Nutritional Regulation for Meat Quality and Nutrient Metabolism of Pigs Exposed to High Temperature Environment

Xianyong Ma, Zongyang Jiang*, Chuntian Zheng, Youjun Hu and Li Wang

Institute of Animal Science, Guangdong Academy of Agricultural Sciences, The Key Laboratory of Animal Nutrition and Feed Science (South China) of Ministry of Agriculture, State Key Laboratory of Livestock and Poultry Breeding, Guangdong Public Laboratory of Animal Breeding and Nutrition, Guangdong Key Laboratory of Animal Breeding and Nutrition, 510640, Guangzhou, PR China

Abstract

High ambient temperatures not only affect animal production but also pig welfare. The decline of the production performances and meat quality of pigs during heat stress were traditionally considered to a cause of the decreased feed intake. However, it recently has been shown that heat stress disturbed the nutrients metabolism including protein, lipid and carbohydrate, and made the body reorganizes the utilization of the nutrition. High temperature also disturbed the cell function and antioxidant system. This paper reviewed the effect of heat stress on growth performance, meat quality and nutrients metabolism of pigs and their nutritional regulation for meat quality.

Keywords: Meat quality; Nutrient metabolism; Heat stress; Nutritional regulation; Growth performance

Introduction

According to the Food and Agriculture Organization of United Nations (FAO) statistics, over 50 percent of pig industries were in tropical and subtropical regions. The long-term hot weather of these regions would have a greater negative effect on pig production, especially with the development of intensive high density production, the effect of high temperature stress on pig production has become more and more serious, not only affecting the pig production performance, meat quality, but also affecting the sustainable development and economic benefits of the pig industry. In this paper, the effects of heat stress on pig production performance, meat quality and its molecular mechanism, and the nutritional regulation methods are reviewed, those results provide theoretical basis for reducing the effect of heat stress on the production and meat quality of pigs.

Effect of heat stress on growth performance of pig

Because the sweat gland of the pig is not developed, pigs maintain the body temperature mainly through breathing and stretching in the high temperature environment. The suitable environmental temperature of finishing pigs is 10-23.9°C, when the ambient temperature is higher than 24°C, finishing pigs begin cooling through breathing, and when the temperature continue to rise, the frequency of pigs lying on the ground increase and their activity decrease [1,2].

Le Dividich et al. [3] reported that when the environmental temperature was between 20°C and 30°C, the feed intake decreased by 40-80 g per day with the temperature increasing by 1°C. The sensitivity of pig to the environment temperature in different stages is different, usually the effect of high temperature on the feed intake and daily gain of pigs increased with the increase of pig weight. Ai et al. [4] found that under high environmental condition (28-35°C), the daily feed intake of pigs in the phase of 15-30 kg, 30-60 kg and 60-90 kg decreased by 9%, 41% and 20%, and the daily gain decreased by 9%, 21% and 23% respectively. Guo et al. [5] studied the effects of different environmental temperature (23°C, 26°C, 29°C, 32°C and 35°C) on the daily feed intake of pigs at different weight stages (40-60 kg, 60-80 kg and 80-100 kg), and found that when the temperature rose, the feed intake decreased linearly with the temperature increasing from 23 to 32°C, the heavier the body weight, the greater the effect of temperature.

When the temperature was over 32°C, the daily feed intake decreased by 101 g with the temperature increasing by 1°C.

Quiniou et al. [6] reported that the daily feed intake of 60-90 kg pig decreased by 128 g with the temperature increasing by 1°C under the 22-29°C condition. Le Bellego [7] also found that the daily feed intake of 65-100 kg pig decreased by 78 g with the temperature increasing by 1°C under 22-29°C condition. Shi et al. [8] reported that the daily feed intake of 80-100 kg pig decreased by 116 g with the temperature increasing by 1°C under 24-35°C condition, the daily weight gain also decreased significantly. These results above were confirmed by Yang et al. [9].

In conclusion, the effect of environmental temperature on the growth performances of pigs was related with feed intake, but the relationship between the environmental temperature and the feed intake of pigs was different for the different temperature, feeding time and pig weight, it need to be analyzed according to the specific circumstances.

Effect of heat stress on meat quality

Meat quality also is influenced by environmental temperature. A large number of studies have reported that heat stress before slaughter stimulated the catecholamine secretion in finishing pigs, which caused muscle glycogen rapid decomposition, producing large amounts of lactic acid, the muscle pH decrease and PSE meat formation [10]. Yang et al. [9] reported that continuous high temperature significantly reduced the pH of longissimus muscle at 24 h postmortem, increased...
the drip loss at 48 h postmortem and shearing force of longissimus muscle. The environmental temperature in summer is usually higher than in winter, and the meat quality also is inferior to in winter [11]. High temperature also decreased the intramuscular fat content and increased the L* value of the muscle in finishing pigs [12], but not in growing pigs [13], because the content of intramuscular fat in growing pigs is very low. Le Dividich et al. [3] indicated that the fat deposition in muscle of finishing pig decreased significantly under high temperature condition, which may be related to the decrease of feed intake and energy consumption. Lefaucheur [14] found that compared with growing pigs less than 10°C temperature condition, the metabolism of muscle fibers of semitendinosus muscle in growing pigs under 28°C condition changed obviously, the fiber types also changed accordingly. High temperature increased the sugar fermentation potential and changed the energy metabolism of the muscle fiber, with the change of the muscular fiber type [15]. Using C1C2 cell line as research model, it was found that the sustained high temperatures induced muscle cells differentiation from fast to slow transformation [16]. Shi [8] reported that high temperature increased the MyHCIIx fiber and decreased the MyHCIIb fiber ratio. While in Mardies et al. [17] studies, higher temperature decreased the MyHCIIb gene. The reason for this difference may be due to the tolerance ability of the pig to heat stress, the setting of the environmental temperature and the duration of the treatment.

**Effect of high temperature on nutritional metabolism of pigs**

In acute or chronic heat stress conditions, animals reduced their feed intake by improving leptin, adiponectin and its receptor expression [18,19]. Leptin activated the hypothalamus axis, resulting in reduced feed intake [20]; adiponectin also regulated feed intake through central and peripheral nervous system [21]. In addition, heat stress reduced feed intake and nutrient digestion and absorption partly through affecting insulin, cortisol and ghrelin secretion [22,23,8].

High temperature also decreased the body protein metabolism and deposition. When the environmental temperature reached 30°C, the amount of body protein deposition in growing pigs decreased directly or indirectly by the decrease of feed intake [7]; Kerr [24] also reported that high temperature (33°C) reduced the content of pig carcass protein. Short term heat stress increased protein degradation, reduced protein synthesis and retention; it also decreased the plasma level of aspartic acid, serine, tyrosine and cysteine in finishing pigs [25]. While long-term heat stress blocked protein synthesis, reduced the protein decomposition and amino acids level in blood (especially sulfur and branched chain amino acids), and increased the plasma level of aspartic acid, glutamic acid and phenylalanine [26,27]. Long-term heat stress reduced protein catabolism might by activating gluconeogenesis pathway, which increased the glucose level to provide more energy and reduce protein usage.

Long term heat stress also decreased the body lipid metabolism and fat distribution; the fat had a trend to transfer from the outer layer to the inner [3], which is more benefit for the body heat dissipation. Kouba [28] found that the high environmental temperature increased the activities of LPL in longissimus muscle and periphery kidney by 144.6% and 90.5%, respectively. Rinaldo and le Dividich [29] also found that high temperature reduced the content of back fat, the activities of malate dehydrogenase (ME) and glucose-6-phosphate dehydrogenase (G-6-PDH) in back fat and periphery kidney fat by 60%. Wu et al. [30] reported that high temperature (33°C) had a trend to decrease the intramuscular fat of longissimus muscle in finishing pigs, it also inhibited the fatty acids de novo synthesis ability by decreasing the activities of acetyl coenzyme A carboxylase enzyme (ACC), high temperature also decreased the content of FAS in the longissimus muscle and beta oxidation of fatty acids in skeletal muscle by decreasing the activity of L (+) P-hydroxyacyl CoA dehydrogenase (HAD). In addition, high temperature decreased the activity of lipolytic enzymes [26] and the level of non-esterified fatty acids (NEFA) [31], which was independent of the reduction of feed intake. Under high temperature condition, the activity of lipolytic enzymes in adipose tissue decreased to limit heat production for adaptation to high temperature environment.

Carbohydrates could easily be converted into intermediate metabolites to generate ATP. The formation of ATP was regulated by three major signaling pathways: glycolysis, tricarboxylic acid cycle and oxidative phosphorylation. Mild heat stress activated muscle glycogen phosphorylase and pyruvate dehydrogenase, but did not affect the content of glucose 6-phosphate, lactoc acid, pyruvic acid, acetyl CoA, creatine and phosphocreatine and ATP [32]. Chronic heat stress reduced the plasma level of glucose, made more glucose enter the tissue from the blood to supply the energy; then the fat supplying energy decreased. As feed intake and blood glucose decreased, the glucose meet the need of the production decreased, so the energy in heat stressed pigs need to be rebalanced.

**Effect of heat stress on cell and its stress protein**

Heat stress interfered with the balance between oxidation and antioxidant in cells, resulting in excessive production of free radicals, damaging the body defense function [33], even producing cytotoxicity [34]. Heat stress also induced iron releasing from ferritin and reacting with H2O2 to produce ferric oxide ion, which was one of the important reasons for heat stress causing dark color of meat [35,36]. In addition, ROS was produced from NADP+ transformed to NADPH [37] by NADPH oxidase under high temperature condition. Shi [8] also found that high temperature enhanced the activity of NADPH oxidase. Moon et al. [38] reported that high temperature activated NADPH oxidase and increased the NADP+/NADPH ratio, NADPH prevented the biosynthesis of NADP+, acting as a cytochrome C reductase inhibitor, indicating that heat stress decreased the oxidation resistance of the body by destroying the oxidative respiratory chain.

Heat stress has cellular toxicity, because it disturbs the biological function and metabolism of the cell, leading to oxidative damage, and even apoptosis necrosis of the cells [39]. Although ROS was produced mainly from mitochondria, it first damaged mitochondria by disrupting oxidative complex I, II, V and IV, resulting in destruction of respiratory chain and reduction of ATP [40]. In rodent animal, the morphology and structure of mitochondrial changed under high temperature condition, oxidative phosphorylation and energy production decreased, which could not meet the needs of cell metabolism, the mitochondrial membrane lipid also was oxidized and mitochondrial protein was degraded [41,42]. Under heat stress condition, free radicals activated the intrinsic apoptotic signaling pathway based on the mitochondrial pathway of mitochondrial membrane [43], once released, the cytochrome c moved to the cell fluid, activating the effective factor of apoptosis proteins (called apoptosis protease), resulting in programmed cell apoptosis. Although cell function and protein synthesis were disturbed under heat stress conditions, heat stress proteins synthesis were stimulated, including HSP 110, HSP 100, HSP 90, HSP70, HSP 60, HSP 40 and HSP 10. As heat stress proteins acted as molecular chaperone and contributed to the protein synthesis, folding, assembly, transportation and degradation of thermal stress degradation [44]. Among these heat stress proteins, HSP70 and HSP
90 were the most important [45]. Shi [8] also found that heat stress increased the expression of HSP70 gene in pig muscle. Heat stress damaged many proteins, while heat stress proteins helped to repair them. Heat stress also influenced the fluidity and stability of the cell membrane and inhibited the function of transporter protein [46] on the cell membrane. When the ambient temperature elevated from 25°C to 35°C or above, heat stress activated sphingomyelinase, phosphatase and phosphatidylinositol phosphate kinase [47], stimulating the accumulation of phosphatidic acid (PA) and phosphatidyl inositol (bisphosphate (PIP2)). PIP2 is a signal molecule of fat, which delayed the activation of upstream signal of cell repair function. Under heat stress condition, the structure of the lipid material is decomposed to produce PA [48], which inserted into different cell membrane sites and decreased the cell membrane fluidity. The concentration of Ca2+, Na+ and K+ ions in the cells also increased with the decrease of cell stability [49] and destroy of the ion channels.

**Nutritional regulation of improving meat quality**

**Protein and amino acids regulation:** Under high temperature condition, decreasing dietary protein levels with balanced amino acids was one of the important methods alleviating the heat stress to pig, which did not reduce the pig net energy intake and production performance. Stahly et al. [50] reported that supplementation of synthetic lysine instead of natural protein in favor of pig production performance. Le Bellego et al. [51] reported that decreasing the dietary protein level of growing pigs and finishing pigs under high temperature condition reduced the pig protein deposition, but fed low protein level diet with balanced ideal amino acid pattern didn’t affect pig growth performance and carcass traits. Peng et al. [52] concluded (according to current literature review) that the appropriate dietary protein level of growing pigs under high temperature conditions was from 14% to 16%, with the equilibrium model of amino acid lysine, threonine, methionine, tyrosine, isoleucine, leucine, valine to dietary ratio was 1.02%, 0.74%, 0.29%, 0.23%, 0.85%, 1.62% and 0.96% respectively; the appropriate dietary protein level of growing pigs under high temperature conditions was from 12% to 13%, with the equilibrium model of amino acid lysine, threonine, methionine, tyrosine, isoleucine, leucine, valine to dietary ratio was 0.84%, 0.58%, 0.27%, 0.17%, 0.53%, 1.09% and 0.66%.

**Supplementation with anti-stress agents**

**Supplementation with vitamin C, vitamin E or niacin:** Pigs were nervous and their glucocorticoid secretion increased under heat stress condition, supplementation with vitamin C reduced glucocorticoid secretion and improved the ability to resist stress of pigs. Frei et al. [47] reported that vitamin C effectively resisted the active oxygen free radicals and prevented the damage of the biological membrane from the oxides. Vitamin C also was the most important antioxidants and improved the meat quality of pigs [54]. In order to reduce the occurrence of PSE meat, the content of vitamin C in the diet should be more than 50 mg/kg. Vitamin E played an important role in the stability of lipid, improving pork color and reducing water loss of pork [55,56]. Cheah et al. [57] showed that when vitamin E in the pig diet was higher than 500 mg/kg, it significantly decreased the drip loss of meat; when vitamin E was above 1000 mg/kg, the release of Ca2+ and the occurrence of PSE meat were significantly decreased. Buckley et al. [58] reported that dietary vitamin E increased from 10 mg/kg to 100-200 mg/kg, the quality of pork was positively correlated with the dose of vitamin E. Real et al. [59] reported that Niacin increased the pH value, reduced the drip loss and L value of longissimus muscle.

**Regulation of electrolytes:** The potassium and carbonate excretion increased, and the sodium and hydrogen discharge decreased in pigs under high temperature condition, which affected the mineral balance. Potassium chloride, chloride or sodium bicarbonate electrolyte should be added to the pig diets appropriately to reduce the damage caused by heat stress [60]. Supplementation of 0.1 to 0.2% sodium bicarbonate or 0.1 to 0.2% vitamin E to the pig diets had good effect on preventing heat stress. Wu et al. [61] found that compared with the control (under the heat stress condition), the average daily weight gain of pigs who drinking the electrolyte solution containing sugar (containing sugar, sodium chloride, potassium chloride, sodium bicarbonate, citric acid et al.) was significantly increased by 15.64%. Feng et al. [62] reported that the average daily gain of pigs was significantly increased by 5% with supplementation of 0.3% sodium bicarbonate, 0.2% potassium chloride and 0.02% chromium nitocinate respectively to the diets of finishing pigs under the high temperature condition. Ao et al. [63] reported that in the summer heat stress conditions, the average daily feed intake of finishing pigs who drinking 2% electrolyte balance agent at the first 5 days and drinking 1.25% electrolyte balance agent at the last 25 days increased by 10.14%, the average daily gain increased by 95 g and feed gain ratio decrease by 9 %, and there were no obvious thermal stress clinical indications of the pigs.

**Supplementation with trace elements or minerals:** Zhang et al. [64] supplemented 300 g/kg chromium picolinate to the diets of pigs under high temperature condition, the average daily gain and average daily feed intake was not different from the control group at the first two weeks; while the average daily feed intake increased by 10.2%, the average daily gain increased by 38.1% at the last 2 weeks, the chromium metabolism also was improved. Wang [65] reported that supplementation of 530 mg/kg zinc methionine and 200 mg/kg pyridine chromium carboxylate to pig diets increased the average daily feed intake and the average daily gain and decreased the feed gain ratio under the high temperature condition, increased the protein decomposition and gluconeogenesis, and improved the production performance. Liu et al. [66] reported that selenium (Se) had a synergistic effect with CAT and SOD in the removal of lipid peroxide, it also played antioxidant role coordinated with vitamin E. Mahan et al. [67] reported that the drip loss of dorsal muscle decreased by supplementation with 0.1 mg/kg Se and a certain amount of VE and VC. Torrent [68] reported that 0.3 mg/kg selenium (Se) in the growing pig diet reduced the occurrence of PSE meat. Alonso et al. [69] found that high level of magnesium (Mg) increased the pH value and decreased the speed of the glycolgen, slow down the pH value and reduced the occurrence of PSE meat. Peeters et al. [70] reported that supplementation with Mg reduced stress, improved the muscle system hydraulic. Manganese also improved the meat quality of pigs.

To sum up, the production performance of pigs is affected by the reduction of feed intake, which is caused by the influence of the pig’s nervous system under heat stress condition. The synthesis of protein, fat and carbohydrate also is affected by the heat stress. Under heat stress condition, pigs how to re-balance the protein, fat and carbohydrate metabolism to adapt the environment need to be further studied. In addition, heat stress affects the body’s antioxidant system directly through the ROS, leading to the damage of cell function and decrease of the meat quality, but till now, there are no reports about the relationship between the environment temperature and PSE meat formation. Whether high temperature causing PSE meat just through ROS production also need to be further researched. Nutrients adjustment can reduce heat stress, slow down the oxidation and improve pork quality, which is also important for human health. In
the further, more effective anti-heat stress additives need to develop to meet the need of pig production.

Acknowledgments

This work was supported by grants from Key project of Guangdong Province Natural Science Foundation (2014A030311010), the earmarked fund for Modern Agro-industry Technology Research System (CARS-36), the National ‘973’ Project of China (2012CB124706-4, 5).

References


