not reached ambient temperature in carcasses averaging 94.0 kg (207.24 lbs). This difference in temperature decline was offered as a potential explanation for the lack of relationship between loin and ham quality (Arkfeld et al., 2016). Increasing HCW also has an effect on chilling rate. Using statistical modeling to analyze a subpopulation of the Arkfeld data, Overholt et al. (unpublished data) demonstrated that the rate of temperature decline differed depending on HCW, with the ham being affected to a greater magnitude than loins in heavier carcasses. Although not statistically different, there was a meaningful difference in rate of decline between heavy and lightweight carcasses. Carcasses weighing 105 kg (231.49 lbs) had a slower rate of temperature decline than those weighing 85 kg (187.40 lbs). Loins equilibrated to ambient temperature before the end of the chilling period, regardless of HCW. On the other hand, in the semimembranosus, each 5 kg (11.02 lbs) increase in HCW from 85 through 105 kg increased the time needed to reach optimal fabrication temperatures. As HCW steadily increases in commercial pork production, packers will need to address this slower rate of temperature decline to ensure all primals reach optimal temperatures required for fabrication to ensure food safety.

Sensory Traits

The overall goal of the producer and packer is to positively influence the consumers purchase intent and eating experience. Consumer purchasing decisions are largely influenced by what they can appraise visually: color and marbling. Historically, consumers have shown an aversion to pale pork, while a preference was shown for more intensely pink pork (Brewer and McKeith, 1999). Moeller et al. (2010a) found that as intramuscular fat content increased from 1 to 6%, consumers expressed a greater likelihood of purchase. This is because some consumers associate a dark color with freshness (Manchini and Hunt, 2005) and color combined with increased marbling content are associated with improved eating experience.

Norman et al. (2003) reported that when consumers were allowed to choose pork of varying colors out of a retail case 52.8% of households chose chops with NPPC color scores of 5 or 6. When allowed to prepare chops on their own, consumers reported that darker chops (NPPC score 5 or 6) were more tender and juicy than lighter (NPPC score 1 through 4) chops. Lonergan et al. (2007) reported that fat content was correlated with tenderness and chewiness, but acknowledged that the strength of correlation indicates that marbling is not the only factor contributing to tenderness. Due to the background differences of these pigs, diet, breed, and transportation differences could be contributing to the variation in tenderness. Cannata et al. (2010) reported that chops categorized as medium (2.50% intramuscular fat) and high (3.56% intramuscular fat) marbled chops were rated as more tender than those categorized as low (1.96% intramuscular fat). Highly marbled chops were rated as more juicy than either medium or low marbled chops.

Even though color and marbling influence purchasing intent, they do not necessarily affect eating experience. Ultimate pH, which is indicative of water holding capacity, is positively correlated with color. A darker, more red color is associated with a greater pH (Brewer et al., 2001b). Wilson et al. (2016) used a wide variety of color (instrumental L* values between 43.11 and 57.60) and marbling (0.80 through 5.52% extractable lipid) to asses color and marbling impact on sensory tenderness, juiciness, and flavor on chops cooked to a medium-rare degree of doneness. Within a tightly controlled genetic subset of pigs, neither loin color nor marbling had any effect on sensory tenderness, juiciness, or flavor. Rincker et al. (2008) reported that marbling varying from 1.6% to 5.7% did not affect tenderness, juiciness, or pork flavor within a temperature group of chops cooked to either 62, 71, or 80°C (145, 160, or 176°F). One of the main differences between the effect of marbling on eating quality in beef and pork is the magnitude of marbling exhibited in each species. Wheeler et al. (1994) reported that steaks with Modest and Moderate marbling (Choice and Top Choice) rated higher in sensory tenderness and juiciness. Rincker et al. (2008) suggested the minimum amount of marbling required for pork chops to produce a satisfactory eating experience is between 2 and 3%. In beef, 2-3% fat would fall between the standard and select quality grades (Savel, 1986), which Wheeler et al. (1994) reported as being tougher and less juicy than steaks with higher marbling scores. Therefore, the marbling found in pork must be discussed in entirely separate context.

Greater 45 min pH, coupled with a slight pH decline postmortem was positively correlated with water holding capacity (Bee et al., 2007). As the pH nears 5.4, the net charges on major proteins start to balance and eventually reach the isoelectric point where there are nearly no net charges on the proteins. This depletion of positive and negative charges cause proteins to lose their repulsion for each other, leading to them stacking closer together and pushing water out (Huff-Lonergan et al., 2005). The greater the ultimate pH, the less this conformation change occurs, meaning a greater ability for proteins to hold water.

Despite its implications in water holding capacity, Richardson et al. (2018) found that if ultimate loin pH was below 5.95, ultimate pH was not a reliable indicator of sensory juiciness or tenderness scores when chops were cooked to a medium-rare degree of doneness. Conversely, in a study analyzing ultimate pH and lipid content influence on sensory characteristics, Lonergan et al. (2007) reported that greater ultimate pH resulted in more tender, less chewy chops compared to low pH chops when chops were cooked to a medium degree of doneness. Ultimate pH was also negatively correlated to cook loss, meaning that chops with a greater ultimate pH lost less cook purge. The discrepancies in these two studies may be due to differing end-point cooking temperatures, with Richardson et al. (2018) cooking to a medium rare degree of doneness (63°C; 145°F) and Lonergan et al. (2007) cooking to a medium degree of doneness (71°C; 160°F). At a greater internal end-point temperature, pH would have a greater effect on tenderness and juiciness, while a lower internal end-point temperature retains more juiciness and is more tender regardless of pH.

Degree of doneness appears to have the greatest effect on consumer eating experience. Historically, recommendations for internal temperature of whole muscle pork in the United States was 71°C (160°F; medium degree of doneness). This was, in part, to prevent the possibility of contracting the pathogen Trichinella spiralis. However, pig production has mostly transitioned from outdoor rearing to indoor rearing thereby reducing the risk and allowing for safe consumption of whole muscle pork cuts at reduced endpoint cooking temperatures. As endpoint cooking temperature (degree of doneness) increases, pork chops become less tender and less juicy (Rincker et al., 2007; Moeller et al., 2010). Because of this, in 2011 the USDA Food Safety and Inspection Service changed the recommended endpoint temperatures of whole muscle cuts of pork from 71°C to 63°C (160 to 145°F) in order to maintain food safety, but improve sensory traits.

Recently, Klehm et al. (2018) evaluated 2 types of packaging systems for whole muscle pork chops and the interactions with cooking chops to either the old recommendations of 71°C (160°F) or to the new recommendations of 63°C (145°F). At 2 d postmortem intact boneless loins were sliced into 28 mm thick chops. Chops cooked to 63°C (145°F) were rated 4.6% more tender than chops cooked to 71°C (160°F). Instrumentally, chops cooked to 63°C (145°F) were 7.3% more tender than chops cooked to 71°C (160°F). Chops cooked to 63°C (145°F) were rated 10.1% juicier than chops cooked to 71°C (160°F). Chops cooked to 63°C (145°F) were rated 2.9% less flavorful than chops cooked to 71°C (160°F). Chops cooked to a 63°C (145°F) had 1.64 percentage units less cook loss than chops cooked to 71°C (160°F; Klehm et al., 2018).

Color and marbling are important factors to consider when producing pork because of their influence on consumer purchase intent. However, recent research indicates that they may not have as much influence over the final eating experience, especially when chops are cooked to the newly recommended medium rare degree of doneness.

Conclusions

Over the last couple of decades, animal agriculture has rapidly evolved. New pressures from a rising global population, reduced land availability, and an increasingly wary consumer have forced livestock producers to adapt new practices to better their product. The pork industry has been on the leading edge of this innovation, with improvements in genetics, efficiency, and meat quality. As quality is not an easily defined term, it is difficult to establish parameters of concern. Nevertheless, both producers and packers must work together to reach quality goals set forth. Diets, proper management, and humane transportation and slaughter provide an opportunity to optimize meat quality. When influencing purchase intent, fresh pork color and marbling are the most important quality factors to consider. Factors such as ultimate pH, water holding capacity, and tenderness all play a role in eating experience, but the best way to influence repeat purchases is to cook whole muscle cuts to 63°C (145°F) as outlined by the National Pork Board. Considerations like those mentioned in this review can continue to push the pork industry to the forefront of innovation within animal agriculture.

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