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Deterioration of Pork Quality Due to the Effects of Acute Ante Mortem Stress: An Overview

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ABSTRACT

The incidence of poor quality meat associated with acute ante mortem stress is a condition that severely affects the pork production chain, so preventing it must become a priority in the pork industry. The aim of this review was to assess the most relevant ante mortem stressors that affect pork quality. Stress-related factors during production, transport, stunning and slaughter must be carefully controlled so as to minimize the proportion of poor quality meat produced. One stress-related effect on pork is called Pale, Soft and Exudative (PSE) meat which occurs as a consequence of numerous factors, some extrinsic, others intrinsic. Thus, it is necessary to undertake a review like the one presented in this article, to discuss such extrinsic factors as: feeding, environmental conditions, types of production (extensive, intensive), farm management, transport, lairage, ante mortem handling at the slaughterhouse and inadequate stunning methods. Second, intrinsic factors must also be analyzed, especially genetic improvement and modified physiometabolic processes and their consequences on the sensory properties of pork meat. The variety of factors that affect pork quality during production, transport, stunning and slaughter must all be carefully controlled in order to minimize the frequency with which this defect occurs.

Key words: PSE, stress, animal welfare, stunning, abattoir

INTRODUCTION

Hog farming is expanding in most countries around the world due to the increase in the indexes of productivity and efficiency of swine producers (Simonetta, 2007).

Currently many researchers studying stress in animals from different approaches (Mota-Rojas *et al*., 2002; Olmos-Hernandez *et al*., 2008; Vahdatpour *et al*., 2009; Konca *et al*., 2009; Sattari *et al*., 2009; Ceylan *et al*., 2009; Dehghan *et al*., 2010; Yildirim and Yurekli, 2010; Hamidi *et al*., 2010; Ince *et al*., 2010; Mota-Rojas *et al*., 2011a, b).

Defining the quality of meat, or meat products, is a complex process: while quality can be assessed on the basis of purely objective characteristics, subjective parameters may also be significant (Maldonado *et al*., 2007; Del Valle *et al*., 2008). What must be clear in any definition is that in the final assessment product quality is the capacity to satisfy the consumer's or user's requirements or expectations (Mota-Rojas *et al*., 2010). Pork is considered normal when it has a final pH of 5.5 and a temperature of 20°C at the moment when rigor mortis sets in. For all these reasons, focusing on meat quality is especially important, as we know that it is a prerequisite for satisfying consumers in different areas of the world (Simonetta, 2007; Mota-Rojas *et al*., 2011a).

Hog farmers, slaughterhouses, meat processors and consumers, both foreign and domestic, often see pork production affected by a particularly important factor that reduces quality: Pale, Soft and Exudative meat (PSE). This condition causes huge economic losses and negatively affects the entire pork production chain (Warriss, 2000; Mota-Rojas *et al*., 2009, 2010). This condition is caused by an accelerated anaerobic conversion of glycogen into lactic acid that alters the meat's final pH. PSE is triggered by a combination of factors that cause stress in the animals and result in a rapid decline in initial pH (Grandin, 1997). Though most commonly seen in pigs, this condition has also been reported in turkeys and chicken (Warriss, 2000).

In visual and physical assessments of the surface of the meat, PSE pork appears to be soft, moist and pale and to have abundant exudate. When cooked, there is greater liquid loss than normal, which results in the meat becoming fibrous and dry (Pradl *et al*., 1994).

PSE meat is also characterized by a rapid and elevated rate of acidification in the muscles after the animal's death (Shen *et al*., 2008). The combination of low pH and high temperature causes the denaturalization of certain muscle proteins and reduces the amount of water in the myofibers (Castrillon *et al*., 2007). The contraction of the structural myofibrillar elements results in fluids being expelled into extracellular spaces (i.e., between muscle fibers) (Warriss, 2000).

The PSE defect occurs as a consequence of numerous extrinsic and intrinsic factors (Mota-Rojas *et al*., 2010). First, this review examines feeding, environmental conditions, different types of production (extensive vs. intensive), farm management practices, transport, lairage at the slaughterhouse, pre-slaughter handling and inadequate stunning (Gonzalez *et al*., 2007; Mota-Rojas *et al*., 2011a). Second, it discusses key intrinsic factors, including genetic improvement, metabolic differences in muscle fibers and the sexual make-up of groups.

FACTORS THAT CAUSE PSE MEAT

Pork quality is affected by ante mortem muscular metabolism that, in turn, is influenced by genetic factors, zootechnical management and environment conditions. Stress is one of the most important agents that can transform normal pork into PSE meat. Stress refers to the physiological adjustments-i.e., changes in the animal's cardiac rhythm, respiration, body temperature and blood pressure-that occur when pigs are exposed to stressful conditions or stressors, such as when their surroundings are uncomfortable or dangerous (Mota-Rojas *et al*., 2005). In those conditions, the hog's responses may include excitation (tension), fatigue and variations in their normal body temperature (Mota-Rojas *et al*., 2006).

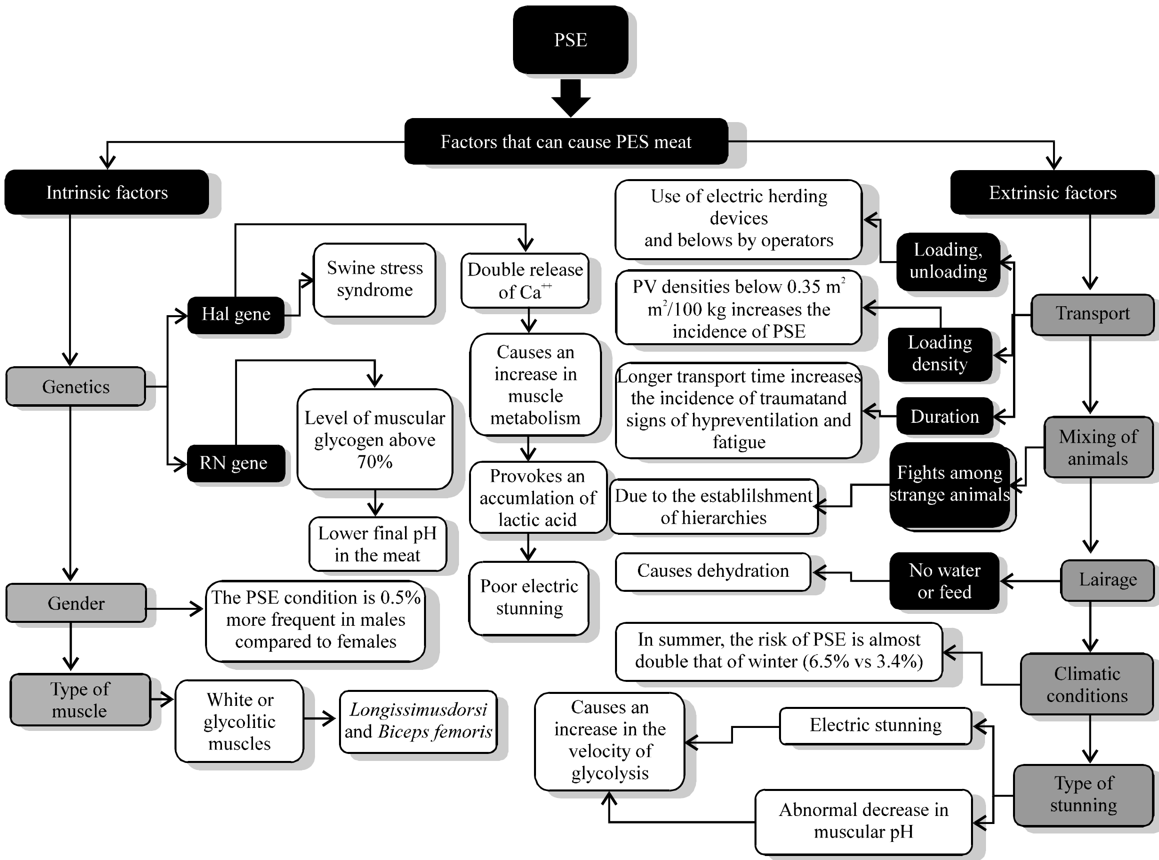

Fig. 1: Factors associated with the appearance of PSE myopathy

This response to stress by the organisms triggers an accelerated glycolysis that occurs primarily post mortem (Pradl *et al.,* 1994) and sets off a rapid production of lactic acid at a high temperature immediately after slaughter. The result is pork that is markedly pale with very poor water retention; characteristics that are undesirable in meat (Silva *et al.*, 2005). Together with other factors, such as transport and the slaughtering method used, conditions in the lairage corrals at the abattoir can also give rise to handling practices that generate stress (Fig. 1).

GENETICS

Over the last 50 years, intensive culling of swine for the purpose of developing muscle and reducing fatty deposits has contributed to increasing the incidence of both Swine Stress Syndrome in live hogs and PSE meat post mortem (O'Neill *et al.*, 2003).

Due to consumer demand and economic expectations, hog farmers the world over have been forced to adopt new production techniques and to select animals that exhibit faster growth and higher yields in meat production. These two factors are associated with animals that are leaner and have better muscular formation (Alarcon-Rojo *et al.,* 2006). However, this technological advance has led to producing pigs that are more sensitive to stress caused by environment conditions and handling (Alarcon *et al.,* 2005). This sensitivity is called Swine Stress Syndrome, a condition particularly closely related to genetically modified animals (Weaver *et al.,* 2000).

The incidence of PSE muscle is usually seen on farms that are more high-tech and breed leaner animals with better muscle tone using genetic lines that are often characterized by greater susceptibility to stress (Alarcon *et al.,* 2005).

Pork quality is affected by two mutations in the hogs' genome: the Napole Yield gene (NY) and the Halothane gene (Hal) (Martinez-Quintana *et al*., 2006).

The Hal gene is known for its susceptibility to Swine Stress Syndrome and to be a cause of PSE meat (Velazco, 2001). Its name derives from the fact that animals with it respond with fibrillations (involuntary movements) when exposed to halothane gas (Velazco, 2001). This susceptibility has been associated with a mutation at the 1843 position of the DNA sequence of the receptor gene for ryanodine (Ryr 1) in pigs which consists in a cytosine being replaced by a thymine (Martinez-Quintana *et al.,* 2006). This change, in turn, leads to arginine being replaced by cysteine at amino acid 615 of the calcium release channel. Because of these characteristics, Hal is also called the Ryr-1 gene, as it codifies for the calcium release channel in the sarcoplasmic reticulum of the skeletal muscle (O'Brien and Ball, 2006).

Turning to the incidence of Swine Stress Syndrome, studies have reported frequencies that vary widely indeed: from 0 to 89%. The breeds most severely affected are Belgian Landrace and Pietrain. In addition, a mortality rate of 0.7 to 1.6% is estimated for pigs during transport from farms that have a high incidence of Swine Stress Syndrome. It is now accepted that Swine Stress Syndrome, Malignant Hyperthermia Syndrome and PSE Syndrome share a common genetic defect; one that alters the calcium release channel in the sarcoplasmic reticulum of the skeletal muscle, also known as the ryanodine receptor (Ryr) because of this alkaloid's affinity for that channel. Kuchenmeister *et al*. (1999) demonstrated that the capacity to capture Ca^{++} of the sarcoplasmic reticulum of the muscle in hogs that are Hal+ is inferior to that of Hal-specimens.

Both of these genes cause enormous economic losses to pork industry due to low yields of processed meat. Carrier hogs usually produce lean pork in the canal but it is of poor quality because those animals so often present the characteristics of PSE meat, compared to the meat in the carcass from Hal-hogs. On the other hand, it might be possible to convince hog farmers that they would receive a return on their investment (cost-benefit) in the form of improved marketing conditions for their pigs thanks to lower mortality rates and lower losses due to the incidence of PSE meat, two factors that could very well lead to considerable savings. However, PSE meat can also occur in Hal-hogs (i.e., those free of the Hal gene), though in such cases the condition is due strictly to environmental causes or handling (Bowker *et al.,* 2000). In fact, studies have estimated that producers are responsible for 50% of cases, while shippers can be blamed for the other 50%. Therefore, several factors must be taken into account and various improvements must be made before hog farmers can eliminate the Hal gene from their stock (Velazco, 2001) (Fig. 1).

TRANSPORT

Transport is considered a stress factor for swine and its effects on meat quality can be significant (Alarcon-Rojo and Duarte-Atondo, 2006; Mota-Rojas *et al*., 2008). Therefore, special attention must be paid to this point in order to minimize tension in transported animals (Becerril-Herrera *et al*., 2009a, b, 2010).

Stressors that affect animal welfare during transport include vibration, variations in velocity, contact with unknown animals and loading densities that exceed the average recommended space per hog of 0.35 m^2/100 kg of live weight, or 200 to 285 kg m^{-2} in the truck's pens (Barton and Christensen, 1998; Alarcon-Rojo and Duarte-Atondo, 2006). This space should be increased by 10% during the hot season and when the routes followed involve passing through zones with heavy traffic or urban areas where ventilation could be restricted due to lower speeds (Tarrant *et al*., 1988). Other stressors include mixing animals from different groups, the establishment of new hierarchies, high humidity and temperature (Grandin, 1997; Mota-Rojas *et al*., 2006, 2009), fasting, strenuous exercise, breakdown of social groups, handling (e. g., loading, unloading) and the unfamiliar nature of recent events which can lead to physical exhaustion and/or psychological stress (Mounier *et al.,* 2006). In some cases, as when animals are moved in poorly-ventilated vehicles, asphyxia may occur due to insufficient ventilation. Vibration is also closely associated with responses to stress. Perremans *et al.* (1998) used the heartbeat of hogs transported under artificial conditions as an automatic indicator of stress responses and found that it was affected by vibration, because the pigs must exert an enormous effort simply to keep their balance. Indeed, the stress provoked by vibration can be greater than that which occurs while the animals are being loaded onto, or unloaded from, a carrier (Grandin, 1997).

With respect to the duration of transport, Mota-Rojas *et al.* (2009) concluded that as transport time increases, the incidence of skin trauma in both the subcutaneous layers and muscle tissue also rises, as do signs of hyperventilation and fatigue. In this regard, females proved to be more resistant than males. Also, hogs carried for shorter distances tend to produce a higher frequency of PSE meat than those moved over longer routes (Grandin, 1997; Velazco, 2001). Pigs transported during the summer for fewer than 30 min became more aggressive and difficult to manage and thus generated an increase in the incidence of PSE meat (Grandin, 1997; Velazco, 2001; Mota-Rojas *et al.*, 2006). Sutherland *et al.* (2009a, b) identified transport time and the pre-slaughter lairage period as factors that strongly affect mortality in pigs but even the type of floor in the transport vehicle can affect meat quality (Guardia *et al.,* 2005). According to Guardia *et al.* (2004), under certain transport conditions, a polyester-based floor reduces the risk of PSE meat by approximately 1.5%, as that type of surface provides a more comfortable environment during movement, mainly because its soft, wrinkled texture reduces noise and slippage. In addition, it is a much better thermal insulator than aluminum or iron flooring that, because the properties of those materials propitiate higher incidences of PSE meat. Guardia *et al.* (2005) state that iron is an unsuitable material for flooring in transport trucks, as contact with it can increase stress in hogs because they slip and find it difficult to maintain balance. Another aspect related to transport is the use of hydraulic systems equipped with elevating ramps, equipment that facilitates the loading/unloading of animals and can also reduce the frequency of PSE meat (Guardia *et al.,* 2004, 2005; Becerril-Herrera *et al.*, 2009a, b, 2010).

Transporting animals under conditions of high ambient temperature, as commonly occurs in the summer months, is another factor that tends to increase the incidence of PSE meat, compared to transport that occurs during the winter. It has been found that the risk of PSE meat is almost double when hogs are transported in summer compared to winter (6.5 vs. 3.4%). This is due to the fact that pigs are particularly sensitive to high temperatures because they have no sweat glands, which makes it difficult for them to dissipate body heat. Also, the risk of the presence of the PSE condition is 0.5% higher in males than females (Guardia *et al.,* 2004; Mota-Rojas *et al.*, 2011b) (Fig. 1).

LAIRAGE

Hogs can experience stress due to many forms of psychological-handling, new events-or physical tension; including, hunger, thirst, fatigue, injuries or extreme temperatures (Grandin, 1997). Lairage functions to both minimize the stress factors triggered by transport and to reestablish glycogen reserves (Price and Schweigert, 1994), thus impeding the development of undesirable characteristics in the meat.

Normally, animals should spend 24 hours-minimum 12- in the holding pens (corrals) before being moved to the slaughtering area. During this period, the pigs should only be allowed to drink potable water. While at rest, they should have plenty of water to drink and access to powerful showering facilities, especially during the hot season (Alarcon-Rojo and Duarte-Atondo, 2006). Ingesting water propitiates the bleeding process, gives the meat a more brilliant color and makes electric stunning more efficacious (Mota-Rojas *et al.*, 2006). Meanwhile, wetting the pigs down with water just after transport confers three advantages: it refreshes them, reduces tension in their cardiovascular system and calms them down, thus diminishing aggressive behavior during lairage, keeping them cleaner and controlling contamination along the slaughtering line (Alarcon-Rojo and Duarte-Atondo, 2006).

During the rest period, pigs may recover as much as 1% of the weight lost during transport. While fasting is favorable in the sense that it facilitates the evisceration process, it can, on the other hand, lead to weight loss in hogs due to excessive water loss, even after the meat is in the canal (Mota-Rojas *et al.*, 2006, 2009).

Viewed exclusively from the perspective of animal welfare, the preferable procedure would be for the pigs to be slaughtered as soon as possible after arriving at the abattoir. However, in most situations this is not practical, because when these animals are sacrificed soon after unloading they tend to produce poor quality meat that lacks the required acidity, because the bleeding process is often incomplete. What happens is that without an adequate rest period, the vascular changes that the hogs suffer during transport do not have the opportunity to become normalized and this results in an increase in the proportion of PSE meat (Gonzalez-Lozano *et al.*, 2007). Alarcon *et al.* (2005) recommend implementing handling measures that reduce stress in the phases leading up to slaughter, especially in the abattoir's holding pens. Sutherland *et al.* (2009a, b) observed that mortality from several causes rose as waiting times increased and suggested that lairage last less than 4 h. Silva *et al.* (2005) reached the conclusion that the degree of stress caused by subjecting hogs to adverse pre-slaughter conditions is a factor that results in PSE. Because both normal and PSE meat have pH between 6.3 and 5.8 at 24 h after slaughter, it is necessary to measure pH within the first 45 min in order to project possible changes in quality, though pH readings taken at 45 min post mortem do not guarantee the final behavior of pH, Water Holding Capacity (WHC) and color unless pH is equal to, or less than, 5.8. At 24 h post-mortem, pH is determinant for the final characteristics of pork, because by that time most of the aerobic biochemical processes have finalized. Other observations show that hogs with 2 h of rest pre-slaughter had pH values closer to normal levels and higher WHC indexes. In addition, it has been determined that pigs with 2 to 4 h of rest ante mortem attained color parameters close to reference values. In light of these findings, it can be suggested that, under the transport and handling conditions used in this study, the optimum ante mortem lairage time for reducing the incidence of the PSE defect in pork was 2 h.

STUNNING METHODS

Slaughter animals are stunned before sacrifice so that the bleeding process causes them no pain, suffering or stress (Guerrero *et al.*, 2007; Mota-Rojas *et al.*, 2008). Stunning must provoke unconsciousness in the animal instantly so as to minimize problems in the carcass and meat quality and assure operator safety (Rodriguez *et al.*, 2006). There are two types of stunning systems: reversible or irreversible. In the first case, the animals may recover consciousness before dying, so the time elapsed between stunning and bleeding is a determining factor in their efficacy. Irreversible stunning occurs when the method used actually kills the animal. In this case, the objective is to bleed the animal after it dies (Becerril-Herrera *et al.*, 2009a).

Becerril-Herrera *et al.* (2009a) stated that most stunning methods increase post-mortem levels of catecholamines, cortisol, endorphins, lactate, glucose, calcium, magnesium and plasma proteins, among other elements. Alterations in the levels of these components can serve as precise indicators that an animal's welfare has been compromised.

Electric stunning (shock) consists in passing an electrical current through the animal's brain at an intensity so high that it depolarizes the CNS and disorganizes normal electrical activity (Gregory, 1996; Rodriguez *et al*., 2006). As current passes through the animal's brain it induces an epileptiform condition marked by tonic and clonic muscle contractions (Rodriguez *et al*., 2006) and a higher concentration of catecholamines in the plasma (Hambrecht *et al*., 2004, 2005). This increases blood pressure and peripheral vasoconstriction (Hambrecht *et al*., 2004; Rodriguez *et al*., 2006). These events propitiate the expulsion of blood from the blood vessels and reduce the amount of residual blood left in muscles (Rodriguez *et al*., 2006).

In pigs, however, electric stunning favors the formation of PSE meat and the appearance of petechiae in the canal (Rodriguez *et al*., 2006; Mota-Rojas *et al*., 2006). Studies have shown that the 5 minutes pre-slaughter are key to meat quality. Stressful antemortem handling (i.e., stunning, bleeding) causes higher cortisol levels in the blood (Hambrecht *et al*., 2005) that increase the frequency of PSE, even in stress-resistant hogs (Alarcon-Rojo *et al*., 2006). This is because the muscular stimulation from electrical stunning is a main cause of higher glycolysis rates upon killing, a process that generates an abnormal decrease in muscular pH, triggers the denaturalization of proteins, reduces the animal's ability to retain water and accentuates paleness (Hambrecht *et al*., 2004; Rodriguez *et al*., 2006). Cortisol levels, however, rise during prolonged periods of stress (e.g., during transport and/or struggles) and produce dark, firm and dry meat (DFD); though this does not occur when stress is short-term, a condition that is more closely related to PSE meat. Hambrecht *et al*. (2004) concluded that there was no relation between cortisol levels and the incidence of PSE. Alarcon-Rojo *et al*. (2006) argued that reducing the time between stunning and bleeding to 4 sec and using a scalding process of no more than 5 min, improves both pH and temperature. On another point, when pigs were herded to slaughter in groups of 5 there was a lower proportion of loss in the carcass due to dripping and a slower decline of pH_{45}, than when they were introduced individually. These authors recommend that the time between stunning and bleeding be less than 10 sec in order to obtain good quality meat.

Another stunning method employs carbon dioxide gas. When inhaled in high concentrations, carbon dioxide produces unconsciousness by suppressing the neuronal function. In this type of stunning, the hogs are placed in a cage and then introduced into a chamber with CO_2 at a concentration above 70%; in this case, the higher the gas concentration, the induction of unconsciousness is faster. Exposure time must be sufficient to assure that the animal remains unconsciousness until death. Rodriguez *et al*. (2006) suggested that hogs stunned by CO_2 may recover within 1 to 3 min after removal from the chamber but will die within 4 to 5 min in a CO_2-charged atmosphere. Hence, exposure time is important; according to some European regulations, it should be 60 sec (Becerril-Herrera *et al*., 2009a).

When animals are stunned in a CO_2 chamber their neuronal function is affected, a condition that leads to hypoxia, hypercapnia and reduced pH in the central nervous system. Stunning in a CO_2 chamber also increases anaerobic oxidative metabolism which, in turn, raises glucose levels in the bloodstream and the intracellular flow of the ion triggers K^+ and H^+, resulting in metabolic acidosis. Exposure to CO_2 stimulates the respiratory rate and can set off a signal of respiratory alarm (Raj and Gregory, 1995; Becerril-Herrera *et al*., 2009a).

Hambrecht *et al*. (2004) carried out studies in two plants-A and B-where hogs were stunned using two methods: electric and CO_2, respectively. Unfortunately, the results of this study are rather confusing, because certain stress factors present in Plant A that raised body temperatures and reduced pH were not found in Plant B. Research has shown that inhaling CO_2 decreases blood pH by forming bicarbonate; thus, animals stunned with CO_2 have lower blood pH than those stunned electrically. However, findings from the experiment by Hambrecht *et al.* (2004) show that stress was related to physical activity and, therefore, energy consumption. Hence, the glycolitic potential decreased due to a high degree of pre-slaughter stress. These authors also suggest that catecholamine levels were extremely high after CO_2 stunning, regardless of the hogs' experience with stressful events before sacrifice and so were not attributable to the use of CO_2 (Fig. 1).

PHYSIOPATHOLOGICAL PROCESSES OF PSE MYOPATHY

One of the main metabolic pathways involved in converting muscle into meat is glycolysis in live tissue which generates ATP. In post mortem muscle, the tissue attempts to maintain homeostasis by conserving the concentration of cellular ATP but due to the circulatory failure that occurs with bleeding, muscles lack the oxygen required for oxidative metabolism (Del Valle *et al.*, 2008). Later, muscular glycogen is metabolized through the anaerobic glycolysis phosphorylation of ADP into ATP. Anaerobic glycolysis is inefficient compared to the aerobic form in terms of its ability to produce ATP; therefore, continuous post mortem metabolism reduces glycogen and ATP levels while, at the same time, lactic acid accumulates and decreases muscular pH. This process results in a total decrease of final pH-from 5.4 to 5.7-at 24 h in the Longissimus muscle in hogs (Bowker *et al.,* 2000; Mota-Rojas *et al.*, 2010) (Fig. 2).

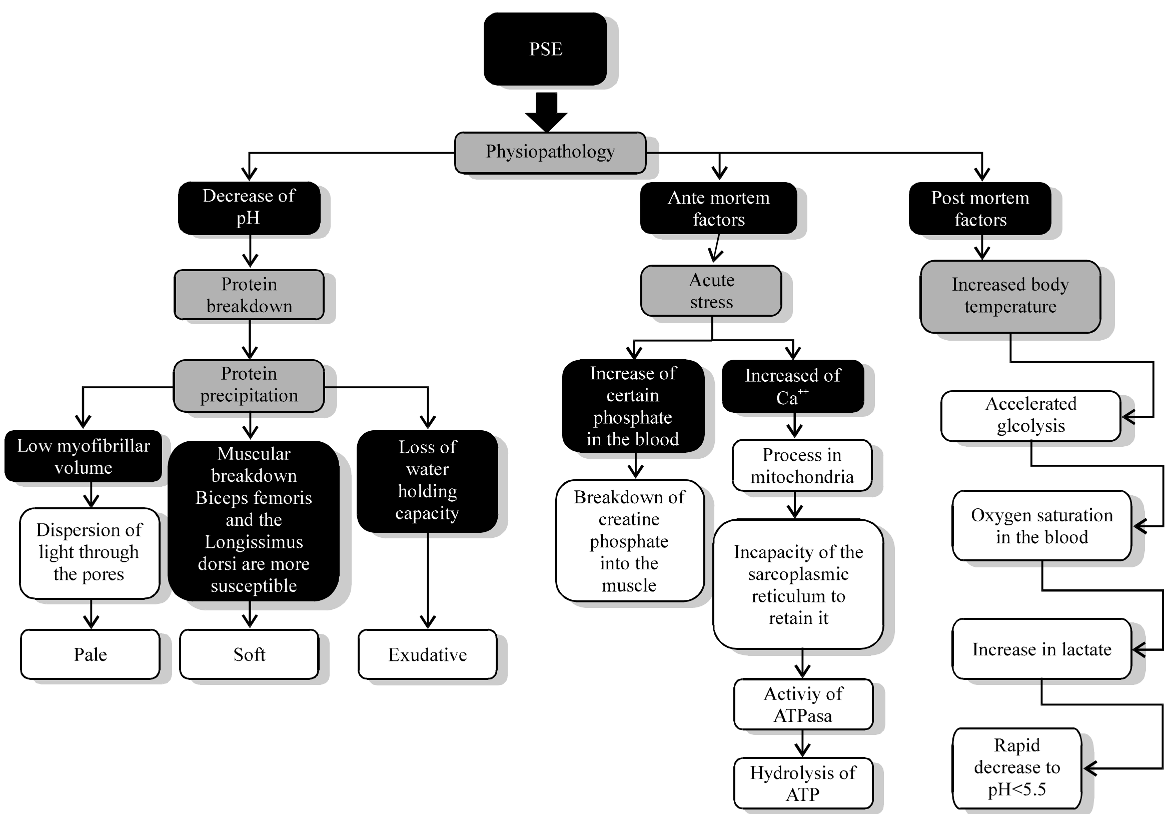

Fig. 2: Physiopathology of the Pale, Soft and Exudative condition

PSE meat is classified as a defect caused by depigmenting exudative myopathy (i.e., muscle degeneration), with the biceps femoris and the Longissimus dorsi being particularly susceptible to the condition (Alarcon-Rojo and Duarte-Atondo, 2006). These muscles have a higher proportion of the so-called white fibers that possess a high glycolitic capacity (O'Brien and Ball, 2006), while other muscle zones are normally less severely affected. Also, fatter pigs produce PSE meat much less frequently than leaner ones (Pradl *et al*., 1994).

Susceptibility to stress is one factor that affects the status of glycogen reserves (Mota-Rojas *et al*., 2010). In live animals, stress and muscular activity generate increases in adrenaline, hormone adrenocorticosteroid (ACT), cortisol and thyroxine levels that in turn raise the concentration of cyclic adenosine monophosphate (AMP) and the activity of muscular phosphatase which breaks down glycogen into glucose-6-phosphate. But, as this substance cannot permeate the cell membrane, in anaerobic conditions it then breaks down into lactate which is reconverted into glucose in the liver through the Coir Cycle, thus regulating glucose (Alarcon-Rojo and Duarte-Atondo, 2006). The blood lactate concentration is a β-adrenergic effect of adrenaline that stimulates the release of insulin and produces glycogenolysis, gluconeogenesis and gluconeogenesis under stress and muscular exercise as a response to the high level of cortisol in the blood which has an antagonistic effect to insulin that prevents the entry of glucose into the muscle and adipose tissue, leaving it available in such organs as the liver and brain (Alarcon-Rojo and Duarte-Atondo, 2006) (Fig. 2).

Alarcon-Rojo *et al*. (2006) mentioned that stress destroys cellular membranes in hogs which produces a lysis of erythrocytes and an increase in the concentrations of pyruvate and creatine kinase. Ca^{++} is released from the mitochondria because the sarcoplasmic reticulum is unable to retain those ions. The result is the onset of muscular rigidity. The cytosolic concentration of Ca^{++} in the muscle fibers plays an important role in muscle metabolism and is a vital component that contributes to triggering a rapid post mortem glycolysis and, therefore, the development of PSE meat. Calcium accelerates glycolysis through two mechanisms: by increasing the activity of calcium-activated ATPasa and/or functioning as a co-factor in various glycolytic reactions (Bowker *et al*., 2000). The appearance of accelerated glycolysis brings with it a drop in pH and oxygen saturation in the blood that raises lactate levels, CO_2 concentrations and body temperature which increases rapidly to 42°C or more, a condition also known as malignant hyperthermia (Alarcon-Rojo and Duarte-Atondo, 2006; Mota-Rojas *et al*., 2010).

Hogs with Swine Stress Syndrome are an excellent model of calcium regulation, its influence on muscular metabolism and, subsequently, on meat quality. As mentioned above, pigs with Swine Stress Syndrome are more prone to developing PSE when they experience stress: they present an exaggerated glycogenolysis which results in an increase in the accumulation of lactic acid, high body temperature and muscular rigidity.

Research at the sub-cellular level of the pig's skeletal muscle have revealed that the heritable defect of susceptibility to stress resides in the membranes, especially the sarcolemma, the sarcoplasmic reticulum and mitochondria, all of which have a lower membrane potential than that of stress-resistant pigs (Alarcon-Rojo and Duarte-Atondo, 2006). This condition modifies permeability, thus producing an accumulation of liquid and mineral salts in the exterior of the cell that raises its conductivity and reflectance. As a live animal experiences greater stress, there will be more cellular destruction and larger amounts of water and salts will be released, thus increasing conductivity of the electric current through the meat (Alarcon-Rojo and Duarte-Atondo, 2006) (Fig. 2). In stress-resistant hogs, rigor mortis sets in normally, while in stress-sensitive animals the rapid glycolysis and lactate production stop ATP synthesis, so rigor mortis sets in at 20-to-30 min post mortem and the meat soon becomes flaccid and deformed in the carcass. When the muscles are cut open, they have a soft consistency, a sunken appearance and internal separations; they lack pigmentation and are pale or grey-to-white with exudate in the form of droplets of a pink-colored liquid. This meat also has a diminished water holding capacity and a final pH of 5.2 to 5.4-very close to the isoelectric point of actomyosin-which facilitates the denaturalization of this protein and ruptures of the myofibrils, conditions that may explain the meat's pale color and the excessive loss due to dripping (Alarcon-Rojo and Duarte-Atondo, 2006). In addition, the release of ammonia increases and the meat develops a marked acidic odor (Alarcon-Rojo and Duarte-Atondo, 2006).

Brown *et al.* (1999) conducted a study to assess the effect of transport times of 0, 8, 16 and 24 h on yields in the canal and on indicators of enzymatic activity and plasma proteins. Their results indicate that as transport time increases, weight loss also rises, while yields in the canal-both hot and cold-decrease, concentrations of Non-Esterified Fatty Acids (NEFA) rise and the levels of cortisol, lactate and creatinine phosphokinase decrease. Similarly, protein levels indicate varying states of dehydration. The aforementioned results concord with those obtained recently by Mota-Rojas *et al.* (2006, 2010), who report that acute stress predisposes hogs to acid pH values and pale-colored meat; i.e., a high incidence of PSE. Also, their study concluded that as transport time increases, the frequency of trauma to the skin, subcutaneous tissues and even the muscles, also rises, as do signs of hyperventilation and fatigue. In this respect, sows were shown to be more resistant than boars (Fig. 2).

CONSEQUENCES AND ADVERSE EFFECTS OF PSE MEAT

PSE muscle constitutes the most frequent quality defect in pork, as the meat becomes very dry during cooking and so is suitable for only low-value processed products. The following indexes of PSE meat have been recorded: United States, 16%; Germany and Belgium, 80%; Spain, 35-to-54%; France, 15% and Denmark 2-to-4% (Grandin, 1997; Alarcon-Rojo and Duarte-Atondo, 2006). In all those nations, efforts to reduce this problem are underway; for example, the Danes have eliminated hogs that carry the halothane gene, are reducing use of the Hampshire breed and are adopting more humanitarian slaughter methods.

Pork quality depends on such factors as breed, type of feeding and the handling to which the animals are subjected before and during slaughter. These three factors affect biochemical phenomena that occur after death, including glycolysis (which impacts water content and the meat's liquid retention capacity), final pH, toughness, color and salt absorption capacity (Vartnam and Sutherland, 1998). In studies based on tasting panels, reports show that PSE muscles show greater shrinkage when cooked and are dryer and less flavorful (Kauffman *et al.*, 1978). This is highly significant because aroma, flavor, color, juiciness and texture are some of the primary factors involved in the sensorial perception of meat quality (Mota-Rojas *et al.*, 2005).

Turning to flavor, this property of pork involves almost 700 chemical compounds found in lean and fatty meat (Mota-Rojas *et al.*, 2006). While it is well known that the formation of some of the compounds in aroma and flavor is favored by conditions of low pH, PSE meat can present a predominantly acidic flavor, possibly due to the high levels of lactic acid (Vartnam and Sutherland, 1998). As final pH rises, aroma diminishes, perhaps as a result of a more turgid structure that interferes with the palate's access to the compounds responsible for aroma and a reduction in the release of the volatile compounds of aroma when the meat is chewed. Under normal conditions, the meat's aroma is due to the volatile or odoriferous compounds produced by phospholipids and triglycerides (Mota-Rojas *et al*., 2005). In addition, product color is another one of the key criteria that consumers use when selecting meat. If the product is pale or too dark in color, consumers will reject it in favor of normal colored meat (red-to-pink) (Warriss, 2000). A bland, exudative consistency is usually accompanied by paleness (PSE). In cases where pork has a bland, exudative consistency it is likely that it has retained liquids and suffered excessive shrinkage during cooking or the processing of meat products (Mota-Rojas *et al*., 2005).

Light intensity is related to muscular structure which, in turn, depends on myofibrillar volume (Mota-Rojas *et al*., 2005). PSE meat has a low myofibrillar volume and shows a high light reflection capacity; i.e., light cannot penetrate the meat from a significant distance without being reflected, so absorption by the myoglobin is relatively small and the meat, as a result, appears pale. The meat's luminosity can be affected by the hogs' origins, as it has been shown to be higher in swine from intensive production farms whose pigs reach slaughter weight at a younger age and with lower concentrations of muscular myoglobin and thus have paler meat. A second factor that has been suggested is the presence of breeds of hogs that are characterized by pale meat and shiny muscles, such as Landrace. The recommendation is that for hogs with genotypes marked by high levels of lean yields, males should be sacrificed at a weight of 104 kg (230 pounds) and females at 127 kg (280 pounds) in order to improve meat color and water holding capacity (Alarcon *et al*., 2005).

SENSORY PROPERTIES OF PORK

The water present in pork is distributed in three different forms: (1) bonded, 4 to 5%, remains strongly adhered to the myofibrillar proteins, even when force is applied to the muscle; (2) immobilized which is bonded more weakly and whose release depends on the amount of physical force exerted on the muscle and (3) free which is held only by superficial forces and is easily eliminated. The latter is the liquid form that comes to play an important role during cooling in the canal and subsequent storage, because that is when most of the losses due to evaporation and dripping occur (Moron-Fuenmayor and Zamorano-Garcia, 2004).

Juiciness is a property of pork that is associated with water holding capacity and marbling (Vartnam and Sutherland, 1998). The intensity of exudate loss in pork is in large part a function of post mortem changes, especially ones that affect final pH. Water loss in fresh meat is extremely important because this product is sold by weight, so the amount of water lost during storage reduces the economic value of hog-farmer's yields (Moron-Fuenmayor and Zamorano-Garcia, 2004). Indeed, the exudate means not only weight loss but also a reduction in the shelf life of fresh pork and its processed products (Kauffman *et al*., 1978; Warriss, 2000). Both tenderness and juiciness also strongly affect the sensorial qualities of pork. The degree of tenderness depends on intrinsic factors, such as muscle type and post mortem biochemical changes (Vartnam and Sutherland, 1998).

CONCLUSIONS

Because the incidence of PSE pork severely affects the productive chain of this commodity, in both economics and quality terms, preventing it must become a priority for the pork industry. The variety of factors that affect pork quality during production, transport, stunning and slaughter must all be carefully controlled in order to minimize the frequency with which this defect occurs. At first, selecting stress-resistant breeds, using humanitarian handling during transport, stunning and slaughter and adopting efficient refrigeration and distribution procedures may seem to entail huge investments. However, these measures will optimize meat quality and assure greater consumer acceptance.

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